THE COUPLING OF CLIMATE AND ECONOMIC DYNAMICS

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THE COUPLING OF CLIMATE AND ECONOMIC DYNAMICS

Essays on Integrated Assessment

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This book is dedicated
to our grand-grand
children, not yet born
but who will see the
impact of climate
change.

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Preface

When the guest editors asked me to write a preface to this book, I immediately presumed they did so because of my double experience as a modeller and as a participant to climate negotiations from Kyoto to Marrakech. They know that the latter experience left me in an ironic mood concerning the contribution an economist can make to "real" policy making. They also know that this skepticism, far from leading me to conclude that any modelling effort were in vain, did reinforce my belief that, without such efforts, the chances of a viable governance of global environment affairs would be even more slim. I would like to explain why in the following lines, and, hopefully, convince some mature scientists and young students in search of intellectually attractive and socially relevant scientific ventures to join the pioneer community of "integrated assessment" of which this collection of essays gives a very representative sample.

Even though the use of models to integrate information coming from various fields of science is not new[1] (One may trace it back at least to the Meadows report to the Club of Rome as early as 1971), its acceptance by specialists from various scientific disciplines, including economists, remained for a long time problematic. One of the first formal references conceded to the concept of integrated model on a scientific arena can be precisely dated; it was in Chapter 10, written under the coordination of John Weyant, in the second assessment report of the IPCC. This timing is not incidental. Up to the middle of the nineties, the intellectual division of labor in climate affairs was simple: let climatologists show how a given GHGs emission scenario results in observed GHGs concentrations levels and temperature increases, let economists scrutinize the best policy to minimize the costs of meeting given emissions constraints at a given point in time (as illustrated by A. Bernard et al. in Chapter 11 of the book), and let policy-makers select the appropriate targets on the basis of ethical and political judgments about the precautionary principle and about the social acceptability of various policy-mixes. In this intellectual setting, an integrated assessment of climate policies did not require any "integrated model". Things started changing when it became obvious that this division of labor could not really tackle the UNFCCC ultimate objective[2] which presumes that one is able

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[1] Meadows D.H., Meadows D.L., Randers J, Behrens WW, Limits to Growth MIT Press.

[2] UNFCCC, Convention on Climate Change, 1992, art. 2.

to assess the greenhouse gas concentrations in the atmosphere "that would prevent dangerous anthropogenic interference with the climate system."

The very fact that this objective was worded in terms of long run concentration ceilings and not in terms of emissions constraints at a given point in time, forced a debate about the appropriate timing of action: to stay below an agreed-upon concentration level, should we curb emissions now at the risk of prematurely decommissioning productive capital stocks, or at a later date and so benefit from technical progress on carbon saving technologies but at a risk of a too much delayed action? This "when flexibility" debate could not be conducted without balancing the dynamics of carbon accumulation in the atmosphere and the dynamics of decarbonization of the economy. In view of the discussions about the Kyoto targets, it motivated the first essays of integration of economic analysis and climate science, sometimes without an underlying formal model such as Wigley et al. in Nature[3] (1997) sometimes through the use of reduced forms of carbon cycle models in optimal control models[4].

But, as correctly anticipated by Nordhaus[5] in his Dice model the need for a deeper integration of climate science and economic analysis increased markedly after "Kyoto". It became obvious that fixing the future targets and timetables of decarbonization could not be done without providing some scientific basis to overcome the tensions between those quarters of public opinion who demand drastic objectives and those who are skeptical about the reality of the dangers of climate change. This definitely opened a new research agenda since assessing climate damages implies "closing the loop" between climate models, impact models and economic models.

This agenda represents an exciting challenge for scientists because of the unprecedented time horizon and the amount of uncertainty to be considered, the controversial character of scientific information and ethical judgments invoked in policy debates, the necessary link between long-term growth models, demographic models and models of many fields of activity such as energy, transportation or agriculture, the coupling of economic models with models of natural and man-made environment at various levels of spatial analysis. Chapter 1 of the book (Edwards et al.) shows the many facets of this agenda and delineates the methodological challenges posed by endogenizing, in the same modelling framework, both the benefits and costs of climate change and of climate policies: models of intermediate complexity, control of oscillations and the instability generated by the feedbacks between systems characterized by different inertia, trade-offs between adaptation and mitigation, problems of in-

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[3] Wigley, T.M.L., et al., 1996, Economic and Environmental choices in the stabilization of atmospheric CO2 concentrations", Nature, 379, 240-243.

[4] Ha-Duong, M. et al., 1997, "Influence socioeconomic inertia and uncertainty on optilmal CO2-emission abatement", Nature, 390, 270-274; Hammit, J.K., et al., 1992, "A sequential-decision strategy for abating climate change, Nature, 357, 315-318; Ambrosi P. et al., 2003, "Optimal control models and elicitation of attitudes towards climate damages". Environmental Modeling and Assessment, 8, 133-147.

[5] Nordhaus W. Managing the Global Commons, MIT Press, 1994.

tergenerational equity posed by the notion of sustainability, etc. The rest of the book illustrates the rapidity of the progress in addressing some of these challenges; it should be read paying attention to the sensitive issues the authors raise.

In Chapter 2 for example, F.Toth builds on the experience gained from the development of the ICLIPS model to demonstrate how the elaboration of modeling tools and the conduct of numerical experiments should not be separated from the selection of the decision framework one intends to adopt. The "inverse approach" which structures the ICLIPS framework is indeed totally motivated by the adoption of a "tolerable window approach" to evaluate various policy scenarios. This approach, like the "viability theory" proposed by Aubin and Saint-Pierre in Chapter 5 is motivated by the conceptual and technical difficulties of applying directly the conventional "willingness to pay" approach to assess climate damages and also by the necessity to work in a flexible manner at various spatial and time scales. Both essays represent attempts to depart from the conventional cost-benefit framework, with its underlying optimization framework and "moneymetric" assessment of damages.

Conversely other chapters of the book use such a cost-benefit framework and this is a merit of this edition to have collected papers related to approaches often presented as underpinned by opposite philosophies, and so to allow the reader to see the complementary insights they bring. In Chapter 10, Yang et al. describe how epidemiological information and a stock model of air pollution exposure can be inserted in a computable general equilibrium model and show how the assessment of air pollution health effects is very dependent not only upon scientific controversies about epidemiological exposure, but also upon parameters such as the discount rate and the representation of age cohorts. Chapter 13 shows how the economic value of climate impacts on Swiss grassland production which result from a balance between a positive effect of warming on production potential and a negative effect of water shortages, will ultimately depend on the possibility to offset negative effects through irrigation which, in turn, confronts the problems of the competition for water among the different uses and of the volatility of climate signals on irrigation investments.

The more general issue of the sources of non-linearity between a temperature increase, a given set of impacts and the economic damages provoked by these impacts is raised by Dumas and Ha-Duang in Chapter 4 which demonstrates that, in case of an optimal response policy under uncertainty and progressive revelation of information about damages, uncertainty on the scale of damages matter less than uncertainty about the existence of thresholds and non regularities in the aggregate damage functions. If such non regularities occur, the inertia of technical and economic systems would make fast track mitigation and adaptation policies ineffective, which argues in favor of earlier action. This interplay between the pace of damages and inertia constraints impinging on mitigation and adaptation measures is more concretely examined by A. Priceputu and H. Greppin in chapter 14 which provides a framework to assess vulnerability to climate change at the local level and by M. Beniston in chapter 12 which gives an overview of the future of extreme climate events in Switzerland. These chapters show the dangers of the temptation to proceed by averaging in the assessment of damages since significant shifts in extremes at a local scale may be one major source of overall non linearity. They indicate also how long is the road towards integrated models since an ensemble of impact models at various scale levels will have to be mobilized together and linked with climate and economic models.

With a quick glance at chapters 8 (Labriet et al) and 9 (Rafaj et al.), the reader may have the impression that the "toolbox" is available to study the technology choices supporting mitigation strategies. This impression is in part true since, contrary to the question of damage assessments, there is a huge amount of accumulated experience, since the oil shocks, on long run energy models able to describe energy systems with a large degree of technical details; these technology rich models are totally able to address, given engineering information of technology performance and costs, a large class of problems such as the impact of international carbon trading on costs of de-carbonization, the role of the "when flexibility", the robustness of technological pathways to uncertainty. But, the non informed reader should be conscious that this accumulated experience of which these chapters provide a convincing illustration, itself raises new interrogations: How do we integrate the impact of uncertainty about both price signals and technology performance of the technology adoption behaviors? how do we integrate induced technological change and "learning by doing" mechanisms? how do we couple a technology rich analysis with general equilibrium models that use a more metaphorical description of technical choices but capture very important macroeconomic feedbacks? how do we treat, both in the same framework, energy systems and land-use changes since the latter are critical to the understanding of the potential of carbon sequestration or of the use of biofuels?

Thus, both on the side of the benefits and costs of climate policies, all this material illustrates the state of the art and suggests the content of a future research agenda. I am inclined to think that the ultimate aim of this agenda, towards which it should be directed is to put some rationale into policy discussions as concrete and political in nature as those treated by C. Kempfert in Chapter 6 and B. Buchner et al. in Chapter 7, who take the risk of applying sophisticated modelling tools such as game theory to understand the conditions under which a viable international cooperation can emerge around global public goods. The gap is still real between the compact way in which damages and technology are treated in these papers and the amount of details contained or called for in other papers of the book. But this gap, which hopefully will be be bridged progressively, does not prevent us from delivering important policy messages: prospects of future climate damages may not be enough to stabilize large coalitions including developing countries and a framework fostering R&D and technological cooperation may be a pre-condition to viable climate regimes. But, having said to what extent this book illustrates a fascinating research agenda, I cannot refrain from giving some caveats. I experienced indeed how and why the outcomes of the "simple" economic models mobilized during the Kyoto process were misused before the failure at COP6 (Den Haguen 2000). The existence of discrepancies in results, instead of being viewed as a symptom of the intrinsic uncertainties about abatement costs and thus inciting one to build a system more apt to cope with this uncertainty[6], fuelled the self-defeating opposition between two camps: the optimistic ones utilized the lower bound of the evaluations to support constraints on carbon trading in order to force countries to adopt long-term structural measures; the pessimistic ones utilized the upper bound to argue that the Kyoto system was likely to trigger an economic disaster. At the end, discussions were conducted through rhetorics overly dominated by pure political stances and disconnected from the consideration of the consistency between proposals and the real interest of the Party endorsing this proposal. Typical examples were a) the proposal of a concrete ceiling to carbon trading the aim of which was to force the US to abate more GHGs domestically instead of importing carbon allowances and which would have resulted in penalizing primarily Japan and the EU b) the proposal by the US of a loose interpretation of the article 3.4 of the Kyoto Protocol about carbon sequestration while this proposal was far less efficient in terms of cost control than a price-cap on carbon[7]. Now, coupling economic and climatic models implies indeed a level of complexity an order of magnitude higher than the simple economic models used at that time and so we can imagine easily how the integrated assessment research agenda can turn into a dangerous trap.

The polysemous notion of sustainability is generating an important demand of expertise for integrated assessment; but we should seriously take in consideration the old saying that "the Tarpeian Rock is not far from the Capitol". This social demand is indeed driven by often contradictory interpretations of the notion of sustainability. It is expressed by administrations or stakeholders who do not systematically internalize the idea that, in such issues, policy making runs ahead of knowledge. My contention is that this paves the way to risks of both political and scientific disqualification: the permanent gap between the content of the scientific responses and the non-stabilized expectations of the decision-makers may indeed generate either a disconnection between (poorly funded) research and the policy making process or the temptation to depart from strict scientific discipline. The problem is that yielding to such a temptation dramatically opens the way to the intertwined dangers of a strategic use of results conveyed by our models and of disqualification vis-à-vis those specialists of fundamental science who remain skeptical about interdisciplinary efforts.

Why then pursue efforts on integrated assessment modelling? Because of the very nature of the public decision-making problem to be solved. Despite pervad-

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[6] Ghersi, F., Hourcade, J.C., 2003, "Viable responses to the equity-responsibility dilemma: a consequentialist view", Climate Policy, 3S1, S115-S133.

[7] Bodansky, "Bonn voyage. Kyoto's uncertain revival." The National Interest, Fall 2001, 45-55.

ing scientific controversies, despite opposed ethical views and despite conflicts of interests, the double inertia of the "natural machine" and of economic systems and technological change demands to embark almost everybody on board of coordinated policies before one can solve these controversies, opposed value judgments and conflicts of interests. The perception of sustainability issues is mostly determined by the way the warnings from scientific community are conveyed to public opinion and policy-makers by mass media. In this context, uncertainty becomes a strategic space for actors (Allais, 1953) and the outcome of decision processes depends greatly on the capacity of their spokepersons to mobilize alternative scientific theories in support of their position. With no tool to conduct discussions on a rational basis between tenants of opposite views, from the convinced ecologist to the skeptical ecologist (à la Lomborg), the emergence of a management of the "global common" may be paralyzed by a regressum ad infinitum of controversies.

This is why the challenge to be responded to by the integrated assessment community is so important: it will provide rigorous tools that will help to disentangle the many reasons for disagreement (scientific controversies, divergences in ethical judgments, beliefs about economic trends, political judgments about the acceptability of incentive structures), narrowing the disagreements and, when they persist, guaranteeing that compromises are passed between Parties with opposite views but well-informed of their own interest.

To meet this objective, and resist the misuses of its works, this community should definitely pay attention, given the level and nature of these uncertainties and controversies in these matters, not to give the impression of pretending to "tell the truth" about future or even to "reduce the uncertainty" when basic science or the very nature of dynamical systems prevents from doing so. This is a source of tension with the policy-makers who are fond of univocal answers. We have to resist this type of demand. Rather, we have to focus on a) checking the internal consistency of various sets of expectations formed by stakeholders b) sorting out the sources of uncertainty and their interplay, propagation and compensation, and determining which of these uncertainties do really matter for today's decisions.

Thus, integrated assessment models should have as their ambition to play a "Janus role": on one side, they are a knowledge tool providing a communication language amongst scientific disciplines, on the other side they provide a negotiation language conveying to various social groups and decision-makers information about the feedbacks between economy, technology and the earth system and about the long term ultimate consequences of their own world views.

The road is long towards such an objective and poses to scientists involved in the field the challenge of avoiding the risks of the infinity of "futuribles", of virtual worlds generated as in a computer game, by combining ensembles of exogenous assumptions corresponding to the worldviews coexisting around the negotiation table.

One strand of response to this risk lies in the very transparency of modelling techniques. Ultimately integrated models are "meta-models" and the connection between models from various fields can be made either through reduced forms or through direct coupling which requires progress in the numerical control such as demonstrated, through the Oracle method, by C. Beltran et al. in chapter 3. This chapter should not be read as purely technical in nature; it addresses and satisfies a precondition to the credibility of modelling efforts, i.e. transparency and scientific control.

The other strand of response is to upgrade the quality of the economic consistency (set of constraints due to the accounting balances and policy-target imbalances in the economies) and the economic relevance of behavioral equations. Indeed, making explicit the economic background of projections will both narrow the set of relevant "futuribles" and sort out the key parameters determining the differences between the remaining scenarios.

But, ultimately, the response will be in some form of cross-education process between modellers and decision-makers; the very concept of precautionary principle implies that the future is unknown but that we have to reason about the future in order to take in due time the appropriate decisions. This is why integrated models should be understood by users as aiding this type of backward induction exercise consisting of accepting the existence of a large class of long-term futures to determine what set of robust decisions are to be agreed upon over the next few decades. They do not provide answers, they help to better frame the questions.

The "toolbox" is not rich enough to respond totally to this challenge, but tool makers are at work. The current strand of of integrated assessment research makes me think back to the tradition of engineer economists in which A.K. Sen[8] sees one of the origins (with the moral science tripos in the United Kingdom) of modern economic sciences. By 1840, an "ingénieur des canaux"[9] who was a contemporary of Jules Dupuit, the "inventor" of the calculation of social surpluses of investment infrastructures, wrote a report about how to decide whether a road should be built and what amount of subsidy would be legitimate. We can imagine him, without computers, struggling with hand traced abacus and simplifying mathematical formulae to make them operational. Dissatisfied by the result he asked himself the question "shall I abandon making any calculation?" The answer was "No" because "this would leave the legislator defenseless against inopportune political appeals"[10]. Its illusion was to protect an "impavide" decision-maker against these "appeals" through the simple help of economic calculation. But this attitude opened the way, one century later, to powerful instruments of programming and pricing of investment infrastructures

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[8] Sen, On Ethics and Economics, Basil Blackwell, 1987, p. 2.

[9] Literally 'canal enigineer'; this category of engineers, now the "bridges and road engineers" (*Ponts et chaussées*) was in charge of the management of infrastructures (beyond the investment on waterways); it provided and still provides a large number of well-known economists, mostly in public economy (from Jules Dupuit to Roger Guesnerie and Jean Tirole nowadays).

[10] In François Etner, Histoire du calcul économique en France, Economica, Paris, p. 129. The original title of the report is " Du choix faire entre divers projets présentés pour le tracé d'une même route ", Boursy fils, Lyon, 1840.

in various social and institutional contexts. We can hope that the pioneering tribe engaged in integrated assessment modelling will not wait one century to see its contribution to social debates fully recognized, because, as demonstrated in this book, its inventive capacity, technical skills and consciousness of decisional issues are of the utmost quality.

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Foreword

This volume is the result of a comprehensive research effort undertaken under the aegis of the NCCR-"Climate", a Swiss strategic research network launched in 2002 to foster interdisciplinary work on the various facets of the climate change issue. This research has been aimed at the representation in a variety of integrated assessment models of the complex interactions between economic and climate subsystems. It has been made possible by a strong collaborative work within the NCCR-"Climate" and with internationally acclaimed researchers in the field. This diversity of sources is reflected in the topics and the panel of authors who have contributed the fourteen chapters of the book. Our journey will begin with a broad perspective on the *Linking of climate and economic dynamics*, followed by a survey of *Recent achievements and unresolved problems* in the coupling of these two dynamics in Integrated Assessment Models (IAM). The three next chapters present modelling tools used to realize a *Hard coupling between fully fledged economic and climate models*, to represent mathematically the *Concept of viability and its relevance to integrated assessment*, and to deal with *Abrupt stochastic damage functions to analyze climate policy benefits*, respectively. Two chapters are dedicated to *Climate Policy Cooperation Games* and the *Issue linking approach*, where a game theoretic analysis combines with integrated assessment models to define the dividends of cooperation. Two chapters are devoted to the modelling of energy options in multi-region world energy-technology-environment models. The first one presents a *15-region world model* which is used to explore robust energy/technology options for tackling the long term emissions reduction problem. The second one uses a *5-region world model* and focusses on the "learning by doing" phenomenon which characterizes the market penetration of new technologies. The following chapter addresses the interesting linkage that exists between global environmental change and local pollution with its *Health effects.* The analysis is conducted from a computable general equilibrium model. The same type of modelling is used in the next chapter devoted to a *Swiss perspective on carbon tax and international emissions trading.* The last three chapters deal with various aspects of impacts of climate change for Switzerland. An *Overview of extreme climatic events*, the analysis of the *Swiss agriculture in a changing climate* and *Modelling Climate Change impacts & vulnerability in Switzerland* conclude this book.

Therefore, the volume begins with very general modelling issues and converges toward implementation issues, using mostly examples from Switzerland.

We take this opportunity to thank all those who helped us in the preparation of this volume, in particular Prof. M. Beniston who invited us to contribute to the series and the NCCR-"Climate" head-office for the financial support that permitted this endeavor.

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University of Geneva
& Swiss Federal Institute of Technology

Geneva, Switzerland, August 2004

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Chapter 1

LINKING CLIMATE AND ECONOMIC DYNAMICS

Neil Edwards
Hubert Greppin
Alain Haurie
Laurent Viguier

Abstract This chapter presents in a broad perspective the links that exist between climate and economic dynamics. We deal in particular with the interactions and feedbacks that may link these two dynamical systems and with possible approaches to modelling, and ultimately controlling, them in order to reach a sustainable development path. The paper provides a general introduction to the different chapters that constitute the rest of the book.

1. Introduction

In 1896 Arrhenius predicted that CO_2 released by the burning of coal, gas and oil would accumulate in the atmosphere causing a warming of the earth's surface by the greenhouse effect (Arrhenius, 1896). After a further century or so of intensive industrial, technological and scientific development, during which global population has tripled and atmospheric CO_2 has increased by around 25%, it is now recognized that warming induced by greenhouse gas (GHG) emissions has already significantly changed the earth's climate[1], and that further damage to climate is in store (IPCC, 2001). The purely natural dynamics of the climate system are therefore now inexorably linked with those

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[1] In a recent "multiproxy" reconstruction of monthly and seasonal surface temperature fields in Europe the authors conclude that (Luterbacher et al., 2004):

> *500-year continental scale surface temperatures provide evidence of current European climate change...the late 20th- and early 21st-century warmth very likely exceeds that of any time during at least the past 500 years...*

A. Haurie and L. Viguier (eds.), The Coupling of Climate and Economic Dynamics, 1–34.

of the global economy. Indeed, recent research has suggested that measurable human-induced climate change may have started thousands of years earlier (Ruddiman, 2003).

Previous, natural variations of the earth's climate revealed by geological and ice-core records are characterised by vacillation between extensively glaciated ice ages and relatively warm interglacials. The largest amplitude changes are related to continental configuration on 10 to 100 million year timescales, while the last million years or so have been dominated by a 100 000 year cycle of long ice ages and shorter interglacials. The periodicity is related to relatively weak changes in solar insolation resulting from variations in earth's orbit. The effects of these variations are amplified strongly by feedbacks in the natural climate system in ways which are not yet well understood. Across a range of timescales from thousands to 100's of million years, past changes in global temperature have been closely related to changes in CO_2 concentration (Crowley and Berner, 2001, Joos and Prentice, 2004), again for reasons which are not yet well understood. The introduction of anthropogenic forcing has raised the levels of CO_2 higher than at any time in the last 400 000 years, creating a coupled system in which changes in climate may feed back on the socio-economic system causing both monetary losses and almost unquantifiable damage to ecosystems, while climate-induced changes in the economy may feed back on climate change itself. This double interaction between climate and economic systems is sketched in Figure 1.1.

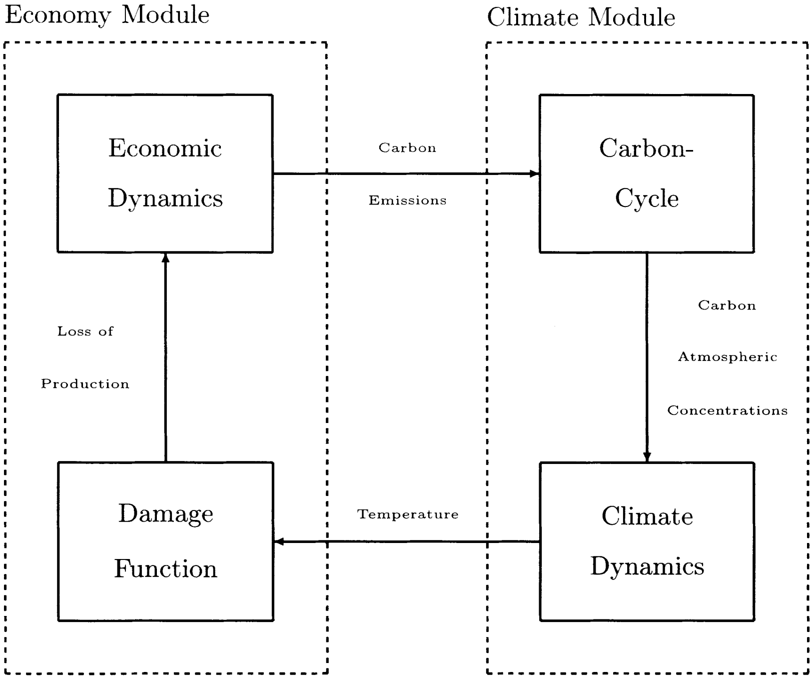

Figure 1.1. Interactions between economic and climate systems

The aim of this chapter is to place in a common perspective those features of climate and economic growth dynamics which may be accessible to joint analysis, in order to better understand the interactions and feedbacks that exist between the two systems, and to identify, in general terms, the type of control that could be exerted in order to maintain a *sustainable* or *viable* development. The chapters of this edited book address in much more detail different particular aspects that are only sketched in this introductory essay.

The chapter is organized as follows: in section 2 we provide a broad view of the fundamentals of climate dynamics with a particular focus on those features which are, or may be, accessible to integrated assessments, including the representation of the carbon cycle which controls the concentration of CO_2 in the atmosphere which is the most important anthropogenic GHG. In section 3 we analyze climate change in terms of impacts and damages and we relate these issues to the concepts of *sustainability* and *viability*. In sections 4 and 5 we study the drivers of economic growth in the historical period 1750-1990; we show the relative influences of demography, technical progress, energy use, trade and development in the economic growth process and the consequence in terms of increase of GHG emissions.

2. Climate dynamics

As mentioned in the introduction, the dynamics of the natural climate system, which have included large and rapid warming events between glacial and interglacial states, are far from well understood. These dynamics are principally driven by incoming short-wave radiative energy from the sun (some of which is reflected back to space) amplified by the greenhouse effect of atmospheric gases, in which the wavelength and energy of the compensating outgoing long-wave radiation is largely set by the very cold, upper levels of the atmosphere. The more energetic long-wave radiation emitted by the warmer surface is effectively trapped inside the "greenhouse". The sun's energy drives complex motions in the atmosphere and oceans, which interact with the land and ocean bio- and cryospheres via exchanges of heat, water, carbon and trace elements on a wide variety of timescales.

Many or all of these active processes are affected by global warming, and of relevance to human well-being and economic activity. An essential parameter in modelling climate change and its economic impact is the so-called climate sensitivity which describes the average surface temperature rise triggered by a doubling of atmospheric CO_2 from preindustrial levels. This parameter is not "well constrained" in the parlance of climate modellers[2]. The situation is the same for the radiative forcing due to aerosols which could have an important mitigating effect in the short-term, potentially leading to an underestimate of the effects of CO_2 -induced warming. Overall, this leads to large uncertainties in global warming simulations. A particularly thorny issue is the response of

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[2] A range of 1.5^o-4.5^o is tentatively proposed by IPCC.

clouds, as an increase in high cloud amplifies the greenhouse effect, but low cloud can have the opposite effect, by reflecting short-wave radiation before it reaches the surface.

The rational approach to the quantitative assessment of uncertainty is to perform large ensembles of simulations (Knutti et al., 2002), but this is not possible with detailed models, as discussed later, and furthermore the statistical analysis is not trivial (Rougier, 2004). To render this hugely complex problem tractible, the simplest possible approach is to reduce the problem to the most fundamental and important quantities, namely the global average surface air temperature and the atmospheric concentration of CO_2 . Below we give a brief introduction to the carbon cycle that controls the accumulation of CO_2 in the atmosphere, then consider various models of GHG-induced climate change used for integrated assessments, starting with the simplest models which represent the global carbon cycle by a single equation. Radiative forcing of the atmosphere is then assumed to depend logarithmically on CO_2 concentration.

2.1 A brief introduction to the carbon cycle

Atmospheric CO_2 concentrations evolve according to complex dynamics describing the biogeochemical *carbon cycle*, which itself interacts very strongly with the other components of the climate system including the circulation and the *hydrological cycle*[3]. In Table 1.1[4] we can see the relative importance of the different mineral and organic carbon pools on earth. Atmospheric CO_2 is exchanged with the oceans and terrestrial ecosystems. As the total dissolved inorganic carbon in the ocean is 50 times that of the atmosphere, we can say that in the very long run (time scale of millennia) the oceans determine atmospheric CO_2 not vice versa. The situation is the same for temperature due to the very high ratio of the oceanic heat capacity compared to that of the atmosphere. Atmospheric CO_2 variations are regulated by several negative (stabilizing) feedback processes, and amplified by further, positive (destabilizing) feedback processes. Some of the negative feedbacks may be weakened or reversed in sign by global warming. The principal CO_2 feedback processes and mechanisms are (Falkowski et al., 2000):

Surface ocean uptake. This amounts to 90 Gt of carbon per year. When dissolved CO_2 forms bicarbonate that will be buffered at a rate which is much slower than the rate of anthropogenic CO_2 emissions. So in the very long run the ability of the surface ocean to absorb CO_2 will decrease. Ocean carbon uptake is driven by two processes, referred to as the solubility and biological "pumps".

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[3] Which includes the role of clouds and ice, including sea ice.

[4] Partly reproduced from Falkowski et al., 2000. Note that the figures quoted are estimates and may be affected by climate change.

Table 1.1. Carbon pools in the major reservoirs on earth

Pools	Gt	Residence Time
Atmosphere	760	< 10 yr
Oceans	38,400	
upper part	670	$10\text{-}10^2$ yr
deep layer	36,730	$10^3\text{-}10^4$ yr
Lithosphere	$> 60{,}000{,}000$	$10^6\text{-}10^8$ yr
Terrestrial biosphere	2,000	
living biomass	800	$1\text{-}10^2$ yr
organic dead biomass	1200	$1\text{-}10^3$ yr
Fossil fuels	4,130	

The solubility pump. CO_2 is more soluble in colder water, so the strength of this process depends on the formation of cold, dense water which sinks into the ocean interior, removing excess carbon. Models suggest a weakening of the circulation which drives this process. Warmer surface waters would add to this effect, reducing the efficiency of the pump, and giving a positive feedback on atmospheric CO_2 .

The biological pump. Phytoplankton organic photosynthesis[5] contributes to the absorption of CO_2 from the atmosphere. The resulting organic detritus and inorganic shell material is partially recycled by other organisms, but some (around 25%) sinks into the interior. This biological pump depends on complex biological, chemical and physical processes and interactions, including the supply of nutrients[6] from the deep and via wind-blown and riverine input. The biological pump can be decomposed further into the organic, or "soft", and carbonate, or "hard", biological pumps. Its behavior is hard to predict with confidence.

Deep ocean uptake. Carbon is exchanged between surface and deep ocean reservoirs by circulation, mixing and sedimentation. Largely due to variations in temperature and pressure, ocean carbon concentration increases rapidly with depth. On very long (10^3 to 10^4-year) timescales deep-ocean carbonate can precipitate[7], adding to seafloor sediment, to buffer CO_2 increase.

Terrestrial carbon uptake. Terrestrial ecosystems exchange CO_2 rapidly with the atmosphere. CO_2 is stored in living and dead organic matter and is returned to the atmosphere through different atmospheric pathways

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[5] 40% of total photosynthesis.

[6] N,P,S and oligo-elements such as Fe

[7] $Ca^{2+}_{aq} + CO^{2-}_{3aq} \rightleftharpoons CaCO_{3\text{solid}}$.

(respiration, fermentation, production of volatile compounds, etc). Carbon storage occurs primarily in forests[8]. The turnover time of terrestrial carbon is on the order of decades[9]. A negative feedback exists at present as increased CO_2 concentrations lead to higher forest production. Increased respiration could lead to a sign reversal of the feedback beyond some "optimal" state (Ramade, 2002).

Other biogeochemical cycles. The carbon cycle interacts with other biogeochemical cycles. N, P, S, oligo-elements, and eolian iron fluxes all influence CO_2 uptake. Iron fluxes have been implicated in paleoclimate variability, and as a mechanism for macro-technological mitigation.

Other interactions and feedbacks. The strong reflectivity (albedo) of snow and ice-covered surfaces induces a strong positive feedback on temperature changes, reflecting more solar energy back to space in colder conditions. Climatic change in peat and permafrost regions can lead to methane and CO_2 release and consequently feed back on global warming. Another very important feedback is due to water vapor which is the most important GHG: due to greenhouse warming more water evaporates and so the concentration of GHGs increases. However, as noted earlier, this effect can be counteracted by increased cloud reflectivity. Ultimately the Venus syndrome illustrates an amplification of the greenhouse effect due to CO_2 where most of the water is in the atmosphere[10] and the greenhouse effect is extreme (740 K; GHG-coeff[11]= 2.2). The paleoclimate record tends to show that despite the positive feedbacks the evolution of the climate system has allowed living species to remain in a "viability envelope" through a continuous evolutive adaptation. The anthropogenic CO_2 and its speed of accumulation in the atmosphere introduce a new element in the natural regulation of the climate system[12] and this could prove to be the most destabilizing interaction between a living species and the climate system yet seen. In summary[13]:

> *[although]...on geological time scales the anthropogenic emissions of CO_2 is a transient phenomenon... there is no natural savior waiting to assimilate all the anthropogenic CO_2 in the coming century... Potential remediation[14] strategies... are being seriously considered...*

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[8] Approximately 2/3 of photosynthesis on emerged surfaces.

[9] It is longer for the soil organic dead biomass.

[10] Decomposed in H_2SO_4, etc.

[11] The GHG-coeff. gives the ratio between absolute temperatures with and without GHG effect.

[12] One may consider that this regulation has been effective for 3.8×10^9 years.

[13] Again quoting Falkowski et al., 2000.

[14] Potential direct remediation strategies mean purposeful manipulation of biological or chemical processes to accelerate the sequestration of atmospheric CO_2. Because of the imprecise knowledge of these mechanisms these manipulations could have unpredicted consequences and should be assessed with caution.

2.2 The carbon cycle in integrated assessment models

A variety of models have been proposed to represent carbon cycle dynamics in Integrated Assessment Models (IAMs). J.A. Viecelli proposed a single-equation model in which atmospheric emissions are buffered by a deep-ocean reservoir, which is assumed to have infinite capacity (Enting et al., 1994). The DICE-94 model (Nordhaus, 1994) used an equivalent formulation but with altered coefficients. With these specifications, a steady-state concentration level is approached asymptotically for any constant emission level. Radiative forcing of the atmosphere is then assumed to depend logarithmically on CO_2 concentration. In the DICE-99 version of the IAM developed by W. Nordhaus (Nordhaus and Boyer, 2000) a three-reservoir model is used to represent the exchanges that take place between the atmosphere, the upper layer and the deep layer of the ocean. In contrast to DICE-94, this model does not allow for removal of carbon from any of the three reservoirs. The long-term asymptotic behavior is therefore a steadily increasing atmospheric concentration for any non-zero emission rate. However, even though it predicts a constant asymptotic growth of CO_2 concentrations for any sustained emission rate, CO_2 concentrations in DICE-99 can be stabilized in the case of a steadily decreasing emissions rate.

ICLIPS (Füssel and Klein, 2004; Toth et al., 2003a; Toth et al., 2003b) is a much more complex IAM which has been well received by the scientific community. The model has a description of the carbon cycle with 4 reservoirs in the atmosphere and the ocean and two reservoirs in the biosphere. This model has been developed by the Max Plank Institute. The ICLIPS carbon cycle model predicts a slower growth of the atmospheric CO_2 concentration than DICE-99, although it also predicts an asymptotic sustained growth for any constant emissions level. It also suggests that, at a millennium time scale, reducing the emissions to a level of 2 GtC per year will tend to stabilize atmospheric carbon concentrations around 800 GtC.

The carbon cycle is only crudely represented by simple systems of a few differential equations. Generally, climate models divide the climate system into a grid of discrete spatial cells to represent spatial variation of properties. To each averaged property within each cell will typically be associated one differential equation describing the temporal variation of the property. The larger the number of cells the more accurate the representation but also the greater the complexity and the computational cost of the model. We discuss more complex models with thousands or millions of cells (and equations) below.

2.3 Models of intermediate complexity

One of the most fundamental properties of the climate system is the circulation of the atmosphere and oceans. Differential heating and cooling, complex topography and, in particular, the rotation of the earth, make these circulations intrinsically three dimensional and highly complex. The vast range of spatial scales of these circulations is associated with a vast range of timescales from minutes to millenia, while the details of the circulation strongly affect all other properties of the climate system. For this reason, physical climatological research is focused on General Circulation Models (GCMs) that resolve these 3-D flows. So far, IAMs have only used the results of high-resolution 3-D GCMs in parameterized form. The ICLIPS model, for instance, uses impulse response functions and scaled spatio-temporal patterns (EOFs) from two different GCMs. Such derived parameterizations are severely limited in their application. They may be accurate for short-term changes, but nonlinear changes involving significantly altered circulation states may lie outside their range of validity, while their representation of dynamical feedbacks is limited.

Here we explicitly make the distinction between high-resolution atmosphere-ocean (AO) GCMs such as HadCM3 (Gordon et al., 2000) and Earth System Models of Intermediate Complexity, or EMICs. Models in the latter category may also technically include 3-D models of the general circulation of the ocean (C-GOLDSTEIN (Edwards and Marsh, 2004) and UVic (Weaver et al., 2001)) or atmosphere or both (ECBILT-CLIO (Goosse et al., 2001)), although the term GCM is often assumed to refer exclusively to high-resolution models. EMICs typically have lower spatial resolution, and are often dynamically simplified as well neglecting, for example, dynamical atmospheric processes (Edwards and Marsh, 2004). The number of spatial cells in C-GOLDSTEIN is around 10^4 whereas high-resolution GCMs have millions of cells. The principal advantage of EMICs is computational efficiency: the integration speed of extant EMICs ranges from minutes (Bern 2.5-D model Knutti et al., 2002) to days (UVic model) or weeks (ECBILT-CLIO), for a 1000-year simulation, but high-resolution AOGCM integrations of this length would typically take months.

Clearly, the continued development of more efficient and faithful EMICs offers great potential to improve the representation of climate in IAMs. A thorough review of the issues and challenges of integrated assessments, and of the state of the art in extant models, as represented by ICLIPS, is given by Ferenc Toth in the next Chapter of this volume. This is a rapidly developing field, however, and in Chapter 3 of this book, an indication of possible future developments in IAMs is given by the demonstration that an EMIC with fully 3-D ocean circulation (in this case C-GOLDSTEIN) can be incorporated effectively into an IAM with two-way coupling between climate and economic models (in this case a version of DICE). Although this is a prototypical example, the potential implications are clear. With a 3-D ocean, the earth's surface, where climate-economic interaction is localized, becomes fully two dimensional, creating the possibility for a fully regional representation of interactions.

Against the obvious limitations of detail inherent to EMICs, the label Earth System Model, or ESM, carries the implication that such models often include representations of processes which are not always included in high-resolution GCMs such as ocean biogeochemistry and sedimentation, ice-sheet dynamics and dynamical land-surface processes. These may be highly relevant to IAMs. For instance melting of the Greenland ice sheet in the long term may be irreversible (Toniazzo et al., 2004) while HadCM3 simulations including a dynamical land-surface scheme have indicated the possibility of Amazonian deforestation (Cowling et al., 2004). The 2003 summer drought, which had severe socio-economic consequences, was strongly amplified by short-term soil moisture effects[15], while the long-term fate of excess carbon in the climate system is effectively controlled by ocean biogeochemistry.

Efficient climate models, or EMICs, thus offer the possibility of inclusion of important processes, regional impacts, and circulation effects, at a computational cost which is within the range of useful IAMs. The evolution of certain types of extreme events such as a collapse of the North Atlantic ocean circulation, can be directly calculated when the circulation is represented. The analysis of such catastrophic events can lead to much more cautious policy recommendations (Wright and Erickson, 2003). Another very important potential application of efficient models is the calculation of uncertainties via large ensembles of runs (Hargreaves et al., 2004). In contrast, the computational cost of high-resolution GCMs makes it extremely difficult to assess the uncertainties associated with their forecasts.

2.4 Climate-economy feedbacks

The justification for building integrated models of climate and economic dynamics, beyond the convenience of joint analysis and presentation, is the possibility of representing feedbacks between the two systems. Economic development is a principal driver of climate change, thus the effects of climate change on the economy, such as enhanced damages from droughts and floods, represent a feedback on the economy. If the effects of climate on the economy lead directly, or indirectly via policy, to changes in climatic forcing factors such as GHG emissions, then this represents a feedback of the economy on the climate. Land-use changes represent another area of potentially important feedback on climate via changes in surface reflectivity (albedo) and soil moisture content. Such feedbacks typically involve delays across a wide range of timescales, one of the major challenges of integrated modelling (Toth, 2004). Global warming related to GHG emissions will take hundreds or thousands of years to fully take effect due to the inertia of the ocean circulation and ocean carbon cycle, whereas inertia in the socio-economic system is also important on short timescales. On the other hand the economic system will respond to scientific projections of future climate change, inducing what is technically a negative delay. This effect may be difficult to incorporate in a pure simulation IAM (i.e. a pure initial-value problem), but be overestimated in an optimization model such as DICE which assumes perfect foreknowledge.

In a general system, strong delays and feedbacks may cause oscillations, or in the case of over-reaction, (oscillatory) instability. It is therefore of interest to ask what the strengths of the feedbacks between climate and economy may be.

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[15] As noted by Schär et al., 2004.

This is not necessarily an easy question to formulate. Feedbacks in the climate system are often represented in a simplified control-theoretic form as a parallel series of gains (Peixoto and Oort, 1992) but such an analysis may involve an unphysical separation of processes and an inherent assumption of linearity. Moreover, the strength of a feedback is always a function of the timescale of the perturbation considered. As an example, we consider a modification of the prototype IAM described in this book (Drouet et al., 2004) in which the economy and climate are linked in cost-benefit mode (Drouet et al., 2005) and attempt to calculate the strength of the feedback of economy on climate. One measure of this strength is a comparison of the behavior of the climate model forced by an uncoupled DICE emissions scenario, with the behavior of the climate model in the fully coupled optimal solution. However, this difference is not necessarily equivalent to the strength of the feedback in the coupled system.

To arrive at the latter we consider the effect of an exogenous addition of radiative forcing, in this case by an enhancement of the solar constant (the average solar forcing) by 4 Wm^{-2}. The feedback strength will be the degree of reduction of this exogenous forcing by the coupled system. compared with the effect of such an additional forcing on the uncoupled climate (given the emissions relating to the unperturbed coupled solution). The feedback strength is a function of timescale, but we can at least calculate it for a given perturbation, initially an impulsive change in solar forcing. The result is shown in Figure 1.2. The increase in solar forcing leads to a significant, additional warming of around 0.4 C, which is reduced by the response of the economy. This reduction is delayed, and at 200 years amounts to about 0.04 C, or a 10% reduction of the net additional warming.

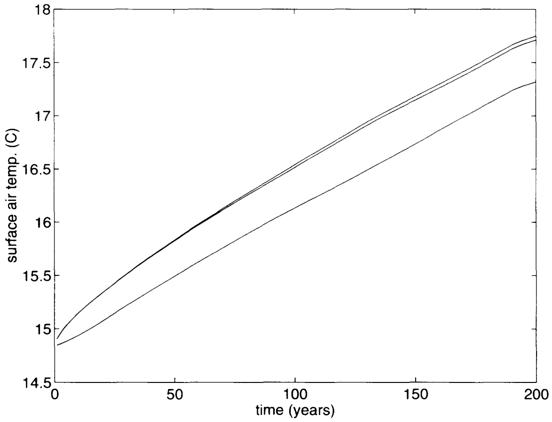

Figure 1.2. The effect of the feedback of economy on climate in the IAM of Drouet et al., 2005. The lower line is the unperturbed solution of the cost-benefit optimization, the middle line is the solution under perturbed forcing (increased solar constant), the uppermost line is the response to perturbed forcing of climate with no feedback from economy to climate. The feedback reduces the warming by 10% at 200 years.

2.5 Asymptotic goals for climate change control

Investigating policy options consistent with acceptable sustainability is the main motivation for integrated assessment modelling. Figure 1.3, reproduced from Edwards and Marsh, 2004, shows the response of an ensemble of runs of the EMIC C-GOLDSTEIN to a single, illustrative scenario in which CO_2 equivalent GHG concentrations in the atmosphere increase at a constant rate of 1% per year for 100 years then remain constant. The figure shows the mean surface air temperature (SAT) for the forced warming period and for the following 1000 years. The spread is due to uncertainty in model parameters. Of interest is the increase of SAT after model year 2100 when GHG concentration is held constant. The implication of this increase is that realistic analysis of sustainability will have to reckon with continued increases in global temperature, and associated increasing global change, resulting from inertia in the physical system. In this particular model ensemble experiment, the increase in SAT in the 200 years immediately following the cessation of emissions is around 1/2 degree C per hundred years. Changes of a similar order are believed to have occurred during the last 500 years (Luterbacher et al., 2004) but future changes will take place in the context of a previously unknown, anthropogenically warmed world.

Similar behavior is observed in simulations of global warming using high-resolution GCCMs, as summarized by the IPCC (IPCC, 2001). These models consistently predict a sensible long-term climate impact of anthropogenic CO_2 emissions. We notice that the stabilization scenario (with a target temperature increase of 1.5 degree C) asks for a drastic reduction of CO_2 emissions by the end of the century. This is consistent with the report in Enting et al. where a variety of carbon cycle models have been used to define the evolution of emissions that would lead to a stabilizing of the atmospheric CO_2 concentration; they consistently lead to an asymptotic 2GtC/yr emission rate to be reached by year 2100 (Enting et al., 1994). Results from the full range of available models therefore predict severe climate change in the long run if the CO_2 emissions are not curbed. However the climate system has considerable inertia and, therefore, the current generations will not witness all the impacts of their economic decision to (or not to) curb CO_2 emissions. On the other hand, if GHG emissions continue unabated, the temperature and sea-level changes predicted for the next millennium greatly exceed those of the next hundred years (Hasselman et al., 2003). Over a time horizon of a century, our societies should be able to reduce considerably the yearly emissions of carbon in the atmosphere, probably to a level around 2GtC/y, which is very low in comparison with the current level (around 8 GtC in 2004). In the next section we consider the question of sustainability in more detail from a socio-economic perspective.

3. Sustainability

Anthropogenic climate change is an archetypal issue for sustainable development. In this section we explore the most important linkages that exist between climate and societies. We first revisit the concepts of sustainability and viabil-

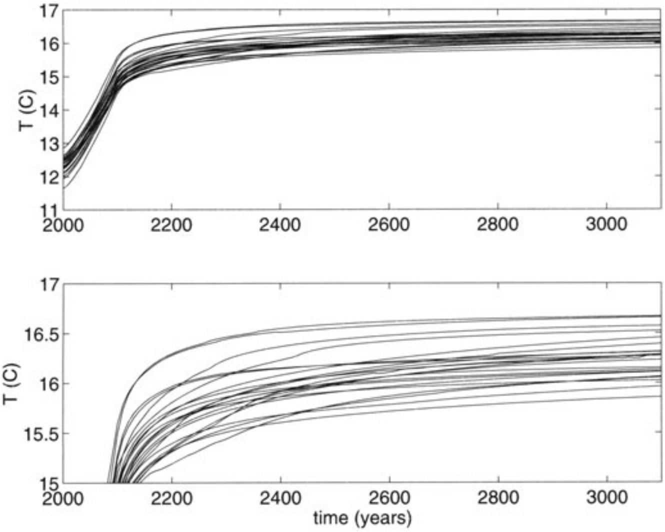

Figure 1.3. Global average surface air temperatures for an ensemble of simulations of the EMIC C-GOLDSTEIN. CO_2 is forced to increase at 1% per year for 100 years then kept constant. The lower panel is an enlargement. The spread is due to uncertainty in model parameters.

ity which propose an analytic framework to study such interactions. We then focus on the impacts that can be expected from climate change and we discuss the relative importance of mitigation and adaptation in the societal response to a climate change threat.

3.1 Sustainability and viability

Sustainable development is generally defined as

> *... paths of social, economic and political progress that meet the needs of the present without compromising or endangering the ability of future generations to meet their own needs.*

This heuristic definition, self-adjusted to human activities, corresponds to an ethical management of the earth resources (responsibility, equity, solidarity between generations or social groups and territories, respect of ecological equilibria, prevention, precaution). This programme is clearly not realized currently in any part of the world. Since paleolithic times a form of "global" sustainability has been achieved at the expense of the transformation or disappearance of "local" cultures and civilizations. Consequently, the biosphere, ecosystems and environment[16] have been modified and this has changed the burden of human

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[16] Biomass, biodiversity, food and other resources, climate, etc.

activity on the local resources. The proposal to implement a global and local sustainability is therefore an ambitious challenge that has never been realized before in human history.

A scientific approach to sustainable development calls for a deep understanding of the structure and dynamics of the *biosphere-society-environment* system. The study of the coupling between climate and economic dynamics is part of this endeavor. The scientific approach should be accompanied by an axiology that will have some effects on cultural values. This would trigger socio-economic actions compatible with a high quality human life in a heterogenous cultural perception by different societies[17]. Deep knowledge of the structure and dynamics of the systems composing the triad *biosphere-society-environment* is necessary for the design of a global management toward real and progressive sustainability during this century. Many indicators or variables have been proposed to describe and analyze the complex socio-economic, environmental and ecological networks that sustain human life and societal organization. Since these variables don't all share the same significance a hierarchy could be made to first identify the most limiting factors for a sustained, secured and robust life viability of human species (and of the rest of the biosphere.) This would define *viability envelopes*[18] which would dictate the long-term mitigation or adaptation absolutely necessary for a sustainability policy at the socio-economic, biosphere and environmental levels. The earlier the detection of such a *hard limit* the lower will be the cost to mitigate or to adapt (Schellnhuber and Wenzel, 1998).

3.2 Climate change impacts

How will the economic system be impacted by climate change? Among the different economic sectors, agriculture is certainly one of the most directly linked with climatic conditions. Other sectors may also suffer from output losses when temperature and precipitations change, and some may gain. We briefly review these impact evaluations.

3.2.1 Agriculture. Since the Neolithic times (10'000 years ago), agricultural activities have been the main factor of economic and social progress in terms of security and organization. Recently, as a result of scientific and industrial progress, this activity has evolved rapidly and has considerably transformed the natural ecosystems and landscape of the world. More than a third of land is utilized for agriculture (47% if we exclude deserts and high altitudes). To sustain the photosynthetic activity agriculture needs large surfaces to access

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[17] From equi-finality to sustainability.

[18] At the limit one could consider viability in a more restricted sense: "alive or dead" for human population and ecosystems. This would correspond to the minimal platform for viability. Some sentinel variables like mean life expectancy, biodiversity , biomass evolution, temperature, water variation, surface concentrations in O_2, CO_2 , CH_4, etc, could be used to delineate these envelopes (Greppin et al., 2002).

light, a considerable flux of water[19], CO_2 , nitrogen, phosphate, sulfate, potassium, etc., as well as a soil of high quality. The influence of climate is therefore significant, and this whatever the state of economic development of the region concerned. Between 1650 and 2000, the world population has increased by 1100%, to reach 6.4×10^9 inhabitants, the agricultural surface has increased by 500% (crop cultures 1.5×10^7 km^2, pastures 3.3×10^7 km^2) and a limit is imposed by the necessity to maintain sufficient forest areas. The decrease in *per capita arable land* has been compensated by a considerable increase of the yield (300 to 600 %). Despite its overall capacity to offer sufficient per capita feeding (4.6 GJ/y/h), a fraction of the population (0.8×10^9 people) remains chronically undernourished and a quarter of the world population is affected by food insecurity even in the absence of climate change.

A great diversity characterizes the importance of the agriculture sector in different countries: from 2 to 40% of GDP, 3 to 70% of working population, consumption of 0.5 to 80% of the natural flux of water. Over the last 40 years irrigation has progressed by 110%, 40% of the crop production comes from the 16% of land which is irrigated, although 64% of crop surfaces are in developing countries where 2/3 of the world population lives with only 1/4 of the annual rainfall. The use of fertilizers and pesticides has considerably increased, accompanied by pollution effects. About 40% of the arable land is degraded to some degree. The mechanization, fertilizer and energy use contribute to GHG forcing. The great sensitivity of the agro-ecosystem to climatic change is amplified by yield management practices and by its insulation from neighbouring ecosystems (Alexandratos, 1995; P.A. Matson, 1997; Reilly and Schimmelpfenning, 1999). Agricultural vulnerability in respect of predicted climate change could be very variable according to the area of the globe that is concerned. Crop cultivation capacity may increase in North America (Alaska, Canada, Eastern USA) and Europe (in particular Russia), as well as in South-East Asia (China, Indonesia), African and South American equatorial regions, and some Eastern regions of South America. The loss could be severe in other regions, especially in developing countries. Agriculture will gain in strategic importance for economic growth, access to territorial space, and the global security of nations (Fisher et al., 2002).

3.2.2 More general impacts.

Other economic sectors than agriculture may be directly affected by climate change: tourism and also energy production are very much climate dependent (heat waves may impact both on electricity demand and power supply[20]). More generally the GHG climate forcing will modify the earth's landscape at all scales (spatial and temporal) as it will change the distribution of dynamic climatic conditions. This will trigger a redistribution of environmental risks such as strong winds, hurricanes, fires,

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[19] Around 700 t of water are necessary to produce 1 t of organic food.

[20] The Summer 2003 heat wave in France triggered a decline in nuclear power supply because of cooling failures. It also triggered a rush to air conditioning and an increase in demand.

floods, drought, desertification, landslides, lightning, ecosystem biotic perturbations by pests and pathogens, etc. All these perturbations have economic consequences.

According to the different scenarios proposed by IPCC (SRES scenarios), and simulated by HadCM3, CSIRO and NCAR, the following changes are possible: in the northern hemisphere the global warming could provoke a northward shift in thermal regime and, as a consequence, a significant reduction (around 60 %) of boreal and arctic ecosystems. A large expansion of temperate climate area in Siberia, Canada and Alaska may occur, accompanied by an extension of the forest fire season in the boreal part (risks of severe forest fires). Soil respiration could be stimulated (GHG source). In the southern hemisphere, however, the temperate zone of Argentina and Chile may disappear almost completely. The subtropical zone would keep its extent. A major expansion may occur in the tropical zone that will cover most of Africa. The diminution of the thermal difference between the poles and the equator would affect the oceanic and continental water balance (evaporation and precipitation zones). A large drying of the extended Mediterranean basin, South Africa and Western Australia, and part of Eastern Brazil and central America may be envisaged. This diminution of precipitation in the intertropical zone would be compensated by more humidity in higher latitudes (Scandinavia for example) and in the Pacific ocean. In general this would result in an increase of arid areas, mostly in developing countries. At a more local scale, the impact of global warming is more uncertain and difficult to predict. The changes in rainfall patterns in addition to shifts in thermal regimes would influence the local, seasonal and annual water balance. Probably in many regions one could observe a change in the frequency of occurrence of extreme events (intensive rainfall, gales, floods, snow-stones-mud avalanches, etc...).

3.3 To mitigate or to adapt?

Given the level of past emissions and the inertia of the climate and economic systems, some degree of climate change cannot be prevented. Adaptation to climate change is therefore an issue (Füssel et al., 2003). There are still divergent views on whether climate change will seriously affect society. Some authors identify a set of fundamental characteristics of natural systems to be taken into consideration to analyze adaptation strategies (Reilly and Schimmelpfenning, 2000). They are: Short-term autonomous flexibility; short-term non-autonomous flexibility; knowledge and capacity to undertake short-term actions; long-term autonomous flexibility; long-term non-autonomous flexibility; and knowledge and capacity to plan for and undertake adaptations that require changes in long-lived assets. Adaptation is certainly a significant societal issue that should be an important part of the climate research agenda in the coming years. We can relate the choice between mitigation and adaptation to the different time scales involved in the dynamics of the climate and economic systems. Climate change is a long lived phenomenon; reducing emissions today will not prevent some warming; therefore the mitigation activities are to be inscribed in a long-term environmental policy. The dynamics of climate change assures that some warming and precipitation changes are already under way and that strong impacts will be effective at the end of the century. So, during this century the economy will have to adapt to the new climatic conditions. Some adaptation decisions will have to be taken on a much shorter time scale, as different societies will sense the changes in climate variables and assess their vulnerability to these changes.

3.4 Sustainability, viability and Intergenerational Equity

The very long time horizon and the slow time scale associated with climate change dynamics offer a new challenge to economists when they try to implement a cost-benefit analysis in the *management of the global commons.* The fundamental question addressed in this analysis is (Chao and Peck, 2000):

> *"How much and who pays"?*

The archetypal cost-benefit analysis model is DICE-94 (Nordhaus, 1994) or its close descendant DICE-99 (Nordhaus and Boyer, 2000). In these models, the driver of the economic systems is the maximization of a discounted sum of the utility derived from consumption; more precisely

$$\max \int_0^\infty e^{-\rho t} L(t) U(c(t))\, dt \tag{1}$$

where ρ is the *pure time preference rate*, $L(t)$ is the population level, and $U(c(t))$ is the utility derived from per-capita consumption level $c(t)$. In the economic growth paradigm the economic output can be used for consumption or capital accumulation. However emissions abatement and climate change both induce a loss of output. The representative economic agents have thus to trade-off consumption today versus investment for consumption tomorrow but also loss of output due to climate change versus loss of output due to abatement. Because these decisions imply a comparison between consuming today and consuming at a future date, the discounting factor $e^{-\rho t}$ is introduced in the criterion. The choice of the parameter ρ has a considerable influence on the asymptotic behavior of the economic growth model. The asymptotic steady states of the DICE-94 model have been compared for values of ρ ranging[21] from 0 to 10 % (Haurie, 2002). The asymptotic level of capital would be 3 times higher in the $\rho = 0$ case than in the 10 % case. The GHG concentrations would be 50 % higher in the 10 % case than in the $\rho = 0$ case. Sustainable consumption will be 10 % higher when $\rho = 0$ than when $\rho = 10$ %. So, in brief, discounting induces a long-term economy which is less equipped, more polluted and which consumes less. This is an illustration of the thorny issue of discounting and

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[21] One can easily overcome the difficulty of dealing with a nonconvergent integral in (1) when $\rho = 0$.

intergenerational equity discussed by a group of eminent economists (Portney and Weyant, 1999). Even though a low discount rate seems more attractive in the long run, no rational economic agent will accept the proposal to base its investment decision on 0-discount rate.

Chichilnisky has introduced an axiomatic for the decision rules that would avoid both *dictatorship of the present* and *dictatorship of the future*[22]. According to this prescription the driver of the economic growth system should take the form

$$\max \left[\beta \int_0^\infty e^{-\rho t} L(t) U(c(t))\, dt + (1-\beta)\Phi(c(\infty)) \right] \tag{2}$$

where $0 \leq \beta \leq 1$ and $\Phi(c(\infty))$ is a utility associated with the very long-term (asymptotic) per-capita consumption rate. However, the use of this criterion would lead to a decision path which is not *time-consistent* (Lecocq, 2000). This criterion will commit forthcoming generations to use a decision criterion which does not correspond to their rate of time preference. A solution to this difficulty has been hinted at by Arrow, 1999 who formulated a noncooperative game among successive generations of economic agents[23]. This idea has been exploited in different articles where intergenerational equity is obtained through the computation of an intergenerational equilibrium, which, by definition does not commit the decisions of forthcoming generations but assumes that they will share the same level of altruism as the current generation (Lecocq, 2000; Haurie, 2003; Haurie, 2005). Also one assumes that the current generation takes into account, in its utility function, the well-being of forthcoming generations[24].

4. Demographics, economic development and GHG emissions

As explained in section 2, the net global GHG emissions to the atmosphere must eventually decline substantially to maintain any stable steady-state atmospheric carbon concentration. To estimate the GHG emissions reduction effort and to assess the associated economic costs, one has first to evaluate the global future GHG emission levels if nothing is done. However this future is highly uncertain (IPCC, 2000). Almost all driving forces are controversial: long-term population growth, economic growth, technological change; fossil-fuel reserves; non-climate environmental policies, etc. The controversy concerns not only the dynamics of each variable, but also their mutual interactions (between economic growth and population; technological change and economic growth; technological change and fossil-fuel reserves, etc.) In this section, we revisit

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[22] See Chichilnisky, 1996 and Chichilnisky et al., 2000.

[23] Arrow referred to a formalism proposed long ago (Phelps and Polak, 1968) to represent selfishness in a multigeneration investment process.

[24] For a more detailed analysis of the technical aspects of these new classes of criteria that have to be introduced when economics has to deal with the very long lived effects of current decisions concerning climate change, see Ambrosi et al., 2003.

the IPCC projections for carbon emissions from fossil fuels[25]. We focus on the key assumptions in GHG emissions for these scenarios and address the uncertainty concerning the main driving forces in the dynamics of carbon emissions. We then compare the IPCC scenarios with historical trends for the 1750-1990 historical period. To decompose the effect of demographic, economic, and technological dynamics and transitions on the evolution of global CO_2 emissions from fossil fuels, we use the Kaya identity[26]. In other words, total world CO_2 emissions at time t depend on per capita emissions and population. In its turn, the per capita CO_2 emission rate can be decomposed into (i) per capita GDP and (ii) CO_2 emissions per unit of GDP (GHG emission/GDP intensity factor). Finally, one can decompose the intensity factor defined as the ratio GHG emission/GDP into two subcomponents (i) the energy/GDP intensity and (ii) the emissions per energy unit that reflects the GHG emission intensity of energy consumption.

4.1 Global CO_2 emissions from fossil fuels

In 1992 the Intergovernmental Panel on Climate Change (IPCC) released six emissions scenarios providing alternative GHG emissions trajectories over the 1990-2100 period (Leggett et al., 1992)[27]. It has been argued that, for the purposes of driving atmospheric climate models, the CO_2 emissions trajectories of the IS92 scenarios provide a reasonable reflection of variations found in the open literature (Alcamo et al., 1995). Other analysts have noted that the IPCC growth assumptions were generally conservative (Eckaus, 1994) and

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[25] In 1992 and 2000 the Intergovernmental Panel on Climate Change (IPCC) released alternative GHG emissions scenarios over the 1990-2100 period (Leggett et al., 1992; IPCC, 2000). These scenarios embodied a wide array of assumptions affecting how future GHG emissions might evolve in the absence of new climate change policies. The different emissions projections reflect contrasted assumptions in terms of economic, social and environmental conditions.

[26] Recall that this identity is based on the following elementary relation:

$$C = \frac{C}{E}\frac{E}{Y}\frac{Y}{P}P \tag{3}$$

where C, E, Y, P stand for world CO_2 emissions from fossil fuels in metric tons of carbon, final energy consumption in tons of oil equivalent, GDP in 1990 U.S. dollars, and population, respectively. Data on C are based on United Nations estimates of national energy consumptions (Marland et al., 1999). Data on P and E are from the International Energy Agency (IEA/OECD) and other studies (Kremer, 1993; Darmstadter, 1971; Etemad et al., 1991). Data on Y are real GDP for the world at purchasing power parity estimates in 1990 international dollars (Maddison, 1995).

[27] The IPCC scenario "IS92a" represented an average situation with medium population and economic growth, and access to a mix of conventional and renewable energy sources. The highest carbon emissions IPCC scenario "IS92e" used, among other assumptions, moderate population growth, high economic growth, high fossil fuel availability and possible phasing-out of nuclear power. At the other extreme, "IS92c" has a CO_2 emissions path that eventually falls below its 1990 starting level. It assumes that the population is growing initially and then declines by the middle of the century, it also assumes a low economic growth and severe constraints on fossil fuel supply (see figure 1.4).

Table 1.2. Characteristics of the IPCC-SRES storylines

Scenario Group	**A1B**	**A2**	**B1**	**B2**
Population growth	low	high	low	medium
GDP growth	very high	medium	high	medium
Energy use	very high	high	low	medium
Land-use changes	low	medium/high	high	medium
Fossil-fuels availability	medium	low	low	medium
Technological change	rapid	slow	medium	medium
Change favoring	balanced	regional	efficiency & dematerialization	"dynamics usual"

that emissions forecasts based on recent historical patterns give much higher worldwide CO_2 emissions than predicted in the IPCC IS92 emission scenarios (Schmalensee et al., 1998).

In its 2000 report on emissions scenarios (IPCC, 2000), the IPCC proposes four alternative scenario "families", or "storylines", describing different GHG emissions futures based on contrasted dynamic changes and transitions. The IPCC does not put any particular order among the storylines. The main characteristics of the four IPCC-SRES scenario families are presented[28] in Table 1.2. As shown in Figure 1.4, the new IPCC-SRES emissions projections are in a lower range compared with the IS92 scenarios. The IPCC projects the highest carbon emissions from fossil fuels (27.5 GtC in 2100) in scenario "A2" by assuming high population and energy growth combined with medium GDP growth. For the low population and energy-growth scenarios "B1", worldwide carbon emissions are projected to come back more or less to the 1990 level by 2100. In the average scenarios "A1B" and "B2", the emissions trajectories vary greatly but converge to a level around 15 GtC/y in 2100.

4.2 Demographics and CO_2 emissions

The growth in worldwide carbon emissions results from population growth and the evolution of per capita emissions. As shown in Figure 1.5, the world population cannot be simply extrapolated from historical population patterns. The world population multiplied by two in 150 years between 1700 and 1850 (+0.45% per annum) and multiplied by 5 in 150 years between 1850 and 2000 (+1.1% per annum). The theory of the demographic transition states that population might stabilize at a high standard of living as a result of fertility decline and a high life expectancy at birth. But the speed and extent of this demographic transition is difficult to predict. If we consider the fertility rate of 2.1 children per woman as corresponding to the replacement level, in conditions of low mortality (life expectancy around 70 years), in 2003, about 50% of the

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[28] The IPCC report is based on simulation results coming from six different economic models. We use the average of the six models' projections for comparison purposes.

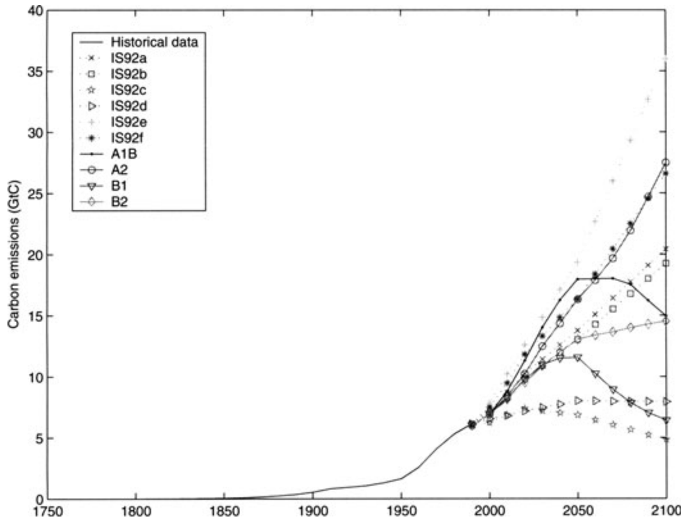

Figure 1.4. Comparison of global CO_2 emissions forecasts for the IPCC IS92 scenarios (x-axis represents time in years)

world population is in that situation or below this rate (15% under 1.5)[29]. A great diversity in fertility exists in the developing world where the demographic transition is not reached for the moment: 32% of the world population ranges between the rate of 3 to 6 children per woman (i.e. northern India, Pakistan, Afghanistan, Arabian Peninsula, sub-saharan Africa). Most future growth will be produced in these areas (Baldwin, 1998). Because of this uncertainty, the IPCC retains three contrasted population trajectories that reflect future demographic uncertainty (see Figure 1.5). Historical per capita emission patterns are plotted in Figure 1.6. Not surprisingly, per capita emissions increased very rapidly with the early stage of industrial development. At the world level, per capita emissions have tended to grow over the entire period[30]. However, industrialized countries have had a two-phase pattern for per capita emissions (Lanne and Liski, 2003). The first phase was characterized by fast growth of per capita emissions as early industrialization and development was heavily based on coal (1750-1910). The second phase showed a lower growth of per capita emissions due to the change in the fuel mix (i.e. the shift from coal to oil and gas), and to technological progress. By contrast, there is little historical evidence for a third phase characterized by declining per capita emissions. However, one finds evidence for early downturns in per capita trends in developed countries

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[29] See Wilson, 2004.

[30] The reduction of per capita emissions at the world level in the end period is mainly due to the sharp decline in per capita emissions associated with the economic recession in the former Soviet Union and Eastern European countries.

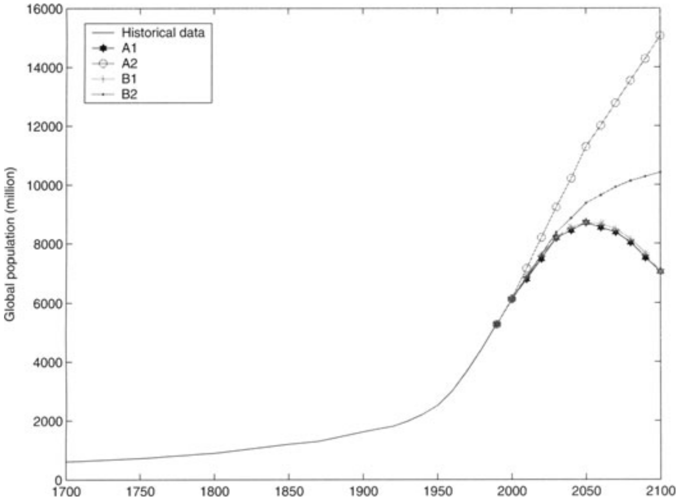

Figure 1.5. Global population trends (x-axis represents time in years)

in the first decade of the 20th century (Lanne and Liski, 2003). Figures 1.5 and 1.6 show that the medium emission scenarios "A1B" and "B2" are based on different assumptions about population and per capita emission growth. The "A1B" scenario combines low population growth with high per capita emission coefficient whereas the "B2" scenario is built on medium population and per capita growth. The low emissions scenario " B1" is explained by a sharp decline of population and per capita emissions from 2050. The high-growth scenario "A2" assumes medium per capita emission growth but high population growth. As defined by the IPCC, scenario "A2" might be considered as a rather pessimistic scenario. However, one might imagine a similar scenario in terms of emission forecast based on the U.N. medium population scenario used for the "A2" scenario and a per capita emissions forecast that would fit with historical patterns used in scenario A1B. This "conservative" scenario would give emissions from fossil fuels totalling 22 GtC/y by 2100.

4.3 CO_2 emissions and economic growth

Most research concerning the relationship between the environment and economic growth uses the paradigm of the *Environmental Kuznet Curve* (EKC)[31]. A number of studies have cautioned the EKC hypothesis on theoretical grounds

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[31] The EKC is an empirical proposition according to which an indicator of environmental degradation is an inverted U-shaped function of income per capita (Grossman and Krueger, 1991; IBRD, 1992). It basically says that in the early stage of economic growth environmental degradation and pollution increase, but beyond some level of income per capita the trend reverses and the environment indicator improves with structural changes in the economy, the

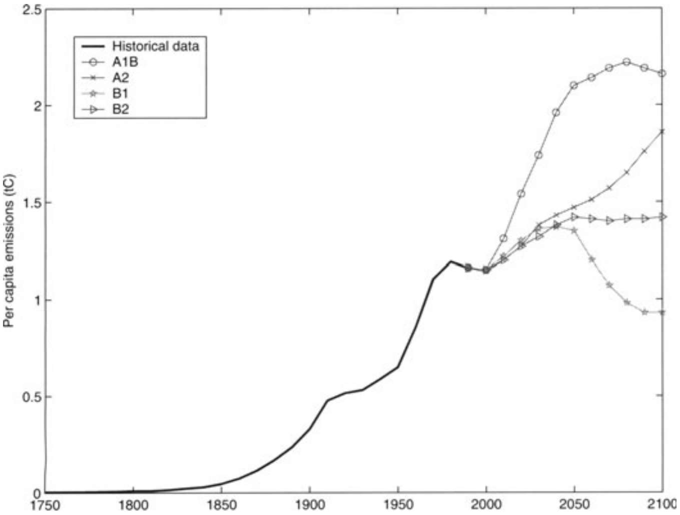

Figure 1.6. CO_2 emissions per capita for different scenarios. (x-axis represents time in years)

(Arrow et al., 1995; Stern et al., 1996). Others have criticized the EKC model on econometric grounds (Stern and Common, 2001; Stern et al., 1996). It has been shown that environmental improvements are possible in developing countries and that pollution peaks might be lower than in early developed countries[32]. This indicates that EKC curves may shift down for developing countries, and that emissions may decline simultaneously in low and high income countries over time[33]. The existing literature shows little evidence for a common inverted U-shaped curve that countries follow as their income rises (Stern, 2003). In the CO_2 case one observes that per capita emissions have tended to rise with per capita gross domestic product (GDP) but to stabilize or even reverse in highly developed countries from 1950 to 1990 (Schmalensee et al., 1998). As shown in Figure 1.7, there is a regular increase of per capita emissions with per capita GDP at the world level over the 1750-1990 period. Two IPCC scenarios are consistent with the EKC hypothesis: on average, the six models used for evaluation of scenario "A1" and scenario "B1" find a turning point in 2080 and 2040-50, respectively. In scenario "A2" and "B2", per capita CO_2 emissions are projected to increase monotonically with per capita

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development of better technology, changes in the fuel mix, and the enforcement of stricter environmental regulations.

[32] See Dasgupta et al., 2002.

[33] The income elasticity of emissions is likely to be less than one but hardly negative in wealthy countries as proposed by the EKC literature.

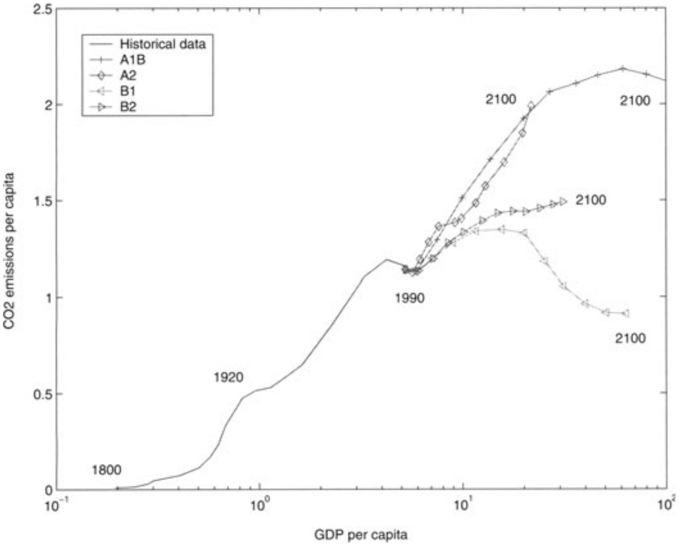

Figure 1.7. CO_2 emissions and GDP Growth (1800-2100) for different scenarios. (x-axis represents time in years)

income. The income elasticity of emissions is supposed to be close to one in "A2" and approximately 0.4 in "B2" by 2100.

The decomposition of per capita carbon emissions into carbon intensity of GDP and per capita income is presented in Figure 1.8. At the world level, per capita emissions have increased as a result of the two components from 1800 to 1910. The carbon intensity of GDP reached a peak in 1910, and then reduced from 1910 to 1990 by 1.2 % per year. The reduction of carbon intensity has been too low to compensate the effect of income growth on per capita emissions. The EKC model assumes implicitly that the growth in per capita income can be more than compensated by a decline in carbon intensity of GDP. This hypothesis is easier to support if one supposes that income growth were to decline over time, and that the economy should be in steady state in the long run[34]. The IPCC emission scenarios are built on assumptions of declining GDP growth rates. This has been criticized by some experts who believe that IPCC's growth assumptions are generally conservative in light of recent experience, and that there is no historical basis for the common assumption

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[34] This kind of reasoning, assuming an exogenous rate of technological progress, has been introduced by Ramsey and Solow, and popularized by the neo-classical optimal growth theory (Ramsey, 1928, Solow, 1956). By contrast, endogenous growth models are characterized by increasing return to scale and generate sustained growth over long periods of time (Lucas, 1988; Romer, 1990).

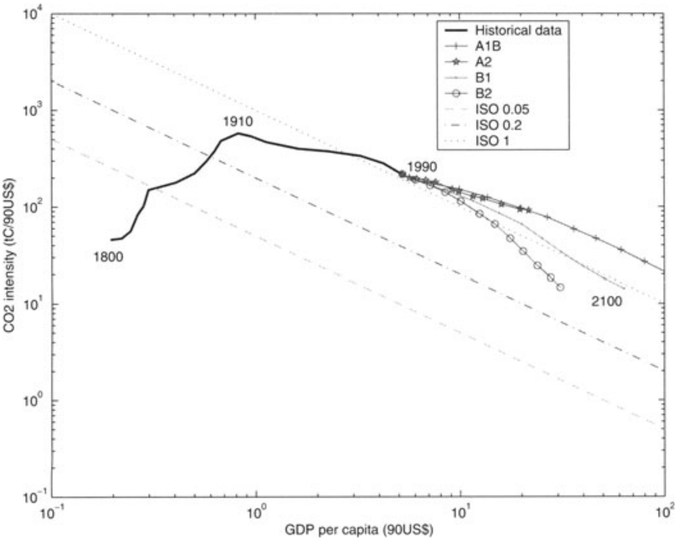

Figure 1.8. Decomposition of CO_2 per capita (1800-2100). The straight lines are contours of constant per capita emission rate.

that per capita income growth slows down over time in developed countries[35]. Indeed, the exchange rates approach overstates the income gap between rich and poor countries in the base year. As a result, the IPCC may assume too high economic growth in poor countries as per capita income may be expected to converge in the long run. However, the choice of the market exchange rates approach does not necessarily lead to an overestimation of developing countries' emission growth if one expects a closure of the emission intensity gap between rich and poor countries with the convergence of per capita income among countries. This latter driving force may well compensate the bias in GDP growth (Manne and Richels, 2003).

5. Energy and economic development

Several authors have also used a decomposition approach to analyze changes in carbon emissions in industrialized countries into structural (e.g. output mix), technological and fuel mix effects (Selden et al., 1999; Viguier, 1999; Schipper et al., 2001). These studies show that the reduction of energy intensity has played a major role in the decline of carbon intensity as compared to the fuel

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[35] For example, see Eckaus, 1994; Nordhaus, 1994; Schmalensee et al., 1998. Other experts have also criticized the IPCC emission scenarios for using GDP weights based on exchange rates rather than purchasing power parities (Castles and Henderson, 003a; Castles and Henderson, 003b).

composition effects and structural changes in the economy[36]. The comparison of modelling results shows that none of the projections expect a decline in carbon intensity of fuels, similar to the historical rate, to continue beyond 2020 (Viguier et al., 2003). At the world level, GHG emission intensity has been caused by a continuing reduction of energy intensity since 1910 (see Figure 1.8). The carbon intensity of energy consumption has been very stable in the whole period 1800-1990. However, one can see on the graph that all IPCC's scenarios except the "A1B" scenario assume a sharp decline in emissions due to rapid energy substitutions from carbon intensive energy (e.g. coal) to less-carbon intensive energy or carbon-free energy. Can we expect such a change in the composition of fuel consumption in a baseline emission scenario? Will energy intensity continue to decrease over time without new environmental policies?

Most economic models include exogenous technical change represented as a single scaling factor – the autonomous energy efficiency improvement (AEEI) – that makes aggregate energy use per unit of output decline over time, independently of any changes in energy prices. Although the definition of the AEEI varies from model to model, in all models it implicitly represents the effect of technological progress. In some models it also represents one or both of two additional trends: (1) changes in the structure of the economy, resulting in a shift in the relative contribution of energy-intensive industry output to total economic output; and (2) an improvement in energy efficiency over time, reflecting the gradual removal of market barriers that prevent some energy consumers from choosing more efficient energy technologies. In reality, higher prices do spur greater innovation and more rapid diffusion of energy-saving technologies (Huntington and Weyant, 2002). AEEI is critical because even small rates (e.g. 1% per year) can generate large reductions in energy use and carbon emissions when applied over a long time horizon. However, it is not clear what an appropriate rate for AEEI should be.

The extent to which technical change is saving energy is a source of considerable controversy (Jorgenson and Wilcoxen, 1993). Hogan and Jorgenson present econometric evidence that aggregate technical change may be slightly energy-using (Hogan and Jorgenson, 1991). Modelling technical change with a deterministic trend may also overestimate future AEEI. A deterministic trend implies that AEEI will continue *ad infinitum*. However, one should model technical change as a stochastic process and account for the limits on the structural changes responsible for AEEI (e.g. the ability of households to substitute non-energy goods and services for energy purchases; resource and technical limits on the ability to reduce energy intensity) (Kaufmann, 2004). One should better represent technological change by incorporating some degree of price sensitivity

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[36] For example, it is shown that the reduction of the carbon intensity of US GDP has been mostly due to the reduction of energy intensity (Viguier et al., 2003). In Europe, both the decline of energy intensity and the evolution of the fuel mix are responsible for a falling emissions intensity of GDP for the 1960-1995 period. Historically a decline in the carbon intensity of fuels has been a significant contributor to the decline in carbon intensity of GDP for the EU.

(Huntington and Weyant, 2002). Recent econometric studies that take into account the presence of price-induced technical change and the stochastic nature of technical change conclude that current estimates for AEEI may overstate future reductions in energy use and thus underestimate the welfare effect of climate change policies (Kaufmann, 2004).

In the IPCC scenarios "A1B", "B1", and "B2", the reduction of carbon intensity of energy consumption is generally obtained through a shift from fossil fuel to biomass and carbon-free energy. But the fuel-by-fuel composition of energy consumption may greatly differ from one economic model to another. In general, the projected fuel mix is characterized by less coal and oil, and a high share for natural gas and renewable energy in the three scenarios[37] by 2100. By contrast, Manne and Richels have included new assumptions about oil and gas resources in the MERGE model[38]. In the reference case where a production-reserve ratio of 5% and a resource depletion factor of 2% are assumed, world oil and gas production are supposed to decline to 87.6 and 101.3 exajoules (EJ) per year in 2100, respectively. As shown in Figure 1.9, almost fifty percent of total primary energy supply would come from coal, and oil and gas would represent around 6% each. This picture is rather different from all the IPCC's scenarios. Under this fuel mix, the decline of carbon intensity of energy consumption might be more limited than expected in IPCC scenarios depending on the penetration of new clean-coal technologies.

As a final remark we may notice that baseline emissions scenarios produced by the economic models generally assume (i) a rapid shift from fossil fuels to carbon-free energy in the baseline scenario, and (ii) constant AEEI rates which are typically in the range 0.5% to 2.5% per year. If one challenges these underlying assumptions, GHG emission intensity might be higher than projected by the IPCC. *Ceteris paribus*, worldwide carbon emissions might then be higher than one might expect from the IPCC – or closer to the "A2" scenario than the others. Consequently, both the environmental burden *and* the economic costs of mitigation policies (i.e. Kyoto targets) tend to be underestimated.

6. Conclusion

To summarize this rapid survey of the interplay between climate and economic dynamics we may draw the following conclusions:

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[37] If one takes the IPCC projections from the Asian-Pacific Integrated (AIM) model as an example, the share of oil in total primary energy supply is supposed to reduce to 6% in "A1B" and to 12% in "B1" in 2100; the share of coal ranges from 10% to 13%; natural gas ranges from 10% to 25% and renewable energy goes from 21% in "B2" to 44% in "A1B".

[38] They estimate oil and gas supply curves by 2100 based on estimates of the quantities of conventional oil, gas, and natural gas liquids outside the United States that have the potential to be added to reserves in the next 30 years (1995 to 2025) from the U.S. Geological Survey "World Petroleum Assessment 2000".

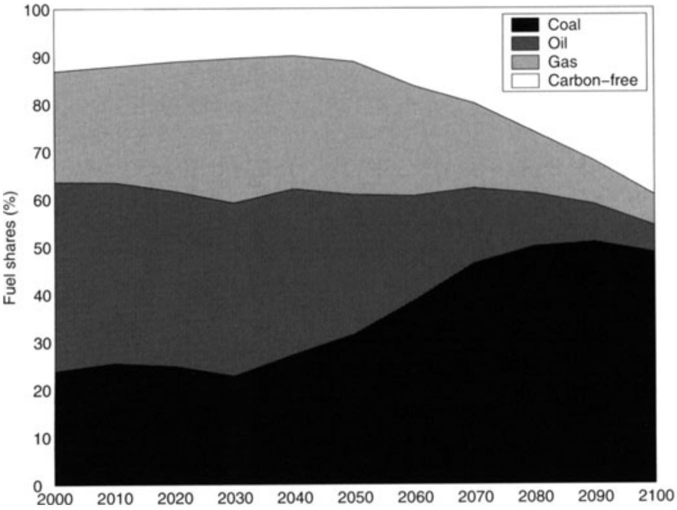

Figure 1.9. Fuel Shares in Total Primary Energy Supply (MERGE 5 - Reference case)

- Knowledge of the dynamics of the carbon cycle and the forcing by greenhouse gases permits us to predict global climate change due to anthropogenic influences on a time scale of a century (albeit with uncertainty).
- Stabilizing the global mean temperature change to an acceptable level calls for a drastic worldwide reduction of the GHG emissions level (to around a quarter of the 1990 level) over the next 50 years.
- Climate inertia implies that many of those who will benefit (suffer) most from our mitigation actions (lack of mitigation) are not yet born.
- The climate change impacts may be large and unequally distributed over the planet, with a heavier toll for some DCs.
- The rapid rise of GHG emissions has accompanied economic development since the beginning of the industrial era; new ways of bypassing the *Kuznets curve* phenomenon have to be found for permitting DCs to enter into a necessary global emissions reduction scheme.
- The energy system sustaining the world economy has to be profoundly modified; there are possible technological solutions but their implementations necessitate a drastic reorganization of the infrastructures with considerable economic and geopolitical consequences.
- The policies to implement at international level must take explicitly into account the intergenerational and interregional equity issues.

- The magnitude of the changes that will be necessary impose the implementation of market-based instruments to limit the welfare losses of the different parties (groups of consumers) involved.

The global anthropogenic climate change problem is now relatively well identified. The decision process which has to be implemented in order to solve it must be adapted to the particular spatial and dynamic structure of the interplay between climate and economic dynamics. As exemplified by the difficulties of the Kyoto protocol[39], viable policy options will have to be designed as *equilibrium solutions to dynamic games played by different groups of nations.* The paradigm of dynamic games is particularly well suited to represent the conflict of a set of economic agents (here the nations) involved jointly in the control of a complex dynamical system (the climate), over a very long time horizon, with distributed and highly unequal costs and benefits. Already many papers have proposed such an approach (Carraro and Filar, 1995). The time has come to construct models based on a more precise description of climate dynamics; the economic response to the need for drastic mitigation actions; the costs incurred by the different regions, and the possibility of integrating mitigation policies within an incentive for clean development. Some dynamic games involving detailed economic descriptions of the consequences of climate change policies have recently been proposed ((Haurie and Viguier, 2003; Bernard et al., 2002; Viguier et al., 2004)). In another vein a game-theoretic approach to the long-term dynamic management of the world energy system has been sketched out (Labriet and Loulou, 2003).

In this book the papers by Carraro and Kemfert address specifically, in a dynamic game setting, the issue of linkage between development or R&D and mitigation policies. The other papers gathered in this book are a contribution to the identification of the parameters that could define the models that will be required.

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[39] For an interesting economic analysis of this protocol, see Guesnerie, 2003.

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Chapter 2

COUPLING CLIMATE AND ECONOMIC DYNAMICS: RECENT ACHIEVEMENTS AND UNRESOLVED PROBLEMS

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Abstract Anthropogenic climate change poses unprecedented challenges for the scientific and policy communities alike. The intermingled socio-economic and biogeophysical processes involved in the problem require joint work of many disciplines culminating in integrated climate-economy models. Distinctive attributes of the climate change problem make it difficult for modelers trying to replicate the dynamics of the climate-economy interactions to provide guidance for policymaking. Processes ranging across multiple time horizons, geographical scales, decision-making levels, and response options, all with multiple layers of detail of their own complexities, need to be consolidated at a level that properly depicts key features of the individual component and permits integration with others. The inverse assessment framework and its implementation in an integrated economy-climate model are presented to illustrate one attempt to resolve this conundrum. Due to the diversity of the policy-related questions and the conceptual, methodological, and computational difficulties of integration, a promising strategy involves flexible problem-oriented coupling of selected elements of a compatible set of models developed in an internally consistent integrated assessment framework.

1. Introduction

Ever since the issue of anthropogenic climate change arose in the international policy agenda two decades ago, economic analyses intended to support policymaking to tackle climatic change have been struggling with the need to accommodate conflicting demands. The long-term nature of the climate problem requires the analyst to look into the distant future of multiple centuries. At the other extreme, public policymakers and the business community are interested in the options and costs of reducing greenhouse-gas emissions over the

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next 5-10 years. Long-term assessments should provide information about the rate and magnitude of anthropogenic climate change, its impacts on climate-sensitive ecological and social systems, and the scope for adaptation in the affected sectors. This information about the long-term aspects should guide medium-term (30-50 year) concentration and emission limits and associated emissions pathways to abide them. Finally, the desirable medium-term path sets the boundary conditions for near-term emissions reductions and the policies and measures necessary for their implementation. Similar challenges arise about the geographical scales where the global problem needs to be addressed as impacts, vulnerabilities, and mitigation options vary immensely in small geographical regions. Another problem arises from the contrast between the need for broad solutions over the long term and for technological and regulatory details for near-term actions.

This chapter briefly reviews recent attempts to resolve the above dilemmas. In addition to different approaches to truly integrated models, a number of attempts have been made to incorporate the necessary amount of biophysical details into economic models. A recent effort to consolidate short- and long-term aspects, climate change, impacts, and economic details in an integrated assessment framework is then presented. The chapter concludes with a short elaboration of a range of open problems and proposes approaches to tackle them in future research efforts. The chapter is structured around the following questions: what are the main types of attempts and analytical frameworks to resolve the problems arising in the integration of economic and climate models (Section 2), how was the problem tackled in a project that developed the so-called inverse integrated assessment approach and modelling framework (Section 3), what kind of results can be obtained from the inverse approach (Section 4), and finally, what might be the promising future direction towards better integration (Section 5). Throughout the chapter, the emphasis is on the conceptual and methodological issues of model linkages and integration in the context of the climate change problem. Short presentations of model results serve only illustrative purposes.

The fundamental characteristics of the climate change problem are difficult to tackle one by one. Yet the deep and dynamic linkages among the climate and economy components render integration indispensable. But what should one integrate in what type of decision analytical framework to keep the integrated model transparent and computationally tractable? How deep should be the model integration? In which cases is it sufficient that modules representing single problem components are simply linked in a sequential information flow? Which scientific and policy questions require deeply integrated models incorporating the diverse feedback loops among the components? And finally, at what level of detail should the various components be depicted in the integrated model?

Different scientists and research teams give different answers to the above questions. The reason behind this is simple: it is not possible to specify the criteria for the "best" integration. Most linked climate-economy models or integrated assessment models in the literature are based upon properly argued and well-justified frameworks. The result is a rich diversity of models most of which provide useful information about selected aspects of the problem. Given the characteristics of the problem and the diversity of associated policy dilemmas, it is difficult to conceive an integrated model that will be able to provide the best answers to all questions. Instead, as argued by Yohe (1999) the relative strengths and weaknesses of the different frameworks ensure that the combined contributions rather than individual models provide really valuable policy insights to which new approaches and new frameworks for coupling economic and climate models can contribute. These statements are valid for the integrated assessment framework and the models incorporated into it as it is presented in the rest of this chapter.

2. Traditional analytical frameworks to support climate policy

The intricate features of global climate change outlined in the previous section and the emerging need for policy response have triggered a host of research activities over the past fifteen years. One cluster of efforts attempts to adopt and improve traditional decision-analytical frameworks. Examples include the early applications of cost-benefit analysis by Nordhaus (1992, 1994) and Cline (1992). Another array of research involves a series of new efforts to create frameworks specifically tailored to the climate change problem and focusing on selected aspects of it. Uncertainty, for example, has attracted considerable attention and is the key concern in the contributions by Dowlatabadi and Morgan (1993a,b, 2000) and by the group at the University of Cambridge (Hope et al., 1993, Plambeck and Hope, 1996, Plambeck et al., 1997). All these frameworks involve integrated assessment models (IAMs) that combine models of the most relevant components of the society-biosphere interactions. IAMs have come a long way from their beginnings as emerging and later trendy gadgets to become instruments generally recognized as useful sources of scientific insights for climate policy.

2.1 Policy evaluation and policy optimization models

The integrated models developed in climate change research incorporate the full cycle of anthropogenic greenhouse gas (GHG) emissions, the options and costs of their mitigation, the resulting climate change, its impacts, and the related options and costs of adaptation. IAMs are traditionally classified into two main groups: policy evaluation models and policy optimization models. Examples of policy evaluation models are IMAGE (Integrated Model to Assess the Greenhouse Effect; Alcamo et al. (1998), the IMAGE team (2001) or the more recent exploratory modeling technique developed to find robust strategies (Lempert et al., 2000, Lempert and Schlesinger, 2000). Technically speaking, these are simulation models that take user-defined assumptions about a specific course of future policy (e.g., determining the emissions as drivers) and calculate the implications of the specified policy for all explicitly modelled variables of interest to the policymaker: temperature change, ecosystem and agricultural yield changes, sea-level rise, etc. Although simulation models cannot say much about the optimality features (cost efficiency, environmental effectiveness, or social equity) of the scenarios prepared by the modelers or drawn-up by the user, modern software technologies make it easy for the user to experiment with and compare any number of scenarios and conclude about policy implications.

The second cluster includes policy optimization models. They summarize the relevant boundary conditions in a set of externally defined parameters in a scenario, separate key policy variables that control the evolution of the climate-economy system (typically emission levels or, for example, carbon tax levels that influence emissions), and determine the values of these policy variables in an optimization procedure according to clearly defined objectives. In a cost-benefit framework, like the DICE/RICE (Dynamic/Regional Integrated Model of Climate and the Economy) family of models (Nordhaus and Yang, 1996, Nordhaus and Boyer, 2000), the criterion for optimal policy is an equalized marginal cost and marginal benefit such that the marginal cost of mitigation (the opportunity cost in terms of what societies give up for reducing GHG emissions by an additional unit) and the marginal benefit of mitigation (the climate change damage, expressed in monetary terms, avoided by an additional unit of emission reduction) are the same. As a result, a cost-benefit model determines optimal values for both emissions and impacts. In a cost-effectiveness framework, the acceptable impact is specified as an environmental target (typically in terms of CO2-equivalent concentrations), and the optimization is restricted to finding the least-cost emission path to reach that target (see Wigley et al., 1996, Manne and Richels, 1997, Valverde and Webster, 1999, Yohe and Jacobsen, 1999, Tol, 1999a). Optimization models are typically concerned with global optima and tend to pay less attention to equity concerns, like the widely diverging implications for specific regions pertaining to both impacts of climate change and the costs of mitigation.

From a narrow economic perspective, global cost-benefit analysis appears to be the policy analytical framework to provide guidance for an efficient policy. The difficulties of setting up, calibrating, and interpreting the results of a global cost-benefit model have been widely discussed (Munasinghe et al., 1996, O'Riordan, 1997, Portney, 1998, Toth, 1998) over the last decade.

The difficulties start with estimating the marginal cost function. Fossil fuels and the products and services produced by using them are widely traded in national and international markets. Accordingly, one needs to estimate not only the direct but also the indirect and induced effects of any emission reduction policy in terms of changes in relative prices and the corresponding shifts in demand and supply. Global multi-region and multi-sector general equilibrium models are the appropriate tools to provide these cost estimates. The problem is that as resource endowments and technologies change, intersectoral relationships within regions and international trade flows among regions will inevitably be altered over time. These changes are difficult to predict and represent into these models. As a result, cost estimates derived from general equilibrium models become increasingly unreliable beyond three or four decades into the future.

To provide marginal cost estimates at the century scale, economists have adopted aggregated energy-economy models (like the MiniCAM/GCAM model family of Edmonds et al., 1994, 1996a) or extended production functions (like the MERGE model, see Manne et al., 1995; or the Connecticut model, see Yohe and Wallace, 1996, Yohe and Jacobsen, 1999). These aggregated representations provide the basis for assessing the impacts of technological development on the long-term evolution of carbon emission reduction costs. Globally aggregated marginal cost functions nevertheless may hide large regional differences in the actual mitigation burden. In principle, the differences in the regional marginal costs could be reduced by implementing flexibility mechanisms (like emission trading or joint implementation as established in the Kyoto Protocol to the UN Framework Convention on Climate Change [UNFCCC]). However, the associated transaction costs (of which we have very few reliable estimates) and the need for hedging against possible implementation failures and the associated penalties might significantly reduce the cost-saving benefits of flexible mechanisms.

The estimation of a global benefit function is even more difficult and controversial. The marginal benefit curve is traditionally derived by estimating the damages avoided by incremental emission reduction efforts. Similar to the global cost function, the globally aggregated marginal benefit curve is likely to hide enormous regional differences. Some regions are expected to gain from a modest magnitude of warming (Smith et al., 2001), while other regions seem to be on a losing track from the beginning. Another broadly shared concern is that establishing a marginal benefit function requires all impacts to be evaluated in monetary terms and some mechanisms (typically discounting) to make them comparable over time. This is highly controversial irrespective of whether we estimate the benefit function at the globally aggregated level or at regional or national scales.

Even if it were possible to find a generally acceptable solution to the above problems, the actual benefit curve should also reflect the very different risk perceptions and risk-taking behavior of different societies. This is partly related to the current situation and to future expectations about the adaptive capacity to cope with the disturbances caused by a changing climate. Another part of this problem is rooted in the widely differing attitudes toward risk in different cultures (Douglas, 1985, Baron et al., 1993).

The applicability of well-established analytical frameworks like cost-benefit analysis and routinely used procedures like discounting costs and benefits arising in different time periods at market-based discount rates to their present values have been challenged and debated in the literature for over a decade. A collection of essays edited by Portney and Weyant (1999) presents the diversity of the positions leading economists take on this subject (see Toth, 2000 for a short overview). Bradford (1999) points out that using the positive net benefit as the sole criterion for implementing or rejecting a project is not sufficient in any public policy dilemma. Even if the cost-benefit test fails, the project may still be worth implementing if the redistribution effect favors those social groups whose support is politically desirable. Bradford also indicates that the compensation test underpinning the cost-benefit analysis is difficult to be conceived as being operational in the climate change context because the transfers involve many generations over time and many nations and subnational social groups across space. Nevertheless, the cost-benefit analysis of climate change must make clear the distributions of gains and losses over time and across space. Even if a strict cost-benefit test of the policy fails, the emission reduction should be favored if beneficiaries (presumably distant in time and place from those who need to carry the burden) are likely to be poor. Bradford notes two difficulties associated with cost-benefit analysis. First, the distribution of gains and losses of specific groups should be based on the discounted consumption values as indicators but the effects cannot be reliably added together. Second, monetary valuation of non-market goods and ecosystem services is the most serious problem.

2.2 The need for new approaches to coupling economic and climate models

The decades- or even centuries-long delay between incurring the emission reduction costs and redeeming the resulting benefits due to the inertia of the climate system, the rather asymmetric uncertainty positions (in which relatively reliable cost assessments stand out against highly uncertain benefit estimates), and the need to discount for both lead to a relatively modest GHG abatement as the efficient policy emerging from a cost-benefit framework. Nordhaus (1997) notes that, according to the results obtained from the RICE model, along the economically efficient emission path "... the long-run global average temperature rises sharply. After 500 years, it is projected to increase 6.2 ° C over the 1900 global climate. While we have only the foggiest idea of what this would imply in terms of ecological, economic, and social outcomes, it would make most thoughtful people – even economists – nervous to induce such a large environmental change. Given the potential for unintended and potentially disastrous consequences, it would be sensible to consider alternative approaches to global warming policies" (Nordhaus, 1997).

Nordhaus then explores alternative approaches: changing the discount rate in the cost-benefit model, introducing limits to the increase in global mean temperature, greenhouse gas concentrations, and global emissions in selected years – these are different versions of the cost-effectiveness framework. After evaluating the environmental effectiveness and the economic efficiency of various alternatives, he concludes that "[t]he best approach will be to identify the long-term objective and to take specific steps to override market decisions or conventional cost-benefit tests so as to achieve these long-term goals" (Nordhaus, 1997).

In reviewing the difficulties of applying cost-benefit analysis to the climate change problem and especially the problems of establishing the marginal benefit curve, Portney (1998) suggests that an alternative to the generally used damage function approach might be to conduct a survey of the current generation about their willingness to pay to reduce the threat of climate change in the future. One impediment with this proposition is that it is difficult for the respondents to know what they would actually be buying. Portney proposes to make available the best scientific information we currently have about the possible impacts of climate change to alleviate this information problem. As the next section demonstrates, this is exactly the strategy followed in the ICLIPS project by developing climate impact response functions (CIRFs) for climate-sensitive sectors. This formulation and the option of specifying the cost constraint in terms of the upper limit to loss in current consumption any generation may need to endure are also in line with the arguments by Lind and Schuler (1998) concerning the appropriate way to evaluate intergenerational equity.

The difficulties associated with establishing marginal benefit curves for global climate change led many analysts to abandon the cost-benefit framework and use cost-effectiveness analysis instead. This approach will not produce the economically efficient policy of controlling GHG emissions to equate its marginal costs with its marginal benefits, but it can provide information about the least-cost strategy for reaching an externally defined target. The cost-effectiveness framework has been successfully used to provide guidance for environmental legislation, technology and personal safety regulations, and other public policy issues in many countries. Cost estimates of different emission paths to reach the same concentration targets by pursuing different implementation strategies are the best-known examples in climate change (Wigley et al., 1996, Ha-Duong et al., 1997, Manne and Richels, 1999).

Morgan et al. (1999) discuss six basic assumptions of conventional policy analysis tools (including the single-problem/single-actor perspective, manageable impacts valued at the margin, known and static exogenously determined values, exponential discounting as an adequate representation of decision making, modest and manageable uncertainties, linear system properties) and their validity with a view to the special features of global change problems. They conclude that "conventional tools of policy analysis, routinely applied, can lead to wrong or silly answers in studies of global change. To avoid such failures, analysts ... must think much more carefully about the assumptions ... " (p. 278). Morgan and his co-authors suggest that more attention should be devoted to devising new analytical strategies to overcome the prevailing difficulties. One such attempt is presented in the next section.

3. The inverse approach and the ICLIPS framework

The previous section presents arguments for the need to experiment with new decision analytical frameworks to assist climate policy. In response to the complexities discussed above, a new decision analytical framework has been developed and implemented in the form of an Integrated Assessment Model (IAM). This framework and associated model stem from the project on Integrated Assessment of Climate Protection Strategies (ICLIPS) directed by the present author at the Potsdam Institute for Climate Impact Research (PIK) between 1996 and 2001. The core concept of the ICLIPS project is the tolerable windows approach (TWA) or inverse approach. It is based on an inverse modeling concept that derives climate protection strategies from perceived unacceptable impacts of climate change as well as from intolerable socioeconomic implications of mitigation measures. Based on these constraints, the inverse model produces complete sets of solutions in a multidimensional state-control space, of which permitted carbon emission paths are the most relevant control variables for policy making. The inverse approach seeks to investigate implications of and trade-offs among several constraints related to different domains in the climate-society system. This section presents the conceptual framework first followed by a concise description of the integrated model system.

3.1 Conceptual framework and comparisons

The relationships among the cost-benefit, cost-effectiveness, and tolerable windows frameworks are illustrated in Figure 2.1. It is important to emphasize that the figure shows only the conceptual linkages of the three frameworks and not the actually modelled relationships. In the TWA we do not know the exact positions of the marginal cost and marginal benefit curves. The curves in Figure 2.1 serve to show that the user-specified impact and cost limits can be lower or higher than the cost-benefit optimum. Moreover, Figure 2.1 presents a static sketch of the TWA. Bruckner et al. (2003a) present the mathematical specification of the comprehensive dynamic model.

The economically efficient solution is provided by cost-benefit analysis at the intersection of the marginal cost and marginal benefit curves. Cost-effectiveness analysis is characterized by a vertical marginal benefit curve, and the associated marginal cost will be provided by its intersection with the lowest marginal cost curve (for visual clarity, only one marginal cost curve is depicted in Figure 2.1.) Cost-effectiveness attempts to get around the problem that no good measure of the benefit function exists and therefore it is not possible to find an efficient allocation (equating marginal costs and marginal benefits). The vertical damage function (MB|CE) represents the environmental (impact or damage) target, and its intersection with the lowest-lying marginal cost curve denotes the associated cost. Note that Figure 2.1 provides a highly simplified picture because only two parameterized constraints are considered. The TWA analysis with the ICLIPS model provide the opportunity to explore the effects of variations of many more parameters.

The TWA is based on the recognition that we can say something about the benefits (avoided damages), but not enough to specify them in the form of a marginal benefit function. The ICLIPS framework includes climate impact response functions (CIRFs) in terms of physical units that portray the changes

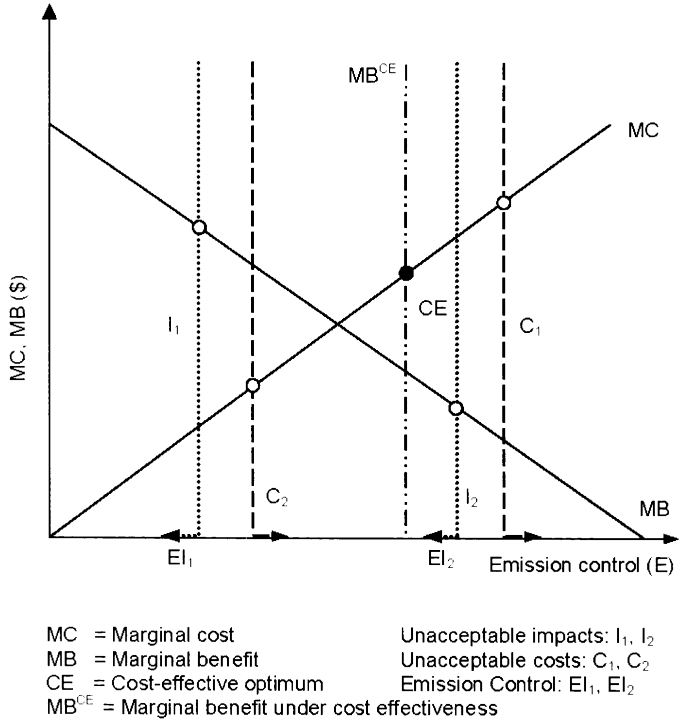


Figure 2.1. The relationships between the cost-benefit, cost-effectiveness, and the tolerable windows frameworks

induced in a given impact sector by incremental climate change and increases in carbon concentration. The social decision problem is then to settle on the maximum acceptable climate change impact. Any impact beyond this level is unacceptable. Two independent cases are illustrated by the vertical lines I_1 and I_2 and the connected arrows in Figure 2.1. Each case corresponds to the willingness to accept any amount of damage between zero and the marginal benefit equivalent to the specified total damage. The hypothetical judgment behind I_2 illustrates the social unacceptability of climate change impacts that result if the level of emission control is less than EI_2. In contrast, the judgment behind I_1 implicitly assumes that the society can cope with a larger amount of climate change and unacceptable impacts loom beyond a much lower level of minimum reduction (EI_1).

The associated social decision on the cost side is similar: what is the society's maximum willingness to pay for climate change mitigation? Again, two independent cases are represented by the vertical lines C_1 and C_2 and the connected arrows in Figure 2.1. Each case corresponds to the willingness to pay for mitigation any amount between zero and the marginal cost equivalent to the specified total cost. The hypothetical judgment behind C_2 implies a much lower willingness to pay for climate protection than the social decision associated with C_1.

It is easy to see from the figure that, while the cost-benefit and cost-effectiveness frameworks lead to single optimum points, different types of outcomes can emerge from the tolerable windows specifications. A whole range of feasible emission strategies exist for the combinations of I_1+C_1, I_1+C_2, I_2+C_1; that is, whenever the marginal benefits representing the specified unacceptable impact level are located to the left of the marginal cost corresponding to the specified unacceptable mitigation cost level. In contrast, not a single emission path (thus no emission corridor) exists for the combination I_2+C_2. This situation corresponds to the social decision in which the level of climate change impact the society is willing to accept is too low compared to its willingness to pay for avoiding it. In accidental cases the specified I and C levels may coincide. This would lead to a single feasible emission path. This path would be equivalent to the cost-effectiveness outcome of the specified environmental constraint, but it would not necessarily coincide with the cost-benefit optimum.

Another important distinctive feature of the cost-benefit and cost-effectiveness frameworks, on the one hand, and the TWA, on the other, is that the first two would always imply reaching the actually specified environmental and cost limits. By specifying the range of feasible policy options in terms of upper limits to impacts and costs, the actually chosen emission paths (recall that the choice among the feasible ones is based on non-climatic considerations) may well lie inside the corridor so that neither the impact nor the cost limits will be reached. These paths are clearly suboptimal in a purely climate-policy sense, but they may represent a sort of joint optimum with respect to the non-climatic objectives considered in combination with the specified climate change constraints.

The above feature is much more important and characteristic of the inverse approach than the speculation about possibly looming disasters if a path is chosen that would temporarily leave the corridor by a marginal amount, thereby generating an infinitesimal surpassing of the most binding impact constraint. The problem of infinitesimal threshold crossing characterizes all environmental policy analysis conceived in the vein of cost-effectiveness. No matter how much better the actual quality of drinking water is relative to the specified quality standards, there is no bonus to earn. However, even a slight violation of the prescribed standard would trigger penalties although the health implications are uncertain but presumably negligible.

The TWA contains cost-effectiveness as a special case. The numerical results of the integrated model contain not only carbon emission corridors but also the least-cost paths within the corridor. Therefore, the relationship of the TWA to the concept of a cost-effective optimum in a cost-effectiveness framework needs some additional explanation. Although there are constraints imposed on the implementation costs that might be incurred in any given time period by any region, the concept of cost-effectiveness still remains relevant in the tolerable windows analysis. The cost-minimizing emission path in the inverse model really takes the climate system to the specified impact limit and it is really the least-cost path that stays within the climate constraints. This is not the optimal policy in the traditional cost-effectiveness sense because it does not minimize mitigation costs across the board by equating marginal costs across all regions over the entire time horizon. However, it is optimal with respect to the entire set of the user-specified normative constraints, including those that foreclose imposing extreme burden on some regions or some generations for the sake of the overall cost-minimization.

"Zero damage within, infinite damage outside the emission corridor" is not the appropriate interpretation of the TWA framework. The emphasis is on the level of unacceptable damage outside the corridor. The actual damage inside the corridor varies, of course, according to which one of the permitted emission paths is actually chosen. But the very essence of the TWA is that the choice is not based on minimizing the mitigation cost, the damage, or the cost-benefit ratio of the most binding constraint. The choice is assumed to be driven by non-climatic considerations that are impractical or outright impossible to include in a comprehensive integrated assessment model. The differences between the opportunity costs of those policy options may well exceed the strictly climate-related cost differences across the permitted emission path. Hence this "underdetermined" climate policy space is likely to provide useful flexibility in the broader policy context.

In the intended applications of the ICLIPS integrated assessment framework, model users specify the minimum requirements for climate protection, including, in particular, the maximum acceptable impacts of climate change and the maximum acceptable cost of mitigation. The resulting emission corridor is a "relaxed" cost-effectiveness strategy field because the "target" (the maximum acceptable impact) is not necessarily reached, and it is a relaxed cost-benefit outcome because benefits need not be specified in monetary terms and not necessarily equalized with costs at the margin. But the main distinctive feature is that the inverse approach provides a range of policy options (a set of emission paths) whereas both cost-benefit and cost-effectiveness analysis produce single optimal paths.

Several authors comment on the conceptual design and practical features of the TWA. Dowlatabadi (1999) emphasizes the purposeful search for threshold relationships between climate conditions and life systems as a prominent characteristic. Yohe (2000) calls attention to the importance of adaptation opportunities in defining the acceptable climate change limits. He discusses three types of adaptation: response to short-term fluctuations, reaction to long-term change, and activity switching. The key distinction to be made in discussing adaptation is between biophysical climate sensitivity (and the associated "virtual thresholds") and the actual socioeconomic vulnerability (determined by social, economic, technological, and other factors) that crucially shape the actual tolerability levels.

Toth et al. (1997) present a preliminary version of the ICLIPS IAM to calculate emission corridors for environmental constraints defined in terms of the magnitude and rate of global mean temperature change as proposed by the German Advisory Council (WBGU). The climate change limits proposed by the Council were largely based on past climate-ecosystem relationships. In his appraisal of this effort, Dowlatabadi (2000) highlights that "the current distribution of ecosystems can neither be defined in terms of an equilibrium, nor is it an optimum in traditional sense of the term" (p.392). This observation clearly points to the potential deficiencies of the current CIRFs (van Minnen et al, 2000; Füssel et al, 2003) and indicates the need for using the new class of dynamic global vegetation models in innovative ways to develop the next generation of response functions.

Future versions of the ICLIPS model need to incorporate a systematic treatment of uncertainties, the baseline emissions and controls of non-CO2 GHGs, and the possible socioeconomic thresholds associated with too stringent emission reductions. The current version of the ICLIPS model indeed incorporates a scenario-based, fully dynamic treatment of non-CO2 GHGs and the possibility to explore emission corridors under the same impact and cost constraints but under different non-CO2 scenarios, as well as the possibility to explicitly specify the maximum level of acceptable social costs of emission reductions.

3.2 The modeling framework and its components

The inverse analytical concept is operationalized in the form of the ICLIPS IAM. Key features of this model framework are presented in Figure 2.2. The core of the ICLIPS framework is a fully integrated climate-economy model, incorporating results from technological development and agriculture/land-use modelling. The framework also includes impact assessment tools and a detailed model of the world economy. The core model of the ICLIPS framework combines a reduced-form GHG and climate model and a highly aggregated economic model. In forward mode, the model can simulate how different GHG emissions pathways affect climate and produce biophysical changes in selected impact sectors across the world. In inverse mode, the model generates permitted corridors for future carbon emissions that would keep the climate system within tolerable ranges at acceptable costs, both specified externally by model users, eventually policymakers. To help the users make these arduous choices, the project has also developed pilot CIRFs that indicate how a particular climate-sensitive sector reacts to changes in relevant climatic attributes across a plausible range.

An important characteristic of the inverse approach or TWA is the intention to support climate change decision making by clearly separating risk perception, value judgments, and associated uncertainties, on the one hand, and scientific analysis and related uncertainties, on the other. Accordingly, a TWA application always involves a "decision step" (the explicit formulation of normative constraints or "guardrails" that delineate unacceptable climate change impacts and mitigation costs) and an "analysis step" (the model-based scientific analysis of the global climate-economy system to obtain the corridor of all emission paths that satisfy the pre-defined constraints).

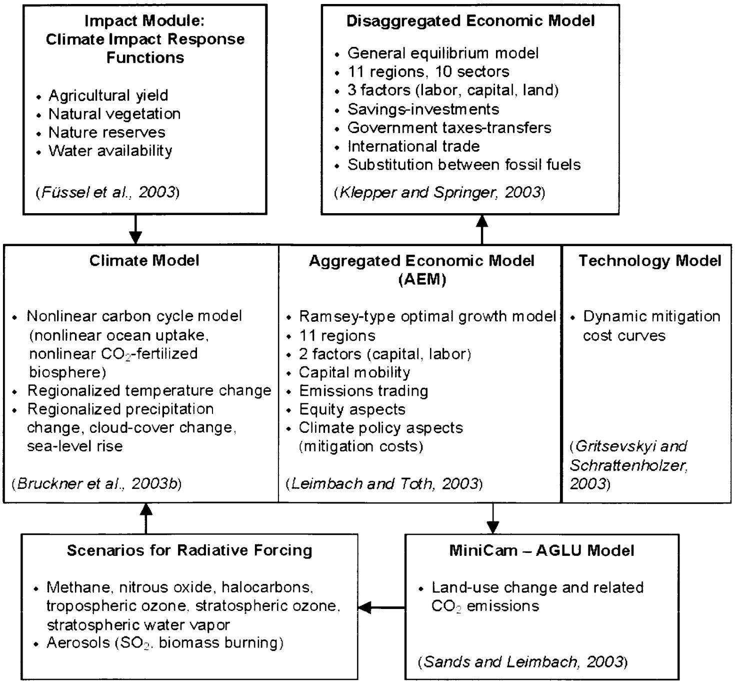


Figure 2.2. The ICLIPS IAM framework.

The mathematically correct procedure to obtain the bundle of all permitted emission paths would require a complete inversion of an appropriately formulated integrated assessment model. This is not yet possible given the current state of the pertinent mathematical theory and numerical methods. Nevertheless, as shown by Bruckner et al. (2003a), useful results, like emission corridors depicting important aspects of the most comprehensive solution, can be obtained without knowing the bundle of all admissible emission paths beforehand.

The attempt to identify the main characteristics of a whole family of admissible emission paths is fundamentally different from the methodological issues involved in applying traditional approaches to integrated assessment. Policy evaluation and policy optimization methods primarily deal with a single emission path either by investigating the consequences of a predefined scenario or by deriving the (usually unique) optimal emission path that maximizes welfare (as in cost-benefit analysis) or minimizes mitigation costs subject to climatic constraints (as in cost-effectiveness analysis). Another way to look at this relationship is to consider the marginal cost and marginal benefit curves. The cost-benefit rule implies that the optimal level of mitigation is at the point where the two curves intersect. The TWA relaxes this optimality rule. It lets the user specify the level beyond which costs and damages become unacceptable. Recall the relationship between cost-benefit analysis, cost-effectiveness analysis, and the TWA illustrated in Figure 2.1.

The inverse approach takes the form of a "relaxed" control problem in the sense that a multitude of permitted control paths is sought (rather than a single optimal path) leading to a set-valued problem. To handle the set-valued character of the solution sought by the TWA, the basic methodological problem is reformulated in terms of the theory of differential inclusions. This theory has been developed expressly to deal with the above dynamical non-uniqueness. It provides appropriate definitions, a consistent theoretical background (e.g., theorems of existence), and even some solution methods that are applicable as long as the underlying climate and economy models remain relatively simple.

For large-scale models, the ICLIPS framework includes a transparent and generally applicable method to derive emission corridors. The basic idea is to sequentially maximize (minimize) the amount of emissions in order to calculate the upper (lower) bound of the emission corridor for a series of interesting points over time. The respective intertemporal optimization has to take into account simultaneously the predefined environmental, climatic, social, and economic constraints as well as the dynamic relationships connecting climate impacts, climate, and society. The corridor calculation problem is therefore formulated as a series of optimal control problems that can be solved by well-established numerical algorithms applied routinely in standard intertemporal optimization tasks. Framing the corridor calculation problem in such a way considerably enhances the comprehensibility of the TWA. Moreover, this procedure emphasizes that the TWA is a general concept that can be operationalized by different numerical methods and (integrated assessment) models.

Ever since the signing of the UNFCCC in 1992, scientists and policymakers alike have been pondering the meaning of its Article 2: what constitutes a "dangerous anthropogenic interference with the climate system" (see for example, Moss 1995, Parry et al. 1996). The IPCC Second Assessment Report devoted a special conference (IPCC, 1994) to the topic and its synthesis document attempted to summarize the most important findings in the spirit of Article 2 (IPCC, 1995). The question of "dangerous anthropogenic interference" is also one of the nine policy-relevant scientific questions addressed by the Synthesis Report of the IPCC's Third Assessment (IPCC, 2001). Traditional climate impact assessments study effects of a 2xCO2-equivalent climate on selected sectors in relatively small regions. They are very useful for giving some broad estimates of the risks, but they are not very helpful in providing clues for answering the "dangerous interference" question. Neither can their results be used in the context of the inverse approach as required by the ICLIPS IAM. There is clearly a need for alternative formulations of climate impact assessments in order to make them more policy relevant. Recent work by Mendelsohn and Schlesinger (1999), Mendelsohn et al. (1999), Tol (1999a, 1999b), and Nordhaus and Boyer (2000) represent efforts in rather different directions. The contribution by the ICLIPS project to alleviating this problem is the development and implementation of the concept of CIRFs.

According to its definition (Toth et al., 2000), a CIRF describes how a particular climate-sensitive sector responds to changes in relevant climatic attributes across a whole range of plausible climate change patterns under a broad diversity of socioeconomic conditions. Füssel et al. (2003) present a detailed description of the procedure for deriving CIRFs. The procedure starts with applying the scaled scenario approach to concisely describe future climate states while taking into account the spatial and seasonal variability in the climate anomalies as simulated in transient general circulation model (GCM) experiments. The resulting representative samples of future climate states or scenarios are used as input to drive simulation runs of sectoral impact models. This leads to a CIRF that denotes a kind of dose-response relationship between a small number of climatic variables, on the one hand, and an indicator of sectoral impacts of climate change, on the other. CIRFs thus constitute an efficient way of representing simulated impacts of climate change across a wide range of plausible futures. It is important to note that the CIRFs developed so far and presented in this special issue consider only the biophysical processes of climate impacts. The next big research task will be the development of the socioeconomic dimensions of CIRFs in order to properly account for features of vulnerability and processes of adaptation in all impact sectors where adaptation is conceivable.

Füssel et al. (2003) first define the most important requirements for modeling climate change impacts in the context of the TWA as implemented in the ICLIPS IAM. The discussion focuses on the different application modes of CIRFs, on the climatic input to the respective impact models, and on the choice of the appropriate impact indicators. The paper then presents exemplary CIRFs for natural vegetation, agriculture, and water availability that cover a wide range of spatial and thematic aggregation levels. Relevant aspects of a CIRF to be used in the forward and inverse mode are visualized by response surface diagrams, impact isoline diagrams, and balance diagrams. The authors also report the results of selected sensitivity tests conducted to assess the effects of different climate scenarios and aggregation levels on the CIRFs, and on the admissible climate windows derived from them.

CIRFs can be used off-line to study the relationships between incremental climate change and the response of a given impact sector at different levels of spatial aggregation. However, in the ICLIPS framework they are most typically used to define maximum acceptable levels of sectoral impacts in different regions or globally. This ultimately determines the constraints for the respective climate variables of the integrated climate-economy model. To derive the corridor of permitted future carbon emissions, the boundaries of the corridor need to be determined by successively solving a multitude of dynamic optimization problems subject to predefined intertemporal constraints. The resulting enormous computational burden excludes the application of complex GCMs. Therefore, the climate system can only be represented by highly aggregated reduced-form models that are numerically efficient and reproduce the results of GCMs with sufficient accuracy.

Bruckner et al. (2003b) demonstrate that the climate model developed for the ICLIPS IAM fulfils both requirements. The ICLIPS climate model provides data for important climate variables. The model takes into account all major GHGs (CO2, CH4, N2O, halocarbons, SF6, tropospheric and stratospheric O3, and stratospheric water vapor) as well as the radiative effects of aerosols originating from SO2 emissions and from biomass burning. The model produces transient patterns for temperature, precipitation, and cloudiness change supplemented by transient information about various factors (thermal expansion of the ocean, melting of glaciers and ice sheets) leading to sea-level rise.

The biogeochemical modules convert emissions into concentrations whereby CO2, well-mixed gases with well-defined lifetimes, aerosols, and not directly emitted gases are treated differently. The radiative transfer modules calculate radiative forcing values from concentrations. The climate module (in the strict sense) translates radiative forcing into temperature, precipitation, and cloud-cover change. Finally, sea-level rise modules calculate sea-level change from thermal expansion of oceans and ice melting. The scales and complexity of the ICLIPS climate model are comparable to those of the MAGICC model of Hulme et al. (1995) or the reduced-form model by Schlesinger and Jiang (1991).

In contrast to most optimizing IAMs, the intertemporally optimizing ICLIPS model includes carbon cycle and non-CO2 chemistry as well as climate (in the strict sense) and sea-level rise modules that reflect the state-of-the-art understanding of the dynamical behavior of the systems involved. In addition to descriptions of all modules mentioned, Bruckner and his colleagues present climate change pathways resulting from a set of IPCC scenarios published in the Special Report on Emissions Scenarios (IPCC, 2000) and examples of "reachable climate domains" defined as feasible combinations of values of at least two model variables under given restrictions for plausible emission scenarios.

Similarly to all other IAMs, GHG emissions provide a well-defined interface between the economic and the climate systems in the ICLIPS framework. The full impact of these emissions on the climate system, however, will manifest itself over decades or even centuries. Portraying the dynamics of the economic system over such time spans is meaningful only in highly aggregated models. Leimbach and Toth (2003) present a Ramsey-type optimal growth model that has been developed as the appropriate economic model to be coupled directly to the ICLIPS climate model.

The economic growth path is determined by exogenous population and endogenous investment dynamics, as well as by assumptions on productivity change hidden in a technological diffusion model. According to this diffusion model, developing countries close the productivity gap to the most developed countries at different speeds. The model is calibrated for 11 world regions, thereby focusing on interregional linkages that influence the economic growth paths. There are two types of interregional linkages: intertemporal trade and capital mobility. Global capital flows balance out in each period, but regions might build up net foreign assets. Assets are valued at a globally averaged rate of return on capital. To avoid unrealistic magnitudes of capital transfer, all regions are prescribed to have zero net foreign assets in the final period (i.e., in the year 2135).

Climate policy triggers another type of interregional linkage in the model in the form of emission permit trading. The model determines the volume of traded and allocated emission rights at each time step endogenously. This results in a more efficient solution than could be obtained from models with a fixed amount of emission rights to be allocated. However, the initial share of each region in the total budget is predefined by a particular allocation principle. It is a combination of the grandfathering and the equal per capita allocation principles, with a smooth transition from the former to the latter. The point in time when the equal per capita principle becomes fully effective can be exogenously defined. The model allows the implementation of emission ceilings as well as the temporal divergence of obtaining and paying for the permits. With the integration of emission trading, intertemporal trade mainly functions as its balance counterpart (i.e., as payment for emission permit imports/exports). The economic model is nested within a master problem to obtain an equilibrium solution. Within the master problem, the welfare weights of the regions are adjusted to offset intertemporal trade balance deficits that might cause an unreasonable redistribution of income.

3.3 Incorporating technological learning and land-use change

Probably the most ferociously debated issue in climate change mitigation over the past few years has been the timing of various mitigation actions. Several factors influence the relationships between the near-term and long-term mitigation portfolio, but the central thread of the debate revolves around technological development. How ambitious should near-term emission reductions be in order to trigger the development of low-carbon, non-carbon, and energy-efficiency technologies that will decrease the reduction costs decades later? Is it efficient or wasteful to undertake massive reductions in the near term when technologies improve rapidly and there is a non-negligible risk of premature lock-in to inefficient technologies? Finally, how much "doing" is needed for "learning" about emerging technologies to drive down their costs? Recent attempts to come to grips with these questions include those of Grubb (1997), Schneider and Goulder (1997), Goulder and Schneider (1999), and Grübler and Messner (1998).

Traditional approaches to the problem of establishing mitigation cost curves assume static relationships between the magnitude and the costs of carbon reduction over time and do not provide regional details. An explicit evaluation of uncertainties is usually omitted as well. In most cases, carbon mitigation costs are incorporated in a "generic" form without any real comparison of the assumptions behind the baseline scenarios and their variants. This largely explains the wide spread of estimates of carbon reduction costs in the literature, as demonstrated by recent comprehensive surveys of mitigation costs by Hourcade et al. (2001), Barker et al. (2001), and Toth et al. (2001).

The ICLIPS framework incorporates a new approach to estimating dynamic regional carbon mitigation cost functions, a contribution by Gritsevskyi and Schrattenholzer (2003). The procedure is based on the integrated modeling framework developed at IIASA. The authors consider processes of technological changes in energy systems over the long term in the context of macroeconomic models and establish relatively simple relationships between mitigation actions, technological changes, and their effects on economic development. They use the IIASA scenario database, which contains a number of mitigation cases based on a multitude of scenario runs, and derive dynamic carbon mitigation cost curves through statistical analysis of available data from iterations with the MESSAGE-MACRO model. This global model operates at the level of 11 world regions and includes detailed information on several hundred technologies. It can consistently explore complex emission reduction policy questions by combining the virtues of energy system models and macroeconomic models.

The regionalization, calibration, and underlying assumptions of the IIASA dynamic mitigation cost functions and the ICLIPS aggregated economic model have been harmonized to the maximum possible extent. This permitted the full integration of the cost functions into the ICLIPS IAM. The derivation of carbon emission corridors in ICLIPS model applications has benefited from the IIASA effort to model technological learning.

Besides fossil energy, changes in land use and land cover and activities in different sectors of agriculture are also important sources and potential sinks of GHGs. It is therefore essential to consider the most important processes governing emissions in land use and agriculture. Instead of venturing into the development of a new model, the ICLIPS project adopted the Agriculture and Land Use (AgLU) model developed as part of the MiniCAM system by the Battelle Pacific Northwest National Laboratory in Washington, D.C. (Edmonds et al., 1996a, 1996b). The contribution by Sands and Leimbach (2003) explains the main features of this module and how the original model was modified to fit into the ICLIPS framework.

The AgLU module of the ICLIPS framework is designed to simulate carbon emissions from land-use change. As energy prices rise, commercial biomass expands its share of land. The model provides estimates of carbon emissions from land-use change over the next century in response to changing populations, incomes, and agricultural technologies. It can evaluate the role of commercial biomass and its impact on land use in a carbon-constrained world.

The model allocates land to crops, pasture, or forests in the 11 world regions of the ICLIPS model according to the economic return from each land use. Economic return is calculated as crop revenue per hectare less costs of production. Land allocation is affected by the demand for agricultural products, which is driven by population growth and economic development as computed by the ICLIPS aggregated economic model. Land allocation may also be affected by changes in yield, by technical change, and by carbon mitigation scenarios that provide an incentive for biomass crops. Carbon densities are applied to each land-use category to provide an estimate of the carbon stock during each 15-

year time step. Carbon emissions from land-use change are calculated as the difference in carbon stock between periods.

Specific routines are provided to couple the AgLU module with the ICLIPS core model. The latter is programmed in a different language and runs on a different hardware platform. At run-time, AgLU is called from ICLIPS' core model iteratively, receiving data on population development, GDP growth, and carbon price evolution. The resulting emissions profiles for CO2 are sent back to the core model, changing the total GHG emissions in forward mode and modifying the shape of the emission corridor in inverse mode. Convergence is reached after a few iterations.

3.4 Soft coupling with a medium-term economic model

The inverse approach as analytical framework and the ICLIPS IAM as modeling tool are developed to serve the main objective of the project: to provide policy-relevant insights for long-term climate policy. The emission corridors computed by the ICLIPS model contain all permitted century-long emission paths under a given set of constraints. However, when it comes to implementation, more detailed information is needed about the relative short- to medium-term virtues of "promising" or "interesting" long-term paths. The Dynamic Applied Regional Trade (DART) model developed and presented by Klepper and Springer (2003) for the ICLIPS project serves this objective. It is a useful addition to the group of medium-term models that have been extensively used recently to estimate the costs of different medium-term emission reduction policies, including the Kyoto Protocol (see the G-Cubed model by McKibbin et al. (1999), the MS-MRT model by Bernstein et al. (1999a, 1999b), the Oxford Global Macroeconomic and Energy Model by Cooper et al. (1999), the GREEN model by Mensbrugghe (1998), and many others).

DART is a global, recursive-dynamic, multi-region, multi-sector computable general equilibrium (CGE) model. It disaggregates the world economy into 11 regions and 10 sectors. The regions are linked by bilateral trade flows. The economic structure is fully specified for each region and incorporates production, consumption, investment, and governmental activity. All markets are perfectly competitive. A detailed model of the energy sector allows substitutions between fossil fuels with different carbon intensities in the production and consumption patterns of the private agents. The model dynamics are characterized by off-steady state growth. This specification is especially important for the analyzed time span of about 40 years for regions like China, Africa, Latin America, and some Asian countries.

The DART model is calibrated regionally for different parameters like exogenous technological progress, savings rates, population growth rate, and the growth rate of human capital. For the initial period, the CGE model is calibrated by using the Global Trade Analysis Project (GTAP) database version 3 for 1992 (McDougall, 1997). This GTAP data set is adjusted for primary energy flow data from the International Energy Agency (IEA, 1997a, 1997b, 1997c), which provide statistics on physical fossil fuel flows and prices for industrial and household demand. The CO2 emissions stemming from the use of fossil fuels over the simulation horizon are calibrated on the projections of the "back to coal" scenario by IIASA and the World Energy Council (Nakicenovic et al., 1998) for each type of fossil fuel. This scenario is the most carbon-intensive one among those energy projections and thus represents the least favorable case for an international climate protection policy. Worldwide GHG emissions start from around 6 gigatons of carbon (GtC) in 1993 and rise up to 12 GtC in 2030.

To the greatest extent possible, the calibration and scenario assumptions of the DART model are harmonized with the ICLIPS IAM. Nevertheless, there are limits to the extent of this harmonization. The present version of the DART model assumes across-the-board technological improvement for the economy as a whole but does not include autonomous energy efficiency improvement, cost decline due to learning by doing, or backstop technologies. Mechanisms for international emission trading are not implemented either. These features of the model explain why its cost estimates tend toward the high end of the spectrum compared with results from similar models.

Klepper and Springer (2003) use the DART model for a case study based on a modified version of the proposal by the German Advisory Council on Global Change (WBGU). The Council proposes an annual CO2 emission reduction by 3 percent from 2000 onward for the industrialized countries (the Klepper-Springer version starts this mitigation in 1995) and constant emissions for the developing countries after 2010. These reduction targets would keep global carbon emission nearly constant at 6 GtC over the simulation horizon until 2030. Not surprisingly, the authors find that these drastic emission reductions result in high welfare costs that amount to global welfare losses of 16 percent relative to the benchmark in 2030 measured in Hicksian Equivalent Variation. (This welfare measure indicates the maximum amount losers from the policy would be willing to pay in order to prevent the policy). This global welfare loss is not equally distributed across the regions. Pacific Asian countries and India gain in terms of welfare while all other regions lose from the policy proposal by the WBGU. The emission reduction objectives can only be fulfilled through a considerable decrease in output of production, especially in the energy-intensive sectors, because adjustment potentials via expenditure switching are exhausted. Thus, the reduction in output of the energy-intensive sectors ranges between 20 and 80 percent relative to the benchmark in 2030.

The attempt to build the ICLIPS aggregated economic model and the DART model as a harmonized model set and the modest achievements of the effort reconfirm the necessity and the difficulties of developing different but harmonized tools to address different aspects of climate policy, in this case long-term climate stabilization (ICLIPS IAM) and medium-term emission reduction (DART). One possibility might be a telescope-like model that properly blends high-resolution general equilibrium models (with increasingly aggregated sectors over time ending up with a single production function for each region beyond 70 to 80 years) and optimal growth models that keep track of the long-term intertemporal optimization features (e.g., consumption, capital accumulation, and capital transfer).

4. Illustrative results from the ICLIPS model

The ICLIPS IAM presented in the preceding section can be used in "forward mode" for policy simulations to determine the implications of a given set of assumptions about socioeconomic development and associated greenhouse gas emissions on climate change and its impacts. But its unique feature stems from the possibility to demarcate the emission policy space under exogenously specified environmental and social targets in inverse mode. Whatever form the inverse application of the ICLIPS model takes, it always consists of three steps. The first step is to solicit the climate-change-related constraints from the participating social actors. The most convenient way to explore what might be the limits to manageable climate change impacts is to use the CIRFs for the impact sector of concern. Limits to the social costs of emission reductions also need to be specified. This is the normative or social decision part of the exercise. The second step is to apply the ICLIPS model to check whether there exists a corridor of long-term emission paths that satisfy the specified policy constraints. The third step is to formulate additional (secondary) climate-related concerns or, more typically, general non-climatic but mitigation-related targets, policy concerns, or hypotheses, and to select among the permitted paths accordingly. This step also involves supplementary runs of the ICLIPS model. The full cycle can then be repeated in several rounds in which model users can explore the implications of what they want in terms of acceptable/unacceptable climate change impacts and what they can get given their willingness to sacrifice a fraction of their income in terms of acceptable mitigation costs. This iterative application process reinforces the TWA as a policy exploration framework.

Some of the "additional concerns" solicited and analyzed in step 3 above are rather obvious and can be easily implemented with the integrated model. Additional information about the least-cost path, for example, can be extracted from any given model run. Leimbach and Toth (2003) present total and discounted costs, burden-sharing implications, permit trade flows, and other relevant information about selected emission paths within the corridor. They also demonstrate the ability of the ICLIPS model to illustrate how the CO2 emission corridor would change under different assumptions about non-CO2 emissions even if the same impact and cost constraints are used.

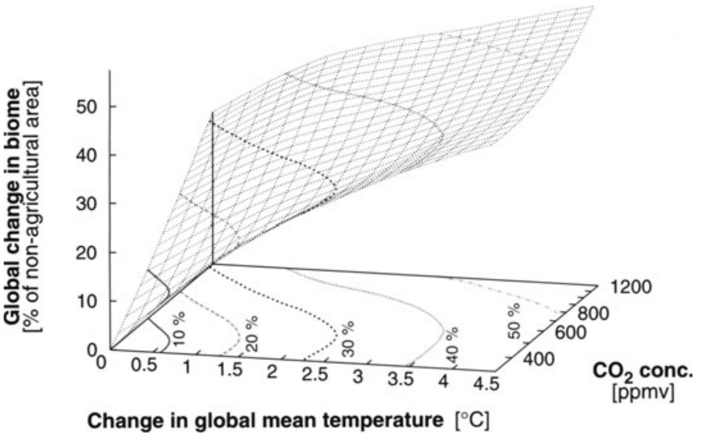
Thus an inverse application of the ICLIPS IAM always starts with the "decision step" in which users define normative constraints to exclude climate change impacts and socio-economic consequences of mitigation measures that they perceive to be unacceptable. In the second, "analysis step", the model is applied to derive a carbon emission corridor that comprises all admissible climate protection strategies, i.e., the bundle of all emission paths that are compatible with the pre-defined constraints.

To foster an informed choice of what might be an unacceptable climate change impact, climate impact response functions (CIRFs) have been developed to describe how a particular climate-sensitive sector responds to changes in relevant climatic attributes (see previous section). CIRFs are produced by applying the scaled scenario approach first to concisely describe future climate states while taking into account the spatial and seasonal variability in the climate anomalies as simulated in transient GCM experiments. Representative samples of future climate states are then used to drive simulation runs of geographically explicit sectoral impact models. The resulting CIRF indicates the relationship between the relevant climatic variables and a sectoral impact indicator and efficiently represents simulated impacts of climate change across a wide range of plausible futures. A pilot set of CIRFs has been developed for agricultural crops, water availability, and natural vegetation (Füssel et al., 2003). The latter is taken here to illustrate the application of the ICLIPS IAM in inverse mode.

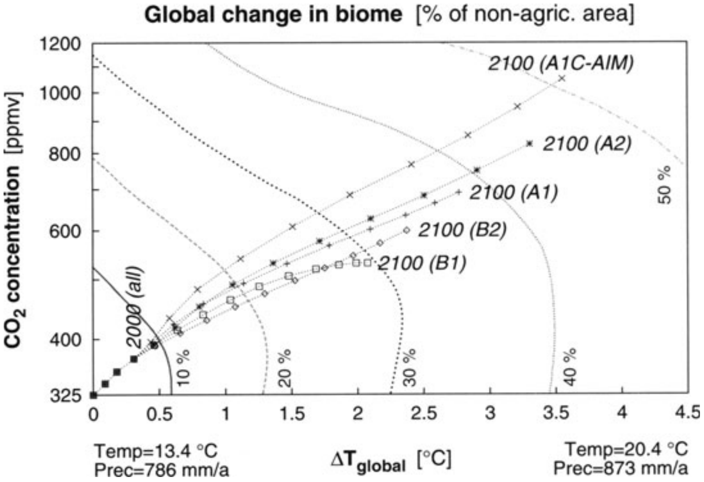
In order to establish CIRFs of the terrestrial ecosystems, a suitably adopted version of the BIOME 1 global vegetation model (Prentice et al. 1992) has been used to assess the response of ecosystems to the incremental forcing by combinations of climate change and CO2 concentrations. For each 0.5° by 0.5° grid cell of the land surface (agricultural areas masked out), the model determines which one of the 14 distinguished biomes will dominate on the basis of local climate, atmospheric CO2, and soil conditions. Figure 9.3a shows the resulting response surface diagram as a dose-effect relationship between the two forcing variables in the horizontal plane and the fraction of non-agricultural areas undergoing a biome change as impact indicator on the vertical axis. Figure 9.3b displays the associated impact isoline diagram in the climate-CO2 concentration plane, together with the implications of a series of emission scenarios developed by the IPCC on CO2 concentration and climate.

Let us assume a global policy agreement that transforming more than 35% of the earth's ecosystem would constitute a dangerous climate change impact, while mitigation costs exceeding 2% of the per-capita consumption of any present or future generation in any region would be socially unacceptable as well. For the purposes of this analysis we also assume that a compromise-based allocation of emission rights starts with the status quo and will be gradually transformed to an equal per-capita entitlement by 2050.

Figure 9.4a shows the resulting carbon emission corridor, selected interesting paths to illustrate its internal structure, and the cost-effective path. It follows from the conceptual foundations of the inverse approach that any point within the corridor can be reached by at least one permitted emission path, but an arbitrary path is not necessarily a permitted path. For example, the upper boundary of the corridor can be reached in 2065 only if emissions remain far inside the corridor (substantially below baseline emissions) for several decades in the first half of the 21^{st} century. The cost-effective path (the least-cost emission path for the given environmental target in terms of global welfare losses), in contrast, follows the baseline up to about 2040 and switches to an accelerating reduction path as both autonomous and learning-by-doing types of technological development make mitigation efforts less expensive.

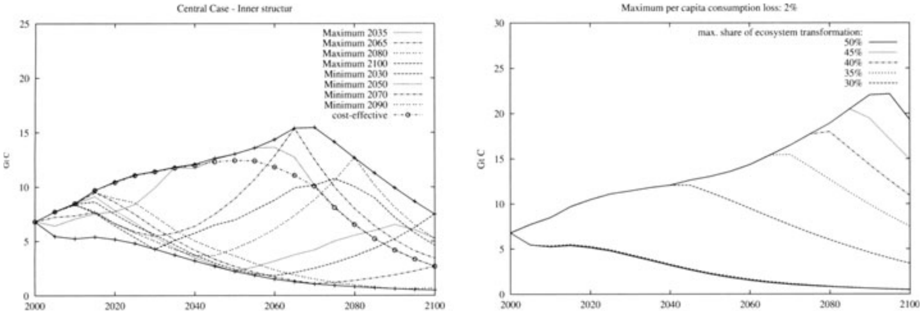


(a) Three-dimensional response surface diagram



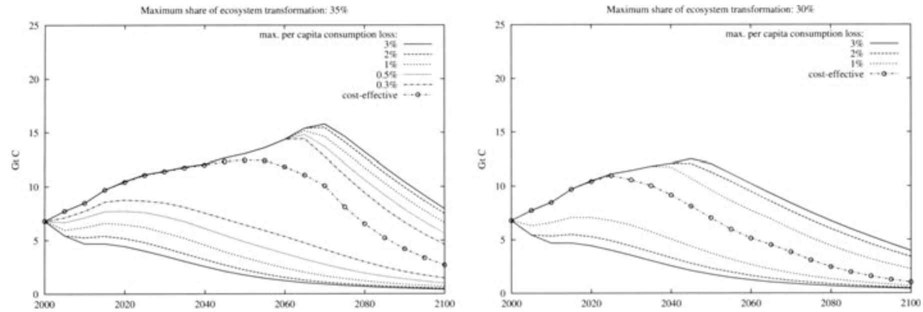
(b) Isolines of global biome change and CO2-climate change paths of selected IPCC SRES scenarios

Figure 2.3. Climate impact response function of global natural vegetation change in non-agricultural areas. The underlying climate change pattern has been derived from the ECHAM4 general circulation model (Roeckner et al., 1996). The change in global mean temperature (ΔT- -global) is specified relative to the baseline climate (1961-1990). Values under the horizontal axis indicate ranges for annual mean temperature (T) and precipitation (P) from the baseline climate (left) to the upper limit of climate change considered in the model runs (4.5 ^{o}C increase, right) over the continental land surface.



(a) Energy-related carbon emission corridor for the central case (maximum 35% ecosystems change, maximum 2% per capita consumption loss), its internal structure and the cost-effective emission path.

(b) Emission corridors for different ecosystems transformation limits with maximum 2% per capita consumption loss

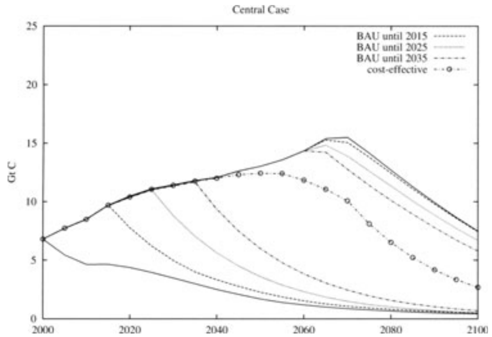


(c) Emission corridors for 35% ecosystems transformation limit with different per capita consumption loss due to climate protection

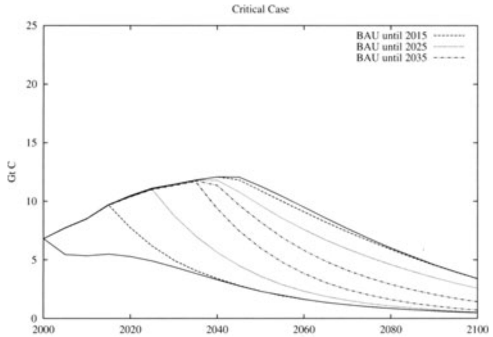
(d) Emission corridors for 30% ecosystems transformation limit with different per capita consumption loss due to climate protection

Figure 2.4. Corridor for energy-related CO2 emission in the 21^{st} century for the central policy target when ecosystem transformation in non-agricultural areas is not permitted to exceed 35% globally and carbon mitigation costs are limited to 2% of per capita consumption. The internal structure is illustrated by emission paths that hit the upper/lower boundary of the corridor in selected years (4A). Sensitivity of corridors to varying the limit to ecosystem transformation combined with 2% consumption loss ceiling (4B), to varying the cost constraint combined with 35% (4C) and 30% (4D) ecosystem transformation limits.

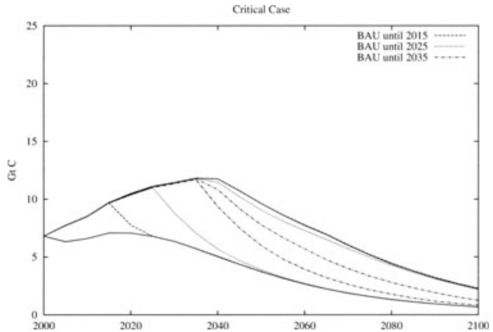
Figure 9.4b shows the sensitivity cases when the acceptable share of ecosystem transformation is varied in the range of 30 to 50%. The 30% limit results in a drastically narrower emission corridor requiring a departure from the baseline emission path within the next three decades (see also Figure 9.4d). Conversely, if the global society was willing to allow half of the world's ecosystems undergo biome changes, the corridor of acceptable carbon emission paths would be much wider permitting higher annual and cumulative emissions. Reducing



(a) Emission corridors for the central case (maximum 35% ecosystems change, maximum 2% per capita consumption loss) with incremental delays in the diversion from the baseline emission path.



(b) Emission corridors for the case of maximum 30% ecosystems change, maximum 2% per capita consumption loss with incremental delays in the diversion from the baseline emission path.



(c) Emission corridors for the case of maximum 30% ecosystems change, maximum 1% per capita consumption loss with incremental delays in the diversion from the baseline emission path.

Figure 2.5. The sensitivity of the energy-related CO2 emission corridor to delaying the diversion from the baseline emission path for up to several decades for the central policy target (5A), when the ecosystem transformation limit is set to 30% (5B), and when the latter is combined with a mitigation cost limit of 1% (5C).

the acceptable consumption loss due to climate protection costs to 1% leads to marginally narrower emission corridors for the same environmental targets.

Another set of corridors (Figure 9.4c) indicates the sensitivity of the resulting policy space to societies' willingness to pay for climate change mitigation. The limit to acceptable mitigation costs is varied between 0.3 and 3% consumption loss for the central case of maximum 35% ecosystem transformation. The corridor is only modestly sensitive to the cost limitation. Setting the limit of ecosystem transformation to 30%, however, leads to much narrower corridors (Fig 4D). It requires at least about 1% consumption loss, and the policy space cannot be substantially increased even if we allowed income losses reaching 3%. The results imply that, due to the emissions already in the atmosphere and the inertia in the earth system, a transformation of ecosystems in about 30% of non-agricultural areas would not be possible to avoid by reducing carbon emissions alone. Future extensions of the model should allow the exploration of how much flexibility will be provided by mitigating other greenhouse gases.

The timing of mitigation action has been the subject of fierce debates in climate policy in recent years. We investigate the implications of proceeding along the baseline emission path until 2015, 2025, and 2035, respectively, while the impact and cost constraints remain those specified for our central case above (Figure 9.5a). The implications for the corridor of delaying emission reductions are rather modest. The cost-effective path for the base case without prescribed delay lies comfortably within the corridor of the 35-year delay case. The situation is dramatically different if the limit to ecosystem transformation is set to 30% (Figure 9.5b). The already narrow corridor of the no-delay case becomes a very tight lane of sustained emission reduction. If the cost limit is set to 1% consumption loss, the corridor of feasible paths still exists but it is practically reduced to a slim path of decarbonizing the world economy at the maximum rate required by the environmental target and permitted by the declining-cost technologies and the reduction rate constraint (Figure 9.5c).

The results show the extreme importance of the environmental target in defining the climate policy space. The existence and the shape of the emission corridor is more sensitive to the choice of the acceptable climate change impact than to the limits to mitigation costs, emission rights allocations or the timing of emission reductions. This reconfirms the fact that CO2 is a stock pollutant, its management requires long-term perspectives to secure both climate protection and sustainable development, and the effectiveness of near-term action, even with high willingness to pay, is limited. The results also highlight the importance of improving our understanding of the implications of climate change and of the options for and costs of reducing the vulnerability and increasing the adaptive capacity of the affected systems (although this may be rather limited in the case of natural ecosystems). Nonetheless, the emission corridors clearly show that over the long-term carbon emissions must decline significantly below their current levels for any plausible target of avoiding major transformations of the world's ecosystems and socioeconomic sectors influenced by climate.

5. Summary and conclusions

More than two decades of exponentially increasing efforts to tackle the problem of anthropogenic climate change by linking economic and climate models have produced a large array of impressive innovations. They range from conceptual groundwork concerning the incorporation and treatment of uncertainties in integrated models to massive number crunching operations to explore a large array of socioeconomic development and emissions scenarios or technology dynamics paths and their implications. The ultimate objective of most activities is to contribute to solving the multiple-scale policy puzzle of managing the risk of climate change. To this end, suitably modified versions of traditional decision analytical frameworks (cost-benefit and cost-effectiveness analysis, game theory, etc.) are used or new theoretical frameworks are developed to support integrated climate-economy modelling. One of the new developments in recent years is the tolerable windows or inverse approach.

The inverse approach can be taken as a policy exploration framework that incorporates elements of the policy evaluation and policy optimization frameworks. It can be used as a policy evaluation model by specifying assumptions about the future evolution of exogenous (scenario) variables to track their implications for GHG emissions, climate change, and impacts in sectors for which climate impact response functions (CIRFs) are available. It can also be used as a policy optimization model in cost-effectiveness mode to identify the least-cost emission path under an externally specified climate change or impact constraint. Nonetheless, the distinctive feature of the tolerable windows framework is its ability to demarcate a range of permitted emission paths according to externally specified combinations of impact and mitigation cost ceilings.

One key consideration in developing the TWA is the following. It is always difficult (and often controversial) to account for all costs and benefits of even a relatively small, local/regional environmental project where the economic, social, and cultural characteristics of the affected communities are likely to be much more homogeneous than is the case for a pervasive global risk like climate change. Moreover, climate policy at the national scale cuts across many other sectoral policies ranging from energy, agriculture, regional development, transport, and forestry all the way to industrial development and foreign trade policies. This suggests that there might be substantial value in establishing a field of GHG emission paths that satisfies some basic climate-related concerns and permits the selection of the actual emission path to follow within the field by observing additional concerns that were not explicitly represented in the climate policy model.

The ICLIPS integrated assessment framework includes several elements that are required for a truly comprehensive treatment of the climate change problem: climate impact response functions, a deeply integrated economy-climate model with optimization capability and incorporating technological learning in the form of dynamic cost functions as well as land-use dynamics and related emissions and sequestration opportunities as an integrated sub-module. Moreover, harmonizing some features between the highly aggregated optimal growth model and a disaggregated computed general equilibrium model is one of the first attempts to explore the issues of and linkages between long-term climate and GHG-concentration stabilization and near-term emission reductions in a coordinated manner in the same assessment framework.

Notwithstanding the many achievements in the field, of which the ICLIPS work reported in this chapter is but one, lots of unresolved issues remain. The multiplicity of temporal, spatial, and jurisdictional scales, the diversity of possible strategic responses and their implications for other sectors of the economy and society not affected by climate change directly call for a fully integrated analytical framework. This is necessary for proper representations of the numerous cross-scale and cross-sectoral linkages and feedbacks in the analysis to provide usable and reliable assessments of trade-offs and synergies among policies and implementation strategies. Yet full integration of all relevant models in their full depth would be impractical if at all feasible. One solution might be a multi-layer integrated assessment framework that incorporates vertically integrated modules of the relevant components of the climate-economy-society system at different levels of aggregation. For example, the economic module should consist of a telescope-type model that spans across three layers: a highly aggregated optimal-growth model to deal with the long-term dynamics of investments, consumptions, and climate protection expenses; a medium-resolution multisectoral and multiregional computed general equilibrium model to assess intersectoral and trade implications, and a high-resolution technology-economy model or generally equilibrium model with nested production functions down to deep technological details to explore the implications of innovation, technology dynamics, sectoral repercussions of different response strategies. A similar telescope-type climate model could span from the currently used highly aggregated carbon-cycle, greenhouse gas, and climate models to the so-called medium-complexity climate models to the high-resolution coupled general circulation models. Such an integrated framework would enable horizontal (coupling the highly aggregated sectoral modules in an analytical framework suitable for the questions being asked) as well as vertical assessments of the detailed sectoral implications of the results from the aggregated analysis.

Observing the diverse and intense debates at the international negotiations and in many countries at the national and sectoral levels, climate change appears to be one of the most difficult environmental problems public policymakers and private stakeholders need to cope with. The complexities and uncertainties of the issues involved raise considerable conceptual and methodological challenges for the scientific community. Integrated assessment models and coupled climate-economy models have emerged as the bridge between climate change science and policy. As this chapter demonstrates, the numerous open questions and the diverse modelling challenges will require more innovative approaches and a lot of additional concentrated efforts in model integration in order to provide improving and usable knowledge for policymaking.

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Chapter 3

AN ORACLE METHOD TO COUPLE CLIMATE AND ECONOMIC DYNAMICS

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Abstract This paper deals with an oracle method to couple economic and climate models. The approach permits a dialogue between two models pertaining to two different scientific domains, the climate module being a fully-coupled ocean-atmosphere-sea ice model, whereas the economic module is an adaptation of the neo-classical optimal economic growth paradigm. The paper explains how the Analytic Center Cutting Plane Method (ACCPM) is implemented to integrate in the optimal economic growth model a constraint on climate change that is computed from the climate model runs. Several experiments show the usefulness of the approach to build new types of integrated assessment meta-models.

1. Introduction

The aim of this paper is to describe an oracle method that is used to couple an economic growth model, namely an adaptation of the DICE99 model of Nordhaus and Boyer, 2000, with an efficient climate model with three-dimensional ocean dynamics, in our case C-GOLDSTEIN (Edwards and Marsh, to appear). The coupling is implemented through the use of a large-scale convex programming method, called ACCPM[1] (Goffin et al., 1992). In this approach, a dialogue is established between the economic model and the climate model through the exchange of a coupling vector of variables, namely the schedule of atmospheric concentration of GHGs over a series of milestones encompassing a 200 year planning horizon. The two models play the role of "oracles" which respond to

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[1] Analytic Center Cutting Plane Method.

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a proposed concentration schedule with an economic growth scenario and a distribution of temperature increases respectively. In ACCPM, a master program controls this exchange of information between the two models in order to obtain an optimal economic growth that satisfies a climate impact constraint represented by a bound on an "area over threshold" (AOT) temperature functional. This method has already been successfully used to couple a techno-economic energy model and a local air pollution (ozone) model, as reported by Carlson et al., 2004. The advantage of the method is that it permits the analyst to retain each model in its full generality and level of detail and to overcome the difficulties tied with the different time and space scales involved in economics and climate models respectively. This approach is similar in spirit to the *Community integrated assessment* advocated by Jaeger et al., 2002 for coupling insights gained from different modelling communities.

The paper is organized as follows: in section 2 we discuss the challenge of developing integrated assessment models for climate policies in which economic, climate and impact submodels have to be linked together in a coherent whole; in section 3 we briefly describe the main features of the C-GOLDSTEIN model; in section 4 we present an adaptation of the DICE99 model where the equations representing temperature increase and impacts have been removed; in section 5 we describe the implementation of ACCPM to realize the coupling; in section 6 we present numerical results for a set of simulations and in Conclusion we envision other possible implementations of the method and we discuss its usefulness for the creation of a new class of integrated assessment meta-models.

2. The challenge of integrated assessment

DICE94 (Nordhaus, 1992; Nordhaus, 1994) and IMAGE (Alcamo, 1994) are the archetypal integrated assessment models[2] for climate change policies. In

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[2] We quote below the definition proposed in the Ulysses project web site http://www.zit.tu-darmstadt.de/ulysses

> Integrated Assessment (IA) can be defined as an interdisciplinary process of combining, interpreting and communicating knowledge from diverse scientific disciplines in such a way that the whole cause-effect chain of a problem can be evaluated from a synoptic perspective with two characteristics: (i) it should have added value compared to single disciplinary assessment; and (ii) it should provide useful information to decision makers.
>
> Integrated Assessment Model (IAM) : a computer simulation program representing a coupled natural system and a socio-economic system, modelling one or more cause-effect chains including feedback loops, and explicitly designed to serve as a tool to analyze policies in order to guide and inform the policy process, mostly by means of scenario analysis. This explicit policy purpose defines the difference between IAMs and Earth System Models (ESMs) such as Atmosphere

the case of DICE94, a neo-classical economic growth model has been augmented to include simplified representations of the accumulation of GHGs and of the resulting increase in average atmospheric temperature, as well as the economic impact (represented as a production loss) of this temperature change. In the case of IMAGE the model contains representations of three major subsystems, namely climate, biosphere and society. The global model components corresponding to these subsystems describe the atmosphere and ocean, the terrestrial environment and the energy and industry. Several other IAMs have been proposed recently. We shall refer in particular to DICE99 and RICE that are the successors of DICE94 with an improved description of the carbon cycle and a multi-regional description of the economic growth process, and to ICLIPS (Leimbach et al., 2003) that has been developed and used for the definition of *tolerable windows* in climate change scenarios. Another strand of IAM development is represented by the MERGE model (Manne et al., 1995) based on a combination of a macro-economic growth, an energy use and a temperature change sub-model.

In all these examples of IAMs the modellers have created a single system that integrates the descriptions of the different sub-systems in modules that are interconnected. In doing this integration the model developers have had to solve delicate problems of time and space scaling in the joint representation of the dynamics in different submodules. Typically in IAMs the description of the temperature change dynamics is reduced to a very schematic form, compared to the description used in GCMs. In such a representation the IAM remains highly computationally efficient, the simple form of the climate representation allowing optimal solutions to be obtained, often by relying on the analytical form of the representation to invert the relation between climate forcing and climatic response. In contrast, the models most widely used in the climate modelling community to predict possible climatic responses to anthropogenic forcing, have high spatial resolution and can take months of computation to simulate a few hundred years, while the dynamics of the system are such that the full impact of the forcing is only realized on a timescale of thousands of years. Furthermore, each integration of such a model is only a single realization of a chaotic system. The analysis of the expected feedback between policy choices and climatic responses, and the associated uncertainties, in a coupled IAM would clearly be exceptionally difficult using such climate models. However, simpler climate models are severely restricted in their ability to faithfully represent dynamical responses and regional contrasts.

Taking a step towards the use of more complex climate modules in IAMs (Bahn et al., in preparation) use the reduced dimensionality Bern 2.5D model

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Ocean General Circulation Models (GCMs) and geochemical models, which are designed primarily for scientific purposes. It should however be noted that ESMs such as GCMs could also be used (and in fact they are) to look at policy questions.

to estimate constraints on total atmospheric warming and rate of warming to avoid a collapse of the Atlantic thermohaline circulation (THC). These constraints are then applied to the extremely simple, analytical climate submodule within MERGE. In this approach MERGE is therefore able to make use of results from a somewhat more realistic climate model although not in a fully consistent way. In this paper we demonstrate the possibility of incorporating a climate model, in our case with a fully 3-dimensional ocean component, within the solution procedure of the IAM. Thus the climatic response to forcing assumed by the economic module is consistently produced by the climate module itself at every iteration. Our approach is still not completely consistent, since the climate module does not include a complete, closed carbon cycle, thus the transfer of atmospheric carbon to the surface and deep ocean is still represented by the simple, 3-equation system of DICE99. However, this inconsistency could be removed by the inclusion of the appropriate climatic processes without modification to the fundamental structure of our integrated modelling approach. The present system, although simplified, is therefore sufficient to demonstrate the effectiveness of the coupling strategy itself. In a subsequent paper we plan to repeat the experiment, directly simulating the ocean and land carbon cycle using the coupled Earth System Model developed in the GENIE (Grid Enabled Integrated Earth System Model) project[3], which includes C-GOLDSTEIN as a subcomponent.

3. The climate model: C-GOLDSTEIN

We use a simplified climate model, C-GOLDSTEIN, which is intermediate in complexity and computational efficiency between the intensively studied and very costly general circulation models (GCMs) such as HadCM3 (Gordon et al., 2000) or CCSM (Boville and Gent, 1998), and highly efficient models of lower dimensionality such as the Bern 2.5-D model. The latter uses 2-D representations of the flow in each ocean basin following Wright and Stocker, 1991, whereas C-GOLDSTEIN has low resolution, but includes a fully 3-D global ocean, coupled to a 2-D atmosphere and a dynamical and thermodynamical sea-ice component. Largely as a result of low resolution and simplified dynamics, the model is significantly more efficient than other intermediate complexity climate models described in the literature, such as the UVic model (Weaver et al., 2001), FORTE (Sinha and Smith, 2002) and ECBILT-CLIO (Goosse et al., 2001), taking one or two hours to complete a 1000-year integration on a PC. The model is described in detail by Edwards and Marsh, (to appear) who show that it gives a reasonable representation of modern climate and also investigate the model's parameter sensitivity using an ensemble of 1000 runs of 2000 years in length. Using the same model, Marsh et al. consider the possibility of a collapse of the North Atlantic thermohaline circulation in an extensive study representing around 40 million years of total integration time. It is thus an

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[3] http://www.genie.ac.uk

appropriately simple and efficient model, capable of representing at least some of the expected large-scale climatic responses to anthropogenically induced climate change. Below we give a concise summary of the dynamics of each model subcomponent.

3.1 Ocean component

The ocean model is based on the thermocline (or planetary geostrophic) equations with the addition of a linear drag term in the horizontal momentum equations. We therefore refer to the model as a frictional geostrophic (FG) model. Dynamically, the model is therefore similar to classical GCMs, but neglects momentum advection and acceleration. The ocean density, ρ, depends nonlinearly on the local values of temperature T and salinity S, which obey separate advection-diffusion equations and are also subject to convective adjustment. Earlier versions of the model were used by Edwards and Shepherd, 2002, Edwards et al., 1998, Edwards, 1996.

Referred to spherical polar coordinates (ϕ, s, z), where ϕ is longitude, $s = \sin\theta$, θ is latitude and z is measured vertically upwards, the governing equations can be expressed in the dimensionless form

$$-sv = -\frac{1}{c}\frac{\partial p}{\partial \phi} - \lambda u \tag{1}$$

$$su = -c\frac{\partial p}{\partial s} - \lambda v \tag{2}$$

$$-\rho = \frac{\partial p}{\partial z} \tag{3}$$

$$0 = \frac{\partial}{\partial \phi}(\frac{u}{c}) + \frac{\partial}{\partial s}(vc) + \frac{\partial w}{\partial z} \tag{4}$$

$$\rho = \rho(S,T) \tag{5}$$

$$\frac{D}{Dt}X = \kappa_{\mathrm{h}}\nabla^2 X + \frac{\partial}{\partial z}(\kappa_{\mathrm{v}}\frac{\partial X}{\partial z}) + C \tag{6}$$

The horizontal momentum equations, (1) and (2), express the "geostrophic balance" between the Coriolis term on the left hand side and the gradient of perturbation pressure p, on the right, with the addition of a drag term with coefficient λ. The coefficient $c = \cos\theta$. Horizontal lengths have been scaled by the Earth's radius r_0; vertical lengths by a typical mid-ocean depth H; the horizontal velocity components (u, v) in the (ϕ, s) directions have been scaled by a typical horizontal velocity U; and the vertical velocity w has been scaled by UH/r_0. The vertical pressure gradient in Eq. (3) is in "hydrostatic balance" with the gravitational force. Scalings for p and density ρ are derived from the geostrophic and hydrostatic relations respectively. Eq. (4) expresses mass conservation and Eq. (6) the advection and diffusion of a tracer X representing temperature T or salinity S. D/Dt is the total (or material) derivative[4]. Scal-

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[4] $D/Dt = \partial/\partial t + \mathbf{u}.\nabla$ where $\mathbf{u} = (u, v, w)$ is the three-dimensional velocity vector.

ings for S and T are not necessary because they appear linearly in equation (6); their magnitudes depend on the boundary forcing. The advective time scale r_0/U is used. In practice the horizontal and vertical diffusion of ocean tracers, represented by the second and third terms in Eq. (6), is replaced by an isopycnal diffusion and eddy-induced advection parameterization in which a considerable simplification is obtained by setting the isoneutral diffusivity equal to the skew diffusivity representing eddy-induced advection, as suggested by Griffies, 1998. $\mathcal{C}$ is the convective adjustment term, which acts to remove gravitational instability while conserving S and T. The equation of state, Eq. (5), is linear in salinity S and cubic in temperature T. At all boundaries, the normal component of velocity is set to zero. The ocean is forced by fluxes of heat and salt through the upper boundary and by wind forcing, which is included as a source term in Eqs. (1) and (2) in the uppermost grid level. The fluxes of heat and salt through the lateral and lower boundaries are set to zero. A further modification to the ocean model is the inclusion of a variable upstream weighting for advection.

The equations are discretized on an Arakawa 'C' grid using simple, second order, centered differences in space. A simple forward difference in time provides adequate accuracy, since the time step is limited by numerical constraints, and is twice as efficient as a centered difference in time, since the allowed time step is longer. At each time step the velocity field is determined diagnostically from the density field, and then relaxed back to the velocity used at the previous timestep. The barotropic (or depth-averaged) component of the flow is obtained by direct inversion of the elliptic equation resulting from the vertical integral of the momentum equations. Additionally, a set of linear constraints applies to the barotropic flow around islands. In the vertical there are normally 8 density levels on a uniformly logarithmically stretched grid with vertical spacing increasing with depth from 175 m to 1420 m. The maximum depth is set to 5 km. The horizontal grid is uniform in the (ϕ, s), longitude sin(latitude) coordinates giving boxes of equal area in physical space. The horizontal resolution is normally 36 by 36 cells.

3.2 Atmosphere and land surface

We use an Energy and Moisture Balance Model (EMBM) of the atmosphere, similar to that described by Weaver et al., 2001. The prognostic variables are surface air temperature T_a and surface specific humidity q for which the governing equations can be written

$$\rho_a h_t C_{pa} \left(\frac{\partial T_a}{\partial t} + \nabla.(\beta_T \mathbf{u} T_a) - \nabla.(\kappa_T \nabla T_a) \right) = Q_{SW} C_A + Q_{LW} - Q_{PLW} + Q_{SH} + Q_{LH}, \tag{7}$$

$$\rho_a h_q \left(\frac{\partial q}{\partial t} + \nabla.(\beta_q \mathbf{u} q) - \nabla.(\kappa_q \nabla q) \right) = \rho_o (E - P) \tag{8}$$

where h_t and h_q are constant atmospheric boundary layer depths for heat and moisture respectively, κ_T and κ_q are eddy diffusivities for heat and moisture respectively, E is the evaporation or sublimation rate, P is the precipitation rate, ρ_a is air density, and ρ_o is a constant reference density of water. C_{pa} is the specific heat of air at constant pressure. The parameters β_T, β_q allow for a linear scaling of the advective transport term. This may be necessary as a result of the overly simplistic, one-layer representation of the atmosphere, particularly if surface velocity data are used in place of vertically averaged data, as in our standard runs. The values $\beta_T = 0, \beta_q = 0.4$ or 0 are used by Weaver et al., 2001. We allow $\beta_T \neq 0$ but only for zonal advection, while β_q takes the same value for zonal and meridional advection. In view of the convergence of the grid, winds in the two gridpoints nearest each pole are averaged zonally to give smoother results in these regions.

In contrast to Weaver et al., 2001, the short-wave solar radiative forcing is temporally constant, representing annually averaged conditions. In a further departure from that model, the relevant planetary albedo is given by a simple cosine function of latitude. Over sea ice the albedo is temperature-dependent. The constant C_A parameterizes heat absorption by water vapor, dust, ozone, clouds, etc. The diffusivity κ_T, in our case, is given by a simple Gaussian function centered on the equator with specified magnitude, north-south slope and width. κ_q is spatially constant.

The remaining heat sources and sinks are as given in Weaver et al., 2001: Q_{LW} is the long-wave imbalance at the surface; Q_{PLW}, the planetary long-wave radiation to space, is given by the polynomial function derived from observations by Thompson, 1982, cubic in temperature T_a and quadratic in relative humidity $r = q/q_s$ where q_s is the saturation specific humidity, which is exponential in the surface temperature. For anthropogenically forced experiments a greenhouse warming term is added which is proportional to the log of the relative increase in carbon dioxide (CO_2) concentration C as compared to an arbitrary reference value C_0.

The sensible heat flux Q_{SH} depends on the air-surface temperature difference and the surface wind speed (derived from the ocean wind-stress data) and the latent heat release Q_{LH} is proportional to the precipitation rate P, as in Weaver et al., 2001. In a departure from that model, however, precipitated moisture is removed instantaneously, as in standard oceanic convection routines, so that the relative humidity r never exceeds its threshold value $r_{\max}$. This has significant implications as it means that the relative humidity is always equal to $r_{\max}$ wherever precipitation is non-zero, effectively giving q the character of a diagnostic parameter. Here, since the model is used to represent very long-term average states, regions of zero precipitation only exist as a result of oversimplified representation of surface processes on large landmasses.

To improve efficiency we use an implicit scheme to integrate the atmospheric dynamical equations (7) and (8). The scheme comprises an iterative, semi-implicit predictor step (Shepherd, 2003) followed by a corrector step which renders the scheme exactly conservative. Changes per timestep are typically small, thus a small number of iterations of the predictor provides adequate convergence.

The model has no dynamical land surface scheme. The land surface temperature is assumed to equal the atmospheric temperature T_a, and evaporation is set to zero, thus the atmospheric heat source is simplified over land as the terms $Q_{LW} = Q_{SH} = Q_{LH} = 0$. Precipitation over land is added to appropriate coastal ocean gridcells according to a prescribed runoff map.

3.3 Sea ice and the coupling of model components

The fraction of the ocean surface covered by sea ice in any given region is denoted by A. Dynamical equations are solved for A and for the average height of sea ice H. In addition a diagnostic equation is solved for the surface temperature of the ice T_i. Following Semtner, 1976 and Hibler, 1979 thermodynamic growth or decay of sea ice in the model depends on the net heat flux into the ice from the ocean and atmosphere. Sea-ice dynamics simply consist of advection by surface currents and Laplacian diffusion with constant coefficient κ_{hi}.

The sea-ice module acts as a coupling module between ocean and atmosphere and great care is taken to ensure an exact conservation of heat and fresh water between the three components. The resulting scheme differs from the more complicated scheme of Weaver et al., 2001 and is described fully by Edwards and Marsh.

Coupling is asynchronous in that the single timestep used for the ocean, sea-ice and surface flux calculation can be an integer multiple of the atmospheric timestep. Typically we use an atmospheric timestep of around a day and an ocean/sea-ice timestep of a few days. The fluxes between components are all calculated at the same notional instant to guarantee conservation, but are formulated in terms of values at the previous timestep, thus avoiding the complications of implicit coupling. All components share the same finite-difference grid.

3.4 Topography and runoff catchment areas

The seafloor topography is based on a Fourier-filtered interpolation of ETOPO5 observationally derived data. A consequence of the rigid-lid ocean formulation is that there is no mechanism for equilibration of salinity in enclosed seas which must therefore be ignored or connected to the ocean. In our basic topography the depth of the Bering Strait is a single level (175 m), thus it is open only to barotropic flow, which we usually ignore, and diffusive transport, while the Gibralter Strait is two cells deep and thus permits baroclinic exchange flow.

Equivalently filtered data over land were used - along with depictions of major drainage basins by Weaver et al., 2001 and the Atlantic/Indo-Pacific runoff catchment divide of Zaucker and Broecker, 1992 - to guide the subjective construction of a simple runoff mask.

3.5 Freshwater flux redistribution

The single-layer atmosphere described above generates only around 0.03 Sv moisture transfer from the Atlantic to the Pacific (1 Sv= 10^6 m^2s^{-1}), whereas Oort, 1983 estimated a value of 0.32 Sv from observations. This typically leads to very weak deep sinking in the north Atlantic in the model unless the moisture flux from the Atlantic to the Pacific is artificially boosted by a constant additional redistribution of surface freshwater flux. Following Oort, we transfer fresh water at a net rate F_a, subdivided into three latitude bands in the proportions found by Oort. Many ocean and climate models, including HadCM3 and the UVic model, artificially alter the geometry of the Denmark Strait to achieve the same effect on Atlantic deep sinking. An advantage of the approach used here is that the parameter F_a can easily be adjusted for sensitivity studies in altered climate states (Marsh et al.). Note that our adjustment of surface freshwater fluxes is a pure redistribution and serves a quite different purpose from the flux adjustments used in early coupled climate models to prevent climate drift. Climate drift in higher-resolution models typically arises because the models are too costly to integrate to equilibrium. An important advantage of efficient climate models is that they do not suffer from this particular problem.

3.6 Default parameters and forcing fields

In principle, values used for oceanic isopycnal and diapycnal diffusivities, κ_h and κ_v and possibly momentum drag (Rayleigh friction) coefficient λ may need to be larger at low than at high resolution to represent a range of unresolved transport processes. In FG dynamics, the wind-driven component of the ciculation tends to be unrealistically weak for moderate or large values of the frictional drag parameter λ, for reasons discussed by Killworth, 2003, while for low drag unrealistically strong flows appear close to the equator and topographic features. This problem is alleviated by allowing the drag λ to be variable in space. By default, drag increases by a factor of three at each of the two gridpoints nearest the equator or to an upper-level topographic feature. In addition, we introduce a constant scaling factor W which multiplies the observed wind stresses in order to obtain stronger and more realistic wind-driven gyres. For $1 < W < 3$ it is possible to obtain a wind-driven circulation with a reasonable pattern and amplitude. Annual mean wind-stress data for ocean forcing come from the the SOC climatology (Josey et al., 1998). Wind fields used for atmospheric advection are long-term (1948 to 2002) annually averaged 10 m wind data derived from NCEP/NCAR reanalysis. Default parameters are given in Table 3.1.

3.7 Climate change assessment

To simulate the response to GHG forcing, we first need a quasi-steady initial condition representing the pre-industrial climate, which we obtain by integrat-

Table 3.1. Default values of parameters for the climate model. The value given for λ is the minimum value in the ocean interior, while the value for κ_T is the maximum value at the equator. The full specification of variable drag, ocean density, isoneutral and eddy-induced mixing, surface fluxes, outgoing longwave radiation, specific humidity and freezing temperature involves a total of about 75 parameters, details of which are given or referred to by Edwards and Marsh.

parameter	**notation**	**value**
	ocean	
isopycnal diffusivity	κ_{h}	2000 $\text{m}^2\ \text{s}^{-1}$
diapycnal diffusivity	κ_{v}	$1 \times 10^{-5}\ \text{m}^2\ \text{s}^{-1}$
friction	λ	$1/2.5\ \text{days}^{-1}$
wind-scale	W	2
density	ρ_o	1000 kg m^{-3}
	atmosphere	
T diffusivity amp.	κ_T	$8 \times 10^6\ \text{m}^2\ \text{s}^{-1}$
q diffusivity	κ_q	$8\times10^4\ \text{m}^2\ \text{s}^{-1}$
T advection coeff.	β_T	0.1
q advection coeff.	β_q	0.25
FWF adjust.	F_a	0.32 Sv (1 Sv=$10^6\ \text{m}^2\text{s}^{-1}$)
heat absorption	C_A	0.3
boundary layer depth (T)	h_t	8400 m
boundary layer depth (q)	h_q	1800 m
density	ρ_a	1.25 kg m^{-3}
specific heat capacity	C_{pa}	1004 $\text{J kg}^{-1}\ \text{K}^{-1}$
threshold relative humidity	r_{max}	0.85
	sea ice	
sea-ice diffusivity	κ_{hi}	2000 $\text{m}^2\ \text{s}^{-1}$

ing from a uniform state of rest with constant solar forcing for a period of 5600 years. We then integrate forwards in time using observed CO_2 concentrations from 1795 to 1995. The resulting state is then used as an initial condition for the fully coupled integrations in which the CO_2 concentrations are supplied by the economic growth model (the RCEG model to be introduced in Section 4). The origin on the time axis is henceforth taken to correspond to this initial condition at 1995.

The climate model supplies to the economic growth model a measure of climate change in the form of a set of criteria defined as scalar functionals of the trajectories of the climate state variables, for example atmospheric temperature T_a and humidity q, sea-ice area A or ocean temperature T and velocity $\mathbf{u}$. Later we experiment with several alternative criteria, but by default we use an Area Over Threshold (AOT) criterion for the globally averaged surface air temperature

$$D_{0,\theta} = \frac{\int_{\Omega} \mathrm{I}[T_a(\omega, 200) \geq \theta]\, d\omega}{\int_{\Omega} d\omega}, \tag{9}$$

where $T_a(\omega, 200)$ is the surface air temperature at location ω at horizon 200 years, Ω is the global domain, $\mathrm{I}[\cdot]$ is the indicator function and θ is a critical temperature rise. Another possible criterion is the weighted AOT (WAOT) defined as follows

$$D_{\alpha(\cdot),\theta} = \frac{\int_{\Omega} \alpha(\omega)\, \mathrm{I}[T_a(\omega, 200) \geq \theta]\, d\omega}{\int_{\Omega} \alpha(\omega)\, d\omega}, \tag{10}$$

where $\alpha(\omega) \geq 0$ is a weighting function.

4. The economic model: RCEG

In this section we propose an aggregate economic growth model that represents the fundamental world economic dynamics, in the form of a control system where investment and emissions abatement are the control variables whereas capital stock and GHG concentrations, nominally in atmosphere, shallow and deep ocean, are the state variables, respectively. We use a reduced version of the DICE99 model which represents the economic growth process as a Ramsey model (Ramsey, 1928; Nordhaus, 1994; Nordhaus and Boyer, 2000); for this reason we name our model RCEG for *Ramsey-Concentration-and-Economic-Growth*. In simple terms and continuous time[5] the model we use can be summarized as follows.

The state and control (policy) variables, the exogenous dynamic variables and the auxiliary variables that serve to define the reward function and the state equations are given in Table 3.2. The mass of greenhouse gases are expressed in billions tons of carbon.

The equations of the model are listed below. The equations have been regrouped in different sets that will help to explain the structure of this economic model.

G1 – **utility criterion**

$$\max \quad \int_0^{\infty} e^{-\rho t} U(c(t), L(t))\, dt \tag{11}$$

$$U(c(t), L(t)) = L(t) \frac{c(t)^{1-\alpha} - 1}{1-\alpha} \tag{12}$$

G2 – **exogenous population, technical progress,**

– **deforestation growth**

$$\dot{L}(t) = g_L(t) L(t) \tag{13}$$

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[5] We prefer to use a continuous time control formalism to represent the economic growth model, although we shall use a discrete time version in the numerical experiments.

$$\dot{g}_L(t) = -\delta_L g_L(t) \tag{14}$$

$$\dot{A}(t) = g_A(t)A(t) \tag{15}$$

$$\dot{g}_A(t) = -\delta_A g_A(t) \tag{16}$$

$$ET(t) = ET(0)e^{-\delta_T t} \tag{17}$$

G3 – production and emissions

$$Q(t) = (1 - b_1\mu(t)^{b_2})A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{18}$$

$$E(t) = (1 - \mu(t))\sigma(t)Q(t) + ET(t) \tag{19}$$

G4 – Production usage

$$Q(t) = C(t) + I(t) \tag{20}$$

$$c(t) = \frac{C(t)}{L(t)} \tag{21}$$

G5 – capital accumulation

$$\dot{K}(t) = I(t) - \delta K(t) \tag{22}$$

G6 – GHG accumulation

$$\dot{\overbrace{MA}}(t) = E(t) - \delta_{MAA}(MA(t)) + \delta_{MAU}(MU(t)) \tag{23}$$

Table 3.2. List of variables in the RCEG model

List of endogenous state variables		
$K(t)$	=	capital stock
$MA(t)$	=	mass of GHG in the atmosphere (b.t.c.)
$MU(t)$	=	mass of GHG in shallow oceans (b.t.c.)
$ML(t)$	=	mass of GHG in lower oceans (b.t.c.)
List of control variables		
$I(t)$	=	gross investment
$\mu(t)$	=	rate of GHG emissions reduction
List of exogenous dynamic variables		
$A(t)$	=	level of technology
$L(t)$	=	labour input (=population)
$O(t)$	=	forcing exogenous GHG
List of auxiliary variables		
$C(t)$	=	total consumption
$c(t)$	=	per capita consumption
$D(t)$	=	damage from GH warming
$E(t)$	=	emissions of GHGs
$ET(t)$	=	emissions due to deforestation
$Q(t)$	=	gross world product

$$\begin{aligned}
\overbrace{ML}(t) &= -\delta_{MLL}(ML(t)) + \delta_{MLU}(MU(t)) && (24)\\
\overbrace{MU}(t) &= -\delta_{MUU}(MU(t)) + \delta_{MUA}(MA(t)) + \delta_{MUL}(ML(t)) && (25)\\
\mathbf{G7} &- \textbf{bounds on GHG concentrations} &&\\
MA(t_i) &\leq MA_i^{\text{sup}}; \quad i = 1, \dots, k && (26)\\
MA(t) &\leq MA_i^{\text{sup}}; \quad t \geq t_k. && (27)
\end{aligned}$$

Eqs. (11)-(12) in group G1 describe the utility accumulation process. When $\alpha = 1$ the utility function takes the form $L \log(c)$. A key parameter is the discount rate ρ which is here geometrically decreasing over time; utility is derived from consumption by a growing population.

Eqs. (13)-(17) in group G2 describe the dynamics of some exogenously defined processes. They are the population growth, the technical progress and the deforestation processes, respectively. One notices that the population growth and the technical progress will tend to stabilize and the deforestation will also tend to disappear in the long run.

Eqs. (18)-(19) in group G3 describe the output and emissions processes. Output is the result of two production factors, labor L and capital K; the abatement effort μ has a cost expressed as a loss of production. Emissions are a function of the carbon intensity of the production technologies (parameter σ), and are reduced by the abatement effort μ. Exogenous emissions ET are due to deforestation.

Eqs. (20)-(21) in group G4 show that the output can be consumed or invested. Per-capita consumption is obtained from gross consumption and population level.

Eq. (22) in group G5 describes the capital accumulation process. The parameter δ is the depreciation rate of capital.

Eqs. (23)-(25) in group G6 describe the carbon accumulation process in a three-reservoir system, composed of atmosphere, shallow and deep ocean respectively. While it would be a relatively simple matter to replace these equations by directly simulating the transfer of carbon to the deep ocean within the climate model, we have not done so in this initial investigation.

Finally, Eqs. (26)-(27) in group G7 describe the bounds that will be imposed on the atmospheric concentrations of GHGs at some predetermined milestones (dates t_i, $i = 1, \dots k$) and after time t_k. These constraints will be the linking variables with the climate model.

The parameter values are indicated below in Table 3.3, in the units proposed by Nordhaus and Boyer.

In comparison with DICE99, the new control problem (11)-(27) defining the RCEG model no longer contains the equations which deal with temperature and forcing. The equation (18) was also modified as the production loss due to temperature impact is removed from the production function. We now run the model in a cost-effectiveness manner instead of the cost-benefit approach implemented by Nordhaus. For that purpose we introduce upper bounds on

Table 3.3. Parameter values

$\alpha = 1$
$b_1 = 0.045$
$b_2 = 2.15$
$\beta = 0.64$
$\gamma = 0.25$
$\delta_K = 0.10$ (per year)
$\delta_T = 0.01$ (per year)
$\delta_M AA = 0.33384$ (per decade)
$\delta_M AU = 0.27607$ (per decade)
$\delta_M UU = 0.39103$ (per decade)
$\delta_M UA = 0.33384$ (per decade)
$\delta_M UL = 0.422$ (per decade)
$\delta_M LL = 0.0422$ (per decade)
$\delta_M LU = 0.1149$ (per decade)
$\lambda = 1.41$
$\theta_1 = 0.0007$
$\theta_2 = 3.57$
$\sigma = 0.033$

atmospheric concentrations (26)-(27) at milestones distributed 50 years apart along the time axis. The objective is to maximize the total welfare of the economic system subject to the concentration limits.

In our calculations we used a discrete-time version of the model, written in the GAMS modelling language, with time steps representing 10 years. This version will be used for numerical implementation.

5. The reduced order problem

We denote by $x = (MA_1^{\text{sup}}, \ldots, MA_k^{\text{sup}})'$ the vector of upper bounds on GHG concentration limits at milestones t_i $(i = 1, \ldots, k)$, that will serve as the coupling variables between the economic and the climate models (technically we make a conversion here from mass to concentration). Normally $k = 4$ and $t_i = i \times 50$ years. In the climate model the values x_i are taken as actual concentrations at times t_i. The concentration at intermediate times $MA(t)$, also denoted as $x(t)$, is defined by linear interpolation. We call $V(x)$ the optimum value (maximal utility) given by the solution of the control problem (11)-(27), when the concentration upper bounds are defined as x. In section 3.7 we have shown how to define an impact function, say, $\widehat{h}(x)$ by using the climate model and an AOT criterion. In order to couple the economic and the climate model, we consider the reduced order[6] optimization problem

$$\max_{x \in \mathbb{R}^k} \{V(x) \mid \widehat{h}(x) \leq \Theta\}, \tag{28}$$

where Θ is a limit imposed on the impact. In what follows, to ease the notation, we use $h(x)$ instead of $\widehat{h}(x)$, with $h(x) := \widehat{h}(x) - \Theta$.

5.1 A cutting plane approach

$V(x)$ is concave by construction and for a cutting plane method to converge $h(x)$ must be convex[7]. Since the functions $V(x)$ and $h(x)$ are defined implicitly, we will construct a sequence of supporting planes to the epigraphs of $-V(x)$ and $h(x)$. These supporting planes are called cutting planes in the cutting plane framework.

In the cutting plane procedure we consider a sequence of points $\{x^n\}$ in the domain of $V(x)$. We denote Sv^n a subgradient of $V(x)$ at x^n, that is, $Sv^n \in \partial V(x^n)$, the subdifferential of $V(x)$ at x^n (given that $V(x)$ is concave, properly speaking we should talk about *antisubgradient* and *antisubdifferential*). If x^n is feasible, that is, $h(x^n) \leq 0$, we then define the linear approximation to $V(x)$ at x^n, given by $\widetilde{V}^n(x) = V(x^n) + Sv^n \cdot (x - x^n)$. If x^n is infeasible, that is, $h(x^n) > 0$, we define the linear approximation to $h(x)$ at x^n, $\widetilde{h}^n(x) = h(x^n) + Sh^n \cdot (x - x^n)$ and we introduce the auxiliary constraint $\widetilde{h}^n(x) \leq 0$.

In the cutting plane literature the point x^n is referred to as a *query point*, and the procedure to compute the objective value and subgradient at a query point is called an *oracle*. Furthermore, the hyperplane that approximates the objective function $V(x)$ at a feasible query point and defined by the equation $z = \widetilde{V}^n(x)$, is referred to as an *optimality cut*. The hyperplane that approximates the constraint function $h(x)$ at an infeasible query point and defined by the equation $\widetilde{h}^n(x) = 0$, is called a *feasibility cut* (see Fig. 3.1).

Let $\{x^n\}$, $n \in \mathcal{N} = \mathcal{N}_o \cup \mathcal{N}_f$ be a sequence of query points, where $\mathcal{N}_o$ corresponds to the optimality cuts and $\mathcal{N}_f = \mathcal{N} \setminus \mathcal{N}_o$ to the feasibility cuts, respectively. A lower bound to the maximum value of $V(x)$ is provided by:

$$\theta_l = \max_{n \in \mathcal{N}_o} V(x^n).$$

The localization set is defined as

$$\mathcal{L}_{\mathcal{N}} = \{(x, z) \in \mathbb{R}^{k+1} \mid z \leq \widetilde{V}^n(x)\ \forall n \in \mathcal{N}_o, \quad z \geq \theta_l, \quad \widetilde{h}^n(x) \leq 0\ \forall n \in \mathcal{N}_f, \quad x \in D\}, \tag{29}$$

---

[6] The problem is reduced to the coupling variables only.

[7] Indeed one cannot guarantee the convexity of $h(x)$ which is the result of a complex and highly non-linear numerical process. In practice, however, it is observed that the behavior of $h(x)$ is close to convexity in the domain of interest for x. The nonconvexity of $h(x)$ may generate an empty localization set (a concept to be introduced shortly) during the cutting plane procedure. There are techniques permitting a backtracking in the procedure in order to overcome the local nonconvex behavior (Carlson et al., 2004).

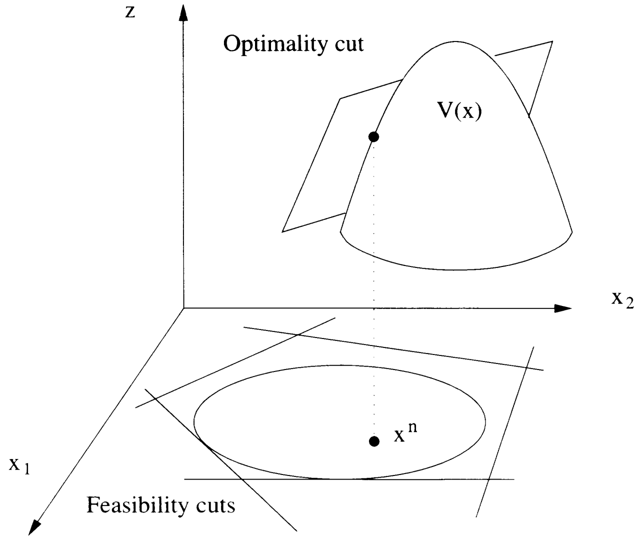

Figure 3.1. Optimality and feasibility cuts

where D is a compact domain defined for example by a set of lower and upper bounds for the components of x. The basic iteration of a cutting plane method can be summarized as follows

1 Select $(\overline{z}, \overline{x})$ in the localization set $\mathcal{L}_{\mathcal{N}}$.

2 Call the oracle at $\overline{x}$. The oracle returns one or several cuts and, if all of them are optimality cuts, a new lower bound $V(\overline{x})$ is computed. Else, go to step 4.

3 Update the bounds:

   (a) If $\overline{x}$ is feasible, $\theta_l \leftarrow \max\{V(\overline{x}), \theta_l\}$.

   (b) Compute an upper bound θ_u to the optimum[8] of problem (28).

4 Update the lower bound θ_l in the definition of the localization set (29) and add the new cuts.

These steps are repeated until a point is found such that $\theta_u - \theta_l$ falls below a prescribed optimality tolerance. The reader may have noticed that the first step in the summary is not completely defined. Actually, cutting plane methods essentially differ in the way one chooses the query point. For instance, the intuitive choice of the Kelley point $(\overline{z}, \overline{x})$ that maximizes z in the localization

---

[8] For example, $\theta_u = \max\{z \mid (z, x) \in \mathcal{L}_{\mathcal{N}}\}$.

set (Kelley, 1960) may prove disastrous, because it over-emphasizes the global approximation property of the localization set. Safer methods introduce a regularizing scheme to avoid selecting points too "far away" from the best recorded point. The approach used in ACCPM (*Analytic Center Cutting Plane Method*) (Goffin et al., 1992; Goffin and Vial, 1999; Peton and al., 2001; Du Merle and Vial, 2002) consists in selecting the *analytic center* of the localization set. Formally, the analytic center is the point $(\overline{z}, \overline{x})$ that minimizes the logarithmic barrier function[9] of the localization set. If the set is bounded[10] the analytic center is uniquely defined. Moreover the point is relatively easy to compute using the standard artillery of Interior Point Methods[11]. ACCPM easily handles both feasibility and optimality cuts. Furthermore, ACCPM is robust, efficient and particularly useful when the oracle is computationally costly —as is the case in this application.

The above basic iteration of the cutting plane method in the present case can be interpreted as follows

1 Select $x^n = (MA_1^{\text{sup}}, \ldots, MA_k^{\text{sup}})'$, a vector of upper bounds on GHG concentrations within the search region.

2 By using the C-GOLDSTEIN oracle, compute the associated AOT^n, that is, compute the value $h(x^n)$.

   (a) If AOT^n is greater than the threshold Θ $(h(x^n) > 0)$, AOT^n is not admissible and a feasibility cut $(\widetilde{h}^n(x) \leq 0)$ is generated at x^n. The role of this feasibility cut is to separate x^n from the localization set $\mathcal{L}_{\mathcal{N}}$.

   (b) Otherwise, AOT^n is admissible and an optimality cut is generated at x^n. The optimality cut is a linear approximation of $V(x)$ at x^n. Obviously, the optimal utility computed by the RCEG oracle, $V(x^n)$, is a lower bound to the optimal utility.

3 The set of feasibility cuts approximates the set of admissible bounds on GHG concentration. On the other hand, the set of optimality cuts approximates the function $V(x)$. Therefore, at each step 2 we generate either a feasibility cut or an optimality cut, which give an increasingly accurate piecewise affine approximation of the problem (28).

5.2 Implementation details

In this section we explain how to compute the subgradients Sv^n, Sh^n and a good starting query point x^0. It can be seen that the set of optimal Lagrangian multipliers λ^n associated to constraints (26-27) when computing $V(x^n)$ gives

---

[9] The logarithmic barrier for the half space $\{x \mid a \cdot x \leq b\}$ is $-\log(b - a \cdot x)$.

[10] In practice, this assumption is met by setting appropriate, possibly very large, bounds on the variable x.

[11] ACCPM is pseudo-polynomial under mild assumptions.

a subgradient of $V(x)$ at x^n. That is, in the cutting plane procedure we set $Sv^n = \lambda^n$, where λ^n is obtained from the solution of RCEG. It is not so easy to compute $Sh^n = (Sh_1^n, \ldots, Sh_k^n)'$, a subgradient of the climate function $h(x)$ at x^n. The only feasible way is to approximate its components by the finite differences:

$$Sh_i^n \simeq \frac{h(x^n + \epsilon e_i) - h(x^n)}{\epsilon}, \quad i = 1, \ldots, k, \tag{30}$$

where $e_i = (0, \ldots, 0, 1_i, 0, \ldots, 0)'$ is the i-th canonical vector and $\epsilon > 0$.

To choose a good starting point, we notice that a no-emissions scenario gives a lower bound for the x values which correspond to the lowest possible carbon accumulation in the atmosphere. An RCEG scenario with no environmental constraints, also called a *Business As Usual* scenario, provides an upper bound for the x values. If we vary x at $t = 100$ and $t = 200$ years, that is, x_{10} and x_{20}, between these bounds, interpolate linearly to obtain $x(t)$ at other times, and compute the corresponding AOT values $\widehat{h}(x)$ at a sparse, uniform grid of points in the enclosed rectangular region of $x_2 - x_4$ space, we obtain the graph shown in Figure 3.2. On this figure, regions with the same subgradient have the same color. We observe that in the region of interest (an AOT greater than 10%) the response is almost linear. A linear regression gives an R^2 of 0.99 and the expression of $L_{\widehat{h}}$:

$$L_{\widehat{h}}(x_{10}, x_{20}) = 5.88 \cdot 10^{-4} x_{10} + 2.20 \cdot 10^{-3} x_{20} - 3.53 \tag{31}$$

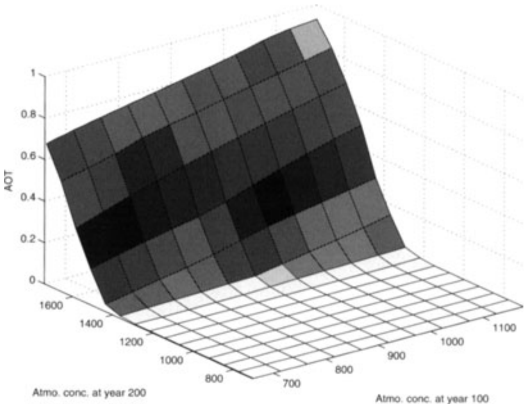

Figure 3.2. The impact $h(x)$ (AOT) from the climate model, as a function of only 2 variables, the concentrations at 100 and 200 years, with intermediate values defined linearly. This approximate form is used to define an initial condition.

The starting point for solving the full coupled problem using ACCPM has been selected by solving the following problem based on this linear approximation:

$$\max_{x\in\mathbb{R}^k}\{V(x) \mid L_{\hat{h}}(x_{10}, x_{20}) \leq \Theta\}. \tag{32}$$

The starting point thus obtained proves to be already quite close to the feasible region.

6. Numerical results

6.1 Reference scenario from DICE99

Table 3.4. Output of an uncoupled run of DICE99 for years 1995-2085

Year	1995	2045	2095	2145	2185
Output	22.563	60.492	102.879	151.949	167.02
Pccon	3	5.194	7.562	10.59	14.138
Savrate	0.2511	0.223	0.2223	0.2236	0.0429
Indem	59.1145	94.978	113.63	148.264	169.672
Sigma	0.272	0.1797	0.1399	0.1153	0.0989
Temp	0.43	1.063	1.927	2.711	3.23
Conc	735	945.44	1146.76	1352.84	1588.82
Ctax	8.15	25.64	46.03	37.45	UNDF
Intrate	0.079	0.042	0.036	0.032	0.075
Discrate	1	0.2452	0.07108	0.02389	0.01098
Prod	0.017	0.022	0.029	0.036	0.043
Exogforc	-0.15	-0.072	0.392	0.53	0.53
Pop	5632.7	9049.7	10580.2	11139.3	11306.5
Etree	11.28	6.6607	3.9331	2.3225	1.5238
Margy	10005.2	1416.9	282.092	67.698	23.299
Margc	10005.2	1416.9	282.092	67.698	23.299
miu	0.038	0.129	0.219	0.17	0
Total emissions	70.394	101.64	117.563	150.587	171.196
Interest rate	0.0789	0.0424	0.0363	0.0319	0.0747
Damages	0.01697	0.2102	1.05427	2.93703	4.47555
Abatement cost	0.00087	0.0168	0.0683	0.05294	0

In Table 3.4 we report the output of a run of the original, uncoupled DICE99 model, over a time horizon of 200 years. Of interest is the accumulation of GHG concentrations and the average temperature increase shown in Figure 3.3-3.4. According to DICE99, the economic growth generates an average temperature increase of 3.2 C over the 200 years. If we use the predicted atmospheric GHG concentrations to force C-GOLDSTEIN in a one-way coupling, with no feedback on DICE99, we obtain an average temperature increase of 2.6 C, while the $AOT_{2.5}[200]$ takes a value of 0.612, *i.e.* C-GOLDSTEIN predicts more than 2.5 C warming, locally, for 61% of the globe at the year 2085, using the concentration path obtained from the DICE99 simulation.

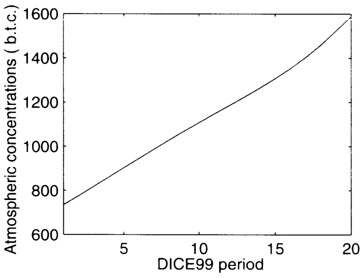

Figure 3.3. Atmospheric GHG concentration from an uncoupled run of DICE99.

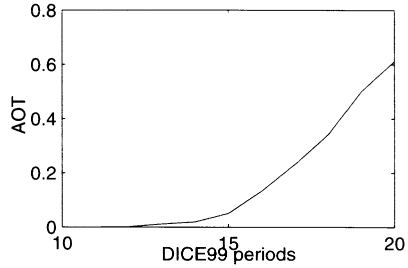

Figure 3.4. Global fraction where warming exceeds 2.5 C (AOT) between 2085 and 2185 from C-GOLDSTEIN forced by GHG concentrations from an uncoupled run of DICE99.

6.2 RCEG with constraints on $AOT_{2.5}[200]$

We now run the model in a coupled mode in which the concentration limits operate as coupling variables. It is important to recall that these upper limits on concentrations will be obtained as a way to ensure that the constraint $AOT_{2.5}[200] \leq 0.5$ is satisfied. ACCPM is used to reach that optimum under constraint. Table 3.5 indicates the sequence of calls to the oracles and the query points. We observe that three feasibility cuts are introduced at the beginning and then an optimality cut is introduced to reach an optimal solution. The desired value $AOT_{2.5}[200] \leq 0.5$ is obtained after only 4 cuts.

Table 3.5. Calls of the oracles and query points in the ACCPM run

	Milestones						
Iter.	50 yr	100 yr	150 yr	200 yr	Criterion	AOT	Cut
1	918.26	1168.78	1422.76	1521.50	-	0.60917	Feas.
2	916.57	1165.31	1416.16	1479.14	-	0.51365	Feas.
3	915.99	1164.79	1415.38	1474.37	-	0.50193	Feas.
4	915.63	1164.58	1415.14	1472.97	27506.02	0.49929	Opt.
5	915.20	1165.53	1414.60	1473.28	27504.74	0.49972	End

Milestones are atmospheric concentration targets in b.t.c.

The same experiment is now repeated with a 19-dimensional coupling variable x (one component for each decade). The result is a smoother concentration path but, in this case, 24 cuts are required to reach a converged solution. Figure 3.5 shows the atmospheric concentration paths from the two experiments (denoted RCEG4 and RCEG20) along with the atmospheric concentration path from the uncoupled run of DICE99.

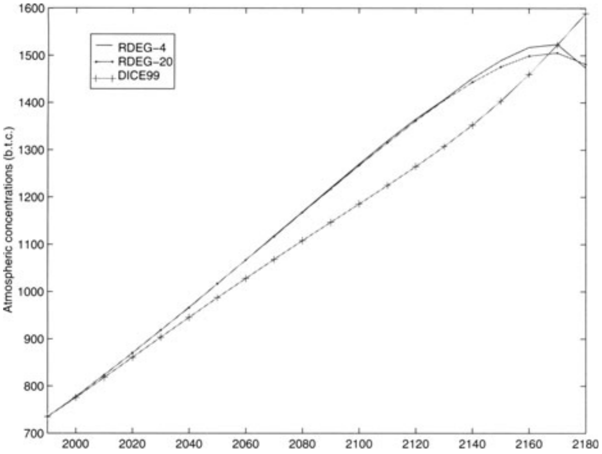

Figure 3.5. Atmospheric concentrations in b.t.c.

6.3 RCEG with constraints on various $AOT_{2.5}[200]$

In the last section, we observed an increase, then a decrease of the level of atmospheric concentrations for the two last decades. This reflects an unrealistic end-of-period effect where the economic system waits for the last moment to realize the abatement required. To reduce this effect, we modify the RCEG model slightly. We add a constraint that the growth of atmospheric GHG concentration is non-negative throughout the 200-year period:

$$MA(t-1) \quad \leq \quad MA(t) \tag{33}$$

Then the time horizon for the RCEG model is increased to 250 years but we still compute an AOT for year 200.

6.4 Target dependence on AOT threshold levels for RCEG

In Table 3.6 we report on the behavior of the CO_2 target values x as a function of AOT threshold value. Note that it is the threshold area which is changed. The temperature threshold remains fixed at 2.5 C local warming. We change the threshold for the control problem (11)-(27) and we allow the method to choose the optimal target values for different AOT values. We note that the target values for the early periods (50 yr and 100 yr) remain essentially constant and the later periods (150 yr and 200 yr) undergo a steady rise with increasing AOT threshold. This rise is attributed to an accumulation of CO_2 in later periods and the delayed adjustment of the economic system to regulations. The relatively smaller target values for reduced AOT thresholds for 150 yr and

200 yr targets (compared to 50 yr and 100 yr targets) are consistent with the "end-of-period" effect described in the previous section.

Another observation is the behavior of the targets 150 and 200 for thresholds below 0.3. The 150 yr target has a larger value for low thresholds and this may be an indication of the importance of short-term target goals (150 yr as opposed to 200 yr) when temperatures bounds are more restrictive. Finally, the 150 year target shows a decline and approaches the 200 year target value for large values of AOT threshold. This behavior is expected in these very non-restrictive scenarios. Figure 3.6 shows the four target behaviors for varying AOT thresholds.

Table 3.6. Results of the change in AOT threshold for C-GOLDSTEIN model

	Milestone targets			
$AOT_{2.5}[200]$	50 yr	100 yr	150 yr	200 yr
0.1	916.12	1151.63	1390.15	1326.39
0.2	917.92	1156.73	1396.21	1369.66
0.3	917.51	1162.32	1369.31	1417.52
0.4	917.78	1166.41	1401.64	1450.25
0.5	918.26	1166.02	1415.96	1486.76
0.6	917.42	1169.13	1422.66	1525.24
0.7	918.22	1170.02	1423.66	1575.77
0.8	918.41	1173.55	1436.73	1638.92
0.9	918.24	1172.02	1427.24	1600.89
1.0	918.17	1168.72	1422.76	1580.72

6.5 RCEG with constraints on weighted $AOT_{2.5}[200]$

The climate has different impacts on the economy depending on the region. We expect a more important impact on the northern continents and polar regions than the southern continents and therefore report an example experiment with the relative weights in these regions set to 2, 1.5 and 1 respectively. Ocean regions have zero weight in this experiment. The computation of the weighted AOT is given by equation (10). Figure 3.7 shows the comparison between the weighted and unweighted AOT runs. Differences are small initially, but the weighted AOT is slightly more restrictive owing to enhanced heating over northern continents.

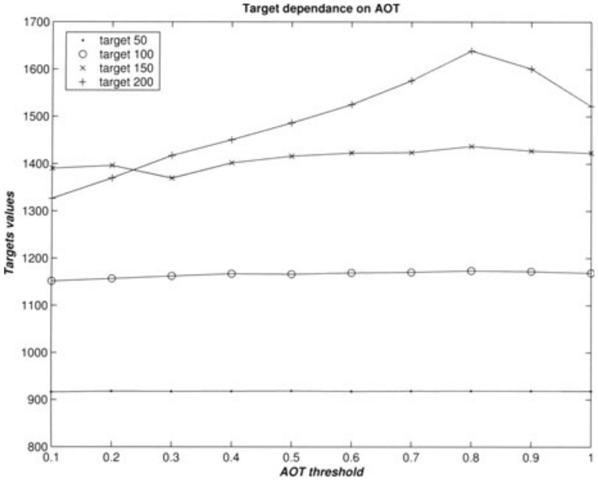

Figure 3.6. Target CO2 dependence on AOT threshold levels

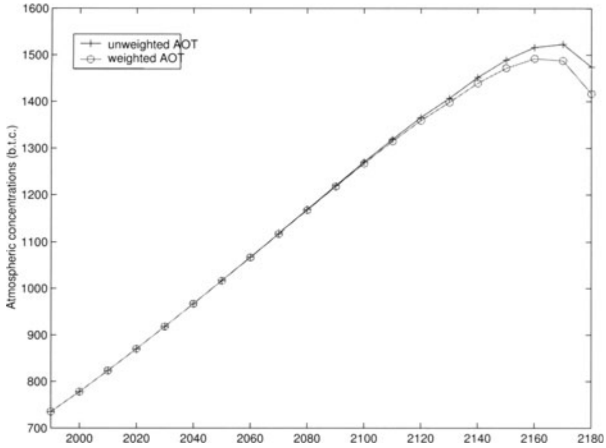

Figure 3.7. Atmospheric concentrations obtained by constraining the regionally weighted AOT to be less than 50%

7. Conclusion

In this paper, we have shown how modern convex optimization techniques can be harnessed to couple an economic model and a climate model characterized by different time and space scales. The coupling variables are the GHG concentrations as a function of time, and a set of impact criteria calculated by the climate model. We have solved a reduced-order problem in which the concentrations are assumed to vary linearly between 4 variable "targets" at 50-year intervals. The optimal solution is located by reducing the volume of the solution domain iteratively using a sequence of cutting planes. A very efficient choice of these planes gives a quick convergence towards the solution. ACCPM fulfills this task. Here the climate model, C-GOLDSTEIN, calculates a single impact criterion, the area of the globe where the surface warming exceeds a given threshold, an "Area Over Threshold" criterion. We have also weighted the "area" by region to represent a more realistic impact on the global economy. In general, the response of the economic model, RCEG, when a given constraint is enforced on the AOT, is a loss of production.

Allowing the two models to interact fully results in changes to the optimal emissions scenarios calculated by the economic model. In this initial test, our use of an impact criterion which depends only on the final state can result in unrealistic end effects. This problem could be addressed by including further impact criteria with more general time dependence such as a maximum rate of warming.

A remaining inconsistency is that the economic model uses a simplified representation of carbon transfer to the ocean. However, the simple experiments we have performed here are sufficient to demonstrate the feasibility and efficiency of our approach. The important feature of the coupling described here is that our technique allows us to maintain the full complexity of each of the submodels. In future, we plan to build on this work by replacing RCEG with a more complex economic model. A modified version of the ICLIPS model would introduce a regional scale for the economy, whereas the MERGE model would add a regional scale and energy response to climate change. To make the coupling completely consistent, the recycling of atmospheric carbon should be calculated by the climate component, for instance by using versions of the GENIE model. With a more comprehensive integrated meta-model, it would become appropriate to study the coupling in more detail and experiment with further constraints, for example changes in Atlantic overturning and changes in precipitation as well as temperature. A further interesting possibility would be to include a simplified representation of the feedback effects of changes in land use.

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Chapter 4

AN ABRUPT STOCHASTIC DAMAGE FUNCTION TO ANALYZE CLIMATE POLICY BENEFITS

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Abstract This paper studies uncertainty about the non-linearity of climate change impact. The DIAM 2.3 model is used to compute the sensitivity of optimal CO_2 emissions paths with respect to damage function parameters. This builds upon results of the EMF-14 uncertainty subgroup study by explicitly allowing for the possibility of threshold effects and hockey stick damage functions. It also extends to the cost-benefit framework previous studies about inertia of energy systems. Results show that the existence of a threshold in the damage function is critical to precautionary action. Optimal path are much less sensitive to uncertainty on the scale of the damages than on the threshold values.

1. Introduction

This paper examines optimal CO_2 abatement policy using a coupled model of climate and economic dynamics under uncertainty. First, we argue that the importance of precaution is magnified by the fact that abrupt changes are likely to happen. We show numerically that this kind of uncertainty consideration cannot be neglected to specify correctly the cost-benefit analysis of climate-energy policies. Second, we show more precisely that uncertainty about the magnitude of climate impact is far less critical than uncertainty about the date at which they could occur.

Our analysis builds upon four simplified beliefs about the danger of climate change: no attributed damage today, small expected future impact, small risk with large consequences and expected arrival of information. In more details: (i) The magnitude of negative socio-economic consequences presently attributed to climate change today is small compared to the measurement errors and the inter-annual variability of social welfare indicators due, for example, to business cycles and weather variability.

A. Haurie and L. Viguier (eds.), The Coupling of Climate and Economic Dynamics, 97–111.

(ii) In expected value, most analysts foresee only a modest direct impact of climate change on economic growth over the course of this century, because most of the value-added in the global economy occurs in sectors relatively insensitive to climate change, and adaptation is possible in other sectors.
(iii) Greenhouse gas forcing in the 21st century could set in motion large-scale, high-impact, non-linear, and potentially abrupt changes in the physical and biological systems over the coming decades to millennia, with a wide range for the associated likelihood. Many natural and managed ecosystems may change abruptly or non-linearly during this century.
(iv) Significant progress is being made on understanding climate change and human responses to it. However, there remains important areas where operational knowledge is decades away, such as the quantification of impacts at the local level, the effects of adaptation and mitigation activities, the definition of sustainable development or what constitutes "dangerous anthropogenic interference with the climate change".

While these beliefs do not constitute *robust findings* in the meaning of IPCC (see IPCC, 2001, p.30), they nevertheless represent the present outcome of over a decade of research about the impacts of climate change. Together, they lead to several difficulties in trying to justify on economic terms policy actions like the Kyoto protocol. Historically, attempts to do so can be reviewed as a movement from deterministic cost-efficiency analysis to stochastic cost-benefit analysis.

Early assessments highlighted that if the atmospheric carbon dioxide (CO_2) concentration is to be stabilized at a level of 450 ppmv or below, economically optimal strategies imply significant abatement of carbon emissions in the short run. On the other hand, if the ultimate concentration target is over 550 ppmv, then models show that the cost of deferring abatement by a decade or two is not very large. Thus, given these results, the near term mitigation objectives are tied with ultimate CO_2 concentration target. Here the difficulty is to justify which target to aim at, given that reasoning only with expected damages is obviously irrelevant to precaution against the risk of abrupt climate change.

Then Ha-Duong et al., 1997 assumed an unknown concentration ceiling of $\{450, 550, 650\}$ ppmv with equiprobability, and found that significant near-term abatement were economically optimal. On the other hand, with thresholds from 550 to 850 ppmv, Yohe and Wallace, 1996 found modest optimal abatement response over the next several decades. This illustrates the difficulty in this kind of a stochastic framework: the results depends upon the considered concentration targets and their probability, especially on the lowest target. As noted in IPCC, 2001, p. 350, figure TS-10a, the degree of near-term hedging in this analysis is sensitive to the fact that the ultimate target must be met at all cost.

This is why we have to turn next to cost-benefit analysis, and examine models without pre-defined CO_2 concentration stabilization target. In a cost-benefit optimum, pollution is reduced to the point where further additional abatements do not bring benefits larger than their costs. Results of cost-benefit models shown in IPCC, 2001, p. 350, figure TS-10b suggest that the optimal hedging strategy against a low-probability, high consequences climate risk is very close to no hedging at all.

In our view, this gap between cost-efficiency models results —early abatement can be valuable— and cost-benefit models results —optimal early trajectory close to the reference case— can be explained by damage function specification problems in the later. Using an S-shaped damage function can change the result of the cost-benefit analysis.

Section 2 discusses in more details results of the existing literature, which has recognized the importance of surprises and non linearities in the climate change issue at the theoretical level. In our opinion previous numerical models have found surprising results because they misspecified the four stylized beliefs enumerated above. Section 3 describes a nonlinear, stochastic climate damage function used to run a cost-benefit version of the Dynamics of Inertia and Adaptability Model (DIAM 2.3). Section 4 discusses the sensitivity of optimal short-term policies to the shape of the damage function. It demonstrates that an abrupt damage function implies a larger near-term abatement policy, and that this result is more sensitive to the date of the nonlinear change than to the magnitude of the catastrophe.

2. Methodological issues

2.1 Climate change impacts and uncertainty

Analyzing the geophysical consequences of climate change remains a very speculative science. Analyzing the economic and human consequences is even more so. Tackling both together to assess the impacts of climate change is one of the biggest difficulties of climate policy analysis. It is therefore not surprising that the representation of risk is one of the least convincing components of long-term energy-climate policy models.

The relationship between climate change and its impact on human welfare is conveniently discussed with the concept of an impact function. This function is mathematically formalized as $D = f(M)$, where M denote the magnitude of climate change and D represent its social welfare impact. The level of change M could be defined as global warming ΔT in degrees. It could otherwise be the increase of the radiative forcing in Watts per square meter, or also the increase of atmospheric carbon dioxide concentration. The damage D includes market and non market impacts. It is usually represented in monetary units, divided by the Gross World Product to have a dimensionless number, so it can be read as a fraction of GWP lost at a given date.

For example if $D = 2\%$ twenty year from now, this can be compared to a decrease in the world growth rate from 1.5% to 1.4% during twenty years. This commonly used order of magnitude, one tenth of a percentage point of growth during two decades, fits the stylized belief that damages are small compared to inter-annual variability.

In its simplest interpretation, f is an increasing function between a real-valued change $M(t)$ and the real-valued impact $D(t)$. This overlooks many essential characteristics of the climate change issue: the issue of the rate of climatic change, that of inter-annual variability, and that of the risk of abrupt large-scale change in the climate system.

- The rate of climatic change is important when it comes to the question of the adaptability of ecosystems and societies. It may turn out that controlling that rate dM/dt is more important, with respect to the near-term policy, than the ultimate long-term greenhouse gases stabilization level.
- Changes in the inter-annual variability of climate are important. While climate and climate change are defined as averages over a time period several decades long, physical variables underlying $M(t)$ (such as temperature or precipitation) are a rapidly varying stochastic function of time. Dalton, 1997 has shown that introducing the second moment of $M(t)$ in the damage function leads to greater climate change effects than without.
- The earth system is known to be nonlinear, therefore abrupt changes in climatic conditions can happen. This is potentially leading to a perceived rapid increase in economic losses. The classical example of such a non-marginal change in the climate system is the collapse of the north-Atlantic thermohaline circulation described by Broecker, 1997.

This paper considers M as an aggregate environmental indicator of climate change that implicitly represents changes in the rate and in the variance, in order to focus on the third point and represent explicitly the risk of abrupt changes.

Gjerde et al., 1999 remarked that in the literature, the modelling of optimal climate policies given the possibility of a catastrophe has been done using either one of the two following approaches: continuous-time real option models solved analytically, or stochastic optimal control models solved numerically.

In continuous time, there seems to be no consensus about the sign of the quasi-option value to reduce emissions. Dixit and Pindyck, 1994, using a real-option model found that more uncertainty implies to delay emissions reduction further. The interpretation of this result is that investment to reduce emissions is more irreversible than greenhouses gases accumulation. But these results assume a linear damage function. Narain and Fisher, 1998 showed in a model with an avoidable climatic catastrophe explicitly included, that the environmental irreversibility effect could be stronger than the investment effect.

The research presented in this paper also explicitly models an avoidable climatic catastrophe, but uses numerical discrete time stochastic optimization. It is in essence an expansion of the previously published DIAM model. It was initially motivated by the necessity of introducing cost-benefit in the analysis as discussed in introduction, and also by a couple of surprising findings arising from previous modelling exercises, namely DICE and the EMF-14 uncertainty studies.

Table 4.1. DICE sensitivity of optimal carbon abatement levels to the impact function parameters, from Nordhaus, 1994, table 6.4 page 109.

DICE model parametrization	Optimal abatement % of global CO_2 emissions in 1995	in 2095
Base case	9.0	14.3
Doubling damage function intercept θ_1	13.0	20.5
Doubling damage function exponent θ_2	8.9	25.9

2.2 Damage function specification: two issues

DICE's damage function is $D \approx \theta_1(\Delta T)^{\theta_2}$. The base value $\theta_2 = 2$, as discussed by Nordhaus, 1994, has greatly influenced subsequent studies, although factually very little is known about it. Table 4.1 exhibits the sensitivity of optimal emissions reduction to a doubling of either θ_1 or θ_2 in the damage function.

Results depend significantly on these unknown parameters. Increasing the exponent θ_2 has a big positive effect on the long run optimal abatement, but a small negative effect on the short run. This negativity disappears when θ_2 is pushed further, for example with $D = .027(\Delta T/2.5)^{12}$, the optimal climate policy for the 1995 period is a 17% abatement. The table suggests that the near term optimal emission reductions appear more sensitive to the scale parameter θ_1 than to the exponent of the damage function.

To some extend, these results can be surprising, as they go in a different direction from those of Peck and Teisberg, 1993 on the importance of non-linearity. Using the general case $D \approx \alpha(\Delta T)^{\lambda}$, with λ being 1, 2 or 3, their computations demonstrated that results were more sensitive to the exponent of the damage function λ than to their absolute magnitude α.

The second set of surprising results arises from a comparative study on uncertainty described by Manne, 1996, done in the Energy Modelling Forum 14. The study was a comparison of seven climate/energy integrated assessment models with stochastic damage functions. One of the main focus of interest was to compare the results between two standardized runs.

- First, in the base case using the model damage function $D = f(\Delta T)$.
- Second, in a potentially catastrophic scenario, where there is a 5% probability that the damages are multiplied by 7.8, therefore having $D = 7.8f(\Delta T)$ as the damage function.

As shown in Table 4.2, it appears that the hypothesis of a catastrophe had very little, if any, effect on the optimal near-term abatement level in these models.

Table 4.2. Inter-models comparison of optimal CO_2 emissions (GtC in year 2000), with and without a catastrophe in the model (damages multiplied by 7.8 with 5% probability, catastrophe occurring and observed from 2020 onwards). Surprisingly, the table shows that these models' near-term optimal results are not sensitive to the possibility of a climatic catastrophe.

	Optimal CO_2 emissions world GtC, year 2000	
Model	Without catastrophe	With catastrophe
CETA	6.51	6.50
DICE	7.46	7.45
DIAM	6.99	6.99
HCRA	6.85	6.84
MERGE	6.66	6.66
SLICE	7.15	7.14
YOHE	7.25	7.14

These results are surprising with respect to the intuition that models should be sensitive to the possibility of non-marginal changes. However, two criticisms can be made to the representations of the impacts discussed above.

First, multiplying the scale of the damage function quickly leads to excessive damages. For example, if a quadratic function is calibrated so that 1 degree Celsius warming implies 1% of damages, then the corresponding impact at 3.5 degree warming is 12.25%. Under these assumptions, a factor of 7.8 on the damages leads to an almost total (>95%) economic disruption: the model is out of its limits. This is in contradiction with the belief that damage will remain relatively small.

Second, increasing the exponent ($\theta_2 = 1, 2, 3, 4$ or 12 have been quoted in the literature) increases the curvature of the damage function everywhere, including near zero. This leads to the paradoxical consequence that the larger the long-term damages, the smaller the short-term impacts. This effect explains the negative relationship in table 4.1 between θ_2 and near-term abatement: 8.9% when $\theta_2 = 4$ versus 9.0% when $\theta_2 = 2$ per cent. Moreover, the exponent increase leads even faster to excessive damages levels.

The hypothesis examined in this paper is that a more non-linear representation of climate change impacts that avoids these two criticisms also contributes to bridging the gap between results and intuition.

3. Model

The DIAM model 2.3 has four non-linear equations and three linear constraints. It is coded in the GAMS language and can be examined at the author's

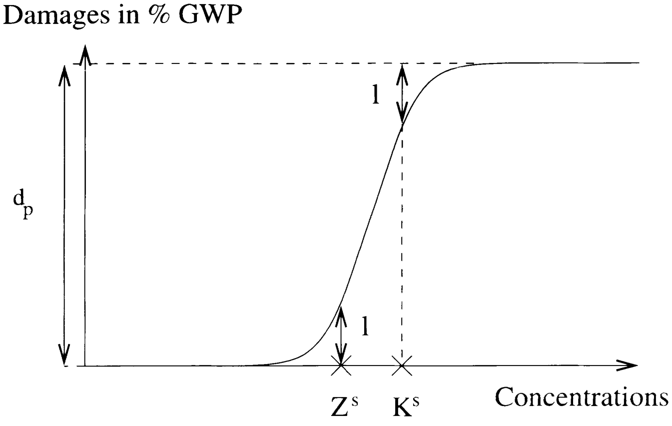

Figure 4.1. Non-linear term g_t^s of the impact function. The jump occurs over the interval $[Z^s, K^s]$. The ceiling d_p was set to 4% of GWP. Abruptness of the jump is parameterized by the $\gamma = l/d_p$ ratio.

electronic homepage[1]. Because DIAM has already been discussed by Ha-Duong et al., 1997 and Ha-Duong, 1998, this section only briefly describes the model, and then focuses on the modifications made to the damage function.

The model finds an optimal strategy that maximizes the discounted sum of inter-temporal utility of the production W_t. The control variable is the reduction level X_t of carbon dioxide emissions at period t, defined so that the realized global emissions are $E_t = E_t^{ref}(1 - X_t)$. The social objective at each period is the logarithm of production. Production at each period can be affected by two factors: the cost of emission reductions, and the climate change impact. The reduction costs depends directly on the abatement level X_t and the abatement speed $X_t - X_{t-1}$. The climate change impact depends indirectly on X_t through a carbon-cycle model relating linearly carbon emissions and carbon dioxide atmospheric concentration.

Uncertainty about climate damages is represented by a subjective probability distribution over three possible states of the world s, denoted respectively L, C et H, and corresponding respectively to low, central and high climate change. Initially, the state of the world is uncertain, but it is known that information will arrive as follows: in 2040, that is period 6 in the model, one knows whether the state is H or not; in 2060, period 8, the information is complete in all cases.

Therefore, the model output is an optimal global CO_2 strategy which depends upon the received information. Before 2040, only one trajectory is prescribed. Between 2040 and 2060 there are two branches: one corresponds to the optimal path in the H state, the other branch corresponds to the other

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[1] At http://www.centre-cired.fr/. This model is available under the terms of an open-source licence: the published code can be re-used, modified and redistributed.

two confounded states of the world. After 2060 at last, each one of the three branches corresponds to a known state of the world.

The nonlinear, stochastic damage function depends upon CO_2 concentration only. Represented as a fraction of reference production W_t at date t, the climatic impact is the sum of two terms f and g, that is:

$$B_t^s = (f_t^s + g_t^s)W_t \tag{1}$$

The first term f is, as in most models, a power function. Its magnitude is parameterized by θ_1^s, which represents the damage occurring at a doubling of CO_2-equivalent radiative forcing. The concavity depends upon the exponent θ_2^s. These parameters θ_1^s et θ_2^s are lower in the L state of the world, and larger when the state of the world is H.

$$f_t^s = \theta_1^s (1-\sigma)^{t-t_0} \left(\frac{M_{t-L}^s - M_0}{M_{2x} - M_0}\right)^{\theta_2^s} \tag{2}$$

In equation (2), the lag $L = 30$ years represents oceanic thermal inertia. Impact is set to zero in the first period, which correspond to a lagged CO_2 concentration of $M_0 = 314$ ppmv. Over time, the impact function's scale declines exponentially at a constant rate $\sigma = 1\%\text{yr}^{-1}$ to represent adaptation and structural change in the economy. The linear part of the damage function is scaled by reference to a doubling of pre-industrial CO_2 concentration, that is $M_{2x} = 550$ ppmv. At this level, damage is assumed to be $\theta_1^C = 1.5\%$ of the Gross World Product (GWP) in the central state of the world. The alternate two values for θ_1^s also corresponds to the IPCC estimates of a few percent of GWP. With respect to θ_2^s, values 1, 2 and 3 will be considered following the literature.

The second term g of damages is the threshold function represented in figure 4.1. This term increases from practically zero to the level d_p over a concentration interval $[Z^s, K^s]$. The nonlinear jump was set to a significant $d_p = 4\%$ of Gross World Product. The economic interpretation of a 4% damage per decade can be understood as follows. In the context of a global economy expanding at 2% per year in the reference case, that damage occurring is equivalent to saying that the global economy grows only at 1.8% per year during a span of 20 years.

$$g_t^s = \frac{d_p}{1 + \left(\frac{2-\gamma}{\gamma}\right)^{\left(\frac{K^s + Z^s - 2M_{t-L}^s}{K^s - Z^s}\right)}} \tag{3}$$

The thresholds parameters were set as illustrated in figure 4.2 . The intuitive story is that the climate system undergoes a transition process when carbon dioxide concentration rises from Z^s to K^s. The nature of this transition is not explicit in the model. The costs are presumed to represent effects of increased climate variability and the costs of adaptation to the new climatic conditions.

To "guesstimate" Z^s and K^s, we assumed that the nonlinear transition occurred as the long-term equilibrium global warming passed through the [+3.5,

+4.5] degrees Celsius range. In terms of the global warming observed at date t, this corresponds to levels much lower than 3 degrees C, since it takes decades to reach the thermal long-term equilibrium.

Since in the model the state variable is carbon dioxide concentration M_t^s, this temperature range was mapped back into a concentration range using a proportionality coefficient. This coefficient ΔT_{2x}^s is the temperature sensitivity parameter, and depends upon the state of the world. States L, C and H respectively correspond to values +2, +2.5 and +3.5 for ΔT_{2x}^s.

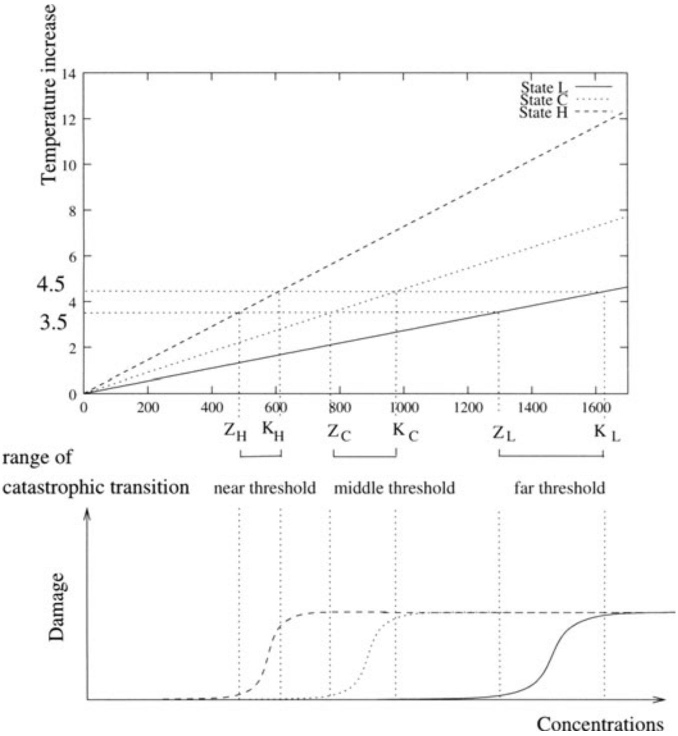

Figure 4.2. Empirical estimation of the non-linear climatic impact jump interval. The top panel's three sloped lines represents a linear relationship between global warming (vertically) and CO_2 increase (horizontally) for three different values of the temperature sensitivity parameter ΔT_{2x}^s. The horizontal lines at +3.5 and +4.5 degrees Celsius represents the interval over which the climatic system bifurcation occurs. For each sloped line, this (vertical) temperature interval defines a (horizontal) CO_2 concentration interval $[Z, K]$. The bottom panel displays g, the nonlinear jumps in the damage function.

The influence of the shape of the damage function on optimal emissions was examined using the model DIAM. More specifically, three runs were compared.

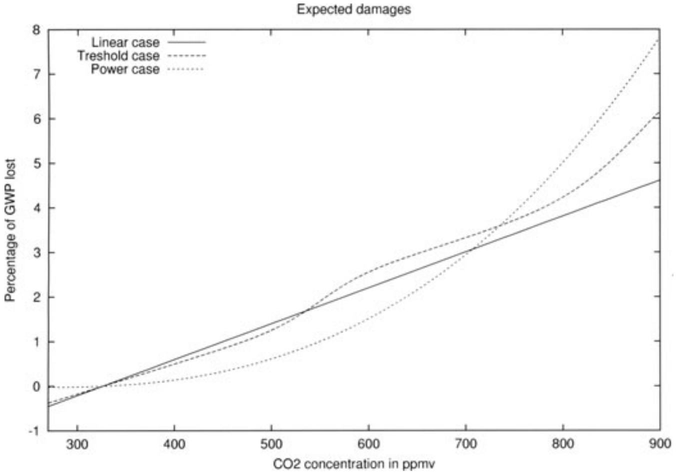

Figure 4.3. Expected climatic damage for three different shapes of stochastic functions. In the linear case, uncertainty is on the slope θ_1^s of the damage function. In the power case, uncertainty is on the exponent θ_2^s. In the threshold case, uncertainty is on the threshold Z^s.

linear In this run, uncertainty is set upon the slope of the damage function $\theta_1^s = \{0.5, 1.5, 4\}$ percent. The function f is linear, $\theta_2 = 1$. There are no catastrophe, so that $g = 0$.

power In this run, uncertainty is set upon the power of the damage function, so $\theta_2^s = \{1, 2, 3\}$ and $\theta_1 = 1$ per cent. There are still no catastrophe, $g = 0$.

threshold In this run, uncertainty is set upon the threshold at which the catastrophe occur, $\theta_1 = 1$ percent, $\theta_2 = 1$ and $Z^s = \{481, 770, 1283\}$.

Figure 4.3 displays the average of these three damage functions. As it was trivial that, all other things being equal, a larger expected damage leads to larger abatement, the different damage functions are calibrated to keep approximately constant the expected value of the damage.

In addition we sought to understand the critical drivers of the abatement strategy in the threshold case. To this end a sensitivity analysis on the threshold function parameters has been conducted. Sensitivity to the ceiling height and the abruptness of the step were examined.

4. Results

The model computes optimal carbon emissions trajectories responding to different assumptions about the climate change risk. Three assumptions were compared, using three different shapes of stochastic damage function: threshold, linear, power. In each case, we examined two parameters: the short-term emission reductions and the effects of learning.

Figure 4.4 presents an optimal emission path and the reference business as usual case. In the reference case, the emissions grow more or less linearly. In the other case, two bifurcations occur, corresponding to the learning dates. These results show a stabilization of the world emissions in about 2050 when the state of the world is the Central state C, but they decrease as early as 2040 in the High state of the world.

Comparing the different optimal emission pathways associated with the different damage functions, the central result is that in the threshold case emissions are lower than in the other two cases. Detailed results for 2020 appear in Table 4.3. They show that the effect of uncertainty on θ_1 (scale of the damages) or on θ_2 (exponent of the damage function) are comparable in order of magnitude, while in the threshold case the percentage of emission reductions are 1.5 points higher than in the two other cases. This result is also valid in the mid term, as that difference grows to 2% in 2030 and 3% in 2040.

While there is only one third of additional emission reduction with the threshold damage function, reduction costs are about one half larger as they are in the other cases. Numerical differences are magnified when moving from abatement levels to reduction costs. This is because faster reductions lead to more than proportionally higher costs, an idea that DIAM is designed to model with a high inertia of the energy systems. On the other hand, the dynamics of the carbon cycle implies that over the next decades the carbon dioxide concentration is very insensitive to policy actions.

In the threshold case the non linearity threshold is only attained in the high change state of the world, at $Z^H = 481$ ppmv. In that case, it is reached as soon as 2050. However, even if non-linear damages appear early, they don't appear to reach very high levels. In these runs, they were never greater than

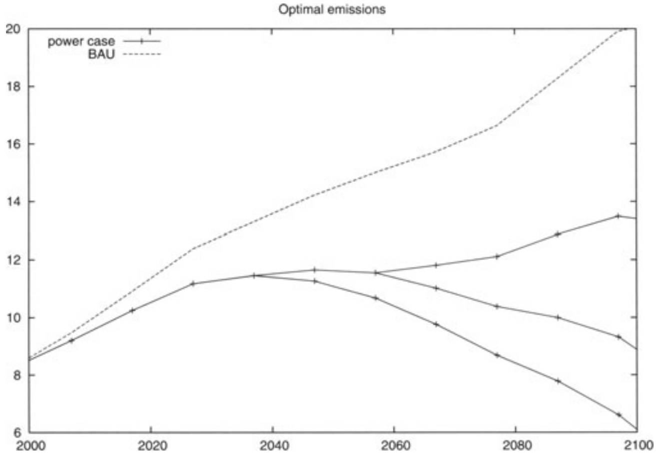

Figure 4.4. Optimal CO_2 emission path for the power stochastic impact function, and the reference business as usual case.

Table 4.3. DIAM 2.3 results for 2020 (optimal Abatements, Emissions, Concentrations, Cost) for each impact function. In the linear case, uncertainty is about the scale of a linear function. In the power case, uncertainty pertains to the exponent of the impact function. And in the threshold case, the uncertainty is on the level of the CO_2 threshold.

	Abatement (%)	Emission (Gt C)	Concentration (ppmv CO_2)	Abatement costs (%)
Baseline		10.91	414	
Linear	7.2	10.21	411	0.04
Power	6.8	10.24	412	0.04
Threshold	8.4	10.09	411	0.06

0.13% of the world GDP, although the ceiling is at 4%. At the time they peak (2100–2110), they represent 14–16% of the total damages and costs.

Note that in the linear and the power case, the damages are different across each state of the world as early as 2020. This is internally inconsistent with the idea that information arrives only in 2040 in the model. In the threshold case, the uncertain non-linear damages are still very low at the date of the resolution of the uncertainty on the H state of the world because the first threshold has not been reached and thus the damages are quasi identical to zero in the three states of the world. This is more consistent with the assumption of unobservability until 2040.

The timing of abatement in the threshold case is also interesting, because some additional abatement is done well before the damages happen. As said above, there is an additional 1.5% of emission reductions in 2020 with regard to the other cases, although the non-linear damage represents only 0.007 of the world GDP in 2070. Thus, this optimal emission path case could be considered as an illustration of a precautionary path: costly additional abatement effort is optimal well before the non-linear damages are even measurable.

Table 4.4. Effects of learning and uncertainty on the abatements in 2020 for three different damage functions (linear, power and threshold cases).

	Optimal abatement of global CO_2 emissions in 2020 in percent				
	Sequential decision (act then learn)	No learning (expected damages)	Perfect information (learn then act)		
Case			L	C	H
Linear	7.2	7.3	2.0	6.0	15.8
Power	6.8	7.1	4.0	7.1	8.4
Threshold	8.4	11.1	6.0	6.9	12.7

Table 4.5. Sensitivity analysis on various parameters of the threshold damage function. The ceiling is doubled and various values for γ, controlling the slope are tested.

	double threshold	vary slope (γ)			reference
	$d_p \times 2$	0.7	0.5	0.3	0.1
abatement %	8.63	15.20	12.02	9.92	8.45

The effect of learning on the optimal emission path is illustrated in Table 4.4. We compare, for each case, the percentage of emission reductions with three possibilities regarding learning. The first possibility is the one already presented with sequential action and learning in 2040 and 2060 (act then learn). The second possibility is a no learning case (expected damages). In the third there is no uncertainty at all, and hence a trajectory for each state of the world (learn then act). It appears that there is a strong effect of learning only in the threshold case.

As discussed above, many previous studies found a very small effect of learning, and had the optimal trajectory with recourse (called 'act then learn') very close to the optimistic full-information trajectory (called 'learn then act'). Our results suggest that one explanation for these results is that they used a power or a linear damage function.

Finally, the sensitivity analysis on the threshold function parameters displayed in Table 4.5 shows that the abruptness of the kink does matter: in this model a sharper kink means less effort. This result may be explained simply: when the step is less abrupt, the concentration threshold is also lower because damages start earlier.

On the contrary, the results are relatively insensitive to the ceiling height, that is the size of the loss on the other side of the nonlinearity. This is because on these optimal trajectories, the worst does not happen. Indeed the results show that as long as the slope isn't too flat the nonlinear region is avoided if possible. This explains why the location of the concentration threshold is the most important parameter of the model. While this is purely a cost-benefit model, that parameter acts as a soft ceiling that limits CO_2 concentration.

5. Conclusion

This paper has revisited the question of the optimal timing of climate policy using a damage function that increases abruptly. This kind of cost-benefit analysis avoids some fundamental problems of cost-efficiency analysis: there is no a priori environmental constraint that must be met at all cost.

In most of the existing literature, J-shaped hockey-stick or power damage functions were used. A common result of the EMF-14 study was that, compared to the expected damage, sequential decision-making justified only a very small amount of additional precaution. In this paper, we used an S-shaped damage function. This is more consistent with the stylized belief that climate damages are expected to remain small. We find that this model of abrupt change justifies a larger amount of precaution in sequential decision making.

We conclude that the introduction of thresholds, and the uncertainty about the value of the threshold in unfavorable cases appears important for the decision, while introducing non-linearities with the exponent of the damage function do not change the timing of the action. With threshold damage functions and information about the bad case arriving in 2040, it is optimal to reduce emissions well before the threshold is attained, and also before the damages happen.

We argue that realistic parameters of the S-shaped damage function g are easier to know than parameters of the power law damage function f. This is because the critical parameter (the location of the dangerous CO_2 concentration threshold) can be related to geophysical knowledge about the climate system. Statistics based on climate simulation models results could be used to calibrate uncertainty on that. Regarding the damage function $D = \theta_1(\Delta T)^{\theta_2}$, it seems comparatively harder to avoid subjective assessments when the uncertain parameters are the scale θ_1 or the exponent θ_2.

Admittedly, the S-shaped damage function also takes a scale parameter d_p that is as hard to know as θ_1. But uncertainty about d_p seems less critical than uncertainty about θ_1. We found the optimal trajectory to be much more sensitive to the location of the threshold than to the magnitude of the loss.

With an S-shaped function, marginal damages can increase rapidly and this acts as a soft ceiling on carbon dioxide concentration in these simulations. We found that the possibility of a relatively low loss of GDP of 4%, if happening early and abruptly can justify some additional efforts of mitigation in the near term. This is in agreement with recent results by Keller et al., 2004, showing that a surprisingly small threshold specific damage (about 0.5%) significantly increases the optimal CO_2 abatement.

With the representation of non-linearity and uncertainty presented here, a kind of precautionary behavior is revealed by the cost-benefit analysis of optimal reduction paths: we can not wait for damages to happen before mitigating more. This result became only visible when the model explicitly integrated an uncertain threshold. Accounting for the possibility of abrupt and near term climate change is crucial to properly understand climate policy.

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Chapter 5

A VIABILITY APPROACH TO GLOBAL CLIMATE CHANGE ISSUES

Jean-Pierre Aubin
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Patrick Saint-Pierre

Abstract The main purpose of viability theory is to explain the evolution of the state of a control system governed by nondeterministic dynamics and subjected to viability constraints, reveal the concealed feedbacks which allow the system to be regulated and provide selection mechanisms for implementing them. It assumes implicitly an "opportunistic" and "conservative" behavior of the system: a behavior which enables the system to keep viable solutions as long as its potential for exploration (or its lack of determinism) — described by the availability of several evolutions — makes its regulation possible. It also happens that these results can be used to study infinite horizon optimal control problems, with intergenerational constraints, with nonstandard inter-temporal optimality criteria bearing not only on the evolutions of the states and the controls, but also on the velocities of the controls, allowing us in particular to minimize maximal inertia. We illustrate these points with simplified Greenhouse Gas models, where we minimize the worst transition cost of changing the short-term pollution rate (or economic growth) in order to maintain the concentration of greenhouse gases bounded.

1. A brief Introduction to Viability Theory

This paper complements the infinite horizon optimization viewpoint exposed in Haurie, 2003, for instance. We shall add to the infinite horizon optimization paradigm intergenerational constraints which may be relevant to the questions of global climate change. We shall also study inertia functions which we presented in the preceding section, which are other infinite horizon optimal problems where we minimize the worst cost of the derivative of the control. The concepts and tools used for this purpose come from viability theory, and in particular, the concept of viability kernel. These concepts may be useful not

A. Haurie and L. Viguier (eds.), The Coupling of Climate and Economic Dynamics, 113–143.

only as mathematical tools for studying and solving numerically optimal control problems, but also interesting by themselves for providing mathematical metaphors and tools for some climatic issues as well. Indeed, contrary to optimal control theory, viability theory does not require any single decision-maker (or actor, or player) to "guide" the system by optimizing an intertemporal optimality criterion[1]. Furthermore, the choice (even conditional) of the controls is not made once and for all at some initial time, but they can be changed at each instant so as to take into account possible modifications of the environment of the system, allowing therefore for adaptation to viability constraints. Finally, by not appealing to intertemporal criteria, viability theory does not require any knowledge of the future[2] (even of a stochastic nature.) This is of particular importance when experimentation[3] is not possible or when the phenomenon under study is not periodic. For example, in biological evolution as well as in economics and in the other systems involving life, the systems are irreversible, their dynamics may disappear and cannot be recreated, forbidding any insight into the future. Hence, forecasting or prediction of the future are not the issues which we shall address in viability theory.

However, the conclusions of the theorems allow us to reduce the choice of possible evolutions, or to single out impossible future events, or to provide explanation for some behaviors which do not fit any reasonable optimality criterion. Therefore, instead of using intertemporal optimization[4] that involves the future, viability theory provides selection procedures of viable evolutions obeying, at each instant, state constraints which depend upon the present or the past. (This does not exclude anticipations, which are extrapolations of past evolutions, constraining in the last analysis the evolution of the system to be a function of its history.)

Viability theory designs and develops mathematical and algorithmic methods for studying the evolution of systems and networks of systems (or organizations, organisms), with the following characteristics:

- under continuous time, discrete time, or an "hybrid" of the two when impulses are involved,
- constrained to adapt to a (possibly co-evolving) environment,

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[1] the choice of which is open to question even in static models, even when multicriteria or several decision makers are involved in the model.

[2] Most systems we investigate do involve myopic behavior; while they cannot take into account the future, they are certainly constrained by the past.

[3] Experimentation, by assuming that the evolution of the state of the system starting from a given initial state for a same period of time will be the same whatever the initial time, allows one to translate the time interval back and forth, and, thus, to know" the future evolution of the system.

[4] which can be traced back to Sumerian mythology which is at the origin of Genesis: one Decision-Maker, deciding what is good and bad and choosing the best (fortunately, on an intertemporal basis, thus wisely postponing to eternity the verification of optimality), knowing the future, and having taken the optimal decisions, well, during one week...

- evolving under contingent, stochastic or tychastic uncertainty. State-dependent uncertainty can also be translated mathematically by parameters on which actors, agents, decision makers, etc. have no controls. These parameters are often perturbations, disturbances (as in "robust control" or "differential games against nature") or more generally, tyches (meaning "chance" in classical Greek, from the Goddess Tyche) ranging over a state-dependent tychastic map. They could be called "random variables" if this vocabulary were not already confiscated by probabilists. This is why we borrow the term of *tychastic evolution* to Charles Peirce who introduced it in a paper published in 1893 under the title *evolutionary love*. One can prove that stochastic viability is a (very) particular case of tychastic viability. The size of the tychastic map captures mathematically the concept of "versatility (tychastic volatility)" — instead of "stochastic volatility": The larger the graph of the tychastic map, the more "versatile" the system.
- using for this purpose regulons (regulation controls), and in the case of networks, connectionist matrices or tensors,
- regulated by feedback laws (static or dynamic) that are then "computed" according to given principles, such as the inertia principle,
- co-evolving with their environment (mutational viability),
- the nonviable dynamics being corrected by introducing adequate controls (viability multipliers) when necessary.

We introduce the viability kernel with target under a nonlinear controlled system (either continuous or hybrid): See Figure 5.1. This is the subset of initial states from which starts at least one evolution that either (i) remains in the constrained set (i.e., is viable) forever; or (ii) reaches (i.e., captures) the target in finite time[5] before possibly violating the constraints. When the target is empty, only the first condition matters, and one says that it is simply the viability kernel of the environment. The set of initial states satisfying only the second condition is called the capture basin of the target viable in the constrained subset.

When these evolutions depend upon a parameter, such parameter can be regarded as (i) a control when actors (agents, decision makers, etc.) can act (pilot, decide, choose, etc.) on it; (ii) as regulatory parameters, in short a regulons, when no clearly identified agent can act on it. These parameters are regarded as genotypes in biology, fiduciary goods in economics, cultural codes in sociology. They range over a state-dependent cybernetic map, providing the system opportunities to adapt to viability constraints (often, as slowly as possible) and/or to regulate intertemporal optimal evolutions.

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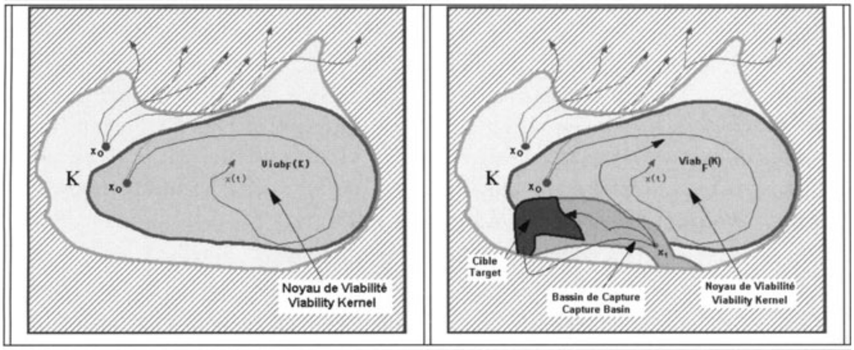
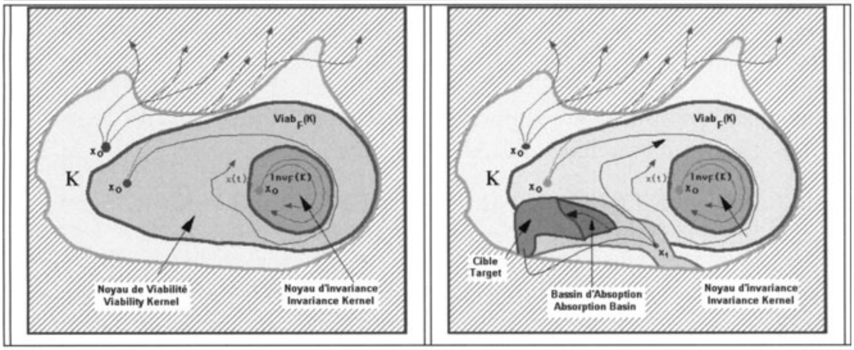
[5] and not only asymptotically, as it is usually studied with concepts of attractors since the pioneering works of Alexander Lyapunov and Henri Poincaré going back to 1892.



Viability Kernel | Capture Basin



Invariance Kernel | Absorption Basin

Figure 5.1. **Kernels and Basins.**

We also introduce the "dual" concept of invariance kernel with target, which is the subset of initial states from which all evolutions either (i) remain in the environment (i.e., are viable) forever or (ii) reach the target in finite time before possibly violating the constraints. The set of initial states satisfying only the second condition is called the absorption basin of the target invariant in the environment. This concept plays a role whenever the evolutions are governed by evolutions depending upon tyches (perturbations, disturbances) on which actors, agents, decision makers, etc.

Tychastic control systems (or dynamical games) involve both regulons and tyches in the dynamics, tyches describing uncertainties played by an indifferent, maybe hostile Nature, regulons being available and chosen by the system in order to adapt its evolutions whatever the tyches. Let us introduce the concepts of tychastic (or guaranteed) viability kernel, which is the subset of initial states from which there exists a regulon such that, for all tyches, the associated evolutions either (i) remain in the environment (i.e., are viable) forever or (ii) reach the target in finite time before possibly violating the constraints. The set of initial states satisfying only the second condition is called the absorption basin of the target invariant in the environment.

It is by now a consensus that many variables describing systems, organizations, networks arising in biology and human and social sciences do not evolve in a deterministic way, and may be, not even in a stochastic way as it is usually understood, but with a Darwinian flavor, where intertemporal optimality selection mechanisms are replaced by several forms of "viability", a word encompassing polysemous concepts as stability, confinement, homeostasis, tolerable windows[6] etc., expressing the idea that some variables must obey some constraints. We quote Petschel-Held et al., 1999:

> *The tolerable windows approach (TWA) allows the climate policy formulation process to be safeguarded in the following way. First, guardrails are defined in order to exclude intolerable climate change impacts, on the one hand, and unacceptable socioeconomic consequences of climate change mitigation measures, on the other. Second, a scientific analysis is conducted to investigate the features of those emission paths that are compatible with the guardrail constraints. The fundamental methodology of the TWA is best described in terms of the theory of differential inclusions...*

Intertemporal optimization is replaced by myopic selection mechanisms that involve present knowledge, sometimes the knowledge of the history (or the path) of the evolution, instead of anticipations or knowledge of the future (whenever the evolution of these systems cannot be reproduced experimentally). Uncertainty does not necessarily obey statistical laws, but only unforcastable rare events (tyches, or perturbations, disturbances) that obey no statistical law, that must be avoided at all costs (precautionary principle or tychastic (robust) control). These systems can be regulated by using regulation (or cybernetical) controls that have to be chosen as feedbacks for guaranteeing the viability of a system and/or the capturability of targets and objectives, possibly against tyches (perturbations played by Nature).

Outline: In the next section 2 we motivate the Viability approach through two simple examples involving ecological constraints, the evolution of greenhouse gas concentration, the evolution of macro-economic interaction and the inertia function which provides the minimal worst effort for regulating pollution. We devote the section 3 to the description of the main concepts and basic results of viability theory: evolutions, viability kernels and capture basins under evolutionary systems. In section 4 we consider specific evolutions by defining inertia functions. We emphasize the relation between these functions and the Viability Theory proving that their epigraphs are viability kernels associated with extended dynamical systems. It follows that the Viability Kernel Algorithm can be implemented for computing approximations of these inertia functions. In section 5 we complement the infinite horizon optimization viewpoint exposed in Haurie, 2003 by characterizing the epigraph of the value function of

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[6] see the contribution by Ferenc, Toth and Petschel-Held et al., 1999, Bruckner et al., 1999, Toth, 2002, etc.

infinite horizon optimal control problems as a viability kernel (epigraphical approach of the Hamilton-Jacobi-Bellman approach). We add to the model some intergenerational constraints which may be relevant to the questions of global climate change. In section 5, we consider another infinite horizon optimal problem where we maximize the worst cost of the derivative of the control. This provides a simple example of minimizing the worst transition cost of changing the pollution rate in order to keep the concentration of greenhouse gas constant. In the last section 6 we characterize, in the viability/capturability frame, the adaptation law for the construction of static dynamic feedbacks.

2. Motivation: Inertia Functions of Simple Examples

Many difficulties of collective decision-making models about climatic risks are due to the interactions between physical and economical requirements. The precautionary principle[7] and economic efficiency are often contradictory[8].

For stylizing the problems and providing a two-dimensional illustration, we begin by isolating two variables:

- the concentration $x(t) \in [0, b]$ of greenhouse gases — say, CO_2 — regarded as a state variable, bounded by a given constant b
- the short-term pollution rate (generated when using a given technology and a level of production) $y(t) \in \mathbb{R}_+$, regarded as controls or regulons (regulatory controls).

The *ecological constraints* being represented by the interval $[0, b]$, the *economic constraints* amount to bound or minimize a transition cost measured in this example by the absolute value of the velocity of the pollution rate. How this cost is a new constraint for a macro-economic model is another question which we examine next.

We assume here that the evolution of the concentration of greenhouse gases is governed by the differential equation

$$x'(t) = y(t) - ax(t).$$

That means that the variation of the concentration of the greenhouse gases depends upon a natural slow absorption phenomenon by the oceans ($-ax(t)$ with a "small") and is proportional to the short-term pollution.

This starting example is chosen for providing analytical solutions. The Saint-Pierre viability kernel algorithm which we shall use later allows nonlinear differential equations that climatologists can propose, such as the ones used by

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[7] stating that one should limit, bound or even forbid potential dangerous actions, without waiting for a scientific proof of their hazardous consequences, whatever the economic cost.

[8] see Aubin, 1996b for certain comments on this topic; we also refer to Doyen et al., 1996; Petschel-Held et al., 1999; Bruckner et al., 1999; Doyen & Gabay, 1999; Doyen & Gabay, 1997; Doyen & Gabay, 1996; Gabay 1994.

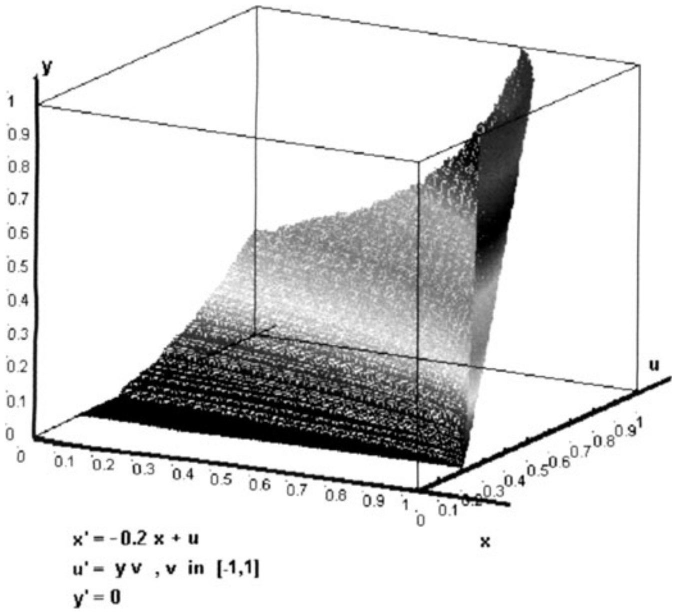

Figure 5.2. **Graph of the Inertia Function** $\alpha(x,y) := inf_{(x(\cdot),y(\cdot))\in\mathcal{P}(x,y)} \sup_{t\geq 0} |y'(t)|$ where $x(\cdot)$ is governed by $x'(t) = y(t) - 0.2x(t)$ defined on $[0,1] \times [0,1]$ (instead of $[0,1] \times \mathbb{R}_+$). The variable y is the pollution rate, the state x is the concentration of greenhouse gases and the inertia function as the minimaximal intertemporal transition cost of changing of pollution rate.

the German Advisory Council on Global Change (WBGU) in its special report for the First Conference of the Parties to the FCCC in Berlin (WBGU, 1997). A forthcoming study by T. Bernado, P. Saint-Pierre and J. Scheffran will adapt some of the methods presented here in the framework of such models.

We denote by $\mathcal{P}(x,y)$ the set of evolutions $(x(\cdot),y(\cdot))$ starting at $x(0) = x$ and $y(0) = y$, viable in $[0,b] \times \mathbb{R}_+$where $x(\cdot)$ is governed by $x'(t) = y(t) - ax(t)$.

The inertia function that we shall study in this paper is defined by

$$\alpha(x,y) := \inf_{(x(\cdot),y(\cdot))\in\mathcal{P}(x,y)} \sup_{t\geq 0} |y'(t)|.$$

Starting with initial greenhouse gas concentration x and emission y, the inertia function provides the minimal worst effort measured by the velocity of the regulon with which the pollution emission should change in order for the greenhouse gas concentration to satisfy the viability constraints $x(t) \in [0,b]$. This in an infinite horizon optimal control problem which is non-standard in at least two respects: (i) The intertemporal optimality criterium bears on the velocities of the controls (and not only on the evolutions of the states and the controls, as it is usually the case); (ii) The criterion is not as usual an integral criterion, but a supremum over time of a Lagrangian function (here, the norm).

One can compute this inertia function with the viability kernel algorithm as we shall explain later (see Figure 5.2) and also compute it explicitly since $\alpha(x,y)$ is the solution to the equation

$$a(x-ay) \;=\; \alpha(x,y)\left(1-e^{\frac{a}{\alpha(x,y)}(y-ab)}\right).$$

The **warning function** $\Xi_c(y) := \{x \in [0,b] \mid \alpha(x,y)=c\}$ is a single-valued function $\mathbb{R}_+ \mapsto \mathbb{R}$ given by

$$\Xi_c(y) \;=\; \frac{c}{a^2}\left(1-e^{\frac{a}{c}(y-ab)}\right)+\frac{y}{a}.$$

It satisfies $\Xi_c(ab)=b$ and $\xi_c(0) = \frac{c}{a^2}\left(1-e^{\frac{-a^2b}{c}}\right)$, which provides the smallest concentration of greenhouse gas that we can obtain by choosing the most drastic reduction strategy using $y'(t)=-c$.

We observe that $\alpha(x,y)=0$ if and only if $(x,y)\in[0,b]\times[0,ab]$. In this case, passive evolutions $x_y(\cdot)$ are viable in $[0,b]$ and converge to the equilibrium $\frac{y}{a}$, which is stable whenever $y\in[0,ab]$. The level sets are defined by the formula

$$\{(x,y)\in[0,b]\times\mathbb{R}_+ \mid \alpha(x,y)\le c\} \;=\; \{(x,y)\in[0,b]\times\mathbb{R}_+ \mid x\le \Xi_c(y)\}.$$

They provide the subsets of state-control pairs for which it is possible to satisfy the viability constraints with control velocities bounded in norm by a given constant $c\ge 0$. The trajectories of evolutions $(x(\cdot),y(\cdot))$ satisfying $\alpha(x(t),y(t))=c$ (called **inert evolutions**) satisfy the equation $x(t)=\Xi_c(y-ct)$. The **heavy evolution** consists in keeping the same pollution as long as the mass of greenhouse gas is smaller than $\Xi_c(y)$. At this level, the technology has to be drastically changed with the velocity equal to $-c$, while the concentration of greenhouse gas increases until it reaches the level b, which is an equilibrium where the heavy evolution stops.

As a second example, we can add a macro-economic interaction, stating that the emissions of pollutants depend upon the economic[9] activity $z(t)$. Hence, at a very elementary level of illustration of the phenomenon, we assume that we have access to the velocity of the pollution rate through a bound of the form $|y'(t)|\le z(t)$ set by economic activity $z(t)$. This ignorance is taken into account by the "meta-inertia function" that we now define.

We denote by $\mathcal{P}(x,y,z)$ the subset of "meta-evolutions" $(x(\cdot),y(\cdot),z(\cdot))$ starting at $x(0)=x$, $y(0)=y$ and $z(0)=z$, viable in $[0,b]\times\mathbb{R}_+\times\mathbb{R}$ where $(x(\cdot),y(\cdot))$ is governed by

$$\left\{\begin{array}{ll} (i) & x'(t)=y(t)-axt) \\ (ii) & |y'(t)|\le z(t). \end{array}\right.$$

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[9] At least one of the authors is not convinced by the validity of the standard macro-economic models, too simplistic to take into account socio-psycho-economico-... behaviors. This issue is well known, and has been tackled in many articles such as the Nordhaus Integrated Assessment Models.

The "meta-inertia function" $(x,y,z) \mapsto \beta(x,y,z)$ associated with this meta-system is defined by

$$\beta(x,y,z) := \inf_{(x(\cdot),y(\cdot),z(\cdot))\in\mathcal{P}(x,y,z)} \sup_{t\geq 0} |z'(t)|.$$

Since the graph of this function is 4-dimensional, we shall represent it by its 3-dimensional level-sets

$$\{(x,y,z) \in [0,b]\times\mathbb{R}_+\times\mathbb{R} \text{ such that } \beta(x,y,z) \leq c\}.$$

We observe that the inertia function α is related to the meta-inertia function β by the relations

$$\mathrm{Graph}(\alpha) = \{(x,y,z) \in [0,b]\times\mathbb{R}_+\times\mathbb{R} \text{ such that } \beta(x,y,z) \leq 0\}.$$

Indeed, we remark that the inertia $z := \alpha(x,y)$ of an evolutions $(x(\cdot),y(\cdot)) \in \mathcal{P}(x,y)$ is finite if and only if, setting $z(t) \equiv z$, the meta-evolution $(x(\cdot),y(\cdot),z(\cdot)) \in \mathcal{P}(x,y,z)$ satisfies

$$\beta(x,y,z) := \inf_{(x(\cdot),y(\cdot),z(\cdot))\in\mathcal{P}(x,y,z)} \sup_{t\geq 0} |z'(t)| = 0. \ \blacksquare$$

3. The Mathematical Framework

For more details on viability theory, we refer to Aubin, 1991 and to the forthcoming book by Aubin et al., to appear. We provide here basic definitions and some results which may be relevant to climate studies.

3.1 Viability and Capturability

Let X denote the **state space** of the system. Evolutions describe the behavior of the state of the system as a function of time $t \in \mathbb{R}_+ := [0,\ldots,+\infty[$ ranging over the set of nonnegative real numbers or scalars $t \in \mathbb{R}_+$. We shall assume all along that (i) the state space is a finite dimensional vector space $X := \mathbb{R}^n$; (ii) the evolutions are *continuous* functions $x(\cdot) : t \in \mathbb{R}_+ \mapsto x(t) \in X$ describing the evolution of the state $x(t)$. We denote the space of continuous evolutions $x(\cdot)$ by $\mathcal{C}(0,\infty;X)$ or, in short, $\mathcal{C}(X)$.

Some evolutions, mainly motivated by physics, are classical: *equilibria and periodic evolutions*. But these properties are not necessarily adequate for problems arising in economics, biology, cognitive sciences and other domains involving living beings. Hence we add the concept of evolutions *viable in a constrained set $K \subset X$ (***the environment***) or capturing a target $C \subset K$ in finite time* to the list of properties satisfied by evolutions. Therefore, we consider mainly evolutions $x(\cdot)$ **viable in a subset** $K \subset X$ representing a constrained set (an environment) in which the trajectory of the evolution must remain forever:

$$\forall\, t \geq 0,\ \ x(t) \in K. \tag{1}$$

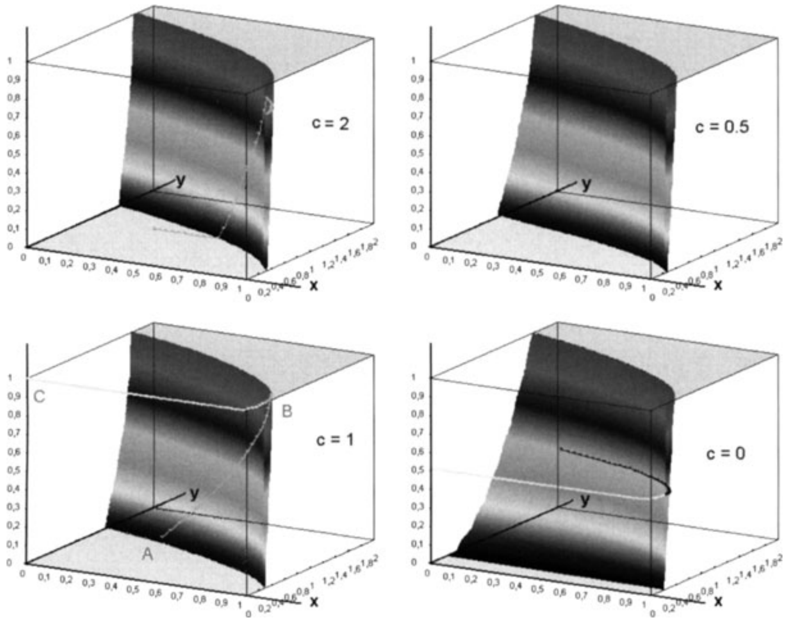

Figure 5.3. **Level-sets of the Meta-Inertia Function** $\beta(x,y,z) := inf_{(x(\cdot),y(\cdot),z(\cdot))\in\mathcal{P}(x,y,z)} \sup_{t\geq 0}|z'(t)|$ when the evolution $x(\cdot)$ is governed by the system $x'(t) = y(t) - 0.2x(t)$ and $|y'(t)| \leq z(t)$ defined on $[0,1]\times[0,25]\times[-1,+1]$ for several values of $c = 0,\ 0.5,\ 1\ \&\ 2$. We assume only that the derivative $y'(\cdot)$ of the pollution rate $y(\cdot)$ is bounded by a measure of the economic activity. The meta-inertia function provides the minimaximal intertemporal economic transition cost of changing of pollution rate. For $c = 0$, we find the graph of the inertia function α, equal to the level set $\{(x,y,z) \in [0,b]\times\mathbb{R}_+\times\mathbb{R}$ such that $\beta(x,y,z) \leq 0\}$. The trajectory of the evolution represented for $c = 2$ is an heavy evolution (for $z := \alpha(x,y)$) and the evolution represented for $c = 0$ is an inert one. For $c = 1$, the trajectory of the evolution starting from B is an heavy evolution of the level set $\{(x,y,z) \in [0,b]\times\mathbb{R}_+\times\mathbb{R}$ such that $\beta(x,y,z) \leq 1\}$ arriving at equilibrium A.

Alternatively, a “target” $C \subset K$ being given, we distinguish evolutions $x(\cdot)$ **capturing the target** C in the sense that they are viable in K until they reach the target C **in finite time**:

$$\exists\, T \geq 0 \text{ such that} \left\{ \begin{array}{l} x(T) \in C \\ \forall\, t \in [0,T],\ x(t) \in K. \end{array} \right. \tag{2}$$

We devote our paper to the study of the set of evolutions **viable in** K **outside** C, i.e. that are viable in K forever or until they reach the target C in finite time.

3.2 The Evolutionary System

Next, we provide the mathematical description of one of the "engines" governing the evolution of the state. We assume that there exists a control parameter, or, better, a regulatory parameter, called a **regulon**, that influences the evolution of the state of the system. This dynamical system takes the form of a **control system with (multivalued) feedbacks** :

$$\left\{ \begin{array}{ll} i) & x'(t) = f(x(t), u(t)) \ \text{(action)} \\ ii) & u(t) \in U(x(t)) \ \text{(contingent retroaction)} \end{array} \right. \tag{3}$$

taking into account the *a priori* **availability** of several regulons $u(t) \in U(x(t))$ chosen in a subset $U(x(t)) \subset Y$ of another finite dimensional vector-space Y subjected to **state-dependent constraints**. Once the initial state is fixed, the first equation describes how the regulon **acts** on the velocities of the system whereas the second inclusion shows how the state (or an observation on the state) can **retroact through** (several) regulons in a multivalued way.

We observe that there are many evolutions starting from a given initial state x_0, one for each time-dependent regulon $t \mapsto u(t)$. The set-valued map $U : X \rightsquigarrow Y$ also describes the **state-dependent constraints on the regulons**. In this case, the system (3) can no longer be regarded as a parameterized family of differential equations, as in the case when $U(x) \equiv U$ does not depend upon the state, but as a **differential inclusion** (see Aubin & Cellina, 1984 for example). Fortunately, differential inclusions enjoy most of the properties of differential equations. A solution to system (3) is an evolution $t \rightarrow x(t)$ satisfying this system for some (measurable) open-loop control $t \rightarrow u(t)$ (almost everywhere).

We associate with the control system the **evolutionary system** $x \rightsquigarrow \mathcal{S}(x)$ associating with any initial state $x \in K$ the subset $\mathcal{S}(x) \subset \mathcal{C}(0, \infty; X)$ of solutions starting at x. Most of the results on viability kernels and capture basins depend upon few properties of this evolutionary system, that are shared by other "engine of evolutions", such as diffusion-reaction systems, path (or history) dependent systems, mutational equations governing the evolution of compact sets.

3.3 Viability Kernels and Capture basins

The problems we shall study are all related to the viability of a constrained subset K and/or the capturability of a target $C \subset K$ under the dynamical system modelling the dynamic behavior of the system. So let us introduce: (i) The subset $\text{Viab}(K)$ of initial states $x_0 \in K$ such that one solution $x(\cdot)$ to system (3)ii) starting at x_0 is viable in K for all $t \geq 0$ is called the **viability kernel** of K under the control system. A subset K is a **repeller** if its viability kernel is empty; (ii) the subset $\text{Capt}(K, C)$ of initial states $x_0 \in K$ such that the target $C \subset K$ is reached in finite time before possibly leaving K by one solution $x(\cdot)$ to system (3)ii) starting at x_0 is called the **viable-capture basin** of C in K. A subset $C \subset K$ such that $\text{Capt}(K, C) = C$ is said to be **isolated** in K.

We say that

- a subset K is *viable* under $\mathcal{S}$ if $K = \mathrm{Viab}(K)$,
- the subset K is a **repeller** if $\mathrm{Viab}(K) = \emptyset$.

In other words, the **viability** of a subset K under a control system is a consistency property of the dynamics of the system confronted to the constraints it must obey during some length of time. To say that a singleton $\{c\}$ is viable amounts to saying that the state c is an **equilibrium** (equi-libra, equal balance) — also called a fixed point. The trajectory of a periodic solution is also viable.

Contrary to the century-old tradition going back to Lyapunov, we require the system to capture the target C in **finite time**, and not in an asymptotic way, as in mathematical models of physical systems. However, there are close mathematical links between the various concepts of **stability** and viability. For instance, Lyapunov functions can be constructed using tools of viability theory. Or one can prove that the attractor is contained in the viability kernel of an absorbing set under the backward (negative) system. This needs much more space to be described: we refer to Chapter 8 of Aubin, 1991 and Chapter 8 of Aubin, 1997 for more details on this topic. One can also prove that *the viability kernel* $\mathrm{Viab}(K)$ *of the subset* K *is the* **largest** *subset of* K *viable under the control system.* Hence, all interesting features such as equilibria, trajectories of periodic solutions, limit sets and attractors, if any, are all contained in the viability kernel.

One can prove that the viability kernel is the **unique** subset $D \subset K$ viable and isolated in K such that $K \backslash D$ is a repeller. If $K \backslash C$ is a repeller, the capture basin $\mathrm{Capt}(K, C)$ of $C \subset K$ is the **unique** subset D between C and D such that D is isolated in K and $D \backslash C$ is locally viable. The viability kernels of a subset and the capture basins of a target can thus be characterized in diverse ways through tangential conditions thanks to the viability theorems. They play a crucial role in viability theory, since many interesting concepts are often viability kernels or capture basins. Furthermore, **algorithms** designed in Saint-Pierre, 1994 allow us to compute viability kernels and capture basins (see also Cardaliaguet et al., (1999) and Quincampoix & Saint-Pierre, 1998). In general, there are no explicit formulas providing the viability kernel and capture basins.

4. The Inertia Functions, Metasystems and Viability Niches

In this section, we consider parameterized system

$$\left\{ \begin{array}{lrcl} (i) & x'(t) & = & f(x(t), u(t)) \\ (ii) & u(t) & \in & U(x(t)) \end{array} \right. \tag{4}$$

where the set-valued map U involves implicitly the viability constraints

$$\forall\, t \geq 0, \;\; x(t) \in K := \mathrm{Dom}(U).$$

Remark: — Conversely, the viability constraint described by a constrained subset K under parameterized system (4) can be taken into account by introducing the restriction $U|_K$ of the set-valued map U to K defined by

$$U|_K(x) := \begin{cases} U(x) & \text{if} \quad x \in K \\ \emptyset & \text{if} \quad x \notin K. \end{cases}$$

This amounts to studying the system

$$\begin{cases} (i) & x'(t) = f(x(t), u(t)) \\ (ii) & u(t) \in U|_K(x(t)) \end{cases}$$

that is the above parameterized system (4) when U is replaced by $U|_K$. ■

We shall devote this section to specific evolutions classified in increasing inertia order.

The most "inert" evolutions are **equilibria** $(x^\star, u^\star)$ of the control system, solutions to

$$\begin{cases} (i) & 0 = f(x^\star, u^\star) \\ (ii) & u^\star \in U(x^\star) \end{cases}$$

since both the state and the controls do not evolve.

We next distinguish passive evolutions, governed by constant controls:

DEFINITION 4.1 *Evolutions governed by systems*

$$\forall\, t \in [t_0, t_1],\ \ x'(t) = f(x(t), u)$$

subjected to viability constraints

$$\forall\, t \in [t_0, t_1],\ \ x(t) \in U^{-1}(u)$$

with constant regulon are called **passive evolutions** *on the time interval* $[t_0, t_1]$.

This is a situation familiar in physics, when the parameters are physical coefficients, that do not change along the evolution. Important properties (set of equilibria, stability or instability of equilibria) are then studied in terms of such parameters, as in bifurcation theory, catastrophe theory, chaotic behavior, etc. Naturally, passive evolutions may not exist, or exist only on a finite time interval, or the class of passive evolutions is too small to contain solutions to given problems (viability, capturability, optimal controls, etc.).

We then consider evolutions regulated by affine open-loop controls of the form $u(t) := u + u_1 t$, nicknamed **ramp controls** in control theory, regulating what we shall call "inert controls".

DEFINITION 4.2 *An evolution* $(x(\cdot), u(\cdot))$ *is said to be* **inert** *on a time interval* $[t_0, t_1]$ *if it is regulated by an affine open-loop controls of the form* $u(t) := u + u_1 t$, *the velocities of which are constant.*

Although we shall concentrate our study on inert evolutions, we shall provide some properties common to evolutions governed by open-loop controls $u(t) := u + u_1 t + \cdots + u_{m-1} \frac{t^{m-1}}{(m-1)!}$ which are $(m-1)$-degree polynomials in time.

More generally, we are interested in evolutions governed by open-loop controls $t \mapsto u(t)$ with bounded derivative $u^{(m)}(t)$ for some $m \geq 1$.

In regulation systems, agents acting on state variables are well identified, but regulons evolve slowly by lack of a definite agent acting on controls or because the change of controls is costly, even very costly. The regulons are thus constrained by some inertia that can be estimated through some measure of their velocities. For instance, in economics, the parameters are prices or other fiduciary variables, and inflation should be bounded. We may even look for heavy evolutions when the regulons evolve as slowly as possible.

Naturally, passive evolutions may not exist, or exist only on a finite time interval. Then the question arises to study when, where and how passive evolutions must cease to be passive and allows the regulons to evolve in order to guarantee the viability: We shall give a name to this property which seems to be shared by so many systems dealing with living beings: In a loose way, the inertia principle states that the *"regulons" of the system are changed only when viability is at stake.* It runs against the teleological trend assigning aims to be achieved (in even an intertemporal optimal way) by the state of the system and the belief that actors control the system for such purposes.

The inertia principle stating that the *"regulons" of the system are changed only when viability is at stake* is a mathematical formulation of the concept of *punctuated equilibrium* introduced in paleontology by Eldredge and Gould in 1972. It runs against the teleological trend assigning aims to be achieved (in even an optimal way) by the state of the system and the belief that actors control the system for such purposes. However, they were anticipated by Darwin himself who added the sentence

> *and lastly, although each species must have passed through numerous transitional stages, it is probable that the periods, during which each underwent modification, though many and long as measured by years, have been short in comparison with the periods during which each remained in an unchanged condition*

to Chapter XI of the sixth edition of *Origin of Species.*

The question arises of how to change constant regulons when the viability condition is about to be violated. This can be done either brutally, by impulses or in a smoother manner, by minimizing some cost function on the velocity. Naturally, there are many other approaches between these two extremes to obey the inertial principle. The brutal changes are the topic of impulse control and/or hybrid systems (see for instance Aubin, 1999). The second one is the topic of this section.

4.1 Inertia Functions

An adequate way to handle concepts of evolutions governed by open-loop polynomial controls and differentiable open-loop controls is by means of inertia functions. They are value functions of optimal control problems where the criterion (i) is no longer an integral one, but involves instead the supremum

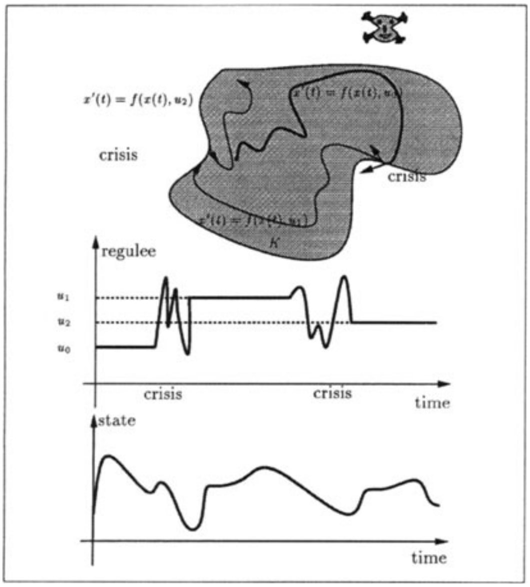

Figure 5.4. *Punctuated Evolution.* Starting from x_0 with the constant regulon u_0, the solution evolves in K until time t_1, (first *punctuated equilibrium phase*) when the state $x(t_1)$ is about to leave K and when the constant regulon u_0 must evolve. Then a *crisis* happens during which velocities also evolve (as slowly as possible) to maintain viability, until time $\bar{t}_1$ where the control can remain constant during a nonempty time interval: *second punctuated equilibrium phase.*

over time of a norm (or, possibly, another criterion function); (ii) is acting on the m-th derivative of the control instead of the state-control pairs.

Let us introduce the $\mathcal{P}_1(x, u) := \mathcal{P}_1(x, u)$ the set of solutions $(x(\cdot), u(\cdot))$ to the above parameterized system (4) starting at (x, u).

DEFINITION 4.3 *The first-order inertia function, or, in short, the* **inertia function** α *of parameterized system (4) is the minimal worst intertemporal inertia* $\alpha_1(x, u)$ *of the evolutions starting from* $(x, u) \in \mathrm{Graph}(U)$ *defined by*

$$\alpha_1(x, u) := \inf_{(x(\cdot), u(\cdot)) \in \mathcal{P}_1(x,u)} \sup_{t \geq 0} \|u'(t)\| \in [0, +\infty].$$

The zero-level set

$$\{(x, u) \in \mathrm{Graph}(U) \text{ such that } \alpha_1(x, u) \leq 0\}$$

is called the **inertia set** *of the system* (f, U). *The set* $N(u) := N_1(u)$ *of elements* $x \in \mathrm{Dom}(U)$ *such that* $\alpha_1(x, u) = 0$ *as the (first-order) viability niche.*

The domain of the inertia function α_1 is the subset of initial state-control pairs from which at least one evolution is governed by open-loop controls with bounded derivatives and its level sets

$$\{(x,u) \in \mathrm{Graph}(U) \text{ such that } \alpha_1(x,u) \leq c\}$$

provide the subset of initial states from which at least one evolution $(x(\cdot), u(\cdot))$ is governed by open-loop controls the derivatives of which are bounded by the given constant c.

We continue our investigation of the regulation by twice-differentiable open-loop controls, and, among them, affine controls of the form $u(t) := u + u_1 t$ (the so-called **ramp controls**). For that purpose, we denote by $\mathcal{P}_2(x, u, u_1)$ the set of solutions $(x(\cdot), u(\cdot))$ to the control system (4) satisfying the initial conditions

$$x(0) = x, \; u(0) = u, \; u'(0) = u_1.$$

DEFINITION 4.4 *The the* **second-order inertia function** α *of parameterized system (4) is the minimal worst intertemporal inertia* $\alpha_2(x, u, u_1)$ *defined by*

$$\alpha_2(x,u,u_1) := \inf_{(x(\cdot),u(\cdot)) \in \mathcal{P}_2(x,u,u_1)} \sup_{t \geq 0} \|u''(t)\| \in [0, +\infty].$$

We regard the zero-level set

$$\{(x,u,,u_1) \quad \text{such that } \alpha_2(x,u,u_1) \leq 0\}$$

as the second-order inertia set and the set $N_2(u, u_1)$ *of elements* $x \in \mathrm{Dom}(U)$ *such that* $\alpha_2(x, u, u_1) = 0$ *as the second-order viability niche.*

We shall prove that

$$\alpha_2(x,u,u_1) = 0 \text{ if and only if } \forall\, t \geq 0, \;\; \alpha_1(x(t), u + u_1 t) = \|u_1\|.$$

Generally, we associate with any integer $m \geq 0$ the set $\mathcal{P}_m(x, u, \ldots, u_{m-1})$ of solutions $(x(\cdot), u(\cdot))$ to the control system (4) satisfying the initial conditions

$$x(0) = x, \; u(0) = u, \; u'(0) = u_1, \; \ldots, \; u^{m-1}(0) = u_{m-1}.$$

DEFINITION 4.5 *The* **m-order inertia function** α_1 *of parameterized system (4) is the minimal worst intertemporal inertia* $\alpha_m(x, u, \ldots, u_{m-1})$ *of the evolutions starting from* $(x, u, \ldots, u_{m-1})$ *defined by*

$$\alpha_m(x,u,\ldots,u_{m-1}) := \inf_{(x(\cdot),u(\cdot)) \in \mathcal{P}_m(x,u,\ldots,u_{m-1})} \sup_{t \geq 0} \|u^{(m)}(t)\| \in [0, +\infty].$$

We regard the zero-level set

$$\{(x,u,\ldots,u_{m-1}) \quad \text{such that } \alpha_m(x,u,\ldots,u_{m-1}) \leq 0\}$$

as the m-order inertia set and the set $N_m(u, u_1, \ldots, u_{m-1})$ *of elements* $x \in \mathrm{Dom}(U)$ *such that* $\alpha_m(x, u, u_1, \ldots, u_{m-1}) = 0$ *as the m-order viability niche.*

In other words, from any x belonging to a m-order viability niche $N_m(u, u_1, \ldots, u_{m-1})$ starts at least an evolution governed by an open-loop control $u(t) := u + u_1 t + \cdots + u_{m-1}\frac{t^{m-1}}{(m-1)!}$ which is a $(m-1)$-degree polynomial in time.

For characterizing the inertia function in terms of viability kernels, we introduce the following auxiliary m-metasystem:

$$\left\{\begin{array}{lrcl} (i) & x'(t) & = & f(x(t), u(t)) \\ (ii) & u'(t) & = & u_1(t) \\ \ldots & \ldots & & \\ (m+1) & u'_{m-1}(t) & = & u_m(t) \\ (m+2) & y'(t) & = & 0 \\ & \text{where } \|u_m(t)\| & \leq & y(t) \end{array}\right. \tag{5}$$

of differential inclusions subjected to the constraint

$$\forall\, t \geq 0,\ \ (x(t), u(t), \ldots, u_{m-1}(t), y(t)) \ \in\ \mathrm{Graph}(U) \times X^{m-1} \times \mathbb{R}_+.$$

THEOREM 4.6 *For any $m \geq 1$, the m-order inertia function is related to the viability kernel of* $\mathrm{Graph}(U) \times X^{m-1} \times \mathbb{R}_+$ *under auxiliary metasystem (5) by the formula*

$$\alpha_m(x, u, \ldots, u_{m-1}) \ =\ \inf_{(x,u,\ldots,u_{m-1},y)\in\mathrm{Viab}_{(5)}(\mathrm{Graph}(U)\times X^{m-1}\times\mathbb{R}_+)} y.$$

If f is continuous and the graph of U is closed, then, from any $(x, u, \ldots, u_{m-1}) \in \mathrm{Dom}(\alpha_m)$ starts at least one evolution $(x(\cdot), u(\cdot)) \in \mathcal{P}_m(x, u, \ldots, u_{m-1})$ such that

$$\alpha_m(x, u, \ldots, u_{m-1}) \ :=\ \sup_{t\geq 0} \|u^{(m)}(t)\|.$$

In particular, from any x belonging to a m-order viability niche $N_m(u, u_1, \ldots, u_{m-1})$ starts at least an evolution governed by an open-loop control $u(t) = u + u_1 t + \cdots + u_{m-1}\frac{t^{m-1}}{(m-1)!}$ which is a $(m-1)$-degree polynomial in time.

Proof — Indeed, to say that $(x, u, \ldots, u_{m-1}, y)$ belongs to $\mathrm{Viab}_{(5)}(\mathrm{Graph}(U) \times X^{m-1} \times \mathbb{R}_+)$ amounts to saying that there exists an evolution $t \mapsto (x(t), u(t), u_1(t), \ldots, u_m(t), y(t))$ governed by control system (4) such that $y(t) = t$ and $u_j(t) = u^{(j)}(t)$, and thus a solution $(x(\cdot), u(\cdot)) \in \mathcal{P}_m(x, u, \ldots, u_{m-1})$ satisfying

$$\forall\, t \geq 0,\ \ \|u^{(m)}(t)\| \ \leq\ y$$

so that $\alpha_m(x, u, \ldots, u_{m-1}) \leq y$.

Conversely, we can associate with any $\varepsilon > 0$ an evolution $(x_\varepsilon(\cdot), u_\varepsilon(\cdot))$ belonging to $\mathcal{P}_m(x, u, \ldots, u_{m-1})$ such that

$$\forall\, t \geq 0,\ \ \|u_\varepsilon^m(t)\| \ \leq\ \alpha(x, u, \ldots, u_{m-1}) + \varepsilon \ =:\ y_\varepsilon.$$

Therefore, setting $u_{\varepsilon_j}(t) := u_\varepsilon^j(t)$ and $y_\varepsilon(t) = y_\varepsilon$, we observe that $t \mapsto (x_\varepsilon(t), u_\varepsilon(t), u_{\varepsilon_1}(t), u_{\varepsilon_{m-1}}(t), y_\varepsilon)(t)$ is a solution to the auxiliary system (5) viable in

$\mathrm{Graph}(U) \times X^{m-1} \times \mathbb{R}_+$, and thus, that $(x, u, \ldots, u_{m-1}, y_\varepsilon)$ belongs to $\mathrm{Viab}_{(5)}(\mathrm{Graph}(U) \times X^{m-1} \times \mathbb{R}_+)$. Therefore

$$\inf_{(x,u,\ldots,u_{m-1},y)\in \mathrm{Viab}_{(5)}(\mathrm{Graph}(U)\times X^{m-1}\times\mathbb{R}_+)} y \;\leq\; y_\varepsilon \;:=\; \alpha(x, u, \ldots, u_{m-1}) + \varepsilon$$

and it is enough to let ε converge to 0.

Since the auxiliary system (5) is Marchaud whenever $m \geq 1$ and f continuous and since the auxiliary constrained set $\mathrm{Graph}(U) \times X^{m-1} \times \mathbb{R}_+$ is closed by assumption, then the viability kernel $\mathrm{Viab}_{(5)}(\mathrm{Graph}(U) \times X^{m-1} \times \mathbb{R}_+)$ is also closed and the upper semi-compactness of the associated evolutionary system implies that there exists a subsequence (again denoted by) of $(x_\varepsilon(\cdot), u_{\varepsilon_0}(\cdot), u_{\varepsilon_{m-1}}(\cdot), y_\varepsilon)(t\cdot)$ which converge to a solution $(x(\cdot), u(\cdot), \ldots, u_{m-1}(\cdot), \alpha(x, u, \ldots, u_{m-1}))$ satisfying

$$\forall\, t \geq 0,\ \ \|u^m(t)\| \;\leq\; \alpha(x, u, \ldots, u_{m-1}).$$

Therefore, the infimum of the m-order inertia function is achieved. In particular, when $\alpha(x, u, \ldots, u_{m-1}) = 0$, we infer that for all $t \geq 0$, $\|u^m(t)\| = 0$ and thus, that $u(t) = u + u_1 t + \cdots + u_{m-1}\frac{t^{m-1}}{(m-1)!}$. ■

The m-order viability niches "lock-in" evolutions which enter them in the following sense:

PROPOSITION 4.7 *If at some time t_f, $x(t_f)$ belongs to the m-order viability niche $N_m(u(t_f), u'(t_f), \ldots, u^{(m-1)}(t_f))$, then for $t \geq t_f$, the evolution $x(\cdot) \in \mathcal{S}(x)$ may be regulated by the open-loop polynomial $u(t) = u(t_f) + u'(t_f)t + \cdots + u^{(m-1)}(t_f)\frac{t^{m-1}}{(m-1)!}$ and remain in this viability niche forever.*

Remark: Hamilton-Jacobi-Bellman Equations One can prove that the **inertia function** α_m is is the smallest nonnegative solution to the Hamilton-Jacobi-Bellman partial differential equation

$$\forall\,(x,u) \in \mathrm{Graph}(U),\ \ \sum_{i=1}^{n} \frac{\partial \mathbf{v}(x,u)}{\partial x_i} f_i(x,u) - \mathbf{v}(x,u)\left\|\frac{\partial \mathbf{v}(x,u)}{\partial u}\right\| \;=\; 0$$

for $m = 1$ and, for $m \geq 2$,,

$$\left\{\begin{array}{l} \frac{\partial \mathbf{v}(x,u,u_1,\ldots,u_{m-1})}{\partial x} f(x,u) + \sum_{j=0}^{m-2} \frac{\partial \mathbf{v}(x,u,u_1,\ldots,u_{m-1})}{\partial u_j} u_{j+1} \\ -\mathbf{v}(x,u,u_1,\ldots,u_{m-1}) \left\|\frac{\partial \mathbf{v}(x,u,u_1,\ldots,u_{m-1})}{\partial u_{m-1}}\right\| \;=\; 0. \end{array}\right.$$

4.2 Metasystems

The level-sets of the inertia function can be obtained as viability kernels of "meta-systems" which we now describe in the case of first-order inertia functions only. Indeed, we ask the model to satisfy an **inertia constraint**: The norm of the velocity of the regulon (or any cost function on the velocity of the regulon) must be bounded by a constant c. Requiring that the norm of the velocity of the control $\|u'(t)\|$ is bounded by a constant c amounts to writing that for all $t \geq 0$, $u'(t)$ belongs to the ball $B(0, c)$ centered in 0 and of radius c. This is just a (simple) differential inclusion $u'(t) \in B(0, c)$ that can be added to the initial differential equation(4)(i) to form a more balanced system

$$\left\{\begin{array}{lrcl} (i) & x'(t) & = & f(x(t), u(t)) \\ (ii) & u'(t) & \in & B(0, c) \end{array}\right. \tag{6}$$

of differential inclusions (the meta-system). The output-input regulation $u(t) \in U(x(t))$ of (4) becomes a constrained set $\{(x(t), u(t)) \in \mathrm{Graph}(U)\}$ of the new system.

However, there is no reason that for any initial pair $(x, u) \in \mathrm{Graph}(U)$, there should exist a solution $(x(\cdot), u(\cdot))$ of system (6) such that $x(\cdot)$ is an evolution of system (4), that is a solution satisfying the set-valued feedback constraint $u(t) \in U(x(t))$, i.e., the viability constraint

$$\forall\, t \geq 0,\ \ (x(t), u(t)) \in \mathrm{Graph}(U).$$

The set of such initial states is the viability kernel of $\mathrm{Graph}(U)$ *under system (6).*

Since the viability kernel $\mathrm{Viab}(\mathrm{Graph}(U))$ is a subset of $X \times \mathcal{U}$, it can be regarded as the graph of a set-valued map U_c defined by

$$\mathrm{Graph}(U_c) := \mathrm{Viab}_{(6)}(\mathrm{Graph}(U)). \tag{7}$$

DEFINITION 4.8 *The* **metasystem** *associated with the parameterized system (4)*

$$\begin{cases} (i) & x'(t) = f(x(t), u(t)) \\ (ii) & u(t) \in U(x(t)) \end{cases}$$

and a velocity bound $c > 0$ *is the system (6)*

$$\begin{cases} (i) & x'(t) = f(x(t), u(t)) \\ (ii) & \|u'(t)\| \leq c. \end{cases}$$

The set-valued map $U_c : X \rightsquigarrow \mathcal{U}$ *defined by (7)*

$$\mathrm{Graph}(U_c) := \mathrm{Viab}_{(6)}(\mathrm{Graph}(U))$$

*is called the c-***regulation map***.*

The pairs (x, u) *are called the* **metastates** *and the derivatives* $v(t) := u'(t)$ *of the regulons are called the* **metaparameters** *(or* **metacontrols**, **metaregulons**, *etc.).*

Starting from an initial metastate $(x_0, u_0) \in \mathrm{Graph}(U_c)$, there exists a *continuous* evolution $(x(\cdot), u(\cdot)) \in \mathcal{P}(x, u)$ satisfying the further condition

$$\forall\, t \geq 0,\ \ u(t) \in U_c(x(t)) \subset U(x(t)).$$

Therefore, U_c provides a regulation map, the selections of which are **(static) feedbacks** governing the evolution of continuous state-regulon pairs. The Viability Theorem provides a regulation map governing the evolution of the velocities of the controls, the selections of which are **dynamical feedbacks**. In economics, dynamic retroactions are **adjustment laws** (that are often given *a priori*, as the supply and demand law, the Walrasian tâtonnement, etc. c-Regulation maps can be studied thanks to the inertia function:

PROPOSITION 4.9 *If f is continuous and the graph of U is closed, the c-regulation map U_c of system (6) defined by (7) is related to the inertia function by the formula*

$$U_c(x) \; = \; \{u \in U(x) \;\; \text{such that}\, \alpha(x,u) \; \leq \; c\}.$$

The level sets $\{(x,u) \mid \alpha(x,u) \leq c\}$ of the inertia function are viable under the metasystem (6). In particular, a c-level sets of the inertia function is viable under $x' = f(x, \widetilde{u}(x))$ if and only if the feedback $\widetilde{u}$ is a selection of U_c:

$$\forall\, x \in [a,b], \;\; \widetilde{u}(x) \; \in \; U_c(x).$$

Proof — The inclusion

$$U_c(x) \; \subset \; \{u \in U(x) \;\; \text{such that}\; \alpha(x,u) \; \leq \; c\}$$

is always true: If (x,u) belongs to the graph of U_c, which is the viability kernel of the graph of U under the metasystem (6), there exists an evolution $(x(\cdot), u(\cdot))$ such that, at each instant $t \geq 0$, $x'(t) = f(x(t), u(t))$, $u(t) \in U_c(x(t)) \subset U(x(t))$ and $\alpha(x,u) \leq \|u'(t)\| \leq c$. The converse is true because there exists an inert evolution $(x(\cdot), u(\cdot))$ such that $\|u'(t)\| = \alpha(x,u) \leq c$ thanks to Theorem 4.6. ■

4.3 Implementing the Inertia Principle by Heavy Evolutions

How can we implement the inertia principle? For instance, one can select at each instant the regulons providing viable evolutions with *minimal velocity*. This is an example that obeys this inertia principle. Evolutions obtained in this way are called *"heavy" viable evolutions*[10] in the sense of heavy trends in economics. To define heavy solutions, *we still fix a bound c on the norms of the velocities of the regulons* and take any initial metastate (x,u) such that $\alpha(x,u) < c$. We then fix the regulon u and consider the passive[11] evolution $(x_u(t), u)$ where $x_u(\cdot)$ is the solution to differential equation $x'(t) = f(x(t), u)$ (evolving with velocity $u'(t) = 0$).

As long as $\alpha(x_u(t), u)$ is smaller than the velocity bound c, the regulon u inherited from the past can be maintained, allowing the system to obey the inertia principle. Since the state $x_u(\cdot)$ of the system evolves while the regulon remains constant and equal to u, the inertia function $\alpha(x_u(t), u)$ evaluated on such an evolution, equal to $\alpha(x,u) < c$ at initial time $t = 0$, measures the intertemporal cost of changing regulons. It may increase and eventually overrun the bound c measuring the maximal velocity of the regulons at some time $\tau_c(x,u)$ at the state $\xi_c(x,u) := x_u(\tau_c(x,u))$ providing warning signals:

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[10] When the regulons are the velocities, heavy solutions are the ones with minimal acceleration, i.e., maximal inertia.

[11] We assume here for simplicity that the solutions to the differential equations $x'(t) = f(x(t), u)$ are unique. This is the case when the maps $x \mapsto f(x,u)$ are Lipschitz or monotone.

DEFINITION 4.10 *Assume that* $c > \alpha(x,u)$. *Then the* warning time $\tau_c(x,u) \in \mathbb{R} \cup \{+\infty\}$ *is the first instant when evolutions* $x_u(\cdot)$ *starting from* x *leaves* $U_c^{-1}(u)$ *at the* warning state $\xi_c(x,u) := x_u(\tau_c(x,u)) \in \Xi_c(u)$ *where* Ξ_c *is the signal map associating with any regulon* u *the set*

$$\Xi_c(u) \;:=\; \{x \in \mathrm{Dom}(U) \;\; \textit{such that}\, \alpha(x,u) \;=\; c.\}\,.$$

Warning signals tell us **when, where and how the regulons must evolve**, defining a period of viability crisis: **when** is given by $\tau_c(x,u)$ and **where** corresponds to $\xi_c(x,u)$. To survive, other regulons must operate such that the new velocity drives the evolution to respect the velocity limit and/or to remain inside the graph of U until the regulon can again remain constant for a new period of time.

4.4 The Transition Cost Function

The inertia function defined in Definition 4.3 offers the simplest example of cost incurred by changing regulons. The general form of costs incurred by changing regulons is given by:

DEFINITION 4.11 *Consider a nonnegative extended cost function* $\mathbf{c} : X \times \mathcal{U} \times \mathcal{U} \mapsto \mathbb{R}_+$, *a cumulated transition cost function of the regulons* $\mathbf{l} : X \times \mathcal{U} \times \mathcal{U} \rightsquigarrow \mathbb{R}_+ \cup \{+\infty\}$ *and a discount factor* $m(x,u)$ *(which may depend upon both of the states and the controls).The* transition function $\alpha_{(\mathbf{c},\mathbf{l})}$ *is defined by*

$$\left\{ \begin{array}{lll} \alpha_{(\mathbf{c},\mathbf{l})}(x,u) & := & \displaystyle\inf_{(x(\cdot),u(\cdot))\in\mathcal{P}(x,u)} \sup_{t\geq 0} \Big(e^{-\int_0^t m(x(s),u(s))ds}\mathbf{c}(x(t),u(t),u'(t))\sigma \\ & & + \int_0^t e^{-\int_0^\tau m(x(s),u(s))ds}\mathbf{l}(x(\tau),u(\tau),u'(\tau)d\tau)\Big)\,. \end{array} \right. \tag{8}$$

Starting from an initial stat x, it will be advantageous to look for an initial regulon $u \in U(x)$ that minimizes the worst transition cost of regulons. To characterize the transition cost function in terms of viability kernels, we introduce the set-valued map

$$S_{\mathbf{c}} : (x,u;y) \rightsquigarrow \{v \in \mathcal{U} \mid \mathbf{c}(x,u,v) \;\leq\; y\}$$

and the following auxiliary metasystem of differential inclusions

$$\left\{ \begin{array}{ll} (i) & x'(t) \;=\; f(x(t),u(t)) \\ (ii) & u'(t) \;=\; v(t) \\ (iii) & y'(t) = m(x(t),u(t))y(t) - \mathbf{l}(x(t),u(t),v(t)) \\ & \text{where}\; v(t) \;\in\; S_{\mathbf{c}}(x(t),u(t);y(t)) \end{array} \right. \tag{9}$$

subject to the constraint

$$\forall\, t \geq 0,\;\; (x(t),u(t),y(t)) \;\in\; \mathrm{Graph}(U) \times \mathbb{R}_+.$$

THEOREM 4.12 *The transition cost function is related to the viability kernel of the graph of U under the auxiliary metasystem (9) by the following formula*

$$\alpha_{(\mathbf{c},\mathbf{l})}(x,u) \;=\; \inf_{(x,u,y)\in \mathrm{Viab}_{(9)}(\mathrm{Graph}(U)\times\mathbb{R})} y.$$

Proof — Indeed, to say that (x,u,y) belongs to the viability kernel of the graph of U under the auxiliary system (9) amounts to saying that there exists an evolution $t \mapsto (x(t),u(t),y(t))$ governed by the auxiliary metasystem such that, for all $t \geq 0$, $u(t) \in U(x(t))$. By definition of (9), we know that for all $t \geq 0$, this evolution satisfies also for all $t \geq 0$,

$$\mathbf{c}(x(t),u(t),v(t)) \;\leq\; y(t)$$

where

$$y(t) \;=\; e^{\int_0^t m(x(s),u(s))ds}\left(y - \int_0^t e^{-\int_0^\tau m(x(s),u(s))ds}\mathbf{l}(x(\tau),u(\tau),v(\tau)d\tau)\right).$$

Therefore

$$\sup_{t\geq 0}\Big(e^{-\int_0^t m(x(s),u(s))ds}\mathbf{c}(x(t),u(t),u'(t)) + \int_0^t e^{-\int_0^\tau m(x(s),u(s))ds}\mathbf{l}(x(\tau),u(\tau),u'(\tau)d\tau)\Big) \leq y.$$

and thus, $\alpha_{(\mathbf{c},\mathbf{l})}(x,u) \leq \inf_{(x,u,y)\in\mathrm{Viab}_{(9)}(\mathrm{Graph}(U)\times\mathbb{R}_+)} y$.

Conversely, we know that for any $\varepsilon > 0$, there exists an evolution $(x(\cdot),u(\cdot)) \in \mathcal{P}(x,u)$ such that

$$\sup_{t\geq 0}\Big(e^{-\int_0^t m(x(s),u(s))ds}\mathbf{c}(x(t),u(t),u'(t)) + \int_0^t e^{-\int_0^\tau m(x(s),u(s))ds}\mathbf{l}(x(\tau),u(\tau),u'(\tau)d\tau)\Big) \;\leq\; \alpha_{(\mathbf{c},\mathbf{l})}(x,u)+\varepsilon.$$

Setting

$$y_\varepsilon(t) \;:=\; e^{\int_0^t m(x(s),u(s))ds}\left(\alpha_{(\mathbf{c},\mathbf{l})}(x,u)+\varepsilon - \int_0^t e^{-\int_0^\tau m(x(s),u(s))ds}\mathbf{l}(x(\tau),u(\tau),u'(\tau)d\tau)\right)$$

we infer that $\mathbf{c}(x(t),u(t),v(t)) \;\leq\; y_\varepsilon(t)$ and thus, that $t \mapsto (x(t),u(t),y_\varepsilon(t))$ is a solution to the solution to auxiliary evolutionary system (9) starting at $(x,u,\alpha_{(\mathbf{c},\mathbf{l})}(x,u)+\varepsilon)$. This evolution is viable in $\mathrm{Graph}(U)\times\mathbb{R}_+$ since $(x(\cdot),u(\cdot)) \in \mathcal{P}(x,u)$, and thus, since $x(t) \in U(x(t))$, or, equivalently, since

$$\forall\, t \geq 0,\;\; ((x(t),u(t),y_\varepsilon(t)) \;\in\; \mathrm{Graph}(U)\times\mathbb{R}.$$

Hence $(x,u,\alpha_{(\mathbf{c},\mathbf{l})}(x,u)+\varepsilon)$ belongs to the viability kernel $\mathrm{Viab}_{(9)}(\mathrm{Graph}(U)\times\mathbb{R}_+)$, so that

$$\inf_{(x,u,y)\in\mathrm{Viab}_{(9)}(\mathrm{Graph}(U)\times\mathbb{R}_+)} y \;\leq\; \alpha_{(\mathbf{c},\mathbf{l})}(x,u)+\varepsilon.$$

Letting ε converge to 0, we obtain the converse inequality. ■

5. Infinite Horizon Intergenerational Optimization

We refer to Haurie, 2003 for the relevance of infinite horizon control problems in climate policy assessment. We just propose here a complement to this paper. Indeed, the concept of viability kernel is not only interesting by itself, but it happens to be a mathematical and numerical tool for solving other mathematical problems. In particular, following the papers of H. Frankowska[12], we can characterize the epigraph (see for instance Aubin, 1998) of the value function of infinite horizon optimal control problems as a viability kernel (epigraphical approach of the Hamilton-Jacobi-Bellman approach). We shall bypass the Hamilton-Jacobi-Bellman partial differential equation, since we can compute the value function directly by the Saint-Pierre Viability Kernel Algorithm (and obtain the optimal trajectories). The perverse irony of all that is that viability theory which was conceived in the end of the 1970's as a mathematical metaphor of Darwinian evolution designed to replace intertemporal optimization provided mathematical tools to solve optimal control problems via the Hamilton-Jacobi-Bellman viewpoint, as advocated by Hélène Frankowska.

The usual shape of a criterion on the space $\mathcal{C}(0,\infty;X)$ of continuous functions involves a "transient state" cost function (often called a Lagrangian) $\mathbf{l} : X \times \mathcal{U} \mapsto \mathbb{R}_+$. We introduce an "intergenerational cost function" $\mathbf{d} : X \mapsto \mathbf{R}_+ \cup \{+\infty\}$ and denote by $\mathcal{D}(x)$ the subset of evolutions $(x(\cdot), u(\cdot)) \in \mathcal{P}(x)$ satisfying the intergenerational constraints

$$\forall\, t \geq 0, \quad \int_t^{\infty} e^{-m\tau}\mathbf{l}(x(\tau), u(\tau))d\tau \;\leq\; \mathbf{d}(x(t)). \tag{10}$$

This expresses that, at each instant t, the *future cumulated cost*

$$\int_t^{\infty} e^{-m\tau}\mathbf{l}(x(\tau), u(\tau))d\tau$$

should remain below a given cost $\mathbf{d}(x(t))$ of the value of the state at time t.

DEFINITION 5.1 *The intergenerational valuation function* $\overset{\infty}{V}_{\mathbf{d}}$ *of the infinite horizon intertemporal minimization problem*

$$\overset{\infty}{V}_{\mathbf{d}}(x) \;:=\; \inf_{(x(\cdot),u(\cdot))\in\mathcal{D}(x)} \int_0^{\infty} e^{-m\tau}\mathbf{l}(x(\tau), u(\tau))d\tau$$

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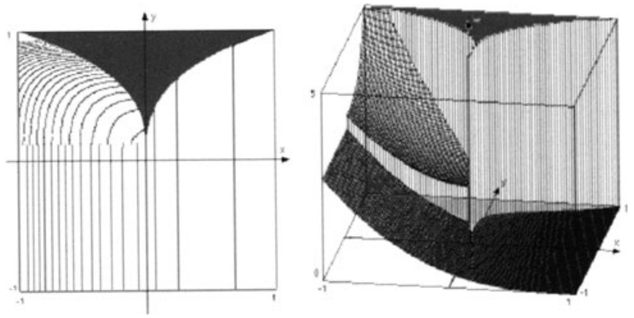
[12] The epigraph of a real-valued function is what is above its graph. The discovery that the main properties of a function involved and used in optimization problems deal with the epigraph of a function took its roots in the sixties in convex analysis after the pioneering works of Moreau and Rockafellar. The viability of the epigraph of a function was used since 1981 in the context of Lyapunov functions. Their more and more frequent use in optimization and control since the sixties is handy because it allows to replace inequalities constraints by membership relations, and becomes more and more familiar. It was taken up by Hélène Frankowska for characterizing value functions of optimal control problems in a long series of papers. Hélène Frankowska proved that the epigraph of the value function of an optimal control problem — assumed to be only lower semicontinuous — is semi-permeable, (i.e., invariant and backward viable) under a (natural) auxiliary system. Furthermore, when it is continuous, she proved that its epigraph is viable and its hypograph invariant (Frankowska, 1989; Frankowska, 1989b; Frankowska, 1993). By duality, she proved that the latter property is equivalent to the fact that the value function is a viscosity solution of the associated Hamilton-Jacobi equation in the sense of M. Crandall and P.-L. Lions. This epigraphical approach in the field of Hamilton-Jacobi equations has since been taken up by other authors.



$$(x_1', x_2') = (u, 0), \quad u \in U = [-1, 1]$$

$$\min \int_0^{+\infty} (x_1(s)-1)^2 e^{-\lambda s} ds.$$

The constraint set is given by

$$K = \{(x_1, x_2) : -1 \le x_2 \le |x_1|^{\frac{1}{3}}, -1 \le x_1 \le 1\}$$

Figure 5.5. Example of the Value Function of an Infinite Control Problem where the dynamic is: $(x_1', x_2') = (u, 0)$, with $u \in \mathcal{U} = [-1, 1]$: Minimize $\int_0^{+\infty}(x_1(s) - 1)^2 e^{-\lambda s} ds$ under the constraint $K = \{(x_1, x_2) \mid -1 \le x_2 \le |x_1|^{\frac{1}{3}},\ -1 \le x_1 \le 1\}$.

over all the evolutions satisfying the intergenerational constraints (10)

$$\forall\, t \geq 0, \quad \int_t^{\infty} e^{-m\tau}\mathbf{l}(x(\tau), u(\tau))d\tau \ \leq\ \mathbf{d}(x(t))$$

is called the intergenerational valuation function.

When $\mathbf{d} \equiv +\infty$, *the intergenerational constraints disappear, and* $\overset{\infty}{V}_{\infty}$ *is the standard value function of an infinite horizon optimal control problem.*

Let us observe that if $x(\cdot)$ satisfies the intergenerational constraints, then

$$0 \ \leq\ \int_0^{\infty} e^{-m\tau}\mathbf{l}(x(\tau), u(\tau))d\tau \ \leq\ \mathbf{d}(x)$$

so that

$$0 \ \leq \overset{\infty}{V}_{\mathbf{d}}(x) \ \leq\ \mathbf{d}(x).$$

Hence, whenever $\mathbf{d}(x)$ is finite, we infer that

$$\begin{cases} \forall\, t \geq 0, \ \displaystyle\int_0^{\infty} e^{-m\tau}\mathbf{l}(x(\tau), u(\tau))d\tau \\ \leq\ e^{-mt}\mathbf{d}(x(t)) + \displaystyle\int_0^{t} e^{-m\tau}\mathbf{l}(x(\tau), u(\tau))d\tau. \end{cases}$$

Let us introduce the auxiliary control system

$$\left\{\begin{array}{lrcl} (i) & x'(t) & = & f(x(t),u(t)) \\ (ii) & y'(t) & = & my(t) - \mathbf{l}(x(t),u(t)) \\ & \text{where } u(t) & \in & U(x(t)). \end{array}\right. \tag{11}$$

THEOREM 5.2 *Assume that the extended function* $\mathbf{d}$ *is nontrivial and non negative and that the Lagrangian* $\mathbf{l}$ *is non negative. Consider the viability kernel* $\mathrm{Viab}_{(11)}(\mathcal{K})$ *of the subset*

$$\mathcal{K} := \{(x,y) \in X \times \mathbf{R}_+ \mid y \leq \mathbf{d}(x) \}$$

under auxiliary the set-valued evolutionary system (11). Then

$$\forall\, x \in \mathcal{K},\ \overset{\infty}{V}_{\mathbf{d}}(x) = \inf\{y \mid (x,y) \in \mathrm{Viab}_{(11)}(\mathcal{K})\}.$$

Being a viability kernel, the epigraph of infinite horizon optimal control problems can be computed by the Viability Kernel Algorithm (see Figure 5.5 for an example of valuation function of an infinite horizon optimal control with state constraints).

6. Characterization of Viability and/or Capturability

The main task is to characterize the subsets having this viability/capturability property. To be of value, this task must be done without solving the system for checking the existence of viable solutions for each initial state.

6.1 Tangent Directions

An immediate intuitive idea jumps to the mind: at each point on the boundary of the constrained set outside the target, where the viability of the system is at stake, there should exist a velocity which is in some sense tangent to the viability domain and serves to allow the solution to bounce back and remain inside it. This is, in essence, what the viability theorem below states. Before stating it, the mathematical implementation of the concept of tangency must be made.

We cannot be content with viability sets that are smooth manifolds (such as spheres, which have no interior), because inequality constraints would thereby be ruled out (as for balls, that possess distinct boundaries). So, we need to implement” the concept of a direction v tangent to K at $x \in K$, which should mean that starting from x in the direction v, we do not go too far from K: The adequate definition due to G. Bouligand and F. Severi proposed in 1930 states that a direction v is tangent to K at $x \in K$ if it is a limit of a sequence of directions v_n such that $x + h_n v_n$ belongs to K for some sequence $h_n \to 0+$. The collection of such directions, which are in some sense inward”, constitutes a closed cone $T_K(x)$, called the **tangent cone**[13] to K at x. Naturally, except if K is a smooth manifold, we lose the fact that the set of tangent vectors is a vector-space, but this discomfort is not unbearable, since advances in set-valued analysis built a calculus of these cones allowing us to compute them. See Aubin & Frankowska, 1990 and Rockfellar & Wets, 1997 for instance.

6.2 The Adaptive Map

We then associate with the dynamical system (described by (f, U)) and with the viability constraints (described by K) the **(set-valued) adaptive or regulation map** R_K. It maps any state $x \in K \backslash C$ to the subset $R_K(x)$ (possibly empty) consisting of regulons $u \in U(x)$ which are **viable** in the sense that $f(x, u)$ is tangent to K at x:

$$R_K(x) := \{u \in U(x) \mid f(x, u) \in T_K(x)\}.$$

We can for instance *compute the* **adaptive map** in many instances.

6.3 The Viability Theorem

The Viability Theorem states that *the target C can be reached in finite time from each initial condition $x \in K \backslash C$ by* **at least** *one evolution of the control system viable in K* **if and only if** *for every $x \in K \backslash C$, there exists at least one viable control $u \in R_K(x)$.*

This Viability Theorem holds true when both C and K are closed and for a rather large class of systems, called **Marchaud systems**: Beyond imposing some weak technical conditions, the only severe restriction is that, for each state x, the set of velocities $f(x, u)$ when u ranges over $U(x)$ is **convex** (This happens for the class of control systems of the form

$$x'(t) \;=\; f(x(t)) + G(x(t))u(t)$$

where $G(x)$ are linear operators from the control space to the state space, when the maps $f : X \mapsto X$ and $G : X \mapsto \mathcal{L}(Y, X)$ are continuous and when the control set U (or the images $U(x)$) are convex).

Curiously enough, viability implies stationarity, i.e., the existence of an equilibrium. Equilibria being specific evolutions, their existence requires stronger assumptions. The Equilibrium Theorem states that *when the constrained set is assumed to be viable, convex and compact, then there exists a (viable) equilibrium.* Without convexity, we deduce only the existence of minimal viable closed subsets.

The proofs of the above Viability Theorem and the Equilibrium Theorem are difficult: The Equilibrium Theorem is derived from the 1910 Brouwer Fixed Point Theorem, and the proof of the Viability Theorem uses all the theorems

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[13] replacing the linear structure underlying the use of tangent spaces by the tangent cone is at the root of **Set-Valued Analysis**.

of functional analysis except the closed graph theorem and the Lebesgue Convergence Theorem. However, their consequences are much easier to obtain and can be handled with moderate mathematical competence.

6.4 The Adaptation Law

Once this is done, and whenever a constrained subset is viable for a control system, the second task is to show how to govern the evolution of viable evolutions. We thus prove that viable evolution of system (3) are governed by

$$\left\{ \begin{array}{ll} i) & x'(t) = f(x(t), u(t)) \\ ii) & u(t) \in R_K(x(t)) \text{ (adaptation law)} \end{array} \right. \tag{12}$$

until the state reaches the target C.

We observe that the initial set-valued map U involved in (3) ii) is replaced by the adaptive map R_K in (12) ii). The inclusion $u(t) \in R_K(x(t))$ can be regarded as an adaptation law (rather than a learning law, since there is no storage of information at this stage of modelling).

6.5 Planning Tasks: Qualitative Dynamics

Reaching a target is not enough for studying the behavior of control systems, that have to plan tasks in a given order. This issue has been recently revisited in Aubin & Dordan, 2001 in the framework of qualitative physics (see Dordan, 1995), Eisenack & Petschel-Held 2002 and Aubin, 1996 for more details on this topic). We describe the sequence of tasks or objectives by a family of subsets regarded as qualitative cells. Giving an order of visit of these cells, the problem is to find an evolution visiting these cells in the prescribed order.

6.6 Static Viable Feedbacks

A (static) feedback r is a map $x \in K \mapsto r(x) \in X$ which is used to pilot evolutions governed by the differential equation $x'(t) = f(x(t), r(x(t)))$. A feedback r is said to be viable if the solutions to the differential equation $x' = f(x, r(x))$ are viable in K. The most celebrated examples of linear feedbacks in linear control theory designed to control a system have no reason to be viable for an arbitrary constrained set K, and, according to the constrained set K, the viable feedbacks are not necessarily linear.

However, the Viability Theorem implies that a feedback r is viable if and only if r is a selection of the adaptive map R_K in the sense that

$$\forall\, x \in K \backslash C, \;\; r(x) \; \in \; R_K(x). \tag{13}$$

Hence, the method for designing feedbacks for control systems to evolve in a constrained subset amounts to find selections $r(x)$. One can design a factory" for designing selections (see Chapter 6 of Aubin, 1991, for instance). Ideally, a feedback should be continuous to guarantee the existence of a solution to the differential equation $x' = f(x, r(x))$. But this is not always possible. This is the case of **slow selection** r° of R_K of minimal norm, governing the evolution of **slow viable evolutions** (despite its lack of continuity).

6.7 Restoring Viability

There are no reasons why an arbitrary subset K should be viable under a control system. Therefore, the problem of reestablishing viability arises. One can imagine several methods for this purpose: (i) keep the constraints and change initial dynamics by introducing regulons that are "viability multipliers";
(ii) change the initial conditions by introducing a **reset map** Φ mapping any state of K to a (possibly empty) set $\Phi(x) \subset X$ of new initialized states" (impulse control), as in Aubin, 1999;
(iii) keep the same dynamics and looking for viable constrained subsets by letting the set of constraints evolve according to mutational equations, as in Aubin, 1999.

7. Conclusion

The purpose of viability theory is to attempt to solve the problem of adaptation to the environment. This is the case in biology, since the Claude Bernard's "constance du milieu intérieur" and the "homeostasis" of Walter Cannon. This is naturally the case in ecology and environmental studies. This is also the case in economics when we have to adapt to scarcity constraints, balances between supply and demand, and many other ones. In this paper we have tried, within this context, to answer different questions arising in climate change models when coupling with economic interaction.

Viability theory is quite appropriate to study dynamical systems where the environment is described by constraints of various kinds (representing objectives, physical and economic constraints, "stability" constraints, etc.) that can never be violated. In the same time, the actions, the messages, the coalitions of actors and connectionist operators do evolve, and their evolution must be consistent with the constraints, with objectives reached at (successive) finite times (and/or must be selected through intertemporal criteria). We must not forget that there is no reason why collective constraints should be satisfied at each instant by evolutions under uncertainty governed by stochastic or tychastic control systems. So this approach leads to the study of how actors may correct either the dynamics, and/or the constraints in order to reestablish this consistency. This also may allow us to provide an explanation for the formation and the evolution of the architecture of the system and of their variables, especially when considering large time scales.

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Chapter 6

CLIMATE POLICY COOPERATION GAMES BETWEEN DEVELOPED AND DEVELOPING NATIONS: A QUANTITATIVE, APPLIED ANALYSIS

Claudia Kemfert

Abstract This paper investigates climate control coalition games of developed and developing nations. It studies whether incentives exist for non-cooperating nations to join a coalition based upon issue linkage. Issue linkage is considered through increased R&D expenditures triggering improved technological innovations that advance energy efficiencies. Model calculations demonstrate that incentives exist for non-cooperating countries to join a climate control coalition if nations cooperate on technological innovations. Restrictions on trade such as sanction mechanisms against non-cooperating countries are not necessarily an incentive to join a coalition. Technological spillover effects lead to improved economic situations and increased energy efficiencies in non-cooperating countries. We compare climate control coalitions of developed and developing nations. Developing nations can benefit by climate control if it is linked with technology cooperation.

1. Introduction

Nearly all scientific reports, including the youngest IPCC report, confirm once more that humankind's impact on the natural environment has never been greater and is causing substantial long-term and irreversible climatic changes. One important source of climate change are anthropogenic greenhouse gas emissions. Increasing atmospheric concentrations of greenhouse gases have a substantial impact on the global temperature and sea level which generate extensive economic, ecological and climatic impacts. Irreversible climate changes induce significant costs, and no future efforts can reverse the resulting damage. International climate control agreements intend to shrink this process. A substantial reduction of GHG emissions requires cooperation between countries.

A. Haurie and L. Viguier (eds.), The Coupling of Climate and Economic Dynamics, 145–171.

However, greenhouse gas emissions reduction is still an international public goal necessitating long term and global economic efforts. The formulation of the Kyoto protocol and the following negotiation attempts represent one initial outcome of cooperative international climate control policy actions.

Latest negotiation outcomes confirm that individual countries are mainly concerned with potential economic disadvantages regarding emissions reduction. Maximization of national welfare leads to either unilateral operations, a formation of small coalitions or free ride actions. Whether a stable coalition can be reached depends on the opportunities to reduce interest conflicts regarding a minimum agreement. A bargaining situation contains opportunities to collaborate for mutual benefits. As real negotiation processes demonstrate, a full agreement of all players is unlikely. More realistically, some players may act independently or unilaterally to maximize their own welfare and self interests, while other players create small and stable coalitions (Carraro and Siniscalo (1992), Carraro and Siniscalco (1993) and Hoel (1994)). The decision to join a coalition or to initiate a partial coalition depends on the difference in net benefits of a cooperative and a non-cooperative strategy (Barrett (1994)). As long as the environment and climate are treated as a public good and there are no penalties or sanction mechanisms for polluting entities, there will be no economic incentives to act environmentally friendly neither unilaterally nor cooperatively. Moreover, as long as cooperative behavior is imposed by voluntarily actions, finding a common or global agreement is driven by the varying interests of negotiating countries. These interests must be harmonized between nations or groups of countries.

A variety of incentives exist to free ride. A free riding position is seen in the recent decision of the US to leave the previously established climate control coalition. This paper explores the scope of cooperation for greenhouse gas emissions reduction by using game theoretic approaches. The purpose of this paper investigates whether incentives for free riding countries exist to join an existing coalition for international climate control cooperation. The payoffs for all players are contrasted and assessed by a world integrated assessment model. Different incentives to cooperate are analyzed by diverse assumptions regarding future impact assessment. Issue linkages are studied by combining climate control targets with increased expenditures of R&D triggering environmentally friendly technologies. Furthermore, Barrett's idea of issue linkage of joint climate control cooperation and trade patterns is compared. Section two of this paper gives a brief overview of international climate control agreements. Section three describes the game theoretic approach of issue linkage. Section four briefly illustrates the modelling framework used to study these impacts, while section five shows the main modelling results. The last section concludes.

2. International Climate Control Coalitions

The greatest success of international climate control policy was the establishment of the Kyoto Protocol. It is one of the leading and most important international environmental agreements in the history of global negotiation and bargaining policies. However, recent climate change negotiation processes confirm that the initial climate change control coalition was not stable: the United States, the world's largest economy and emitter of greenhouse gases (GHGs) left the coalition and now acts as a singleton and free rider. The reason for this behavior can be explained by game theoretic validation: economic payoffs of free riding are higher than joining the coalition.[1] This paper confirms this by using global modelling results. Because the remaining climate coalition partners still intend to reach an international climate control agreement, the environmental effectiveness is potentially diminished. International greenhouse gas reductions imposed by the Kyoto protocol can most likely not be met.

A variety of incentives exist for free riders or instable coalition partners to join or remain in the game. Carraro and Siniscalo (2002) and Carraro and Galeotti (1995) investigate policy strategies for increasing environmental cooperation. One proposal includes the option to pay off countries whose net benefits cannot overcompensate net costs. The stability of the agreement is reached by a redistribution mechanism among signatories. Carraro and Siniscalco (1993) and Hoel (1994) study self-financed transfers used to offset free riding. The symmetry of the coalition group can be reached by a system of transfers. They found that strategic behavior may undermine the implementation of side payments. Free riders tend to overestimate economic disadvantages, whereas coalition members could underestimate the initial gains of cooperation.

The USA's free riding position is (among others) a major problem for international climate policy. Game theory suggests that issue linkage may help increase incentives to join a coalition and overcome free riding. The concept of issue linkage has been introduced to abolish potential asymmetries among counties (see Folmer, Mouche et al. (1993), Cesar and de Zeeuw (1996)). The idea behind this proposal is that countries benefiting from different issues should combine all issues to obtain a stable, symmetric and favorable coalition. Pioneering studies of issue linkages are made by Tollison and Willet (1979), Haas, Keohane et al. (1993) and Sebenius (1983). They propose issue linkages with a public good such as the environment, and other issues, e.g. international security and finance. Barrett (1995) and Barrett (1997) propose linking environmental protection negotiations with trade liberalization. Free riders would have to pay a penalty implemented as a trade sanctions. Barrett finds that the threat of penalties can enlarge the coalition; a grant coalition is therefore hard to obtain. Carraro and Siniscalco (1997), Carraro and Siniscalo (1995) and Katsoulacos (1997) propose linking environmental negotiations with increased expenditures in R&D. Technological cooperation is only possible if countries collaborate on environmental issues. Issue linkage could be an incentive for free riders to join a coalition. Issue linkage is based on the idea that the benefits of free riding regarding a public good must be offset by the gains of a jointly provided club good. Tol, Lise et al. (2000) explore the incentives

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[1] The recent announcement (February 14, 2002) of the US administration proposes a voluntary environmental program avoiding huge economic losses due to economic growth reductions.

of joining a coalition by issue linkage through side payments as capital and technology transfer. They find that technology transfer increases the incentives to cooperate. Model results of this study confirm that finding.

The Kyoto protocol allows flexible ways to reach GHG reduction targets. Emissions diminution can be attained through domestic abatement efforts or by international flexible mechanisms like emissions trading between developed nations, investment transfers of energy efficient projects between developed nations (Joint Implementation JI) or developing nations (Clean Development Mechanisms CDM). If emissions trading is not allowed globally but between industrialized countries, the potential main seller of permits will be Russia due to its recent economic slump[2]. Because the USA is the largest greenhouse gas emitter, they will potentially demand a considerable share of emissions permits. The United States' defection induces a reduction of emissions permits demand and therefore the price of permits. This lowers the revenues for permit sellers like Russia and compliance costs for other coalition members like the European Union and Japan. Because of smaller compliance costs, incentives are lowered to invest in climate-friendly technologies. Furthermore, the remaining coalitions run the risk of becoming unstable because of reduced payoffs for Russia, an important player. In order to not lose the economic gains from emissions trading, Russia will try to act strategically by influencing the market price. They could bank emissions and sell only part of their emissions permits in the beginning of the first commitment period. The recent negotiation agreement draws from formerly discussed limits of emissions permit trading[3].

3. Game Theoretic Approach of Issue Linkage

Emissions reduction is costly for the countries most responsible for climate change. Because of the global character of the climate change problem, each nation could benefit from emissions reductions by other nations. The incentive to reduce emissions in one specific country is very small. This phenomenon is referred to by many authors as a "prisoner's dilemma" (for example Barrett (1994), Barrett (1998), Carraro and Siniscalco (1997), Carraro and Hourcade (1998), Carraro (1999), Cesar (1994)). However, some countries might have an incentive to create a small or grant coalition[4] to improve net benefits; the *game theory of cartel stability* mentions this (see Carraro (1997), Carraro and Siniscalco (1998) and Carraro (1999)). A stable coalition or cartel is characterized

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[2] This is confirmed by many modelling studies such as those done by Manne and Richels (2001), Elzen and de Moor (2001), Böhringer (2001), Buchner, Carraro et al. (2001) and Kemfert (2002a)

[3] Previous negotiations were influenced by the so-called "supplementarity condition" that any emissions trading should only be supplemental to domestic action. Recent negotiations confirm that there should be no trading limits, although they stress a so-called commitment period reserve, whereby countries must demonstrate via recent inventories that they indeed have made emissions reductions and are not selling credits they are unlikely to have. This would not distort trading, as Babiker, Jacoby et al. (2002) demonstrate.

[4] The grant coalition describes that coalition where all negotiating parties agree.

by external and internal stability. *Internal stability* means that no country in the coalition has an incentive to leave the cartel. *External stability* implies that no country outside the coalition has an incentive to join the cartel. A cartel is *profitable* if all members of the stable coalition are better off inside the cartel than outside.

We assume that the coalition of emissions reduction nations occurs between n countries, n ≥ 3, indexed by $i = 1 \ldots n$, $n \geq 3$. Nations can commit (C) or defect (D). The collective action is an n-tuple $(x_1, x_2, \ldots, x_n) \in X^N$ with $x_i \in \{C, D\} = X_i$ that represents the choice of country i and $X^N = X_1 \times X_2 \times \cdots \times X_n$. This can also be written as the pair (x_i, x_{-i}) with x_{-i} as strategies of all other players except i. The climate change "prisoner's dilemma" signifies: $u_i(D, \bar{x}_{-i}) > u_i(C, \bar{x}_{-i})$ for all $i \in N$. It demonstrates that a rejection always brings a better situation than a commitment. This payoff order has the characteristic that the n times D outcome $\underbrace{(D, D, \ldots., D)}_{n}$ is a single pure Nash equilibrium strategy. Other weak "prisoner's dilemmas" with more than two players could induce further Nash equilibria (see Lise et al. (2001) for an overview).

The stability analysis of a cartel game is based on the approaches by Carraro (1997, 1998, 1999). $P_i(s)$ denotes the value for player I to a member of coalition s, $Q_i(s)$ is the value for player i not to be a member of coalition s (see also Kemfert, Lise et al. (2002) and Lise, Tol et al. (2001)). Cooperation of one player is reflected as unilateral action. Payoffs of unilateral action are shown as a "no cooperation" scenario in Table 6.6 (see Appendix). The payoffs are measured as cumulated consumption values in that specific region. If we consider the cartel game as a normal form game with four players, we can summarize the following payoff[5] matrix:

If no players want to leave the coalition, it is internally stable if $Pi(s) > Qi(s \backslash i)$ for all $i \notin s$. If no players want to join the coalition, it is externally stable, that is if $P_i(s \cup i) < Q_i(s)$ for all $i \in s$. A coalition is stable if it is both internally and externally stable.

Our analysis considers four different world regions. In the first part of the analysis, player one is the United States of America (USA,1), player two the European Union (EU,2), player three Japan (JPN,3) and player four Russia and Eastern Europe (REC,4). As can be seen later in the simulation analysis, the payoff matrix illustrates the different combinations of cooperation and defection games by individual players. Table 6.1 shows the individual payoffs as a formal game. In this analysis, only four regions reduce emissions. The other seven regions play a default strategy of zero emissions reductions. We follow the approach of Carraro and Siniscalco (1997) and Buchner, Carraro et al. (2002) where countries play a two-stage game. Negotiation countries ($i = 1, 2, 3, 4$) first decide non-cooperatively whether to join a coalition, i.e., the coalition game. Carraro and Siniscalco (1993) call this a "metagame" or a

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[5] Payoffs usually mean payments to the individual player, measured in utility values.

Table 6.1. Cartel Game as a Formal Game with Four Players

4	3	1	2 Cooperate	Defect
Cooperate	Cooperate	Cooperate	P_1(1,2,3,4), P_2(1,2,3,4,) P_3(1,2,3,4) P_4(1,2,3,4)	P_1(1,3,4), Q_2(1,3,4), P_3(1,3,4), P_4(1,3,4)
		Defect	Q_1(2,3,4), P_2(2,3,4), P_3(2,3,4),P_4(2,3,4)	Q_1(3,4), Q_2 (3,4), P_3(3,4), P_4(3,4)
	3	1	2 Cooperate	Defect
Defect	Cooperate	Cooperate	P_1(1,2,3), P_2(1,2,3) P_3(1,2,3) P_4(1,2,3)	P_1(1,3), Q_2(1,3), P_3(1,3), P_4(1,3)
		Defect	Q_1(2,3), P_2(2,3), P_3(2,3),P_4(2,3)	Q_1(3),Q_2(3), P_3(3), Q_4(3)
		1	2 Cooperate	Defect
	Defect	Cooperate	P_1(1,2), P_2(1,2) P_3(1,2), P_4(1,2)	P_1(1), Q_2(1) Q_3(1), Q_4(1)
		Defect	Q_1(2), P_2(2), Q_3(2), Q_4(2)	Q_1(Ø), Q_2(Ø), Q_3(Ø), Q_4(Ø)

"one-shot" game. In the second stage, they play a non-cooperative, open-loop Nash game to determine their policy variables. That means (depending on the game's outcomes in stage one) players decide whether or not to act cooperatively. Because climate change control is a public good, incentives for free riding could only be offset by benefits resulting from technological or terms of trade improvements. Trade sanctions are imposed on those countries not cooperating on climate control. Incentives to free ride exist only because of potentially positive technology and terms of trade spillover effects. In a formal game, a position G contains the number N of players in the game, the possible outcomes X^G of the game and the related utility functions $u \equiv \{u_i\}_{i \in N}$. The following coalition combinations of the game are compared:

$$G = \left[\begin{array}{l} \{1,2,3,4\}, \left\{ \begin{array}{l} CCCC, CCDD, DCCD, CCDC, CDDC, CDCC, DDCC, CDDD, \\ DCDD, DDDC, DCDC, DCCC, CCCD, DDDD \end{array} \right\}, \\ \left\{ \begin{array}{l} u(CCCC), u(CCDD), u(DCCD), u(CCDC), u(CDDC), u(CDCC), u(DDCC), u(CDDD), \\ u(DCDD, u(DDDC), u(DCDC), u(DCCC), u(CCCD), u(CDDDD) \end{array} \right\} \end{array} \right]$$

4. Applied Modelling Tool

Empirical validation is based on the applied general equilibrium model WIAGEM. WIAGEM is an integrated assessment model merging an economy model based on a dynamic inter-temporal general equilibrium approach combined with an energy market model and climatic sub-model covering a time horizon of 50 years incremented into five-year time steps.[6] The basic idea

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[6] The core economic model code was established by Tom Rutherford in 1998. The model has been enlarged by including a 50-year time period, all greenhouse gases, climate change impact assessment, endogenous technological change and issue linkage. The model is written in the computer language GAMS (MPSGE) and solved by the algorithm MILES, see Rutherford (1993).

behind this modelling approach is the evaluation of market and non-market impacts induced by climate change. The model includes an endogenous determination of technological changes. The economy is represented by 25 world regions aggregated into 11 trading regions with each region covering 14 sectors. The sectoral disaggregation contains five energy sectors: coal, natural gas, crude oil, petroleum and coal products, and electricity. The dynamic international competitive energy market for oil, coal and gas is modelled by global and regional supply and demand, the oil market is characterized by imperfect competition with the intention that OPEC regions can use their market power to influence market prices. Energy related greenhouse emissions occur as a result of economic and energy consumption and production activities. Currently, a number of gases have been identified as having a positive effect on radiative forcing (IPCC (1996)) and are included in the Kyoto protocol as "basket" greenhouse gases. The model includes three of these gases: carbon dioxide (CO2), methane (CH4) and nitrous dioxide (N2O) which are considered the most influential greenhouse gases within the short term modelling period of 50 years. Excluding the other gases is not believed to have substantial impacts on the analysis' insights.

Because of the short term application of the climate sub-model, we consider only the first atmospheric lifetime of greenhouse gases, assuming that the remaining emissions have an infinite lifetime. The atmospheric concentrations induced by energy related and non-energy related emissions of CO2, CH4 and N2O have impacts on radiative forcing, influencing potential and actual surface temperature and sea level. Market and non-market damages determine regional and overall welfare development.

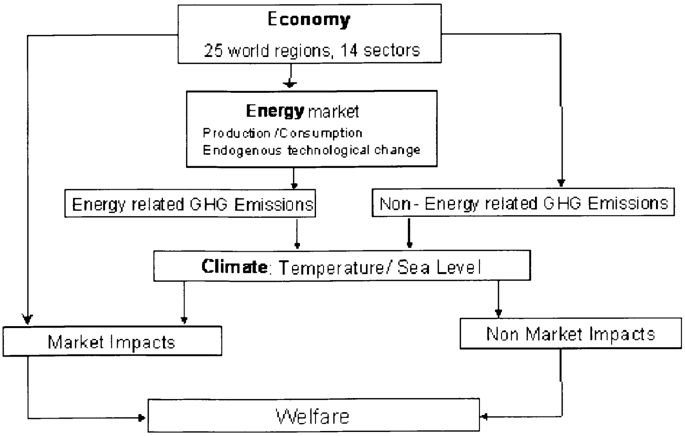

Figure 6.1. Welfare Determination in WIAGEM

In each region, production of the non-energy macro good is captured by an aggregate production function. The production function characterizes technology through transformation possibilities on the output side and substitution possibilities on the input side. In each region, a representative household chooses to allocate lifetime income across consumption in different time periods in order to maximize lifetime utility. In each period, households face the choice between current consumption and future consumption which can be purchased via savings. The trade-off between current consumption and savings is given by a constant inter-temporal elasticity of substitution. Producers invest as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous world interest rate such that the marginal productivity of a unit of investment and a unit of consumption is equalized within and across countries. Domestic and imported varieties for the non-energy good for all buyers in the domestic market are treated as imperfect substitutes by a CES Armington aggregation function, constrained to constant elasticities of substitution. Emission limits can be reached by domestic action or by trading emission permits within Annex B countries allocated (initially) according to regional commitment targets. Those countries meeting the Kyoto emissions reduction target stabilize their mitigated emissions at 2010 levels.

Goods are produced for the domestic and export market. Production of the energy aggregate is described by a CES function reflecting substitution possibilities for different fossil fuels (i.e., coal, gas, and oil), capital, and labor representing trade-off effects with a constant substitution elasticity. Fossil fuels are produced from fuel-specific resources and the non-energy macro good subject to a CES technology.

Induced technological change is considered as follows: Energy efficiency is improved endogenously by increased expenditures in R&D. This means that in the CES production function, energy productivity is endogenously influenced by changes in R&D expenditures. The CES production structure follows the concept of ETA-MACRO combining nested capital and labor at lower levels. Energy is treated as a substitute of a capital labor composite determining (together with material inputs) overall output. Energy productivity is increased endogenously by increased R&D expenditures. The incentives to invest in technology innovations are market driven. Because energy efficiency is improved by increased R&D expenditures, emissions reduction targets can be reached with less production drawbacks. Furthermore, investment in R&D and technological innovation gives a comparative advantage. The share of R&D expenditures of total expenditures is endogenously determined by production changes. However, this also means that investment in R&D expenditures competes with other expenditures (crowding out). Spillover effects of technological innovations are reflected through trade effects and capital flows. That means that non R&D cooperating countries developing technological innovations can benefit from spillover effects through trade of technological innovations and capital flows that can be used for R&D investments. Model calculations show that capital flows increase to non-cooperating countries because of improved competitiveness effects and terms of trade effects. This triggers spillover effects regarding technological innovations and energy efficiency improvements through increased R&D investments.[7]

5. Impacts of Trade Coalitions Cooperating on Climate Control

5.1 Kyoto Climate Blocs

We investigate different coalitions of climate control and issue linkage. "No cooperation" means unilateral action on climate control. Full cooperation incorporates Kyoto greenhouse gas emissions targets by Annex I regions. As mentioned in Section 3, we consider four different players from developed and less developed nations. WIAGEM considers eleven total regions. In this analysis, only four regions reduce emissions. The other seven regions play a default strategy of zero emissions reductions. We distinguish between Climate Control (CC) scenarios where Annex I permit trade (AT) is allowed or not (NT). Issue linkage is covered by cooperation between induced technological change through increased R&D investments (R&D). A potential punishment for non-cooperating countries is concealed by trade barriers (TB). In these scenarios, we assume that coalition partners exclude non-cooperating countries both from climate control, and also from secondary issues such as R&D cooperation and technological improvement. Although in reality it might be difficult to exclude non-cooperating countries or to implement trade sanctions (which might be against WTO laws), an artificial simulation of potential economic consequences might give insights and answers into why some countries act strategically. Model simulations try to restrict technology and economic spillover effects to those countries not cooperating. However, later model results show that a full restriction is not feasible. Table 6.2 summarizes all scenarios. Table 6.6 in the Appendix shows the regional payoffs of all scenarios. It gives the cumulated payoffs up to the first commitment period 2012. The unilateral action on R&D investments and energy efficiency improvement can be seen as the current climate control policy of the United States of America. As other model calculations have also demonstrated, meeting emission reduction targets is costly for those regions facing real emissions reductions, i.e. Europe, USA and Japan. Within the first commitment period, Russia and Eastern European countries benefit from a surplus of emissions permits that can be traded. Because of this, and due to the above-described public good character of climate change, countries with binding emissions targets benefit from climate control free riding. Obviously, countries always benefit from a "do-nothing" climate control strategy. This is also because we consider only a 50-year time period; significant climate damages that exceed economic benefits occur after this period. However, we intend to assess whether opportunities exist that would allow incentives for cooperation both on climate control and

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[7] In this paper, we assume standard parameterization, as illustrated in Kemfert (2002b) and Kemfert (2004)

Table 6.2. All scenarios

Scenario	Description
CC -NT	Climate Control- without emission permit trading- no trade (NT)
CC- AT	Climate Control- with emission permit trading- Annex I permit trade (AT)
R&D	Cooperation of coalition partners on R&D development-permit trading is allowed
R&D- CC	Cooperation of coalition partners on R&D development-permit trading is allowed- with Climate Control activities (CC)
TB	Trade barriers against non-cooperating countries
TB-CC	Trade barriers against non-cooperating countries plus climate control activities of coalition partner

technological improvements. Additionally, it is evaluated whether trade sanctions against non-cooperating countries can lead to cooperative behavior. As Table 6.3 shows, all countries with binding emissions targets can profit from emissions trading with Russia. Unilateral emissions reduction is only profitable if no trading is authorized. Cooperative behavior makes all players better off if emission permit trading is allowed. Small coalitions benefit cooperating nations with binding emissions reductions targets. Russia, as a main seller of permits, wants to cooperate with as many potential buying countries as possible. The USA and EU always prefer joining a coalition with Russia if permit trading is allowed. For the USA, it is profitable to join a small coalition with Japan and Russia because of reduced compliance costs resulting from lower permit demand and a decreased permit price.

Nations cooperating on technological improvements are better off only if they unilaterally apply innovations. Bilateral trade improves competitiveness effects and increases welfare. The most important outcome of this analysis is the USA's incentive to cooperate on technological improvements. However, the USA as a free rider on technological innovations could also benefit from spillover effects resulting from technological improvements in cooperating countries. The USA would prefer to join a coalition with Japan and Russia instead of a coalition with both Europe and Japan who face binding emissions reduction targets. Trade barriers are not a significant incentive to join a coalition. Because of the international principal terms of trade effects from strong nations like the USA, Europe and Japan, it seems that trade restrictions against non-cooperating countries is a punishment against themselves. The only exemption is a partial coalition between Japan, Europe and Russia on climate control and trade barriers against the USA. We find an internally and externally stable coalition where Europe, Japan and Russia cooperate on climate control and apply trade barriers against the USA. However, this small coalition is not profitable. Another externally and internally stable coalition is the small coalition between

Europe and Russia on climate control and potential emissions trading. This coalition is also not profitable.

Table 6.3. Internally and Externally Stable Coalitions

	CC-NT	CC-AT	R&D	CC-R&D	TB	CC-TB
Internally	Ø	{USA,EU,JPN,REC} {EU,JPN,REC} {USA,JPN,REC} {USA,EU,REC} {USA,REC} {EU,REC} {JPN,REC}	{EU,JPN,REC} {USA,JPN,REC} {USA,EU,REC} {USA,REC} {EU,REC} {JPN,REC}	{USA,EU,JPN,REC} {EU,JPN,REC} {USA,JPN,REC} {USA,EU,REC} {USA,REC} {EU,REC} {JPN,REC} {EU,JPN}	{EU,JPN,REC} {USA,JPN,REC} {USA,EU,REC} {JPN,REC}	{EU,JPN,REC}
Externally	{USA,EU,REC}	{EU,REC}	Ø	Ø	{EU,JPN,REC}	{EU,JPN,REC}
Stable	**Ø**	**{EU,REC}**	**Ø**	**Ø**	**{EU,JPN,REC}**	**{EU,JPN,REC}**

The ranking of all payoffs is evidence that the USA always benefits from free riding on climate control. However, there is a visible incentive to join a coalition on technological innovations instead of unilateral action. The USA prefers to join a small coalition on climate control as well as issue linkage with Europe and Russia instead of Japan and Russia. The reasons for this are stronger terms of trade and competitiveness effects in a coalition with Europe and Russia. However, additional to the "business as usual defect" Nash equilibrium, there are three further Nash equilibria where the USA, Japan and Russia cooperate on climate control: emissions trading, climate control and issue linkage of R&D cooperation, and pure R&D cooperation without climate control. By ranking all payoffs according to their different coalition options, we summarize in the following listing the payoff matrices and show the Nash equilibrium in boldface characters.

1. CC-NT

REC	JPN	USA	EU	Cooperate	Defect
Cooperate	Cooperate	Cooperate		5,7,3,11	7,3,9,9
	Defect			4,9,7,2	8,8,8,4
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		2,6,2,10	6,2,11,7
		Defect		3,12,4,1	8,8,8,4
		1	2	Cooperate	Defect
	Defect	Cooperate		10,4,1,3	8,8,8,4
		Defect		8,8,8,4	**8,8,8,4**

2. CC-AT

REC	JPN	USA	EU	Cooperate	Defect
Cooperate	Cooperate	Cooperate		8,6,5,7	**5,7,7,10**
	Defect			7,9,6,9	4,4,4,5
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		1,2,1,1	2,1,12,2
		Defect		3,11,3,4	4,4,4,5
		1	2	Cooperate	Defect
	Defect	Cooperate		11,3,2,3	4,4,4,5
		Defect		4,4,4,5	4,4,4,5

3. R&D

REC	JPN	USA	EU	Cooperate	Defect
Cooperate	Cooperate	Cooperate		8,3,7,8	**5,8,9,9**
	Defect			6,9,5,6	4,5,4,4
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		1,2,1,1	2,1,12,2
		Defect		3,10,2,3	4,5,4,4
		1	2	Cooperate	Defect
	Defect	Cooperate		12,4,3,5	4,5,4,4
		Defect		4,5,4,4	**4,5,4,4**

4. CC- R&D

REC	JPN	USA	EU	Cooperate	Defect
Cooperate	Cooperate	Cooperate		8,6,6,7	**2,7,7,9**
	Defect			5,10,5,6	1,4,2,3
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		7,1,8,1	6,3,12,5
		Defect		3,12,3,2	1,4,2,3
		1	2	Cooperate	Defect
	Defect	Cooperate		12,2,1,4	1,4,2,3
		Defect		1,4,2,3	**1,4,2,3**

4. TB

REC	JPN	USA	EU	Cooperate	Defect
Cooperate	Cooperate	Cooperate		12,4,12,7	9,8,1,10
	Defect			7,12,8,8	8,7,9,5
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		5,3,7,3	11,6,3,4
		Defect		6,1,4,1	8,7,9,5
		1	2	Cooperate	Defect
	Defect	Cooperate		1,2,2,3	8,7,9,5
		Defect		8,7,9,5	**8,7,9,5**

5. CC-TB

REC	JPN	USA	EU	Cooperate	Defect
Cooperate	Cooperate	Cooperate		6,7,8,7	10,6,2,9
	Defect			9,12,11,4	7,5,10,6
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		5,9,6,1	11,8,1,3
		Defect		8,1,4,5	7,5,10,6
		1	2	Cooperate	Defect
	Defect	Cooperate		1,4,9,2	7,5,10,6
		Defect		7,5,10,6	**7,5,10,6**

Europe prefers to join a small coalition on climate control and issue linkage on technological innovation with the USA and Japan instead of Japan and Russia. However, it is more beneficial for Europe to join a coalition with the USA and Russia. As coalitions with Russia demonstrate, all countries with binding emissions reduction targets favor a small or full coalition with Russia. Russia offers the supply of permits; the lower the demand for permits, (i.e. the fewer Annex I regions joining the coalition), the lower the compliance costs and the more profitable the coalition is for nations with binding emissions reduction targets. However, if we include stronger assumptions about climatic impacts of climate change resulting from less stringent emissions reduction targets, benefits of less binding reduction targets always exceed the damages of climate change. Japan favors joining a coalition on climate control and innovations with Europe and Russia or the USA and Europe instead of Russia and the USA. Japan benefits from technological innovations, and their main trading partners are the USA and Europe.

5.2 Developing Country Climate Blocs

As in the previous section, we investigate different climate coalitions of climate control and issue linkage. We assess the impacts of climate blocs and issue linkage of developing countries, and base our analysis on the same assumptions as before. As developing countries do not have binding emission reduction targets, incentives to join a climate coalition are primarily based on economic benefits or secondary benefits of climate control policies, e.g. the reduction of conventional air pollution. We assume that developing countries try to maximize their economic benefits by R&D cooperation or trade coalitions.

No cooperation means unilateral action on climate control. Full cooperation incorporates the greenhouse gas emissions targets of developing countries (China CHN, Sub Saharan Africa SSA, Latin South America LSA and Asia ASIA). The emissions target is represented by these regions following their "business as usual" baseline emissions path. The other seven regions play a default strategy of zero emissions reductions. We distinguish between climate control (CC) scenarios where emissions permit trade (ET) is allowed or not (NT). We investigate different climate control collations between Annex I regions. A potential punishment for non-cooperating countries is concealed by trade barriers (TB). The different combined abbreviations illustrate the climate control blocs. For example, "CHNLSAASIA" shows the cooperative climate policy of the regions China, Latin South America and Asia.

All developing regions prefer to cooperate on climate policy in climate blocs if emissions trading is allowed. A climate control policy means developing regions must reduce their emissions according to their baseline emissions, which results in economic welfare losses (in millions of dollars). This is primarily caused by the assumption that developing countries have to reduce a substantial amount of emissions which leads to binding emissions reduction targets. If flexible mechanisms such as emissions trading cannot be applied, economic costs are even higher. Negative welfare implications induce terms of trade losses. This explains why the regions would prefer to act individually instead of in full cooperation on climate control if no emissions trading is allowed. This can be explained by the fact that countries can economically benefit from emissions trading. If emissions trading is not allowed, countries suffer substantially. A full cooperation means that all countries are reducing emissions, which causes both economic declines within the country but also terms of trade losses by spillover effects. Acting individually results in fewer negative economic spillover effects.

China favors a cooperation with Asia in comparison to Latin South America. Latin South America also prefers to cooperate with Asia. Both effects can be explained by the strong trade relations with Asia. Because of the economic growth assumptions of the regions Latin South America and China, Asia appears to be the main seller of emissions permits. If emissions trading is allowed, a cooperation with Asia is always attractive for China and Latin South America due to reduced emissions reduction costs. As Table 6.4 shows, these climate coalition blocs are stable. Sub Saharan Africa is too small of a trade region to induce major impacts on the world trade market. This also means that the other regions have no incentives to prefer a cooperation with SSA. Latin South America benefits from cooperation on climate control with China and Asia only if emissions trading is allowed. However, because of negative terms of trade effects, positive welfare implications will not reach that extent if only LSA and China or Asia cooperate on climate control. Emissions trading means fewer negative welfare implications. Issue linkage by R&D cooperation seems to be a very beneficial situation for developing countries, i.e. it leads to internally stable coalitions. However, no coalition is also externally stable at the same time.

Trade sanctions in climate blocs do not seem to be a valid instrument for increasing incentives to cooperate on climate control. Although we find internally stable coalitions if China and Asia induce trade sanctions against Latin South America, this climate control bloc does not appear to be a sound strategy, as it induces negative welfare implications. This explains why we cannot find any externally stable coalition. However, climate control coalitions that lead to favorable economic situations due to permissible emissions trading are neither externally nor entirely stable.

Table 6.4. Internally and Externally Stable Coalitions

	CC-NT	CC-ET	R&D	CC-R&D	TB	CC-TB
Internally	{CHN,SSA,ASIA} {SSA,LSA}	{CHN,LSA,ASIA} {SSA,LSA,ASIA} {LSA,ASIA} {CHN,ASIA}	{CHN,LSA,ASIA} {CHN,SSA,ASIA} {SSA,LSA,ASIA} {SSA,ASIA} {LSA,ASIA} {CHN,ASIA}	{CHN,LSA,ASIA} {CHN,SSA,ASIA} {SSA,LSA,ASIA} {SSA,ASIA} {LSA,ASIA} {CHN,ASIA}	{CHN,ASIA}	{CHN,SSA,ASIA}
Externally	Ø	Ø	Ø	Ø	Ø	Ø
Stable	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**	**Ø**

The ranking of all payoffs is evidence that the climate control regions prefer to cooperate with Asia. This explains why Asia benefits the most from a full cooperation (i.e. the grant coalition) on climate control if trading is allowed (see CC-ET scenario). The following listing summarizes the rankings of the different scenarios.

1. **CC-NT**

ASIA	CHN	SSA	LSA	Cooperate	Defect
Cooperate	Cooperate	Cooperate		4,5,3,1	6,4,11,7
	Defect			5,9,5,8	1,11,1,11
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		8,7,12,10	3,1,9,6
		Defect		2,12,8,2	7,6,7,4
		1	2	Cooperate	Defect
	Defect	Cooperate		11,8,2,5	7,6,7,4
		Defect		7,6,7,4	**7,6,7,4**

2. **CC-AT**

ASIA	CHN	SSA	LSA	Cooperate	Defect
Cooperate	Cooperate	Cooperate		8,6,4,12	1,2,1,6
	Defect			7,9,6,3	6,11,11,8
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		5,7,9,11	2,1,12,1
		Defect		3,12,2,2	4,5,5,4
		1	2	Cooperate	4,5,5,4
	Defect	Cooperate		11,4,3,5	4,5,5,4
		Defect		4,5,5,4	**4,5,5,4**

3. **R&D**

ASIA	CHN	SSA	LSA	Cooperate	Defect
Cooperate	Cooperate	Cooperate		7,2,8,8	**4,7,6,5**
	Defect			6,3,2,4	5,1,3,8
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		9,4,1,1	2,8,11,12
		Defect		3,10,4,3	1,5,10,7
		1	2	Cooperate	Defect
	Defect	Cooperate		12,11,7,11	1,5,10,7
		Defect		10,5,8,11	**1,5,10,7**

4. **CC- R&D**

ASIA	CHN	SSA	LSA	Cooperate	Defect
Cooperate	Cooperate	Cooperate		8,6,6,7	**2,7,7,9**
	Defect			5,10,5,6	1,4,2,3
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		7,1,8,1	6,3,12,5
		Defect		3,12,3,2	1,4,2,3
		1	2	Cooperate	Defect
	Defect	Cooperate		12,2,1,4	1,4,2,3
		Defect		1,4,2,3	**1,4,2,3**

4. TB

ASIA	CHN	SSA	LSA	Cooperate	Defect
Cooperate	Cooperate	Cooperate		12,5,10,11	5,3,5,12
		Defect		7,12,6,5	10,11,7,8
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		9,9,2,10	11,6,3,2
		Defect		6,1,8,1	8,8,9,3
		1	2	Cooperate	Defect
	Defect	Cooperate		1,2,1,4	8,8,9,3
		Defect		8,8,9,3	**8,8,9,3**

5. CC-TB

ASIA	CHN	SSA	LSA	Cooperate	Defect
Cooperate	Cooperate	Cooperate		8,9,5,7	5,7,4,1
		Defect		7,12,6,5	12,3,3,8
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		10,8,12,9	11,6,1,3
		Defect		6,1,7,6	9,5,9,4
		1	2	Cooperate	Defect
	Defect	Cooperate		1,4,9,2	9,5,9,4
		Defect		1,4,8,2	**9,5,9,4**

Sub Saharan Africa is an economically small country which does not induce negative terms of trade effects on the world market. Furthermore, because of a low emissions baseline development, SSA does not require emissions permits. Both interrelations induce regions like Latin South America and China that demand emissions permits to cooperate with SSA. On the one hand, the permit prices decrease due to lower demand. On the other hand, SSA does not induce negative terms of trade effects. These effects explain the higher ranking of climate control coalitions cooperating with SSA.

5.3 Combined Climate Blocs

In this section we consider different climate coalition blocs and issue linkage options of both developed and developing regions. More precisely, we compare different climate coalitions of the nations USA, Russia and Eastern Europe (REC), China (CHN) and Latin South America (LSA). As before, we detect that Russia (as the main seller of emissions permits) wants to cooperate with the USA and vice-versa. However, Latin South America and China also prefer to cooperate with the USA instead of Russia. The reason for this is that both China and Latin South America can compete with Russia in sales of emissions permits to the USA. Developing countries can sell emissions permits as they are below their emissions baseline because of emissions reduction caused by carbon-friendly technologies. This is confirmed by Russia's revenues that are reduced if China and Latin South America join the coalition on climate control. This is also shown by fewer welfare increases measured in payoffs.

1. CC-NT

LSA	CHN	USA	REC	Cooperate	Defect
Cooperate	Cooperate	Cooperate		12,10,9,8	11,12,7,10
	Defect			1,6,8,6	2,8,3,5
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		8,5,5,3	5,1,10,10
		Defect		9,4,4,12	10,11,11,7
		1	2	Cooperate	Defect
	Defect	Cooperate		5,1,12,2	10,11,11,7
		Defect		4,8,1,4	**10,11,11,7**

2. CC-AT

LSA	CHN	USA	REC	Cooperate	Defect
Cooperate	Cooperate	Cooperate		9,10,2,5	12,12,10,9
	Defect			7,4,3,1	6,3,6,11
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		11,6,5,12	8,5,4,3
		Defect		3,12,2,2	10,10,12,8
		1	2	Cooperate	Defect
	Defect	Cooperate		4,8,1,4	10,10,12,8
		Defect		5,1,12,2	**10,10,12,8**

3. R&D

LSA	CHN	USA	REC	Cooperate	Defect
Cooperate	Cooperate	Cooperate		7,11,2,5	8,4,6,1
	Defect			6,1,8,10	1,6,9,11
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		2,6,4,7	3,2,11,6
		Defect		4,10,1,4	9,9,5,3
		1	2	Cooperate	Defect
	Defect	Cooperate		10,3,3,12	9,9,5,3
		Defect		5,1,10,2	**9,9,5,3**

4. CC- R&D

LSA	CHN	USA	REC	Cooperate	Defect
Cooperate	Cooperate	Cooperate		9,9,2,7	**6,5,3,1**
	Defect			8,4,7,8	12,11,11,9
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		2,12,4,6	3,3,9,5
		Defect		4,8,1,4	7,7,6,3
		1	2	Cooperate	Defect
	Defect	Cooperate		10,3,3,12	7,7,6,3
		Defect		5,1,10,2	**7,7,6,3**

4. TB

LSA	CHN	USA	REC	Cooperate	Defect
Cooperate	Cooperate	Cooperate		7,11,3,3	1,7,6,5
		Defect		6,2,5,10	12,12,9,9
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		2,8,4,11	2,3,11,7
		Defect		8,5,7,8	5,1,8,1
		1	2	Cooperate	Defect
	Defect	Cooperate		12,4,4,12	5,1,8,1
		Defect		6,5,8,2	**5,1,8,1**

5. CC-TB

LSA	CHN	USA	REC	Cooperate	Defect
Cooperate	Cooperate	Cooperate		7,10,3,7	1,8,4,8
		Defect		10,6,2,11	11,12,12,7
	3	1	2	Cooperate	Defect
Defect	Cooperate	Cooperate		6,5,1,3	2,9,5,5
		Defect		3,3,8,9	5,7,2,4
		1	2	Cooperate	Defect
	Defect	Cooperate		7,6,9,1	5,7,2,4
		Defect		8,4,7,12	**5,7,2,4**

Because of cheaper emissions reduction options, the USA always prefers to cooperate with Russia. Although both China and Latin South America could sell their so-called “hot air” as emissions permits, a cooperation with Russia is always more attractive to the USA. Russia wants to cooperate with the USA alone, especially if climate coalition games are connected with technological innovations. We find some internally stable coalitions where the USA and Russia are involved. R&D cooperation leads to beneficial situations for both developed and developing nations. The USA is always better off if they cooperate with developing nations like China, Latin South America, or Russia. Developing nations can benefit from technology transfer options and increased economic growth options. China especially benefits from a coalition with both Russia and the USA if emissions trading is allowed and coalitions cooperate on technological improvements. However, these coalitions are not externally stable, as potential climate control coalition members will always want to join this coalition.

6. Conclusion

This paper studied international climate control coalition games und investigated incentives for cooperation by issue linkage. Two main findings can be summarized. First, there are incentives for a climate control coalition coupled with issue linkage of technological innovations. A full cooperation on climate control and technological improvements benefit all nations in comparison to a unilateral strategy. There is an incentive for the USA to join either a full coalition or a smaller coalition on climate control and technological improvements with Europe, Japan, Russia and even developing nations like China. Technological innovations improve energy efficiencies, which again offer cheaper opportunities regarding emissions reductions. This leads to enhanced competitiveness effects and trade options. If Russia as the main seller of permits joins the coalition, issue linkage becomes most profitable. Developing countries benefit from cooperation of climate control and issue linkage of R&D cooperation because of positive economic growth effects. In total, for the majority of nations, cooperation on climate control and technological innovation gives stronger incentives to join a coalition than non-cooperating strategies.

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Appendix

Table 6.6. Payoffs in Millions of Dollars by 2010 (Cumulated discounted consumption.)

NO COOPERATION

	JPN	USA	EU	REC
CC-NT	1,849,719.15	3,438,623.75	3,938,267.81	332,098.39
CC-AT	1,853,643.79	3,451,473.35	3,946,925.08	331,932.03
R&D	1,851,774.91	3,455,640.79	3,942,645.43	331,599.30
CC-R&D	1,856,260.21	3,459,460.95	3,952,594.57	332,497.67
TB	1,840,374.77	3,448,695.06	3,934,686.11	332,065.12
CC-TB	1,850,933.92	3,447,167.00	3,941,053.56	331,366.38

FULL COOPERATION

	JPN	USA	EU	REC
CC-NT	1,847,850.27	3,438,137.55	3,929,910.53	330,734.20
CC-AT	1,863,548.83	3,460,597.35	3,947,818.98	332,234.81
R&D	1,871,316.14	3,450,538.79	3,945,221.64	332,209.92
CC-R&D	1,875,681.42	3,464,873.18	3,955,072.78	333,110.02
TB	1,860,529.00	3,446,373.82	3,947,023.05	332,268.08
CC-TB	1,850,279.81	3,455,588.23	3,940,655.60	331,490.61

EUJPNREC

	JPN	USA	EU	REC
CC-NT	1,847,663.39	3,563,948.87	3,937,680.58	331,690.80
CC-AT	1,854,668.35	3,571,898.58	3,948,107.33	332,355.59
R&D	1,852,029.03	3,564,876.05	3,943,396.66	331,813.64
CC-R&D	1,858,405.42	3,559,919.18	3,955,051.78	332,910.25
TB	1,840,499.33	3,493,910.29	3,934,944.23	332,270.80
CC-TB	1,850,959.15	3,470,751.21	3,941,176.68	331,492.06

USAJPNREC

	JPN	USA	EU	REC
CC-NT	1,848,317.49	3,434,664.68	3,943,839.32	332,522.62
CC-AT	1,853,859.03	3,460,996.47	3,952,196.60	333,221.36
R&D	1,851,899.49	3,463,153.15	3,948,216.95	332,888.63
CC-R&D	1,856,362.57	3,466,613.31	3,958,166.09	333,787.00
TB	1,840,474.33	3,449,053.30	3,932,540.97	333,487.54
CC-TB	1,851,521.37	3,449,715.45	3,935,084.08	332,613.63

JPNUSAEU

	JPN	USA	EU	REC
CC-NT	1,845,981.40	3,437,378.52	3,929,512.56	332,730.58
CC-AT	1,846,231.54	3,449,058.12	3,930,399.71	332,031.85
R&D	1,844,529.55	3,449,695.67	3,924,803.07	330,176.05
CC-R&D	1,860,385.46	3,456,336.39	3,962,852.93	330,745.31
TB	1,839,827.54	3,446,238.83	3,934,264.86	332,372.89
CC-TB	1,850,179.68	3,450,292.58	3,940,475.31	329,888.13

EUUSREC

	JPN	USA	EU	REC
CC-NT	1,871,211.21	3,437,138.52	3,935,880.01	331,884.16
CC-AT	1,875,135.85	3,461,347.47	3,955,046.31	334,094.78
R&D	1,873,266.98	3,459,856.02	3,946,770.81	333,071.53
CC-R&D	1,877,752.28	3,466,008.18	3,962,839.82	334,660.42
TB	1,830,120.54	3,453,930.91	3,943,138.23	334,227.87
CC-TB	1,838,347.69	3,458,012.23	3,958,564.05	335,159.51

USAREC

	JPN	USA	EU	REC
CC-NT	1,870,043.17	3,434,500.50	3,969,085.27	333,063.31
CC-AT	1,873,967.80	3,452,376.30	4,002,466.33	333,762.04
R&D	1,872,098.93	3,456,886.02	3,996,771.28	333,746.71
CC-R&D	1,876,584.23	3,464,882.18	4,003,841.92	334,512.52
TB	1,839,129.56	3,452,376.30	3,934,440.88	333,917.57
CC-TB	1,849,461.56	3,467,291.74	3,938,905.31	334,993.15

EUREC

	JPN	USA	EU	REC
CC-NT	1,868,875.12	3,568,877.98	3,937,020.56	332,106.71
CC-AT	1,890,191.91	3,584,047.56	3,953,166.33	332,805.44
R&D	1,881,899.16	3,565,888.20	3,944,237.29	332,011.55
CC-R&D	1,881,581.35	3,547,882.18	3,954,739.82	332,923.51
TB	1,838,922.67	3,447,449.85	3,936,670.36	332,805.44
CC-TB	1,848,785.67	3,443,041.79	3,946,177.79	333,304.54

EUUS

	JPN	USA	EU	REC
CC-NT	1,869,843.38	3,435,150.88	3,923,941.04	332,103.51
CC-AT	1,888,230.91	3,451,258.12	3,945,376.83	332,390.78
R&D	1,887,196.14	3,455,153.54	3,940,803.08	332,472.71
CC-R&D	1,887,505.46	3,459,009.74	3,952,353.36	333,371.09
TB	1,827,922.65	3,444,479.81	3,932,538.86	332,269.24
CC-TB	1,836,698.69	3,445,019.75	3,940,928.71	330,953.80

JAPUS

	JPN	USA	EU	REC
CC-NT	1,847,573.92	3,434,502.52	3,979,656.23	332,312.51
CC-AT	1,851,495.04	3,445,599.23	4,036,499.32	331,519.78
R&D	1,848,626.66	3,449,662.34	4,032,386.68	331,112.05
CC-R&D	1,858,745.33	3,459,045.70	4,042,069.80	332,711.92
TB	1,841,857.02	3,448,477.54	3,933,440.86	332,007.00
CC-TB	1,856,353.66	3,450,292.58	3,934,179.33	331,142.69

JPNREC

	JPN	USA	EU	REC
CC-NT	1,844,571.92	3,597,881.75	4,025,483.04	332,314.67
CC-AT	1,854,111.01	3,611,688.35	4,030,840.31	333,013.40
R&D	1,852,287.15	3,616,482.79	4,032,159.64	332,355.53
CC-R&D	1,857,284.47	3,619,707.95	4,042,051.92	333,186.79
TB	1,841,290.00	3,461,153.29	3,934,427.86	333,013.40
CC-TB	1,856,808.15	3,444,808.77	3,939,808.36	331,626.01

EUJAP

	JPN	USA	EU	REC
CC-NT	1,846,505.03	3,599,464.75	3,934,885.10	331,597.27
CC-AT	1,853,231.56	3,610,727.35	3,945,376.85	332,389.53
R&D	1,850,790.66	3,616,121.79	3,938,120.20	332,056.80
CC-R&D	1,856,712.46	3,620,034.95	3,953,436.80	332,955.17
TB	1,840,249.35	3,438,449.83	3,934,538.86	331,956.98
CC-TB	1,850,475.69	3,427,008.75	3,940,641.31	331,956.98

Table 6.7. Payoffs in Millions of Dollars for Developing Country Climate Blocs by 2010 (Cumulated discounted consumption.)

NO COOPERATION

	CHN	SSA	LSA	ASIA
CC-NT	249,040.70	171,709.81	571,443.50	680,793.98
CC-ET	249,579.31	172,351.55	572,669.28	680,444.86
R&D	249,322.83	172,559.68	572,085.58	679,746.61
CC-R&D	249,938.38	172,750.47	573,544.83	681,631.88
TB	247,758.31	172,212.80	570,918.17	680,724.16
CC-TB	249,207.41	172,136.48	571,852.10	679,257.83

FULL COOPERATION

	CHN	SSA	LSA	ASIA
CC-NT	248,527.74	170,669.14	569,692.40	676,604.48
CC-ET	250,682.16	181,475.55	572,319.06	690,918.61
R&D	268,864.06	167,457.68	574,661.79	680,357.23
CC-R&D	269,359.59	178,162.70	576,023.04	682,244.23
TB	267,912.54	169,891.56	572,202.32	690,988.44
CC-TB	248,861.17	180,557.71	571,268.39	679,382.06

CHNLSAASIA

	CHN	SSA	LSA	ASIA
CC-NT	248,784.22	297,034.93	570,856.27	682,888.73
CC-ET	250,603.87	292,776.78	574,151.53	680,868.42
R&D	249,576.95	281,794.94	572,836.81	679,960.95
CC-R&D	252,083.59	273,208.70	576,002.04	682,044.46
TB	247,634.07	217,428.03	570,682.72	680,929.84
CC-TB	248,786.16	195,720.69	571,304.87	679,132.51

CHNSSALSA

	CHN	SSA	LSA	ASIA
CC-NT	249,297.18	172,056.70	594,207.85	684,285.24
CC-ET	249,794.55	181,874.67	595,433.62	685,751.56
R&D	249,447.41	180,072.04	594,849.92	685,053.31
CC-R&D	250,040.74	179,902.83	596,309.18	686,938.59
TB	247,857.87	172,571.04	568,773.03	686,310.16
CC-TB	249,794.86	174,684.93	592,923.71	680,505.08

SSACHNASIA

	CHN	SSA	LSA	ASIA
CC-NT	249,040.70	170,464.58	593,040.45	682,888.73
CC-ET	242,167.06	169,936.32	556,443.91	681,422.41
R&D	242,077.47	166,614.56	554,243.22	678,323.36
CC-R&D	254,063.63	169,625.91	583,803.19	679,879.52
TB	247,211.08	169,756.57	570,496.92	709,282.59
CC-TB	248,453.17	172,923.92	571,273.85	677,779.58

SSALSAASIA

	CHN	SSA	LSA	ASIA
CC-NT	280,587.57	170,224.58	572,027.21	680,579.75
CC-ET	281,126.17	182,225.67	581,090.51	685,751.56
R&D	280,869.69	176,774.91	576,210.96	681,218.84
CC-R&D	281,485.24	179,297.70	583,790.08	686,938.59
TB	237,504.08	177,448.65	579,370.29	686,030.86
CC-TB	236,621.18	182,981.71	575,354.30	687,985.96

SSAASIA

	CHN	SSA	LSA	ASIA
CC-NT	258,530.41	167,586.56	589,538.24	685,681.74
CC-ET	259,069.01	172,074.04	628,510.53	687,148.06
R&D	258,812.54	173,804.91	626,211.43	681,894.02
CC-R&D	259,428.08	178,171.70	624,792.18	683,646.73
TB	246,513.10	172,074.04	570,672.94	682,576.61
CC-TB	247,735.05	192,261.22	569,703.85	689,731.59

LSAASIA

	CHN	SSA	LSA	ASIA
CC-NT	258,530.41	301,964.04	570,196.25	683,586.98
CC-ET	286,127.43	304,925.76	579,210.53	685,053.31
R&D	279,447.08	282,807.09	573,252.98	680,158.86
CC-R&D	275,259.52	261,171.70	575,690.08	682,057.72
TB	246,306.21	170,967.59	572,902.42	685,053.31
CC-TB	247,059.16	168,011.27	576,976.33	686,100.69

SSALSA

	CHN	SSA	LSA	ASIA
CC-NT	269,164.93	172,403.58	569,108.70	680,799.10
CC-ET	284,166.43	172,136.32	571,421.03	680,903.61
R&D	284,744.06	172,072.43	570,243.23	709,492.07
CC-R&D	281,183.63	172,299.26	573,303.62	711,377.34
TB	235,306.19	167,997.55	568,770.92	680,928.28
CC-TB	234,972.18	169,989.23	571,727.25	678,845.25

CHNSSA

	CHN	SSA	LSA	ASIA
CC-NT	246,895.47	167,588.58	586,619.74	681,008.10
CC-ET	247,430.56	166,477.43	662,543.52	680,032.61
R&D	246,174.58	166,581.23	661,826.83	679,259.36
CC-R&D	252,423.50	172,335.22	663,020.06	681,846.13
TB	249,240.56	171,995.28	569,672.92	680,666.04
CC-TB	250,400.04	172,923.92	564,977.87	679,334.14

CHNASIA

	CHN	SSA	LSA	ASIA
CC-NT	243,893.47	330,967.81	658,658.73	684,285.24
CC-ET	250,092.26	332,566.55	656,884.51	685,751.56
R&D	249,835.07	333,401.68	661,599.79	680,502.84
CC-R&D	250,962.64	332,997.47	663,002.18	682,321.00
TB	248,673.54	184,671.03	570,559.92	685,751.56
CC-TB	255,081.64	169,778.25	570,606.90	679,517.46

CHNLSA

	CHN	SSA	LSA	ASIA
CC-NT	245,826.58	332,550.81	573,194.61	680,292.86
CC-ET	249,167.08	331,605.55	571,421.05	680,165.56
R&D	248,338.58	333,040.68	567,560.35	679,467.31
CC-R&D	250,390.63	333,324.47	574,387.06	681,352.58
TB	247,332.89	161,967.57	570,770.92	679,257.83
CC-TB	248,749.18	151,978.23	571,439.85	679,257.83

Table 6.8. Payoffs in Millions of Dollars of Different Country Climate Blocs by 2010 (Cumulated discounted consumption.)

NO COOPERATION

	CHN	USA	REC	LSA
CC-NT	252,887.88	3,375,625.96	330,401.47	575,529.41
CC-AT	253,426.48	3,382,918.98	331,100.20	575,237.56
TB	253,067.41	3,378,404.25	330,601.10	575,471.04
CC-TB	253,426.48	3,382,918.98	331,100.20	574,245.27

FULL COOPERATION

	CHN	USA	REC	LSA
CC-NT	251,605.49	3,379,098.82	331,399.66	574,945.71
CC-AT	253,759.91	3,388,822.85	346,372.53	583,993.08
TB	254,144.62	3,388,822.85	346,305.99	584,051.45
CC-TB	251,938.91	3,382,571.69	345,773.62	583,000.79

RECCHNLSA

	CHN	USA	REC	LSA
CC-NT	253,400.84	3,538,850.67	332,065.12	570,276.10
CC-AT	253,939.44	3,546,143.69	332,763.85	571,501.87
TB	253,811.20	3,536,766.95	332,697.31	571,618.61
CC-TB	254,631.93	3,537,114.23	333,595.68	572,844.39

USACHNLSA

	CHN	USA	REC	LSA
CC-NT	254,426.75	3,330,478.70	332,065.12	573,194.61
CC-AT	254,965.36	3,344,717.45	332,763.85	574,420.38
TB	254,914.06	3,345,064.73	331,100.20	574,887.34
CC-TB	255,606.55	3,353,746.90	331,333.11	575,996.37

CHNUSAREC

	CHN	USA	REC	LSA
CC-NT	253,400.84	3,406,881.75	337,721.54	592,456.75
CC-AT	253,939.44	3,417,647.64	338,420.27	591,230.98
TB	254,785.82	3,432,060.03	349,999.30	581,249.68
CC-TB	255,273.13	3,440,742.20	350,897.67	582,008.50

RECUSALSA

	CHN	USA	REC	LSA
CC-NT	272,123.77	3,410,354.62	332,065.12	576,113.11
CC-AT	272,662.38	3,417,647.64	332,763.85	577,338.89
TB	272,303.31	3,416,258.49	332,697.31	577,572.37
CC-TB	271,533.87	3,429,455.38	333,961.68	579,206.73

USALSA

	CHN	USA	REC	LSA
CC-NT	258,273.93	3,399,936.02	334,394.23	577,280.52
CC-AT	258,812.54	3,407,229.04	335,092.97	578,506.29
TB	258,453.47	3,407,229.04	334,593.87	578,623.03
CC-TB	258,479.11	3,415,563.92	334,194.59	580,665.98

RECLSA

	CHN	USA	REC	LSA
CC-NT	258,786.89	3,538,850.67	331,066.93	572,610.91
CC-AT	259,325.49	3,546,143.69	331,765.66	573,836.68
TB	258,966.42	3,541,628.96	331,732.39	573,836.68
CC-TB	258,735.59	3,533,641.37	332,597.49	574,712.23

USAREC

	CHN	USA	REC	LSA
CC-NT	256,222.10	3,389,517.42	349,367.11	580,782.72
CC-AT	256,760.71	3,396,810.44	350,065.84	582,008.50
TB	256,401.64	3,397,505.01	349,999.30	581,249.68
CC-TB	256,222.10	3,409,312.76	350,897.67	582,008.50

CHNUSA

	CHN	USA	REC	LSA
CC-NT	254,170.27	3,425,114.30	332,522.62	586,619.74
CC-AT	254,708.88	3,432,407.32	333,221.36	587,845.51
TB	254,785.82	3,432,060.03	332,722.26	587,086.70
CC-TB	255,273.13	3,440,742.20	332,389.53	587,845.51

CHNLSA

	CHN	USA	REC	LSA
CC-NT	252,374.92	3,535,377.80	334,394.23	455,286.96
CC-AT	252,913.53	3,542,670.82	335,092.97	456,512.73
TB	252,913.53	3,538,156.09	334,593.87	456,512.73
CC-TB	253,503.43	3,531,210.36	333,928.41	457,259.87

CHNREC

	CHN	USA	REC	LSA
CC-NT	253,913.79	3,545,796.40	331,690.80	588,370.84
CC-AT	254,452.40	3,553,089.42	332,389.53	589,596.61
TB	254,452.40	3,548,574.69	332,489.35	588,837.80
CC-TB	254,991.00	3,541,281.67	333,221.36	588,337.80

Chapter 7

BACK TO KYOTO? US PARTICIPATION AND THE LINKAGE BETWEEN R&D AND CLIMATE COOPERATION

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Abstract The US decision not to ratify the Kyoto Protocol and the subsequent outcomes of the Bonn and Marrakech Conferences of the Parties drastically reduce the effectiveness of the Kyoto Protocol in controlling GHG emissions. The reason is not only the reduced emission abatement in the US. Lower spillover effects on technology and an increase in Russia's bargaining power were also induced by the US decision. It is therefore crucial to analyse whether an incentive strategy exists that could induce the US to revise its decision and comply with the Kyoto commitments. One solution, occasionally proposed in literature and in actual policymaking, is to link negotiations on climate change control with decisions concerning international R&D cooperation and technology transfers. This paper explores this idea by analysing on the one hand the incentives for the EU, Japan and Russia to adopt an "issue linkage" strategy, and on the other hand the incentives for the US to join a coalition cooperating both on climate change control and on technological innovation. The extended regime in which cooperation takes place on both dimensions (GHG emissions and R&D) will be examined from the view point of countries' profitability and free-riding incentives. The effectiveness and credibility of the "issue linkage" strategy will thus be assessed.

1. Introduction

In the last few decades, international and global environmental issues have become an important concern of the international community. Among the variety of environmental challenges, climate change is often considered one of the most serious threats to the sustainability of the world socio-economic

A. Haurie and L. Viguier (eds.), The Coupling of Climate and Economic Dynamics, 173–204.

system. In order to tackle a global environmental problem like climate change in the most effective way, as many countries as possible – or at least a number of countries which account for a large share of total emissions – have to take action. However, no supra-national authority capable of enforcing climate policies and regulations yet exists. Therefore, climate change control can only be achieved via international agreements among sovereign countries.

A first step towards an international agreement to control climate change was the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992. A second important step was the adoption of the Kyoto Protocol, which introduced binding emissions reduction targets for industrialized countries. In particular, by 2012 the worldwide greenhouse gas emissions should decline by an average of 5,2% below their 1990 levels. However, the Kyoto Protocol determined only targets, methods and timetables for global action, while the definition of specific rules and operational details was postponed to later meetings of the negotiating parties. Most of these rules and operational details were define at COP 7 in Marrakech[1]. Nonetheless, the Kyoto Protocol has not yet come into force. Many countries signed the Protocol, but some of the larger industrialized countries – and key players in climate negotiations – are still missing from ratification[2].

In particular, the world largest economy, the United States, decided not to comply with the Kyoto Protocol. Although being a party to the UNFCCC, in March 2001 the US President George W. Bush announced the US withdrawal from the Kyoto Protocol and justified his decision with the harm that the climate agreement would inflict to the US economy.

The US decision has important consequences on both the effectiveness of the Kyoto Protocol and on the incentives for the other countries to pursue their efforts to control climate change. Several papers have been written on the effects of the US decision to withdraw from the Kyoto Protocol (see Buchner, Carraro and Cersosimo, 2002, for a survey). Three main effects can be singled out:
(i) The US rejection and the new provisions included in the Marrakech agreement imply a strong decline in the environmental effectiveness of the Kyoto Protocol.
(ii) The US defection reduces the demand for emission permits and consequently the permit price, thus lowering abatement costs in the remaining Annex B countries, but also the incentives to abate emissions and invest in climate friendly

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[1] After a political deal concluded in Bonn, an agreement on the outstanding "technical" issues was reached in Marrakech within the 7^{th} Conference to the Parties, where the majority of the missing details relating to the structure of the Kyoto Protocol was negotiated. After heavy concessions were made to some countries (above all to Russia), the agreement was signed by all Annex B countries, excepted the US.

[2] The ratification status of the Kyoto Protocol as of April 15th, 2004 is as follows: 84 countries signed the Kyoto Protocol, and 122 countries ratified it, accounting for 44,2% of the 1990 carbon dioxide emissions of Annex B Parties. For recent updates see http://www.unfccc.de/resource/kpstats.pdf.

technologies in all countries[3].
(iii) The smaller permit price after the US defection reduces Russia's benefits from participating in the Kyoto agreement. This provides additional incentives for Russia not to comply with the Kyoto Protocol and to use its increased bargaining power in climate negotiations[4].

As a consequence, the need to involve the US again in the international efforts to combat climate change is stressed in all the recent literature on climate negotiations (Cf. Stewart and Wiener, 2003 for an overview). Recent papers also emphasize the importance of developing countries' participation in a climate coalition (Bosello, Buchner and Carraro, 2003; Jensen, 2003).

However, broad participation in international agreements to deal with global environmental issues is hard to achieve (Cf. Barrett, 2002; Carraro and Marchiori, 2003). There are probably two main reasons that explain the difficulty for countries to sign a climate agreement. The first reason is the large economic and environmental asymmetries among world regions. Some countries lose from climate change, others gain. In addition, some countries are more penalised by mitigation efforts than others. Because of these structural differences, it is quite difficult to share the burden of emission reductions in a way that makes it convenient for most countries to sign an international agreement.

The second reason is the intrinsic instability of climate negotiations. Even in the absence of structural asymmetries, some countries may prefer to free-ride, i.e. to profit from the cleaner environment provided by signatory countries, without paying the costs (because environmental benefits are not excludable: climate change control is a global public good).

For the above reasons, an important strand of literature focuses on policy strategies that can enhance climate cooperation (Cf. Finus, 2002; Carraro and Galeotti, 2003 for recent surveys). The main economic mechanisms that have been proposed to induce more countries to ratify the Kyoto Protocol are transfers and "issue linkage", even though negotiation rules and treaty design can also be used to enlarge the equilibrium size of environmental coalitions (Cf. Carraro and Siniscalco, 1995).

It is quite natural to propose transfers to compensate those countries that lose out by signing a climate agreement. The idea is that a redistribution

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[3] Some studies highlight feedback effects that can mitigate the fall in the permit price. Strategic market behaviours can indeed modify the size of the expected changes in prices and abatement costs. In particular, these changes are much smaller than initially suggested. For example, banking and monopolistic behaviour in the permit market (Manne and Richels, 2001; Den Elzen and de Moor, 2001a and 2001b; Böhringer and Löschel, 2001) or strategic R&D behaviour (Buchner, Carraro and Cersosimo, 2002) can offset the demand shift and reduce the decline of the permit price consequent to the US withdrawal from the Kyoto Protocol.

[4] A precondition for the Kyoto Protocol to come into force is that at least 55 Parties to the Convention, representing at the same time at least 55% of 1990 carbon dioxide emissions of Annex B Parties, must have ratified the treaty. After the US withdrew from the Protocol, the participation of Russia has thus become crucial. The outcome of COP7 in Marrakech includes considerable concessions to Russia and thereby confirms Russia's increased bargaining power.

mechanism among signatories, from gainers to losers, may provide the basic requirement for a self-enforcing agreement to exist: the profitability of the agreement for all countries. Transfers also play a major role with respect to the stability issue. The possibility of using self-financed transfers to offset free-riding incentives, i.e. to stabilise environmental agreements, is analysed in Carraro and Siniscalco (1993) and Hoel (1994), who show that transfers may be successful only if associated with a certain degree of commitment. When countries are symmetric, only if a group of countries is committed to cooperation, another group of uncommitted countries can be induced to sign the agreement by a system of transfers[5].

However, transfers are hardly ever adopted in actual climate negotiations. One reason is that payments must be provided in advance and this can induce strategic behaviour both in signatories and non-signatories countries. In other words, cooperating players could under-estimate their initial gains in order to decrease the amount of transfers they must provide; while on the other hand, free-riders could over-estimate their loss in order to obtain a larger amount of financial transfers.

For these reasons, both the economic and the political science literature on international environmental agreements propose an alternative approach to increase the number of signatories of an international agreement. The alternative approach, called *issue linkage*, is based on the idea that countries may have incentives to free ride on a global public good, but these incentives become much smaller if negotiations on the global public good are linked with negotiations on another economic issue (typically a club good whose benefits cannot be reaped by free-riders).

Therefore, issue linkage consists in designing a negotiation framework in which countries do not negotiate on just one issue (e.g. the environmental issue), but negotiate on two joint issues (e.g. the environmental one and another interrelated economic issue).

Pioneering contributions on issue linkage are those by Tollison and Willett (1979), Haas (1980) and Sebenius (1983). They propose this mechanism to promote cooperation not only on environmental matters, but also on other issues, e.g. security and international finance. They also emphasise the increase in transaction costs that can result from the use of issue linkage. Issue linkage was introduced in the economic literature on international environmental cooperation by Folmer *et al.* (1993) and by Cesar and De Zeeuw (1996) to solve the problem of asymmetries among countries. The intuition is simple: if some countries gain on a given issue and other countries gain on a second one, by linking the two issues we can obtain a profitable agreement for all countries.

However, issue linkage can also be used to mitigate the problem of free-riding. To do this, negotiations that are affected by this problem, i.e. negotiations concerning public goods, must be linked with negotiations on club or quasi-club

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[5] This constraint is weaker in the case of asymmetric countries (see Botteon and Carraro, 1997).

goods. The intuition is that the incentives to free-ride on the non-excludable benefits of the public good can be offset by the incentives to appropriate the excludable benefits given by jointly providing a club good.

Barrett (1995, 1997), for example, proposes to link environmental protection to negotiations on trade liberalisation. In this way, potential free-riders are deterred with threats of trade sanctions. In Carraro and Siniscalco (1995, 1997) and Katsoulacos (1997), environmental cooperation is linked to cooperation in Research and Development. If a country does not cooperate on the control of the environment, it loses the benefits of technological cooperation. Mohr (1995) and Mohr et al. (1998) propose to link climate negotiations to international debt swaps. All these contributions have shown, from a theoretical point of view, the effectiveness of issue linkage in increasing the equilibrium number of cooperators on the provision of the public good.

The goal of this paper is to analyse whether the linkage of cooperation on climate change control with cooperation on technological innovation and diffusion can actually induce the US to move back to Kyoto. Namely, whether the possibility of getting R&D cooperation benefits, which can be obtained only through cooperation on climate change control, constitutes a sufficient incentive for the US to comply with the Kyoto targets.

This paper explores this idea by analysing on the one hand the incentives for the European Union (EU), Japan (JPN) and Russia (FSU) to adopt the issue linkage strategy, and on the other hand the incentives for the US to join a coalition which cooperates both on GHG emission control and on R&D investment and technological diffusion.

The structure of the paper is as follows. In section 2, we discuss the empirical evidence on the diminished environmental effectiveness of the Bonn/Marrakech agreement without the US. We also discuss some feedback effects arising as a consequence of the US withdrawal from the Kyoto agreement. In section 3, we identify the theoretical conditions that must be met for issue linkage to be able to induce the US to comply with the Kyoto targets. Then, in section 4, by using the RICE model with endogenous and induced technical change – the so-called FEEM-RICE model – we verify whether the theoretical conditions derived in section 3 are actually reproduced by the incentive structure defined by our model. A concluding section summarises the main achievements of this paper and describes future research directions.

2. Environmental and economic benefits of US cooperation

As already outlined in the Introduction, the US decision to withdraw from the Kyoto Protocol has three important negative consequences: (i) it reduces the environmental effectiveness of the Protocol; (ii) it lowers the incentives to undertake energy-saving R&D, and (iii) it increases the bargaining power of permit suppliers, Russia in particular.

Let us discuss the available empirical evidence on the above matters. The effects of the US decision to withdraw from the Kyoto Protocol on the price of

GHG emission permits and on the related compliance costs are shown in Table 7.1, which summarises the results obtained in several recent studies. Notice that, after the US withdrawal, the expected permit price and compliance costs are likely to be much lower. The US withdrawal from Kyoto reduces indeed the demand for GHG emission permits. Therefore, the equilibrium price in the permit market becomes lower. This lower price reduces the costs of complying with the Kyoto Protocol in the remaining Annex B countries (Cf. Table 7.1).

However, the lower permit price also lowers the total amount of emission abatement in Annex B countries (see Table 7.2). In addition, the incentives to undertake environmental-friendly R&D and technological innovation become smaller as well (see Table 7.3).

Table 7.2 summarises recent empirical evidence on the environmental effectiveness of the Kyoto/Bonn/Marrakech Protocol after the US decision not to comply with the targets set in Kyoto. It is clear that the emission abatement achieved by the remaining Annex B countries is much lower than the –5,2% agreed upon in Kyoto. The reason for this result is obvious. The US represents the world's largest economy. Its CO2 emissions made up about 32% of the industrialised countries' emissions in 1990 and are thus responsible for a large share of global GHG emissions. In addition, the Kyoto Protocol imposes a particularly stringent emission target on the US. In order to meet its Kyoto target of -7% – which is higher than the average -5,2% for industrialised countries as a whole – the US would have to reduce their GHG emissions by 25-30% in 2010. Therefore, the US defection from the Kyoto agreement implies the impossibility to achieving the 5,2% global target.

In addition, Table 7.2 suggests that the remaining Annex B countries would react to the US decision by increasing their own emissions. This prediction was confirmed by the outcome of the Marrakech Conference of the Parties, where additional sink provisions have been established which reduce the environmental effectiveness of the Treaty. At the same time, as a consequence of the US withdrawal, the emissions market loses its largest permit demander, which implies that there is a higher amount of hot air available for the remaining Annex B countries and that the permit price falls. This reduces the cost of energy in the remaining Annex B countries, thus mitigating potential impacts on energy demand (which could possibly rise).

Other studies, in addition to those quoted in Table 7.2, achieve similar conclusions. Eyckmans et al. (2001) find that in 2010 world carbon emissions would increase by 25.5% with respect to 1990 compared to an increase of 15.5% if the Kyoto Protocol is implemented including the US.

Table 7.1. Implications of the U.S. withdrawal from the Kyoto Protocol. Changes of permit price and compliance costs in 2010.

	International permit price[1]			Total compliance costs[1]		
	Kyoto Protocol	KP plus sinks	KP plus other provisions	Kyoto Protocol	KP plus sinks	KP plus other provisions
Hagem and Holtsmark (2001)	- 66.7%	-	Ceilings: + 6.7%	Almost no cost	-	-
Kemfert (2001)	- 84.6%	-	-	Almost no cost	-	-
Eyckmans et al. (2001)	- 54.3%	- 54.1% (with CPR)	CPR + ceilings: - 37.3%	Almost no cost	- 27.6% (with CPR)	CPR + ceilings: + 31%
Den Elzen and Manders (2001)	- 63.2%	- 73%	-	- 87.5%	- 92.5%	-
Böhringer (2001)	- 88.5%	- 100%	-	- 96.7%	- 100%	With 60% banking: 50%
Manne and Richels (2001)[2]	-	-	Sinks + banking: - 12.7%	-	-	Sinks + banking: small variat.
Den Elzen and de Moor (2001b)	- 55.6%	- 75%	With 50% banking: - 44.4%	- 81.6%	- 89.5%	With 50% banking: - 72.1%
Böhringer and Löschel (2001)	-	Perfect competition: -100%; Monopolistic supply: - 37.3%	-	-	Perfect competition: - 100%; Monopolistic supply: - 72.3%	-
Buchner et al. (2002)	- 34.9%	-	-	- 66.76%	-	-
Den Elzen and de Moor (2002)	-55.3%[3]	-	Marrakech: - 76.3%	- 81.6%	-	Marrakech: - 92.1%
Babiker et al. (2002)[4]	-	- 90%	Sinks + cartel: - 50%	-	-	-

[1] Percentage changes are computed with respect to the values of permit price and compliance costs in the case in which the US is assumed to comply with the Kyoto Protocol.

[2] This paper assumes that the US will start complying with its Kyoto emissions constraint in 2020.

[3] This result is an updated and corrected version of the analysis in Den Elzen and de Moor (2001b).

[4] This paper takes also non-CO2 gases into account. Furthermore, the authors do not specify the exact permit prices and emphasise that the reduction in permit prices are likely to be understated.

Similar conclusions can be found also in Kemfert (2001), Kopp (2001) and Vrolijk (2001)[6].

Table 7.2. Implications of the U.S. withdrawal on environmental effectiveness

	Annex B CO2 emissions (compared to business-as-usual in 2010)[1]		
	Kyoto Protocol with U.S.	**Kyoto Protocol without U.S.**[2]	**KP plus other provisions**
Hagem and Holtsmark (2001)	- 12.8%	- 3.7%	With ceilings on permit supply: - 7.3%
Den Elzen and de Moor (2001b)[3]	- 5.1%	+ 8%[4]	-
Böhringer (2001)	- 5.8%	- 0.5%	With the Bonn sinks provision: - 0,01%
Böhringer and Löschel (2001)	- 10%	0	If FSU exerts its monopoly power: -3%
Buchner et al. (2002)	- 13.1%	- 6.6%	-
Den Elzen and de Moor (2002)[5]	- 5.2%	- 4.3%[6]	With the Marrakech accords: - 0.6%

All studies apply international emissions trading.

[1] The targets for 2010 imposed by the Kyoto Protocol are related to base year emissions levels, not to the 1990-levels. Therefore, all these studies compare the simulations for emission reductions with respect to the BAU situation in 2010.

[2] Percentage change with respect to the BAU of total Annex B emissions in 2010, including the US emissions.

[3] This analysis compares the CO2 emissions to the 1990-levels.

[4] Excluding the US emissions from the Annex B would imply a reduction in the Annex B emissions of - 4% compared to 1990-levels

[5] This paper uses CO2 equivalent emissions to reflect abatement efforts.

[6] This value does not include the US emissions.

The impact on R&D expenditure – and consequently on technology and the emission/output ratio – of the US decision to withdraw from the Kyoto Protocol has recently been studied by Buchner, Carraro and Cersosimo (2002), where a model with endogenous and induced technical change is used. In their

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[6] Including the effects of the Marrakech Agreement reached at the Seventh Conference of the Parties, the decrease in the world abatement is even stronger: Den Elzen and de Moor (2001a, 2002) include the Marrakech provisions and find that the Annex B CO2 equivalent emissions actually *increase* by almost 2% with respect to the 1990-level.

paper, the effect of the lower permit price on the incentives to undertake GHG emission reducing R&D is quantified. The results are summarised in Table 7.3, which confirms the decline of R&D expenditure in all Annex B countries after the US defection from the Kyoto Protocol. Therefore, not only does the US reduce its own abatement and R&D efforts, but also those of the other Annex B countries, via spillovers and leakage effects. As a consequence, the emission/output ratio deteriorates in all Annex B countries (Buchner, Carraro and Cersosimo, 2002).

Table 7.3. Implication of the US withdrawal on the amount of R&D. Results from FEEM-RICE.

Changes of R&D expenditure in percentage (Annex B without USA compared to original Annex B)				
	USA	**JPN**	**EU**	**FSU**
2010	- 9.7%	- 0.3%	- 0.6%	- 8.3%
2020	- 12.0%	- 0.3%	- 0.7%	- 7.9%
2030	- 13.7%	- 0.4%	- 0.8%	- 6.7%
2040	- 15.0%	- 0.3%	- 0.7%	- 5.0%
2050	- 15.7%	- 0.2%	- 0.5%	- 3.1%

Finally, the US decision, by inducing a fall in the permit price, penalises the permit sellers, namely Russia, that loses most of its benefits from participating in the Kyoto agreement (given hot air, a lower permit price strongly reduces Russia's possible windfall profits). However, being the dominant seller, Russia could be tempted to use the banking provision and its monopolistic power to raise the price of permits (Cf. Manne and Richels, 2001)[7]. Given the low benefits from emission trading, Russia could even question its participation in the Kyoto Protocol.

This latter threat is reinforced by one of the rules of the Kyoto Protocol, which requires that at least 55 Parties to the United Nations Framework Convention on Climate Change, representing at the same time at least 55% of 1990 carbon dioxide emissions of Annex B countries, must ratify the Protocol for it to come into force. Russia is well aware of its importance as a key player for the implementation of the agreement. As a consequence, its bargaining power has sharply increased after the US defection from Kyoto. This increased bargaining power has enabled Russia to obtain important concessions in Marrakech, which further reduce the environmental effectiveness of the Protocol. In addition, although never threatening with the perspective of a defection, Russia attempts

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[7] Other studies which have addressed the possibility of strategic behaviour on the supply side of the permit market are: Böhringer (2001), Böhringer and Löschel (2001), Buchner, Carraro and Cersosimo (2002), Den Elzen and de Moor (2002, 2001a, 2001b), Egenhofer, Hager and Legge (2001), Eyckmans, van Regemorter and van Steenberghe (2001).

to exploit its high bargaining power by postponing its ratification in order to achieve additional economic benefits, in particular from the EU[8].

The results summarised by Tables 7.1, 7.2 and 7.3 support our search for negotiation and policy strategies designed to provide new incentives for the US to ratify the Kyoto Protocol. It is indeed crucial to bring the US back into the international climate regime. Without the US contribution, no effective emission reductions can be achieved. In addition, without the US commitment to reduce its own emissions, developing countries are very unlikely to join the Annex B group. Can "issue linkage", and in particular the linkage between climate and R&D cooperation, be the right policy tool to induce the US to move back to Kyoto?

3. Can "issue linkage" induce US cooperation? A game-theoretic approach.

Let us briefly describe the game-theoretic model upon which our empirical analysis will be based (see Carraro and Siniscalco, 1997, or Carraro and Marchiori, 2004, for a detailed presentation). Assume negotiations take place among n countries, $n \geq 3$, each indexed by $i = 1, \ldots, n$. Countries play a two-stage game. In the first stage – the *coalition game* – they decide non-cooperatively whether or not to sign the agreement (i.e. to join the coalition). In the second stage, they play a non-cooperative open loop Nash game to set their policy variables (emission abatement, investments, R&D expenditure). In the second stage, countries that have signed the agreement play as a single player and divide the resulting payoff according to a given burden-sharing rule[9].

In the empirical model described in the next section, the players are six macro-regions: Europe (EU), Japan (JPN), Former Soviet Union (FSU), United States (US), China (CHN) and Rest of the World (ROW). The starting point of our analysis is a climate regime in which the EU, JPN and FSU are committed to comply with the Kyoto Protocol, namely their abatement rate is such as to achieve the Kyoto target. In the second stage, these countries optimally set their investments and R&D expenditure. In contrast, the other countries – US, CHN and ROW – maximise their own welfare function with respect to their investments, R&D expenditure and also their abatement rate.

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[8] Before proceeding to the ratification of the Kyoto Protocol, Russia asked for the compliance of all developed countries, and in particular of those being members of the UNFCCC, and emphasised the need of an active future participation of the developing countries (The Hindu, Oct. 31st, 2001). The Moscow Conference on Climate Change held in September 2003 added additional doubts on the timetabling of the ratification. Still, recent Russian announcements raise expectations for the Protocol's ratification towards the end of 2004 (taking into account that Russia is likely to wait for the US elections in autumn 2004) (Dow Jones Newswires, Oct. 28th, 2003).

[9] This approach must be contrasted with the traditional cooperative game approach (e.g. Chander and Tulkens, 1995, 1997) and with a repeated game approach (Barrett, 1994, 1997). Moreover, note that the regulatory approach often proposed in public economics is not appropriate given the lack of a supranational authority.

Assume that EU, JPN and FSU identify issue linkage as a strategy to induce the US to accept and ratify the Kyoto Protocol. In particular they want to link climate and R&D cooperation. Is this strategy effective? The issue linkage proposal that EU, JPN and FSU are assumed to make to the US is as follows. All four countries are offered to cooperate on both climate change control and technological innovation and diffusion. If a country free-rides either on climate cooperation or on R&D cooperation (or on both), it keeps the environmental benefits (because climate control is a public good) but loses the R&D cooperation benefits (at least partly, because of technological spillovers). Is this proposal credible?

Note that the incentives to free-ride on the climate agreement come from the public good nature of climate change control, whereas the incentives to free-ride on the R&D agreement arise from the presence of technological spillovers. Therefore, R&D cooperation is assumed to be an imperfect club good. As suggested by theoretical works (Cf. Carraro and Marchiori, 2004), we will see that the parameter identifying technological spillovers plays a crucial role in the analysis of the effectiveness and credibility of the issue linkage proposal.

Let us discuss the theoretical conditions which are necessary and sufficient for the joint agreement, in which all four countries – including the US – cooperate on both climate and R&D, to be profitable and stable[10]. We will focus on the first stage of the game, in which all countries decide whether or not to cooperate on climate and R&D. It is important to recall that the initial environmental coalition formed by the EU, JPN and FSU is assumed to be committed to comply with the Kyoto targets. However, they can set their technological variables in a non cooperative way, if in the first stage they decide not to cooperate on technological innovation and diffusion.

As said, in the business as usual game, the following coalition structure forms[11]:

(1) $[(\mathrm{EU}, \mathrm{JPN}, \mathrm{FSU})_a, \mathrm{EU}_{R\&D}, \mathrm{JPN}_{R\&D}, \mathrm{FSU}_{R\&D}, \mathrm{US}_{a,R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}]$

namely EU, JPN and FSU cooperate to control GHG emissions, whereas the US free-rides; CHN and ROW also play non-cooperatively. Note that the level of R&D expenditure is set non-cooperatively by all players.

If issue linkage is effective, i.e. the US accepts to cooperate on both climate control and technology because they do not want to loose the benefits arising from R&D cooperation, the following coalition structure forms:

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[10] An agreement is profitable if each cooperating player gets a payoff larger than the one he would get when no agreement is signed. An agreement is stable if there is no incentive to free-ride and there is no incentive for other countries to sign the agreement (see Carraro and Marchiori, 2003 for a survey of the theory of coalition stability).

[11] A coalition C is any non-empty subset of the player set N. A coalition structure $\pi = \{C_1, C_2, \ldots, C_m\}$ is a partition of the player set N, i.e. $C_i \cap C_j = \emptyset$ for i ≠ j and $\cup_{i=1}^{m} C_i = N$.

$$[(\mathrm{EU, JPN, FSU, US})_{a,R\&D},\ \mathrm{CHN}_{a,R\&D},\ \mathrm{ROW}_{a,R\&D}] \tag{2}$$

where Annex B countries (EU, JPN, FSU and US) cooperate on both issues. We will refer to this coalition structure as the "joint coalition structure". CHN and ROW set non-cooperatively both their abatement level and their R&D expenditure. The comparison between (1) and (2) enables us to identify the first necessary condition. Issue linkage is profitable to all Annex B countries if:

$$\begin{aligned}&\mathrm{P}_i[(\mathrm{EU, JPN, FSU, US})_{a,R\&D},\ \mathrm{CHN}_{a,R\&D},\ \mathrm{ROW}_{a,R\&D}] >\\ &\mathrm{P}_i[(\mathrm{EU, JPN, FSU})_{a},\ \mathrm{EU}_{R\&D},\ \mathrm{JPN}_{R\&D},\ \mathrm{FSU}_{R\&D},\ \mathrm{US}_{a,R\&D},\ \mathrm{CHN}_{a,R\&D},\\ &\mathrm{ROW}_{aR\&D}]\end{aligned} \tag{3}$$

where $\mathrm{P}_i(.)$ denotes the welfare function of country i and i = EU, JPN, FSU, US.

In other words, if (3) is met, the situation in which Annex B countries cooperate on both climate and R&D is preferred by all countries to the situation in which the EU, JPN and FSU cooperate on climate, the US free-rides and no R&D cooperation takes place.

If the US cooperates on technology but free-rides on climate, the coalition structure is:

$$[(\mathrm{EU, JPN, FSU, US})_{R\&D},\ (\mathrm{EU, JPN, FSU})_{a},\ \mathrm{US}_{a},\ \mathrm{CHN}_{a,R\&D},\ \mathrm{ROW}_{a,R\&D}] \tag{4}$$

This coalition structure leads to a second important group of conditions:

$$\begin{aligned}&\mathrm{P}_i[(\mathrm{EU, JPN, FSU, USA})_{a,R\&D},\ \mathrm{CHN}_{a,R\&D},\ \mathrm{ROW}_{a,R\&D}] >\\ &\mathrm{P}_i[(\mathrm{EU, JPN, FSU, USA})_{R\&D},\ (\mathrm{EU, JPN, FSU})_{a},\\ &\mathrm{USA}_{a},\ \mathrm{CHN}_{a,R\&D},\ \mathrm{ROW}_{a,R\&D}\ ],\quad \mathrm{i = EU, JPN, FSU}\end{aligned} \tag{5a}$$

$$\begin{aligned}&\mathrm{P}_{USA}[(\mathrm{EU, JPN, FSU, USA})_{a,R\&D},\ \mathrm{CHN}_{a,R\&D},\ \mathrm{ROW}_{a,R\&D}] <\\ &\mathrm{P}_{USA}[(\mathrm{EU, JPN, FSU, USA})_{R\&D},\ (\mathrm{EU, JPN, FSU})_{a},\ \mathrm{USA}_{a},\ \mathrm{CHN}_{a,R\&D},\\ &\mathrm{ROW}_{a,R\&D}\ ]\end{aligned} \tag{5b}$$

Conditions (5a) and (5b) state that (EU, JPN, FSU) should prefer cooperation on both climate and R&D rather than cooperation on R&D only, otherwise it would not be profitable for these players to propose to the US a linked cooperation on both issues. By contrast, the US should prefer to cooperate on R&D only, otherwise there would be no need to introduce issue linkage because the US would find it profitable to cooperate on both issues anyway. Therefore, (3) is the usual profitability or rationality condition, whereas (5a) and (5b) guarantee that issue linkage is not a trivial situation which profits all players. Let us now focus on the stability of the joint agreement. If the US free-rides on either R&D cooperation or climate cooperation (or on both), it loses all benefits because of issue linkage. Therefore, the following coalition structure forms:

$$[(\mathrm{EU, JPN, FSU})_{a,R\&D},\ \mathrm{US}_{a,R\&D},\ \mathrm{CHN}_{a,R\&D},\ \mathrm{ROW}_{a,R\&D}] \tag{6}$$

As a consequence, the US has no incentive to free-ride (subject to issue linkage) if:

$$\begin{aligned}&\mathrm{P}_{USA}\ [(\mathrm{EU, JPN, FSU, US})_{a,R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}] >\\ &\mathrm{P}_{USA}\ [(\mathrm{EU, JPN, FSU})_{a,R\&D}, \mathrm{US}_{a,R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}]\end{aligned}\tag{7}$$

The other Annex B countries, the EU, JPN and FSU, are committed to climate cooperation. Therefore, they can only free-ride on R&D cooperation. If the EU free-rides, the coalition structure is

$$[(\mathrm{EU, JPN, FSU, US})_{a}, (\mathrm{JPN, FSU, US})_{R\&D}, \mathrm{EU}_{R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}]\tag{8}$$

Therefore, the EU has no incentive to free ride on the joint agreement if:

$$\begin{aligned}&\mathrm{P}_{EU}\ [(\mathrm{EU, JPN, FSU, US})_{a,R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}] >\\ &\mathrm{P}_{EU}\ [(\mathrm{EU, JPN, FSU, US})_{a}, (\mathrm{JPN, FSU, US})_{R\&D}, \mathrm{EU}_{R\&D}, \mathrm{CHN}_{a,R\&D},\\ &\mathrm{ROW}_{a,R\&D}]\end{aligned}\tag{9}$$

Similar conditions must hold for JPN and FSU. As a consequence, the joint agreement is stable if (7), (9) and:

$$\begin{aligned}&\mathrm{P}_{JPN}\ [(\mathrm{EU, JPN, FSU, US})_{a,R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}] >\\ &\mathrm{P}_{JPN}\ [(\mathrm{EU, JPN, FSU, US})_{a}, (\mathrm{EU, FSU, US})_{R\&D}, \mathrm{JPN}_{R\&D}, \mathrm{CHN}_{a,R\&D},\\ &\mathrm{ROW}_{a,R\&D}]\end{aligned}\tag{10}$$

$$\begin{aligned}&\mathrm{P}_{FSU}\ [(\mathrm{EU, JPN, FSU, US})_{a,R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}] >\\ &\mathrm{P}_{FSU}\ [(\mathrm{EU, JPN, FSU, US})_{a}, (\mathrm{EU, JPN, US})_{R\&D}, \mathrm{FSU}_{R\&D}, \mathrm{CHN}_{a,R\&D},\\ &\mathrm{ROW}_{a,R\&D}]\end{aligned}\tag{11}$$

are met. Let us recall that the stability condition (7) is conditional on the adoption of the issue linkage strategy and on its credibility.

There is a final important condition that must be checked for an issue linkage proposal – e.g. the one in which climate and R&D cooperation are linked – to be an effective tool to induce the US to participate in the Kyoto agreement. This last condition is the credibility of the issue linkage proposal[12]. Is it credible that the environmental coalition (EU, JPN, FSU) actually excludes the US from R&D cooperation if the US does not comply with the Kyoto agreement? To answer this question, we need to compare the payoffs under the coalition structures (4) and (6). The issue linkage proposal is credible if:

$$\begin{aligned}&\mathrm{P}_{i}[(\mathrm{EU, JPN, FSU})_{a,R\&D}\ , \mathrm{US}_{a,R\&D}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}] >\\ &\mathrm{P}_{i}[(\mathrm{EU, JPN, FSU, US})_{R\&D}, (\mathrm{EU, JPN, FSU})_{a}, \mathrm{US}_{a}, \mathrm{CHN}_{a,R\&D}, \mathrm{ROW}_{a,R\&D}],\\ &\mathrm{i} = \mathrm{EU, JPN, FSU}\end{aligned}\tag{12}$$

i.e. if the EU, JPN and FSU prefer the situation in which they implement the threat implicit in the issue linkage proposal to the situation in which they accept the US free-riding on climate, but cooperate with the US on R&D. If condition (12) is met, the threat implicit in the issue linkage proposal is credible. Indeed, were condition (12) not satisfied, the EU, JPN and FSU would prefer to maintain at least R&D cooperation with the US.

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[12] The issue of the credibility of the threat implicit in the issue linkage proposal has been raised by Tol *et al.* (2000).

The above conditions (3), (7), (9), (10), (11), (12) are necessary and sufficient for the profitability and stability of the coalition structure [(EU, JPN, FSU, US)$_{a,R\&D}$, CHN$_{a,R\&D}$, ROW$_{a,R\&D}$] and for the credibility of the implicit threat upon which it is based. In the next section, we will analyse from an empirical viewpoint whether the above conditions are likely to be met.

4. The role of issue linkage: some empirical evidence

In this section, the main assumptions and the modelling framework that will be used to assess the effectiveness of the issue linkage proposal will be described. In particular, the main features of the FEEM-RICE model will be presented. Then, our assumptions about scenarios and policy strategies will be implemented into the FEEM-RICE model to check under what conditions the profitability, stability and credibility conditions presented above are actually met.

4.1 Main assumptions and modelling framework

The empirical part of this paper is based on optimisation results obtained using the FEEM-RICE model, a version of Nordhaus' RICE model in which endogenous and induced technical change are explicitly represented. In this version, technical change plays a twofold role: on the one hand, via increasing returns to scale, it yields endogenous growth; on the other hand, by affecting the emission/output ratio, it accounts for the adoption of cleaner and energy-saving technologies[13]. In addition, international technological spillovers are accounted for.

In the FEEM-RICE model, six countries/regions (US, EU, Japan (JPN), former Soviet Union (FSU), China (CHN) and rest of the world (ROW)) optimally set the intertemporal values of four strategic variables: investments, R&D expenditure, abatement effort and net demand for emission permits[14]. When coalitions form, countries belonging to the same coalition maximise their joint welfare. When no coalition forms, each country/region maximises its own individual welfare given the other countries' strategy. Given the interdependency of countries' decisions, the equilibrium values of the policy variables are obtained by solving a dynamic open-loop Nash game between the six countries/regions.

Two important assumptions qualify our results. First, it is assumed that all countries/regions which adhere to the Kyoto/Bonn/Marrakech agreement meet

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[13] The FEEM-RICE model has already been used in Buonanno, Carraro, Castelnuovo and Galeotti (2001), Buonanno, Carraro and Galeotti (2002) and in Buchner, Carraro and Cersosimo (2002). A brief description is contained in the Appendix.

[14] Notice that, in all climate regimes, abatement is a strategic variable, which is optimally set at its welfare maximising level by countries both inside and outside the coalition. Coalition members adopting the emission targets decided in Kyoto may decide to reduce emissions below the target.

the Kyoto constraints from 2010 onward[15]. We therefore adopt the so-called "Kyoto forever" hypothesis (see, for example, Manne and Richels, 1999 and many others). As a consequence, our reference to the Kyoto/Bonn/Marrakech agreement is partly imprecise because, for the sake of brevity, we will sometimes call "Kyoto Protocol" or "Kyoto/Bonn/Marrakech agreement" a "Kyoto forever" scenario. In another paper (Buchner and Carraro, 2003) we test the robustness of the results with respect to changes in the assumption about future commitments.

A second important assumption concerns the policy scenario. We will analyse the effectiveness of issue linkage in inducing the US to comply with the Kyoto Protocol under the assumption that all GHG abatement is carried out through domestic emission reduction policies. In other words, we analyse only the case in which international emission trading is not allowed since our goal is to check the effectiveness of R&D issue linkage. To do this, we adopt the most favourable situation for issue linkage to be effective. This situation is the one in which there is no international trading.

It is well known that an international trading scheme is a cost-effective way to reduce GHG emissions, i.e. the cost of reducing emissions is lowest, if an international and competitive trading market is at work. At the same time, recent studies have highlighted the strong impact of an international emission trading market on R&D and technological innovation. In particular, Buonanno, Carraro and Galeotti (2002) show that an international trading system, by lowering the cost of complying with the Kyoto targets, also lowers the incentives to undertake environment-friendly R&D. Therefore, at the equilibrium, R&D expenditure is lower in all countries that benefit from emission trading. Hence, R&D and emission trading are strategic substitutes. As a consequence, countries have the largest incentive to attain the benefits yielded by R&D cooperation when international emission trading is not allowed. The issue linkage proposal, which prevents the US from attaining the R&D cooperation benefits if they do not comply with the Kyoto targets, is thus most effective when the US actually needs R&D and technological innovation to achieve the Kyoto targets. In other words, we evaluate the impact of issue linkage in a situation in which environmentally committed countries (EU, JPN and FSU) have the maximum possible amount of R&D to offer to convince the US to move back to the Kyoto agreement.

It is important to clarify the role of spillovers in the model. In order to capture the idea that countries which do not belong to the R&D coalition are excluded from the benefits produced by R&D cooperation, we add a new parameter to the standard FEEM-RICE model, denoted by β. This parameter

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[15] The use of the "Kyoto forever" hypothesis is a strong assumption. However, the CO2 concentration levels implicit in this assumption (if RICE is a good description of the world) coincide with those in the A1B scenario (IPCC, 2001) which can be considered the "median" scenario among those currently proposed. We thus use the "Kyoto-forever" hypothesis not because it represents a realistic scenario, but as a benchmark with respect to which policy alternatives can be compared.

quantifies the increased share of world knowledge which is appropriated by countries belonging to the R&D coalition. This parameter is equivalent to the "differential technological spillover" or "coalition information exchange coefficient" in the theoretical model by Carraro and Siniscalco (1995, 1997).

Therefore, in the model there are two types of technological spillovers and related parameterisation (see the Appendix for a more detailed presentation of the model equations). Spillovers, parameterised by ε, which are appropriated by all countries; and spillovers, parameterised by β, which are beneficial only to coalition members. As shown in the Appendix, technical change is induced by knowledge accumulation, which is the sum of past R&D expenditures. We assume that part of the technological benefits yielded by this knowledge accumulation are a global public good, whereas part of them are a club good that can be appropriated only by the R&D coalition members. Given the crucial role of β in the analysis of the effectiveness of issue linkage, we will explore how the empirical assessment of the theoretical conditions described in the previous section depends on the value of β.

4.2 Empirical analysis

Let us start by evaluating the non-triviality of the issue linkage proposal. As formalised in eqs. (5a) and (5b), in order to ensure that issue linkage does not represent a dominant strategy, the environmental coalition (EU, JPN, FSU) should prefer to cooperate on both climate and R&D than to cooperate on R&D only. By contrast, the US should prefer cooperation only on R&D.

Table 7.4 provides an empirical assessment of (5a) and (5b) both in the short term (the first commitment period) and in the medium term (up to 2050). It shows that the issue linkage proposal is not trivial. In the short run for $\beta \geq 0.66$. In the medium run, for all values of β[16]. In particular, for these values of β, the US prefers to cooperate only on R&D rather than on both climate and R&D.

These results are therefore consistent with our initial conjecture. Cooperation on both climate and R&D can emerge only if the US is threatened to be excluded from R&D cooperation if it does not cooperate on climate change control.

The next question concerns the profitability of the issue linkage proposal. Is it convenient for all Annex B countries to cooperate on both climate and R&D (with respect to the present situation)? The answer is provided by Table 7.5, where the profitability condition (3) is assessed both in the short and in the medium term. Table 7.5 shows that, if $\beta \geq 0.66$, all Annex B countries find it profitable to move from the current situation to an international regime in which all Annex B countries cooperate on both GHG emission control and on technological innovation and diffusion.

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[16] For simplicity, in all tables we do not write the entire coalition structure but we omit developing countries (CHN and ROW). The reason is that, as explained in section 3, these countries are assumed not to cooperate in all coalition structures.

Table 7.4. Non triviality of the issue linkage proposal.

First commitment period (1990-2010)

	P[(USA, JPN, EU, SU)$_{A,R\&D}$]						P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]					
β	0.10	0.20	0.33	0.66	1.00	1.50	0.10	0.20	0.33	0.66	1.00	1.50
USA	12.0621	12.0745	12.0897	12.1231	12.1524	12.1881	12.0808	12.0944	12.1096	12.1435	12.1730	12.2090
JPN	6.4105	6.4107	6.4111	6.4121	6.4133	6.4149	6.4084	6.4087	6.4090	6.4098	6.4107	6.4124
EU	14.9212	14.9281	14.9364	14.9549	14.9712	14.9908	14.9200	14.9264	14.9349	14.9533	14.9692	14.9891
FSU	1.8844	1.8845	1.8845	1.8847	1.8848	1.8850	1.8843	1.8844	1.8845	1.8846	1.8847	1.8849

P[(USA, JPN, EU, SU)$_{A,R\&D}$] $\geq$ P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]						
β	0.10	0.20	0.33	0.66	1.00	1.50
USA	no	no	no	no	no	no
JPN	yes	yes	yes	yes	yes	yes
EU	yes	yes	yes	yes	yes	yes
FSU	yes	yes	no	yes	yes	yes

Medium term (1990-2050)

	P[(USA, JPN, EU, SU)$_{A,R\&D}$]						P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]					
β	0.10	0.20	0.33	0.66	1.00	1.50	0.10	0.20	0.33	0.66	1.00	1.50
USA	22.4161	22.4425	22.4741	22.5429	22.6031	22.6777	22.5083	22.5339	22.5665	22.6366	22.6952	22.7742
JPN	12.1728	12.1736	12.1757	12.1797	12.1843	12.1875	12.1704	12.1711	12.1725	12.1761	12.1788	12.1840
EU	27.9150	27.9287	27.9468	27.9862	28.0161	28.0618	27.9043	27.9185	27.9367	27.9758	28.0095	28.0506
FSU	3.8871	3.8872	3.8875	3.8879	3.8883	3.8887	3.8868	3.8870	3.8872	3.8876	3.8880	3.8884

P[(USA, JPN, EU, SU)$_{A,R\&D}$] $\geq$ P[(USA, JPN, EU, FSU)$_{R\&D}$; (JPN, EU, FSU)$_A$ USA$_A$]						
β	0.10	0.20	0.33	0.66	1.00	1.50
USA	no	no	no	no	no	no
JPN	yes	yes	yes	yes	yes	yes
EU	yes	yes	yes	yes	yes	yes
FSU	yes	yes	yes	yes	yes	yes

P(.): payoffs (cumulated discounted consumption)

β : differential technological spillover or coalition information exchange coefficient

Note that the country for which the profitability condition is most difficult to be met is the US. In all other Annex B countries, the profitability of issue linkage is achieved for all values of β. There are two reasons that explain this result.

Table 7.5. Profitability of the issue linkage proposal

First commitment period (1990-2010)

	P[(JPN, EU, FSU)$_A$ USA$_A$]	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]					
β		0.10	0.20	0.33	0.66	1.00	1.50
USA	12.1126	12.0621	12.0745	12.0897	12.1231	12.1524	12.1881
JPN	6.3642	6.4105	6.4107	6.4111	6.4121	6.4133	6.4149
EU	14.8579	14.9212	14.9281	14.9364	14.9549	14.9712	14.9908
FSU	1.8838	1.8844	1.8845	1.8845	1.8847	1.8848	1.8850

P[(USA, JPN, EU, FSU)$_{A,R\&D}$] $\geq$ P[(JPN, EU, FSU)$_A$USA$_A$]						
β	0.10	0.20	0.33	0.66	1.00	1.50
USA	no	no	no	Yes	yes	yes
JPN	yes	yes	yes	Yes	yes	yes
EU	yes	yes	yes	Yes	yes	yes
FSU	yes	yes	yes	Yes	yes	yes
All	no	no	no	Yes	yes	yes

Medium term (1990-2050)

	P[(JPN, EU, FSU)$_A$USA$_A$]	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]					
β		0.10	0.20	0.33	0.66	1.00	1.50
USA	22.5259	22.4161	22.4425	22.4741	22.5429	22.6031	22.6777
JPN	12.1190	12.1728	12.1736	12.1757	12.1797	12.1843	12.1875
EU	27.8559	27.9150	27.9287	27.9468	27.9862	28.0161	28.0618
FSU	3.8860	3.8871	3.8872	3.8875	3.8879	3.8883	3.8887

P[(USA, JPN, EU, FSU)$_{A,R\&D}$] $\geq$ P[(JPN, EU, FSU)$_A$USA$_A$]						
β	0.10	0.20	0.33	0.66	1.00	1.50
USA	no	no	no	Yes	yes	yes
JPN	yes	yes	yes	Yes	yes	yes
EU	yes	yes	yes	Yes	yes	yes
FSU	yes	yes	yes	Yes	yes	yes
All	no	no	no	Yes	yes	yes

P(.): payoffs (cumulated discounted consumption)
β : differential technological spillover or coalition information exchange coefficient

Firstly, the US moves from a situation of no cooperation on both climate and R&D to a situation of cooperation on both issues, whereas the other countries already cooperate on GHG emission control. In particular, the US, by leaving the situation in which they free-ride on climate control, start paying for abatement costs.

Secondly, the US is characterised by high R&D expenditure levels. Therefore, when cooperating on R&D, the US provides, via spillovers, important technological benefits to the other partners. As a consequence, these partners – EU, JPN and FSU – achieve profitability even for low values of β. In other words, even when the technological spillover is small, the EU, JPN and FSU receive a large amount of knowledge transfer from the US, because of the high R&D expenditure levels in this country.

Now, let us analyse the free-riding incentives which could de-stabilise the joint agreement in which all Annex B countries cooperate on both climate control and R&D. The US has no free-riding incentives if condition (7) is met. The empirical assessment of condition (7) is shown in Table 7.6.

Table 7.6. U.S. incentives to free ride on the issue linkage proposal

First commitment period (1990-2010)

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]						P[(JPN, EU, FSU)$_{A,R\&D}$USA$_{A,R\&D}$]					
β	0.10	0.20	0.33	0.66	1.00	1.50	0.10	0.20	0.33	0.66	1.00	1.50
USA	12.0621	12.0745	12.0897	12.1231	12.1524	12.1881	12.0678	11.9631	12.0078	11.9719	12.0332	12.0229
P[(USA, JPN, EU, FSU)$_{A,R\&D}$] $\geq$ P[(JPN, EU, FSU)$_{A,R\&D}$USA$_{A,R\&D}$]												
β	0.10		0.20		0.33		0.66		1.00		1.50	
USA	no		yes		yes		yes		yes		yes	

Medium term (1990-2050)

	P[(USA, JPN, EU, FSU)$_{A,R\&D}$]						P[(JPN, EU, FSU)$_{A,R\&D}$USA$_{A,R\&D}$]					
β	0.10	0.20	0.33	0.66	1.00	1.50	0.10	0.20	0.33	0.66	1.00	1.50
USA	22.4161	22.4425	22.4741	22.5429	22.6031	22.6777	22.5172	22.3200	22.4452	22.3643	22.4379	22.5235
P[(USA, JPN, EU, FSU)$_{A,R\&D}$] $\geq$ P[(JPN, EU, FSU)$_{A,R\&D}$USA$_{A,R\&D}$]												
β	0.10		0.20		0.33		0.66		1.00		1.50	
USA	no		yes		yes		yes		yes		yes	

P(.): payoffs (cumulated discounted consumption)

β : differential technological spillover or coalition information exchange coefficient

Given that the profitability condition is met for $\beta \geq 0.66$, it is important to explore the stability of the linked agreement only for values of $\beta \geq 0.66$. Table 7.6 actually shows that the US has no incentive to free-ride on the coalition which cooperates on both climate and R&D when free-riding on either climate or R&D (or both) implies the loss of the benefits arising from technological cooperation.

A similar conclusion holds for the other Annex B countries. By evaluating conditions (9), (10) and (11), we conclude that no Annex B country has an incentive to free-ride on the linked agreement for values of $\beta \geq 0.66$ (both in the short and in the medium run). Our empirical analysis is summarised by Table 7.7, which shows for which values of β the profitability and stability conditions are met.

Summarizing our results, the proposal of linking R&D cooperation with cooperation on climate change control is thus not trivial, it is profitable, and above all it guarantees the stability of the linked agreement (no incentive to free-ride once the linked agreement is signed). In other words, if the issue linkage proposal is implemented, the participating countries benefit from cooperation even when the coalition-internal technological spillovers are modest.

Table 7.7. Values of β for which the profitability and stability conditions are met.

	1990-2010	1990-2050
$P[(USA, JPN, EU, FSU)_{A,R\&D}] \geq P[(JPN, EU, FSU)_A USA_A]$	$\beta \geq 0.66$	$\beta \geq 0.66$
$P[(USA, JPN, EU, FSU)_{A,R\&D}] \geq P[(JPN, EU, FSU)_{A,R\&D} USA_{A,R\&D}]$	$\beta \geq 0.20$	$\beta \geq 0.20$
$P[(USA, JPN, EU, FSU)_{A,R\&D}] \geq P[(USA, JPN, EU, FSU)_A (USA, JPN, FSU)_{R\&D}\ EU_{R\&D}]$	$\beta \geq 0.10$	$\beta \geq 0.10$
$P[(USA, JPN, EU, FSU)_{A,R\&D}] \geq P[(USA, JPN, EU, FSU)_A (USA, EU, FSU)_{R\&D}\ JPN_{R\&D}]$	$\beta \geq 0.10$	$\beta \geq 0.10$
$P[(USA, JPN, EU, FSU)_{A,R\&D}] \geq P[(USA, JPN, EU, FSU)_A (USA, EU, JPN)_{R\&D}\ FSU_{R\&D}]$	$\beta \geq 0.10$	$\beta \geq 0.10$

P(.): payoffs (cumulated discounted consumption)
β : differential technological spillover or coalition information exchange coefficient

However, is the issue linkage proposal credible? As previously noted, the issue linkage proposal contains the implicit threat to exclude the US from technological cooperation if they do not cooperate on climate change control. Is this threat credible? The answer depends on condition (12), which defines when the EU, JPN and FSU prefer to implement the threat implicit in the issue linkage proposal rather than accepting the US free-riding on climate control and cooperating only on technological innovation and diffusion.

Unfortunately, our empirical results suggest that this last condition is unlikely to be met, i.e. the threat implicit in the issue linkage proposal is unlikely to be credible. Table 7.8 below demonstrates that the credibility condition is not met for all $\beta \geq 0.66$. In particular, the issue linkage proposal is not credible for the EU, for which no value of β is such to meet eq. (12) in the short run. Therefore, for the values of the technological spillover β for which the coalition based on issue linkage would be profitable, there is a lack of credibility that would induce the US not to accept the proposal (we already showed that the US prefers to cooperate on R&D only).

The intuition for this result is as follows. The benefits from technological cooperation are much higher for the EU, JPN, and above all the FSU, than for the US. Therefore, the EU, JPN and FSU suffer a bigger loss when the issue linkage threat is implemented, namely when they exclude the US from the technological coalition. In addition, the environmental benefits arising from cooperation on climate change control are smaller, at least in the FEEM-RICE model, than the technological benefits from R&D cooperation. Therefore, EU, JPN and FSU prefer to lose the environmental benefits than the technological benefits, and thus accept the US free-riding on climate cooperation if the US cooperates on R&D.

5. Conclusions

Large cooperation on global environmental issues is difficult to achieve because of the public nature of the global environment that creates strong incentives to free-ride. This problem, often highlighted in the game-theoretic and economic literature, is also confirmed by recent events in climate policy. The most obvious example is the US decision not to ratify the Kyoto Protocol.

The US defection induces serious environmental and economic problems, ranging from a deterioration of the environmental effectiveness of the Kyoto Protocol to the increase in Russia's bargaining power. Therefore, it is crucial to investigate whether an incentive strategy indeed exists that could induce the US to revise its decision and to comply with the Kyoto commitments.

One solution often proposed in the literature on international regimes is to link cooperation on climate change control (typically a public good) with cooperation on a club or quasi-club good. In this paper, we have considered the linkage of climate cooperation with technological cooperation. The idea is that the incentives to appropriate R&D cooperation benefits, which can be obtained only by cooperating also on climate change control, could offset the incentives to free-ride on the environmental dimension.

Our analysis does not seem to provide empirical support to the issue linkage proposal. Linkage between climate and R&D cooperation is unlikely to be an effective strategy to induce the US to move back to Kyoto. Even though the coalition structure in which all Annex B countries cooperate on both dimensions (climate and R&D) is profitable, the issue linkage proposal is based on an implicit non-credible threat. Countries like the European Union, Japan and Russia prefer to cooperate with the US on technological innovation and diffusion even when the US free-rides on climate cooperation.

Although the issue linkage proposal is therefore improbable to re-involve the US in the Kyoto Protocol, our study reveals a strong incentive for technological

Table 7.8. Credibility of the issue linkage proposal

First commitment period (1990-2010)

	$P[(JPN, EU, SU)_{A,R\&D} USA_{A,R\&D}]$						$P[(USA, JPN, EU, FSU)_{R\&D}; (JPN, EU, FSU)_A \ USA_A]$					
β	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	0.10	0.20	0.33	0.66	1.00	1.50
JPN	6.3711	6.4380	6.1892	6.4358	6.3480	6.1751	6.4084	6.4087	6.4090	6.4098	6.4107	6.4124
EU	14.5540	14.9548	14.8310	14.9629	14.9175	14.8674	14.9200	14.9264	14.9349	14.9533	14.9692	14.9891
FSU	1.8626	1.8849	1.8838	1.8850	1.8573	1.8840	1.8843	1.8844	1.8845	1.8846	1.8847	1.8849

$P[(JPN, EU, FSU)_{A,R\&D} USA_{A,R\&D}] \geq P[(USA, JPN, EU, FSU)_{R\&D}; (JPN, EU, FSU)_A USA_A]$						
β	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
JPN	no	yes	no	yes	no	no
EU	no	yes	no	yes	no	no
FSU	no	yes	no	yes	no	no

Medium term (1990-2050)

	$P[(JPN, EU, SU)_{A,R\&D} USA_{A,R\&D}]$						$P[(USA, JPN, EU, FSU)_{R\&D}; (JPN, EU, FSU)_A \ USA_A]$					
β	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**	0.10	0.20	0.33	0.66	1.00	1.50
JPN	12.0942	12.1824	11.9787	12.1862	12.1073	12.0746	12.1704	12.1711	12.1725	12.1891	12.1788	12.1840
EU	27.6532	27.9117	27.8183	27.9313	27.9804	27.9072	27.9043	27.9185	27.9367	27.9758	28.0095	28.0506
FSU	3.8766	3.8866	3.8879	3.8869	3.8808	3.8890	3.8868	3.8870	3.8872	3.8876	3.8880	3.8894

$P[(JPN, EU, FSU)_{A,R\&D} USA_{A,R\&D}] \geq P[(USA, JPN, EU, FSU)_{R\&D}; (JPN, EU, FSU)_A USA_A]$						
β	**0.10**	**0.20**	**0.33**	**0.66**	**1.00**	**1.50**
JPN	no	yes	no	no	no	no
EU	no	no	no	no	no	no
FSU	no	no	yes	no	no	no

P(.): payoffs (cumulated discounted consumption)

β : differential technological spillover or coalition information exchange coefficient

cooperation among Annex B countries. This insight could constitute an important component of the design of future climate policies[17]. As in previous papers (e.g. Buchner, Carraro and Cersosimo, 2002), our results must be taken cautiously. This paper aims at identifying economic mechanisms and feedbacks, rather than providing precise quantitative assessments of the implications of different climate regimes. The structure of the FEEM-RICE model, albeit simple, clearly identifies the numerous effects that must be taken into account when comparing alternative climate policies and international regimes. The role of endogenous and induced technical change is shown to be very important. The use of strategic R&D investments and R&D cooperation open new possibilities to climate policy. This paper has explored these possibilities by taking into account the economic mechanisms behind endogenous growth, climate-friendly innovation, international R&D spillovers and the possibility to exclude (at least partially) some countries from fully enjoying the benefits of these spillovers (RJVs and patents are obvious tools). The above set of economic mechanisms has been parameterised. As a consequence, the results are sensitive to this parameterisation, even though a sensitivity analysis with respect to the most important parameter – the coalition information exchange coefficient – has been carried out. Further research could be devoted to check the conclusions of this paper by using different models of the global economy.

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Appendix. The FEEM-RICE Model

The FEEM-RICE model is an extension of Nordhaus and Yang's (1996) regional RICE model of integrated assessment, which is one of the most popular and manageable integrated assessment tools for the study of climate change (see, for instance, Eyckmans and Tulkens, 2001). It is basically a single sector optimal growth model which has been extended to incorporate the interaction between economic activities and climate. One such model has been developed for each macro region into which the world is divided (USA, Japan, Europe, China, Former Soviet Union, and Rest of the World).

Within each region a central planner chooses the optimal paths of fixed investment and emission abatement that maximise the present value of per capita consumption. Output (net of climate change) is used for investment and consumption and is produced according to constant returns Cobb-Douglas technology, which combines the inputs from capital and labour with the level of technology. Population (taken to be equal to full employment) and technology levels grow over time in an exogenous fashion, whereas capital accumulation is governed by the optimal rate of investment. There is a wedge between output gross and net of climate change effects, the size of which is dependent upon the amount of abatement (rate of emission reduction) as well as the change in global temperature. The model is completed by three equations representing emissions (which are related to output and abatement), carbon cycle (which relates concentrations to emissions), and climate module (which relates the change in temperature relative to 1990 levels to carbon concentrations) respectively.

In our extension of the model, technical change is no longer exogenous. Instead, the issue of endogenous technical change is tackled by following the ideas contained in both Nordhaus (1999) and Goulder and Mathai (2000) and accordingly modifying Nordhaus and Yang's (1996) RICE model. Doing so requires the input of a number of additional parameters, some of which have been estimated using information provided by Coe and Helpman (1995), while the remaining parameters were calibrated so as to reproduce the business-as-usual scenario generated by the RICE model with exogenous technical change.

In particular, the following factors are included: first, endogenous technical change affecting factor productivity is introduced. This is done by adding the stock of knowledge in each production function and by relating the stock of knowledge to R&D investments. Second, induced technical change is introduced, by allowing the stock of knowledge to affect the emission-output ratio as well. Finally, international technological spillovers are also accounted for in the model.

Within each version of the model, countries play a non-cooperative Nash game in a dynamic setting, which yields an Open Loop Nash equilibrium (see Eyckmans and Tulkens, 2001, for an explicit derivation of first order conditions of the optimum problem). This is a situation in which, in each region, the planner maximises social welfare subject to the individual resource and capital constraints and the climate module, given the emission and investment strategies (in the base case) and the R&D expenditure strategy (in the endogenous technological change case) of all other players.

The Standard Model without Induced Technical Change

As previously mentioned, it is assumed for the purpose of this model that innovation is brought about by R&D spending which contributes to the accumulation of the stock of existing knowledge. Following an approach pioneered by Griliches (1979, 1984), it is assumed that the stock of knowledge is a factor of production, which therefore enhances the rate of productivity (see also the discussion in Weyant, 1997; Weyant and Olavson, 1999). In this formulation, R&D efforts prompt non-environmental technical progress, but with different modes and elasticities. More precisely, the RICE production function output is modified as follows:

$$Q(n,t) = A(n,t)K_R(n,t)^{\beta_n}[L(n,t)^{\gamma}K_F(n,t)^{1-\gamma}] \tag{1}$$

where Q is output (gross of climate change effects), A the exogenously given level of technology and K_R, L,and K_F are respectively the inputs from knowledge capital, labour, and physical capital.

In (1), the stock of knowledge has a region-specific output elasticity equal to β_n *(n=1,... 6)*. It should be noted that, as long as this coefficient is positive, the output production process is characterised by increasing returns to scale, in line with current theories of endogenous growth. This implicitly assumes the existence of cross-sectoral technological spillovers within each country (Romer, 1990). In addition, it should be noted that while allowing for R&D-driven technological progress, we maintain the possibility that technical improvements can also be determined exogenously (the path of A is the same as that specified in the original RICE model). The stock accumulates in the usual fashion:

$$K_R(n,t+1) = R\&D(n,t) + (1-\delta_R)K_R(n,t) \tag{2}$$

where *R&D* is the expenditure in Research and Development and δ_R is the rate of knowledge depreciation. Finally, it is recognised that some resources are absorbed by R&D spending. That is:

$$Y(n,t) = C(n,t) + I(n,t) + R\&D(n,t) \tag{3}$$

where Y is net output (net of climate change effects as specified in the RICE model), C is consumption and I gross fixed capital formation.

At this stage the model maintains the same emissions function as Nordhaus' RICE model which will be modified in the next section:

$$E(n,t) = \sigma(n,t)[1-\mu(n,t)]Q(n,t) \tag{4}$$

where σ can be loosely defined as the emissions-output ratio, E stands for emissions and μ for the rate of abatement effort. The policy variables included in the model are rates of fixed investment and of emission abatement. For the other variables, the model specifies a time path of exogenously given values.

Interestingly, this is also the case for technology level A and of the emissions-output ratio σ. Thus, the model presented so far assumes no induced technical change, i.e. an exogenous environmental technical change, and a formulation of productivity that evolves both exogenously and endogenously. In the model, investment fosters economic growth (thereby driving up emissions) while abatement is the only policy variable used for reducing emissions.

Induced Technical Change

In the second step of our model formulation, endogenous environmental technical change is accounted for. It is assumed that the stock of knowledge – which in the previous formulation was only a factor of production - also serves the purpose of reducing, *ceteris paribus*, the level of carbon emissions. Thus, in the second formulation, R&D efforts prompt both environmental and non-environmental technical progress, although with different modes and elasticities[18]. More precisely, the RICE emission-output relationship is modified as follows:

$$E(n,t) = [\sigma_n + \chi_n \exp(-\alpha_n K_R(n,t))][1 - \mu(n,t)]Q(n,t) \qquad (5)$$

In (5), knowledge reduces the emissions-output ratio with an elasticity of α_n, which is also region-specific; the parameter χ_n is a scaling coefficient, whereas σ_n is the value to which the emission-output ratio tends asymptotically as the stock of knowledge increases without limit. In this formulation, R&D contributes to output productivity on the one hand, and affects the emission-output ratio - and therefore the overall level of pollution emissions - on the other .

Knowledge Spillovers

Previous formulations do not include the effect of potential spillovers produced by knowledge, and therefore ignore the fact that both technologies and organisational structures disseminate internationally. Modern economies are linked by vast and continually expanding flows of trade, investment, people and ideas. The technologies and choices of one region are and will inevitably be affected by developments in other regions.

Following the work of Weyant and Olavson (1999), who suggest that the definition of spillovers in an induced technical change context be kept plain and simple (in the light of a currently incomplete understanding of the problem) , disembodied, or knowledge spillovers are modelled (see Romer, 1990). They refer to the R&D carried out and paid for by one party that produces benefits to other parties which then have better or more inputs than before or can somehow benefit from R&D carried out elsewhere. Therefore, in order to capture international spillovers of knowledge, the stock of world knowledge is introduced in the third version of the FEEM-RICE model, both in the production function and in the emission-output ratio equation. Equations (1) and (5)

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[18] Obviously, we could have introduced two different types of R&D efforts, respectively contributing to the growth of an environmental knowledge stock and a production knowledge stock. Such undertaking however is made difficult by the need to specify variables and calibrate parameters for which there is no immediately available and sound information in the literature.

are then revised as follows:

$$Q(n,t) = A(n,t)K_R(n,t)^{\beta_n} WK_R(n,t)^{\varepsilon_n} [L(n,t)^{\gamma} K_F(n,t)^{1-\gamma}] \tag{6}$$

and:

$$E(n,t) = [\sigma_n + \chi_n \exp(-\alpha_n K_R(n,t) - \theta_n WK_R(n,t))][1 - \mu(n,t)]Q(n,t) \tag{7}$$

where the stock of world knowledge:

$$WK_R(j,t) = \beta \sum_{\substack{i \in coal \\ i \neq j}} K_R(i,t) + \sum_{i \notin coal} K_R(i,t) \tag{8}$$

is defined in such a way as not to include a country's own stock and where β is the coalition information exchange coefficient ($\beta > 0$).

Emission Trading

As mentioned above, throughout the analysis we assume the adoption of efficient policies. As a consequence, the model also includes the possibility of flexibility mechanisms. In particular we compare the two cases in which emission trading takes place amongst all original Annex I countries (including the US), first with one in which trading is allowed amongst Annex 1 countries without the US, and then one in which emission trading takes place amongst all Annex I countries without the US and Russia.

When running the model in the presence of emission trading, two additional equations are considered:

$$Y(n,t) = C(n,t) + I(n,t) + R\&D(n,t) + p(t)NIP(n,t) \tag{9}$$

which replaces equation (3) and:

$$E(n,t) = Kyoto(n) + NIP(n,t) \tag{10}$$

where *NIP(n,t)* is the net demand for permits and *Kyoto(n)* are the emission targets set in the Kyoto Protocol for the signatory countries and the BAU levels for the non-signatory ones. According to (9), resources produced by the economy must be devoted, in addition to consumption, investment, and research and development, to net purchases of emission permits. Equation (10) states that a region's emissions may exceed the limit set in Kyoto if permits are bought, and vice versa in the case of sales of permits. Note that $p(t)$ is the price of a unit of tradable emission permits expressed in terms of the *numeraire* output price. Moreover, there is an additional policy variable to be considered in this case, which is net demand for permits *NIP*.

In terms of the possibility of emission trading, the sequence whereby a Nash equilibrium is reached can be described as follows. Each region maximises its utility subject to its individual resource and capital constraints, now including the Kyoto constraint, and the climate module for a given emission (i.e. abatement) strategy of all the other players and a given price of permits $p(0)$ (in the first round this is set at an arbitrary level). When all regions have made their optimal choices, the overall net demand for permits is computed at the given price. If the sum of net demands in each period is approximately zero, a Nash equilibrium is obtained; otherwise the price is revised as a function of the market disequilibrium and each region's decision process starts again.

Chapter 8

GLOBAL ENERGY AND CO_2 EMISSION SCENARIOS: ANALYSIS WITH A 15-REGION WORLD MARKAL MODEL*

Maryse Labriet
Richard Loulou
Amit Kanudia

Abstract A new version of the advanced multi-region World MARKAL model has been developed and calibrated to the A1B scenario of IPCC over a 50-year time horizon. The analysis of the base and CO_2 constrained cases confirms and refines several conclusions observed by other models. Amongst them: a) the level of non-emitting electricity generation in the base case is a crucial assumption for defining CO_2 reduction opportunities; b) CO_2 capture and sequestration compete directly with renewable electricity generation and contribute to a major reduction in the marginal cost of CO_2; c) the primary consumption of coal may increase in the long term when associated with the capture of flue gas CO_2 at power plants; d) in transportation, the substitution of oil by biomass is robust and much preferred to the other alternative technologies; e) the price-induced reduction of elastic demands also contributes to the emissions reduction. The resulting annualized cost of CO_2 policies remains under 1% of the GDP in 2050 for the stabilization of CO_2 concentration at 550 ppmv (A1B base case). Hydrogen production and end-uses technologies, CO_2 capture and sequestration, as well as non-CO_2 greenhouse gases would deserve more attention. Future work will focus on the modelling and comparison of the cooperative and non-cooperative international frameworks.

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A. Haurie and L. Viguier (eds.), The Coupling of Climate and Economic Dynamics, 205–235.

1. Introduction

Many studies have been or are being undertaken on options for reducing greenhouse gases (GHG) in order to satisfy either the target defined by the Kyoto Protocol or a longer-term target such as the stabilization of carbon dioxide (CO_2) concentrations. The primary objective of this paper is to present a recent version of the advanced multi-region World MARKAL model and some energy and greenhouse gas emissions scenarios over a 50-year time horizon. World MARKAL can be considered as one of the first world bottom-up optimization model with so high a level of detail in end-use and supply sectors.

Section 2 presents the structure and the properties of the World MARKAL model: dynamic optimization, technology explicit model, multi-regional, partial equilibrium framework with price-elastic demands. Because this paper is not mathematics but rather methodology and results oriented, the detailed mathematical structure of the model is not given in this paper. The reference energy and emissions scenario is of critical importance to evaluate CO_2 abatement options and costs. Consequently, Section 3 describes the technical-economic input data and assumptions at both supply and end-use levels, and presents the energy and emission results for the base case scenario. This scenario has no environmental constraint, and is calibrated to the A1B scenario modelled by the Asian Pacific Integrated Model (AIM) for the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (Nakicenovic, 2000). The comparison of this scenario with other world scenarios shows that the A1B scenario could be qualified as one of sustained economic growth but also of high new technology penetration, so that resulting emissions are relatively low compared to those obtained if the current energy situation based on fossil fuels is extrapolated in the future. Finally, the last section explores the CO_2 abatement options available under a carbon constraint representing the stabilization of CO_2 concentration at 550 ppmv in two cases: the A1B scenario and a scenario with lower availability of non-carbon energy resources (nuclear and renewable), completed by sensitivity analyses on the availability of CO_2 sequestration options and end-use demand elasticities.

It must be noted that MARKAL analyses are prospective rather than predictive and the focus is more on the insights gained on the underlying determinants of energy decisions and driving forces of technological choices than on the specific numerical results from any scenario.

2. MARKAL Modelling

MARKAL[1] is a linear programming model of the production, trading, transformation, distribution and end-uses of various energy forms and some materials that affect GHG emissions (see Loulou and Kanudia (1999) and references therein). The model has a long and rich history of methodological develop-

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[1] More detailed information on the underlying principles of MARKAL modelling and the structure of the model is available in Energy Information Administration (2003a, b).

ments and applications to energy and environmental issues in more than 40 countries around the world[2]. The development of the advanced world multi-region MARKAL has been driven by the need to analyze international environmental issues such as climate change. The first two versions of the World MARKAL model were developed through a collaboration of the authors[3] with the US Department of Energy's Energy Information Administration (EIA) and with the International Energy Agency (IEA). The model discussed and used in this article was developed by the authors and differs from the initial versions by a number of technological additions and other modifications discussed in Section 3.

2.1 A technology explicit model

The current version of World MARKAL includes several thousand technologies in all sectors of the energy system of a given region (Figure 8.1). Thus, MARKAL is not only technology explicit; it is technology rich as well.

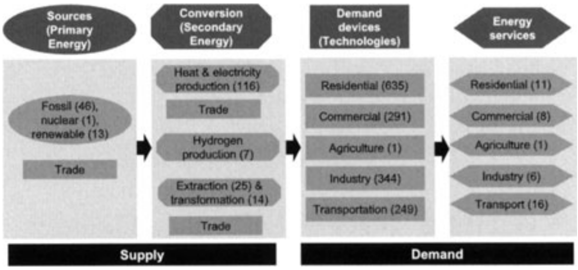

Figure 8.1. The general Reference Energy System

2.2 The 15 regions

Fifteen regions are identified and modelled based upon political, geographical and environmental factors (Table 8.1). They are aggregated into four regions for reporting purposes in this article. Each regional model is a complete, self-contained MARKAL model. In addition, the 15 models are hard-linked by energy trading variables and by emission permit trading variables if desired, so that they form a single global energy model where actions taken in one region may affect actions taken in all other regions. MARKAL also distinguishes

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[2] MARKAL teams around the world belong to the international consortium of Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency. GERAD researchers are among the prime developers of MARKAL in its modern form, and continue to act as expert modelers within ETSAP.

[3] The team that collaborated with USDOE-EIA for the construction of the original model included the three authors plus Kathleen Vaillancourt from GERAD.

between the trading of oil and petroleum products produced by OPEC from that produced by non-OPEC regions[4].

Table 8.1. List of the 15 regions

Code	Region	Aggregated Region
AFR	Africa	DC (Developing Countries)
AUS	Australia-New Zealand	OECD
CAN	Canada	OECD
CSA	Central and South America	DC
CHI	China	ASIA
EEU	Eastern Europe	FSU+EE
FSU	Former Soviet Union	FSU+EE
IND	India	ASIA
JPN	Japan	OECD
MEX	Mexico	DC
MEA	Middle-East	DC
ODA	Other Developing Asia	ASIA
SKO	South Korea	ASIA
USA	United States	OECD
WEU	Western Europe	OECD

2.3 Partial equilibrium

MARKAL computes a supply-demand partial economic equilibrium on energy markets. Operationally, a MARKAL run configures the energy system of a set of regions over 2000–2050 in such a way as to minimize the net discounted total cost of the system (or equivalently maximize the net total surplus, i.e. the sum of producers' and consumers' surpluses), while satisfying the externally defined demands for energy services of the entire system, subject to detailed technological, geographic and environmental constraints (cost-effectiveness analysis[5]). The total cost of the system includes, at each time period: annualized investments in technologies, fixed and variable annual operation and maintenance costs of technologies; cost of energy imports and domestic resource production; revenue from energy exports; delivery costs; losses incurred from reduced end-use demands; and taxes and subsidies associated with energy sources, technologies, and emissions.

The rationale that drives the computation of the equilibrium is based on the following principles:

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[4] OPEC and Non-OPEC won't be distinguished in the rest of this paper, but future analysis could consider scenarios in which OPEC oil production decisions obey different criteria from those in other regions.

[5] Alternatively, MARKAL may be used for cost-benefit analyzes if the cost of damages due to emissions is added to the objective function (see Labriet and Loulou, 2003).

- All agents have *perfect information* on others and *perfect foresight*: MARKAL is run as a dynamic optimization problem where investment decisions are made with full knowledge of the future[6];
- Energy markets are *competitive*: MARKAL simulates the simultaneous competition of all technologies for the satisfaction of economic demands; the model behaves as if every agent minimizes its own cost, and no agent is able to exercise market power (with the notable exception of oil production decisions by OPEC – see Section 3.4).

As a result of these assumptions, the market price of each commodity (except crude oil) is exactly equal to its marginal value in the overall system and each economic agent maximizes its net profit (or utility in the case of consumers).

The MARKAL solution includes, in particular: a set of investments in all technologies selected by the model at each period; a set of operating levels of all technologies at each period; the quantities of fuels produced, imported and or exported at each period; the emissions of pollutants at each period; the implicit prices of all energy services (their shadow prices); the overall system's discounted total cost; the increases or decreases of demands in the current model run as compared to the base case.

2.4 A demand-driven model with elastic demands

In the base case, the model is driven by the demands for a number of *energy services* (also called "useful energy" by some authors) such as: number of apartments to heat, vehicle-kilometers travelled by car, or tonnes of aluminum to produce. MARKAL includes 42 energy service demand categories, which must be specified by the user for the entire time horizon, as well as the seasonal/time-of-day modulation of these demands and their price elasticities, which will serve to define the constant elasticity demand functions. The MARKAL equilibrium for a non-base scenario is then computed by maximizing the total net surplus, defined as the sum of the suppliers and the consumers' surpluses (Samuelson, 1952), which is equivalent to finding the intersections of the supply and demand functions for all commodities in the system. Accounting for price elasticities of demands captures a great deal of the interaction between the energy system and the economy, and MARKAL therefore goes beyond the optimization of the energy sector only since both the supply options and the energy service demands are endogenously computed by the model. The total net surplus has often been considered a valid metric of societal welfare in the microeconomic literature, and this fact confers strong validity to the equilibrium computed by MARKAL. Of course, this still falls short of computing a general equilibrium: to do so would require a mechanism for adjusting the main macroeconomic vari-

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[6] MARKAL can also be run in a time-stepped manner (myopically), in which case investment decisions are made at each period without knowledge of future events.

ables as well, such as consumption, savings, employment, wages, and interest rates, which MARKAL does not. However, the model captures a major element of the feedback effects not previously accounted for in bottom-up energy models.

The initial period is a past period, over which the model has no freedom, and for which the quantities of interest are fixed at their historical values. The initial period's calibration is important because it also influences the model's decisions over several future periods, since the profile of residual capacities is provided over the remaining lives of the technologies existing in the initial period.

3. The Base Case

It is useful to distinguish between a model's structure and a particular instance of its implementation. The model's structure, as presented in Section 2, exemplifies its fundamental approach for representing and analyzing a problem - it does not change from one implementation to the next, whereas the inputs vary from application to application. The current application is based on the A1B scenario of the IPCC.

3.1 Scenario A1B

Our base case (noted BAU-A1B) is inspired by the A1B scenario modelled by AIM for the IPCC (Nakicenovic, 2000). This scenario is the most frequently cited one in the literature and it was the most frequently used in the post-SRES mitigation scenarios (Morita and Robinson, 2001). This does not however mean that we assign a higher probability of occurrence to this scenario amongst the six illustrative scenarios analyzed by the IPCC. In fact, the base case should be seen only as a benchmark for the assessment of alternatives, as it does not aim at predicting what will happen or what is the most probable future (Morita and Robinson, 2001; Nakicenovic et al., 1998).

The A1B scenario is roughly characterized by the objective of maximization of income by people and further globalization, rather than pursuing environmental goals and regionalization (Bollen et al., 2000). The main dynamics are a very rapid economic growth and a strong commitment to market-based solutions, relatively high final energy demand because of low energy prices and high income levels, access of all regions to knowledge, technology, and capital, continued innovation and decrease of the cost for advanced electricity generation (renewable, advanced nuclear), large unconventional oil and gas reserves, no dependence on one particular energy source and finally, improvement of the efficiency of energy exploitation technologies, energy conversion, and transport technologies (Nakicenovic, 2000; Riahi and Roehrl, 2000). It is also described as a technology-driven transition to a post-fossil-fuel-age where the rapid technological change in nuclear and renewable energy technologies results in a phase-out of fossil fuels for economic reasons rather that due to resource scarcity (Nakicenovic et al., 1998).

The base case does not take into account specific energy or environment policies beyond what is already embodied in investment made or regulation actually enforced by law. Nevertheless, the high levels of nuclear and renewable and the transition toward zero carbon sources in the A1B scenario as proposed by AIM make this scenario at least partly normative. Indeed, globalization and fast technological change require the implementation of incentives and policies promoting innovation, adequate investments in energy, capacity building and education, and free trade (Nakicenovic et al., 1998). Section 3.4 will show and justify that some constraints were added to the MARKAL model in order to reflect some of these A1B characteristics.

The commitment to market-based solutions and the globalization assumption of the A1B scenario are particularly well-adapted to the MARKAL paradigm of cost-effectiveness, since the model assumes efficient markets and perfect information across all economic agents in all regions of the world. However, MARKAL also assumes perfect foresight, which perhaps goes beyond what is practically achievable in the real economy. This is one reason why MARKAL analyses are prospective rather than predictive, and why the focus of our work is more on the insights gained on the underlying determinants of energy decisions than on the specific numerical results from any scenario. In order to provide alternate views of the future, several sensitivity analyses are undertaken, and an alternative base case is modelled and described in Section 3.3. In all cases, the insights are produced by the comparison of the different cases, and more particularly the comparison of the base case(s) with the CO_2 constrained case(s).

3.2 Comparison with other scenarios[7]

The comparison of the A1B scenario with the projections provided by other studies or institutions helps to emphasize the characteristics of the scenario. We include: the 2003 International Energy Outlook of the Energy Information Administration (2003c) (noted IEO2003), the 2003 World Energy Outlook of the European Commission (2003) (noted WETO2003) and the other five illustrative scenarios of the IPCC when appropriate (Center for International Earth Science Information Network, 2002a,b). Population growth of A1B is approximately equivalent to IEO2003 and WETO2003. In accordance with its definition (Section 3.1), the A1B is characterized by a higher GDP annual growth (4.1%, 3.0%, 3.2%)[8] and a much higher penetration of nuclear (7.0%, 0.5%, 0.9%) and renewable (4.0%, 1.7%, 2.1%) technologies than IEO2003 and WETO2003 for the period 2000–2025. The growth of its nuclear capacity is also the highest of the six illustrative IPCC scenarios. The growth of electricity consumption is also higher. The comparison of the growth of primary coal, gas and oil is less easy to discuss as it may hide several assumptions or effects like

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[7] See Labriet et al. (2004) for more details.

[8] All data between brackets in this section are respectively from: AIM-A1B, IEO2003, WETO2003.

the growth of demand but also the higher efficiency of energy conversion in A1B. Finally, the annual emissions growth of the A1B scenario is highest for the period 2000–2025 (2.6%, 1.9%, 2.1%), while the increase slows down after 2025. Absolute emissions in 2025 of the different scenarios remain reasonably close (9.6 to 13.1 GtC, including the six illustrative IPCC scenarios) in 2025 but diverge in 2050 (11.2 to 23.1 GtC). The annual emission growth proposed by the A1B between 2000 and 2025 is much more optimistic (i.e. smaller) than the one proposed by the two other studies in OECD (0.3%, 1.1%, 0.7%) and in FSU/EE (0.7%, 1.7%, 1.5%); it is higher in developing countries (4.5%, 2.5%, 3.1%) and intermediate in Asia (3.3%, 3.0%, 3.8%).

To conclude, the A1B scenario could be qualified as one of sustained economic growth but also of high new technology penetration, so that resulting emissions are relatively low compared to those obtained if the current energy situation based on fossil fuels is extrapolated into the future. This scenario can be criticized for its high growth rate, especially in developing countries. Nevertheless, Nakicenovic et al. (2003) explain that R&D expenditures and capital turnover rates required to allow a rapid diffusion of new technologies are correlated with the growth rate, so that the emissions are not systematically correlated to the growth rate. Holtsmark and Alfsen (2004) also argue that the choice of market exchange rates (MER) does not lead to an overestimation of the emission growth because both economic growth and emission-intensity improvements in the poor regions are overestimated in the IPCC-SRES scenarios.

3.3 The alternative base case

The high levels of nuclear and renewable shares of electricity generation in the A1B scenario have several consequences. Among them, we note that the emissions of OECD countries start to decrease before 2050, which is optimistic (see Section 3.2). The increase in nuclear capacity is, especially in OECD and in the short and medium terms, far above what several regions are planning. For example, recent projections for Canada propose an annual increase of nuclear capacity of only 1.6 to 2.6% between 2000 and 2025 (National Energy Board, 2003). Moreover, because nuclear plants belong to the class of base load duty cycle technologies, their high levels may be incompatible with the modulation of electricity production in the various diurnal and seasonal time slices.

The modelling of an alternative base case scenario (labeled BAU-FOS) aims at providing a contrasted vision of the future of energy and emissions. We based it on the assumptions that the future share of nuclear and renewable electricity in electricity generation would be lower than what AIM-A1B proposes (Figure 8.2), in particular:

- The fixed level of nuclear electricity generation is reduced by 90% in AFR, CSA, MEA and MEX, by 70% in FSU and EEU, 50% in OECD and Asia regions except JPN and SKO where it is reduced by only 30% in order to avoid that the growth rates of these regions in 2025 fall below EIO2003 projections; under these assumptions, absolute nuclear electricity generation remains higher than EIO2003 and WETO2003 at the world level but far smaller than A1B values;

- The minimal forced levels of renewable electricity generation between 2000 and 2020 are not modified, but they are gradually reduced after 2025 to reach 50% of the BAU-A1B levels in 2050 in all regions.

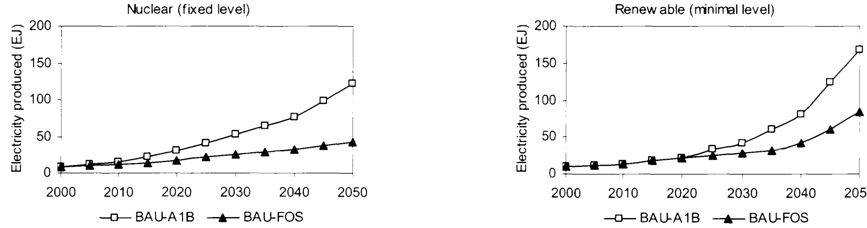

Figure 8.2. Nuclear and renewable electricity generation at the world level

3.4 Key assumptions and calibration approach

Projecting long-term energy and emission scenarios involves many assumptions and the calibration of the two base cases was done via the following approach[9]:

a) General

The *general structure* of the model is as described in Section 2. Values for period 2000 are based on the year 1999 of energy statistics from the International Energy Agency (2001a, b).

Calibration is a delicate and time-consuming process. It is undertaken by changing the *final demands* for energy services and imposing *inflexible constraints* that are adjusted until the optimal solution is close to the desired one. It is important to note that any exogenous constraints that are added to the database for calibration purpose or for accounting for either policy or market behavior - based factors that are not included in MARKAL must remain in the model in all scenarios (with or without CO_2 constraint) in order to guarantee the

consistency of results. Consequently, any constraint that could prejudice CO_2 mitigation options under environmental constraint must be avoided (for example, upper bounding of renewable options or of gas fired equipment should be avoided).

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[9] Any user who would build another base scenario could reproduce this approach. Detailed description of data and assumptions is available in Labriet et al (2004).

The model uses two kinds of *discount rates*. On the one hand, the overall long-term annual discount rate used for calculating the net present value of the system is fixed at 5%. This rate is the social discount rate for the whole economy. On the other hand, the discount rates used for annualizing investment costs incurred at any particular period are sector and region specific, so as to reflect the financial and behavioral characteristics appropriate to each economic agent. In particular, discount rates are higher in developing regions than industrialized ones, reflecting the lower capital availability and higher perceived risk; discount rates are higher in sectors such as residential (between 12 and 28%) and transportation (between 12 and 18%) where decisions are made mostly by individual consumers, reflecting the higher cost of capital (and higher risk aversion) of individuals as compared to firms; discount rates of the electricity sector (between 3 and 9.2%) are closer to the long-term social discount rate, and discount rates in other industries (between 7.5 and 13.7%) are intermediate between those of the electricity sector and of other end-use sectors.

GDP and all costs and prices are expressed in US dollars of 2000,

calculated at *market exchange rates* (MER) in each region. Measuring economic growth and costs in terms of MER is a widely accepted methodology, while the purchasing power parity approach is a preferred measure for assessing differences in economic welfare across different regions (Nakicenovic et al., 2003). Moreover, international trading of energy commodities or carbon permits take place at MER, so that outputs need to be measured in MER for consistency (Nordhaus and Boyer, 1999).

Investment, variable and fixed costs of technologies vary across regions in order to reflect differences of labor costs and productivity, land costs, project boundaries (for example, a new power plant may require the building of a road and new power lines in developing countries). Fixed and variable costs are lower in developing regions compared to industrialized regions, while investment costs of all regions except China and India are higher than those of United States. Regional factors were provided by Dolf Gielen, International Energy Agency (private communication).

b) End-uses

Population and GDP projections are two of the three main driving forces[10] of future energy and GHG emissions (Nakicenovic, 2000; European Commission, 2003). MARKAL future service demands depend on these projections. They are based on the AIM-A1B scenario. Moreover, the choice of appropriate sensitivity of service demands to these drivers helps to increase or decrease future service demands and then influence total energy consumed by each region if needed for calibration purposes.

The *rate of penetration* of new technologies and the rate of change of the fuel proportions at end-use level may be exogenously controlled to reflect non-economic decisions or to reproduce certain behavioral characteristics of ob-

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[10] Technology is the third driving force.

served markets. Indeed, Linear Programming may result in choosing the cheapest resource/technology up to its limit before any other competing alternative is used on the same market. It would then be possible for a single technology to capture the entire market while it is more generally observed that end-users' technological choices result in a market split between several technologies, for a variety of reasons, including individual preferences other than pure financial costs. These constraints are progressively relaxed at future periods. These technology and fuels constraints were adjusted in industrial and residential/commercial sectors in order to accelerate gas and electricity penetration and then calibrate to the rapid introduction of new and more efficient technologies of the A1B scenario. For the same reason, the lower levels of the shares of gas, hydrogen and electricity in final transportation fuels were also adjusted. Moreover, in order to reflect real technical and behavior constraints, biomass in transportation is limited to 40% of energy consumption by the sector.

MARKAL assumes that each demand has constant*own price elasticity* in a given time period, and that cross price elasticities are null (see Section 2.4). The elasticities are higher for developing countries and countries in transition, in line with empirical observations.

c) Resources and international trade

Oil, gas and coal resources are provided for each region, including OPEC and non-OPEC. They cover located reserves (remaining resource volume), reserve growth and new discovery for conventional oil, mined oil sands, ultra heavy oil, shale oil, natural gas, hard coal, and brown coal. Unconventional and unconnected gas resources are also available. Costs of reserves and extraction technologies reflect the actual increase of extraction cost with the cumulative level of extraction. Data were obtained from the database of the base case of the SAGE model developed in collaboration with the International Energy Administration (Summer 2003). At the world level, the reserves of unconventional and unconnected gas and coal reserves are lower than those provided by the IPCC-TAR (Moomaw and Moreira, 2001). Other reserves are close to the IPCC-TAR data.

The international trade of natural gas, liquefied gas and coal is endogenously modelled. In other words, the amount and price of commodity traded is endogenously computed based on reserves availability, resource costs, technical limit on the development of new extraction projects, and of course demands. This means that the international or regional markets of coal and gas are assumed to be competitive. Electricity is not traded at international level, except between USA and CAN, where exchanges are fixed, by default, at their 2000 values.

In contrast, *the international trade of crude oil and refined petroleum products* (prices and quantities) is exogenously modelled as one world market. This is to reflect the non-competitive market for oil. Since the early 1970's, OPEC has acted as a cartel that periodically fixes its production level, leaving the other producers (Non OPEC) produce the remaining part of the world demand. By so doing, OPEC is able to maintain oil prices that are higher than what they would be in a completely competitive market. In this research, we approximated this situation in a simplified manner as follows: Each region is free to import any amount of crude oil and/or refined petroleum product at a fixed exogenous price. Exports are then adjusted *ex-post* to balance imports at the world level[11]. This requires at least two successive runs of the model. The exogenous oil price trajectory was chosen according to forecasts by a number of institutions, resulting in annual price growths of 0.6% for crude oil and of 0.4% for refined products. The scenarios provided by the National Energy Board (2003), the reference case of the IEO2003 (Energy Information Administration, 2003c) and the scenario "Awash in oil and gas" of the Pew Center (Mintzer et al., 2003) consider a similar assumption. WETO2003 considers an annual increase of oil price around 1.6% between 2000 and 2050 (European Commission, 2003).

Primary biomass covers solid biomass, landfill gas, liquids from biomass, energy crops, industrial and municipal wastes. Resource availability in each region is deducted from data provided by Food and Agriculture Organization (Trudel, 2004). They are lower than the potentials provided by the IPCC-TAR (Moomaw and Moreira, 2001), which do not consider all practical/technical constraints on the use of land for bioenergy such as the distance of a biomass production site from demand centers or the land-use conflicts. Biomass was not fully calibrated to the AIM-A1B scenario for two reasons. First, detailed information was missing to properly understand the links between primary biomass and final liquid, solid and gas energy as provided by IPCC. Second, the contribution of biomass to world energy supply is difficult to model properly because the substitution links with the other fuels have hardly been explored and if so, only in rare field studies (European Commission, 2003). Therefore, statistics on biomass often show very contrasted profiles.

d) Electricity generation

Power plants technical-economic data have been reviewed to reflect the literature (European Commission, 2003, Kainuma et al. (2003)) and expert knowledge (MARKAL-Canada developed by the authors; SAGE model developed by the authors in collaboration with the Energy International Administration; Dolf Gielen, International Energy Agency). Available power plants cover technologies such as conventional pulverized coal, integrated coal-gasification combined cycle (IGCC), combined cycle gas turbine (CCGT), diesel plants, fuel cells, biomass plants, wind, solar, etc. (see Labriet et al. (2004) for the detailed description). Co-firing power plants are available for both coal and gas fired plants. Co-combustion of biomass is kept below 15% and 10% of the coal and gas input, respectively.

The base cases do not take into account *specific energy or environment policies* beyond what is already embodied in investments actually made or regu-

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[11] It was important to balance exports and imports to insure, among other reasons, that CO_2 emissions from oil extraction are not distorted.

lation actually enforced by law. For example, the high levels of generation of electricity from nuclear plants provided by the AIM-A1B scenario indicate that the phase-out of nuclear planned for the future in some regions is not part of the scenario. However, the high levels of renewable in electricity generation, especially in the short term, assume that policies promoting renewable will be implemented, such as the European Renewable Directive, which has set national targets for the renewable electricity generation so that the overall target reaches 22.1% of the electricity generated in 2010. This target is almost respected in the BAU-A1B (20.6%). Also, we limited coal use in the electricity sector of the two base cases to reflect actual regulations on local air quality.

Each form of *renewable energy* (geothermal, hydroelectricity, wind) is characterized by its own potential, based on the literature (Table 8.2). The minimal level of total renewable electricity generation (sum of geothermal, hydroelectricity, wind, and solar electricity) is also exogenously controlled in order to reflect the high levels of renewable energy as proposed by AIM-A1B scenario and by the alternate base case (Table 8.3).

The *installed capacity of nuclear power plants* is exogenously fixed at the level provided by the AIM-A1B scenario or by the alternate base case (Table 8.2), reflecting the fact that the decision to invest or not in nuclear plants in mainly motivated by non-economic factors.

Hydrogen can be generated by electrolysis of water, reforming of natural gas and partial oxidation of coal, with and without CO_2 capture. It can be consumed either as a pure commodity in transportation sector or as a mix with natural gas (respectively 15%-85%) in industry and residential/commercial sectors. International trade of hydrogen is not included.

Table 8.2. Potential of renewable power plants in 2050

GW	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND
Wind	1404	634	1500	1037	1368	1037	1431	276
Hydro	359	15	181	555	365	29	416	126
Geothermal	36	48	0	7	68	0	7	0
GW	**JPN**	**MEA**	**MEX**	**ODA**	**SKO**	**USA**	**WEU**	**World**
Wind	214	1028	268	1163	17	1551	866	13796
Hydro	26	20	12	314	5	101	164	2687
Geothermal	125	0	162	649	0	125	113	1342

Sources:
- Hydroelectricity potential reflects the technically exploitable capability as provided by the World Energy Council (2001).
- Wind potential reflects the potential as provided by Moomaw and Moreira (2001).
- Geothermal potential reflects the potential for deep, very deep and shallow geothermal as provided by Dolf Gielen, International Energy Agency (private communication).

e) Zero-emission-technologies and carbon sinks

Because of its impact on the cost of mitigation carbon, sequestration of carbon is included. It includes: *capture*, which may occur at power plants (IGCC,

Table 8.3. Nuclear and renewable assumptions (base cases)

	Nuclear fixed, 2050, EJ		*Nuclear* ann gwth 2000-50		*Renewable* low bnd, 2050, EJ		*Renewable* ann gwth 2000-50	
	A1B	FOS	A1B	FOS	A1B	FOS	A1B	FOS
AFR	3.4	0.3	8.9%	4.0%	20.5	10.2	8.8%	6.4%
AUS	0.0	0.0	na	na	0.7	0.3	2.8%	1.8%
CAN	1.6	0.8	3.1%	1.7%	8.8	4.4	4.2%	2.4%
CHI	25.5	12.7	10.7%	9.2%	29.7	14.8	7.4%	5.2%
CSA	17.0	1.7	12.0%	7.0%	20.0	10.0	4.6%	2.5%
EEU	4.0	1.2	5.6%	3.1%	1.0	0.5	2.9%	1.4%
FSU	4.1	1.2	3.5%	1.0%	14.0	7.0	5.5%	3.3%
IND	8.5	4.2	10.7%	9.2%	8.3	4.1	6.5%	4.4%
JPN	3.4	2.4	2.3%	1.6%	2.4	1.2	4.0%	2.2%
MEA	14.2	1.4	na	na	15.0	7.5	9.2%	6.5%
MEX	10.4	1.0	12.6%	7.5%	4.0	2.0	6.6%	4.7%
ODA	8.3	4.2	8.6%	7.1%	20.2	10.1	7.8%	5.5%
SKO	2.7	1.9	3.9%	3.2%	0.2	0.1	5.6%	3.5%
USA	11.9	6.0	3.0%	1.5%	13.0	6.5	5.3%	3.5%
WEU	7.1	3.6	1.7%	0.3%	10.4	5.2	3.8%	2.1%
World	122.0	426.3	5.3%	3.1%	168.1	60.5	5.8%	3.7%

Sources: see Nakicenovic (2000) for BAU-A1B and calculations by the authors for BAU-FOS

pulverized coal, NGCC, solid oxide fuel cell SOFC) and hydrogen plants[12]; *storage* (oil/gas fields, coalbed methane recovery, aquifers, deep ocean, mineralization) and *transportation* between capture and storage. Sequestration by forests is also available (no capture is needed in this case). It includes four price categories of carbon uptake and has been adjusted to reflect the Bonn and Marrakech agreements for AUS, CAN, EEU, FSU, JPN, USA, WEU, assuming that the agreements are valid for the whole 2000-2050 horizon, while 10% of the annual available potential is used for the other regions. Capture at industry level (iron and steel, ammonia production, cement production) is not included in this version of the model (note that, although some options are cheap, the potential is rather limited).

Table 8.4 presents the storage potentials of the sequestration options at the world level. They are provided by Dolf Gielen, International Energy Agency (private communication). They are similar to data from Kauppi and Sedjo (2001) and Herzog et al. (1997). Potentials, costs and social acceptability of CO_2 sequestration are still uncertain and may constitute barriers to wide implementation of these options (Kauppi and Sedjo, 2001).

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[12] The price of electricity generated by power plants with CO_2 capture is considered to be 50% higher than the electricity price generated by power plants without capture (Moomaw and Moreira, 2001).

The regions with the largest potential of sequestration by forests are AFR, CSA, FSU and ODA. The regions with the largest underground reservoirs are AFR, CAN, CSA, FSU, MEA, ODA and USA

Table 8.4. Sequestration potentials

$GtCO_2$ cum 2000-50	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND
Forests - Limited	5.6	0.0	2.2	1.9	5.9	0.4	6.5	0.2
Underground storage	1550	915	1141	978	1578	411	2061	765
Total Sequestration	1555	915	1143	980	1584	411	2068	765
$GtCO_2$ cum 2000-50	JPN	MEA	MEX	ODA	SKO	USA	WEU	World
Forests - Limited	2.4	0.0	0.6	4.0	0.0	0.7	1.1	31.7
Underground storage	15	1335	425	1707	23	1770	570	15244
Total Sequestration	17	1335	426	1711	23	1771	571	15275

Source: Dolf Gielen, International Energy Agency (private communication). The potential of sequestration by forests, modelled as annual bounds, has been adjusted by the author to reflect the Bonn (Appendix Z related to the maximum increase in sinks due to forest management) and Marrakech agreements (Russia adjustment) see text.

4. Energy and Emission Trajectories with and without CO_2 Abatement

The analysis of energy/emission trajectories aims at exploring the technology decisions and the CO_2 abatement options computed by the model. Although available for the 15 regions of the model, results are presented either for the four regions defined by AIM (OECD, FSU+EE, ASIA, and Developing countries — labelled "DC")[13] or aggregated globally. The analysis of the emission reductions and costs for the 15 regions of MARKAL will be the core of future work focusing on international cooperative and non-cooperative mitigation strategies. Moreover, the study focuses in CO_2 mitigation, as the carbon constraint is the stabilization of CO_2 concentration and because the other GHGs have not yet been calibrated properly.

4.1 Validation of the model: base case BAU-A1B

In order to validate our model, we compare the energy and emissions results computed by MARKAL in the BAU-A1B scenario and the results provided by the A1B scenario from AIM. *Emission* rates in 2050 are very close, but the increase in the annual rate of ASIA and DC in the mid-term is slower in MARKAL than in AIM-A1B (Figure 8.3). The path and the nature of *primary energy* contribute to this difference: in the mid-term, the growth rate of primary energy is lower in ASIA and DC in MARKAL, the share of primary coal in total

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[13] Detailed results are available upon request.

primary energy is also smaller, while the share of natural gas is higher. Because similar differences are not observed in final energy, we can conclude that the penetration and/or the efficiency of power plants might explain this difference. As we do not have full details about the technologies that penetrate in the A1B scenario from AIM, we cannot further explore these differences. In the longer-term, the decrease of oil in primary energy has not been reproduced in MARKAL. The most probable reason is the low penetration of biomass in MARKAL compared to AIM, especially in DC, in other words, the low substitution of oil by biomass in our base case[14].

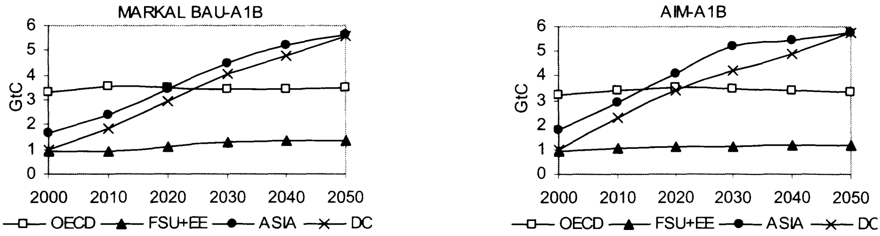

Figure 8.3. Comparison of CO_2 emissions from fossil fuels in AIM and MARKAL (AIB scenario)

Final energy results (Figure 8.4) are very close to AIM-A1B data (the difference is less than 5%) except for the following items. First, gas in FSU+EE is smaller than AIM-A1B; because the other final energy commodities, primary gas consumption and emissions are calibrated, we accepted the lower final gas consumption. Second, solids in DC are higher than projections from AIM-A1B; because solids include solid biomass, we suspect that this difference can be explained by too high a proportion of solid biomass compared to liquid biomass in MARKAL results; indeed, the too high consumption of primary oil and the too low consumption of biomass at primary level tend to confirm this hypothesis. Since we do not have full details about the biomass allocation between solid, liquid and gas in AIM-A1B results, and since emissions results are closed to AIM results, we didn't modify the solids results in DC. Finally, the increase of final energy commodities in Asia in the first periods is lower than what is proposed by AIM-A1B, reflecting a slower increase of final service demands.

The analyses of *the final energy and emissions per sector* shows the following trends. The main contributors to emissions depend on the existing structural characteristics of regions. In 2000, they are respectively (Table 8.5): transport and electricity in OECD, industry and electricity in FSU+EE and ASIA, industry, transportation and electricity in equal share in DC. Two important changes occur in later periods: the contribution of emissions by the electricity

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[14] As explained in Section 3.4, we didn't try to calibrate biomass to the AIM-A1B scenario.

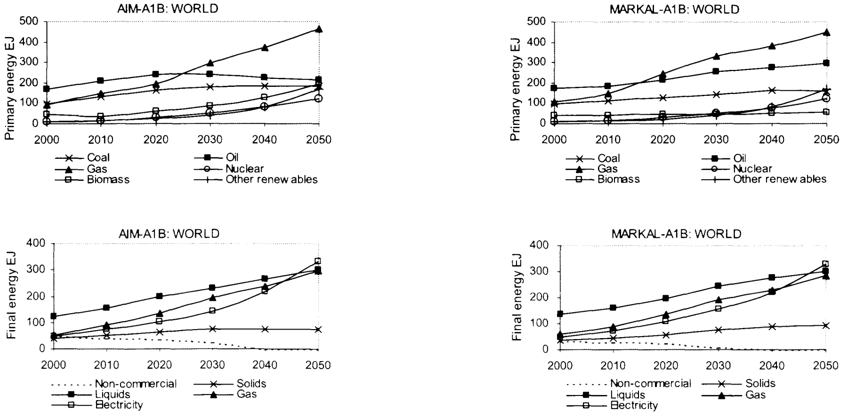

Figure 8.4. Comparison of primary and final energy consumption in AIM and MARKAL (AIB scenario)

sector decreases in all regions but FSU+EE where it stabilizes, and the contribution by the transportation sector remains at the 2000 value or decreases slightly. The reasons are respectively the (exogenous) increase of renewable and nuclear in electricity generation and the (exogenous) increase in biomass, natural gas and hydrogen[15] in the transportation sector. In industry, we observe the substitution of oil and coal by electricity and natural gas while electricity increases its share of energy consumption in commercial and residential (see BAU results in Table 8.7). Energy shares in transportation are the direct result of exogenous constraints forcing the penetration of alternative fuels (biomass, electricity, natural gas and hydrogen). Because no structural change is expected in the agriculture sector, no competition is allowed in this sector, so that energy shares remain almost constant and reflect assumptions. To conclude, changes in end-use sectors reflect the structural transition toward higher shares of advanced and non-fossil energy.

The *price* of gas increases slightly in all regions, from 0.3% to 1.5% per year, depending on the availability and cost of local resources and on the prices and nature (liquefied or gaseous) of imports[16]. The equivalent annual increase of marginal cost of gas in the A1B scenario is around 1.4 % for gas (Nakicenovic and Riahi, 2002). The price of coal varies from -1% to +0.4% per year be-

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[15] Emissions related to the production of hydrogen are allocated to the upstream sector. End-use consumption of hydrogen is emission-free. In fact, the increase of emissions associated to the production of hydrogen compensates for the decrease of refinery emissions due to the decrease in the needs for oil products.

[16] The user might allow trade of gaseous and/or liquefied gas (LNG), depending on the expected future projects for transport and distribution of gas. When LNG is imported, the price of gas for end-uses is of course higher.

Table 8.5. Emission contribution of activity sectors (BAU-A1B)

	OECD		FSU+EE		ASIA		DC	
	2000	2050	2000	2050	2000	2050	2000	2050
Agriculture	1.2%	1.5%	2.0%	2.4%	2.1%	1.1%	1.9%	1.7%
Com/res	12.6%	17.1%	15.6%	13.7%	8.6%	13.7%	9.7%	10.9%
Industry	18.2%	20.1%	31.2%	29.2%	28.8%	29.4%	26.6%	41.2%
Transport	30.4%	27.5%	9.6%	6.1%	16.0%	16.5%	27.8%	21.6%
Electricity	30.5%	21.8%	32.5%	34.6%	37.1%	33.8%	27.1%	20.0%
Upstream	7.0%	12.0%	9.1%	14.0%	7.3%	5.5%	6.8%	4.5%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

tween 2000-2050, reflecting that coal is an abundant resource. As explained in Section 3.4, the price of oil is exogenous; its increase is equivalent to an annual growth of 0.2 to 0.9%, depending on regions. The equivalent annual increase of marginal cost of oil in the A1B scenario is less than 0.8% between 2000-2050 (Nakicenovic and Riahi, 2002). As regards the electricity prices, the high forced levels of activity of nuclear plants, which belong to the base load duty cycle technologies, result in zero marginal cost for electricity during off peak periods in several regions.

We now turn to technological detail in the two sectors that contribute most to emissions, i.e. electricity generation and transportation. Generally speaking, models produce a widely variable portfolio of technologies depending on scenarios, which indicates the high uncertainty attached to the adoption of specific technologies, and also explains the wide range of resulting CO_2 emissions for non-climate policy scenarios (Riahi and Roehrl, 2000). The following trends, characterizing the technologies selected in the BAU-A1B, are observed:

- In the electricity sector, new coal capacity is satisfied by Pulverized coal plants, the least expensive option (considering both capital and operating costs). Although more efficient, new IGCC plants do not penetrate. CCGT, characterized by a low investment cost and high efficiency, satisfies the needs for new gas capacity, replacing the phased-out capacity and producing the new electricity needed. The gas fuel cell also penetrates, favored because it satisfies the needs for decentralized electricity (see Section 4.3.3). The need for decentralized electricity also motivates the penetration of some new capacity of decentralized oil plants. New capacity of nuclear and renewable (geothermal, hydroelectricity, wind and solar) is driven by the exogenous constraints. All the available hydro capacity and shallow geothermal penetrate, being the cheapest renewable electricity sources.

- Transportation technologies reflect the exogenous constraints applied to the sector: electric cars, light trucks and buses, natural gas cars, light, medium, heavy, commercial trucks and buses and finally hydrogen cars and light trucks[17] penetrate the market.

Sensitivity analysis has been undertaken to understand the role of the constraint on coal and renewable electricity generation.

- Eliminating the limit on the use of coal for electricity production provokes an emission increase of approximately 5% at the world level (Figure 8.5). Increase of the use of coal in power plants is particularly high in FSU, EE (primary coal consumption of the region FSU+EE is more than double), WEU and MEA. The increase in emissions is rather limited compared to the energy changes; this is explained by a transfer of electricity generation from natural gas power plants to new efficient coal power plants, resulting in a moderate increase of emissions.
- Moreover, even without any limitation of the use of coal for electricity generation, primary coal consumption remains limited in several regions (i.e. it does not its upper bound) because of the exogenously fixed and high level of nuclear and renewable electricity generation. When renewable electricity generation is left free (no minimum level) and coal electricity is constrained, the electricity generation from coal in AFR, CAN, CHI, CSA and IND is higher than in the case when coal electricity is free but renewable electricity is forced. Resulting emissions are then also much higher (Figure 8.5).

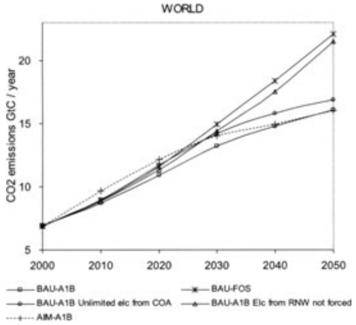

Figure 8.5. CO_2 emissions in base cases and sensitivity analysis

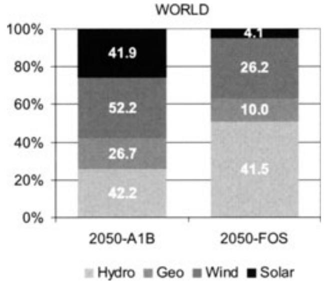

Figure 8.6. Renewable electricity generation in 2050 at world level (EJ)

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[17] Hydrogen vehicles currently available in the model are cars and light trucks. Future versions of the model will include a broader variety of hydrogen vehicles.

This confirms that the level of non-emitting electricity generation is a crucial assumption for projecting future emissions and analyzing future CO_2 policies (even more so than the limit on the consumption of coal by power plants). This also clearly justifies the definition of an alternative base case with reduced nuclear and renewable electricity generation.

4.2 The alternative base case BAU-FOS

Recall from Section 3.3 that the alternative base case assumes a level of carbon-free electricity generation lower than the scenario BAU-A1B. The most striking difference between the two base cases is the large difference between their emissions (Figure 8.5). In the alternate base case, emissions reach 22.1 GtC in 2050 at the world level (OECD 4.5 GtC, FSU+EE 1.8 GtC, ASIA 7.8 GtC and DC 8.0 GtC) compared to 16.0 GtC in the BAU-A1B scenario (OECD 3.5 GtC, FSU+EE 1.4 GtC, ASIA 5.6 GtC and DC 5.6 GtC). The alternate base case emissions are thus in the same range as in the sensitivity case where renewable electricity is not forced.

The decrease of renewable electricity (Figure 8.6) concerns solar (-90% in 2050), and, to a lesser extent, geothermal (-63%) and wind (-50%), compatible with the fact that solar electricity is the most expensive one, so that solar technologies are used as backstop technologies. Hydroelectricity is unchanged, as it is the cheapest renewable electricity. Electricity from coal (+196% in 2050) and gas (+155%) plants replaces renewable electricity. The electricity generated by coal plants, although higher, does not reach the maximum share allowed in most of regions of ASIA and DC. Final energy consumptions remain globally unchanged. Given the higher demands for coal and natural gas, the marginal prices of coal and gas increase slightly compared to BAU-A1B (+0 to +10% for both of them) reflecting the availability of local resources and infrastructures for international trade.

4.3 Carbon constrained scenarios (550 ppm)

Emission mitigation scenarios assume the stabilization of atmospheric CO_2 concentration at 550 ppmv as the global target. This choice reflects the frequent reference to this target in modelling and political discussions, but does not imply an agreed-upon desirability of stabilization at this level (Morita and Robinson, 2001). In order to avoid any distortion due to MARKAL base case results, the absolute difference of emissions between base case (A1B) and stabilization (550 ppmv) scenarios provided by AIM has been used as a target. In other words, the MARKAL environmental constraint reflects the emission path generated by the integrated assessment model AIM in order to stabilize atmospheric CO_2 concentration at 550 ppmv. The target is applied at the world level, so that the mitigation scenario is equivalent to a theoretical situation where all regions of the world participate in a competitive CO_2 permit market. Although not reflecting the expected short-term international policies like the Kyoto Protocol, the mitigation scenario as defined above is helpful to analyze energy and technology options in the long-term.

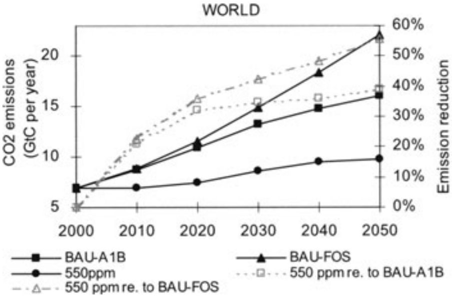

Figure 8.7. CO2 emissions and emission reduction at the world level

The target is applied to the two base cases presented above. The analysis compares energy and technology options of the constrained scenarios labelled "550-A1B" and "550-FOS" with the respective base case scenarios BAU-A1B and BAU-FOS. In addition, sensitivity analyses are conducted, on the availability of carbon sinks and on the elasticities of demands, respectively. These sensitivities are discussed in a separate subsection at the end of Section 4.3. Figure 8.7 presents resulting emissions and emissions reduction rates at the world level. Note that the resulting emission reduction rates in the first decades (for example, 21% for 550-A1B and 22% for 550-FOS in 2010 relatively to their respective baselines) are higher than the emission reduction rates computed by several other models (around 10%) using also an external trajectory as the basis for their mitigation strategy (Hourcade and Shukla, 2001). This difference reflects the emission reduction observed in AIM-A1B and is independent of MARKAL modelling.

The generation of electricity by coal plants is not limited in the mitigation scenarios, contrary to the base cases (see Section 3.4). The expectation is that any new investment in new coal plants would be motivated by the possibility to capture and sequestrate carbon, and these new coal technologies would also control the local pollutants emitted. This expectation is borne out in the results.

4.3.1 Mitigation options. The reduction of emissions depends on mitigation options available in each region. Technological options for reducing CO_2 include[18]: more efficient conversion and combustion of fossil fuels (enhanced energy conservation); switching away from carbon-intensive fuels such as coal; suppressing leakages; de-carbonization of flue gases and fuels,

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[18] See Riahi and Roehrl, 2000; Moomaw and Moreira, 2001.

and CO_2 storage. Another mitigation option is the price-induced reduction of energy service demands. The options, which are identified by MARKAL as cost-effective to meet the 550 ppm target, are, in both scenarios, capture of CO_2 at upstream level (leakages), at power plants and at hydrogen plants, and sequestration in deep aquifers which play an important role. Sequestration by forests is also selected. Sequestration accounts for 40 to 63% of total CO_2 reduction for 550-A1B and 64 to 78% for 550-FOS in 2050 (Table 8.6).

Table 8.6. Regional CO_2 reduction and sequestration

	Reduction wrt BAU				Sequestration wrt total reduction			
	550-A1B		550-FOS		550-A1B		550-FOS	
	2005	2050	2005	2050	2005	2050	2005	2050
OCDE	-9.3%	-38.7%	-9.7%	-38.7%	-24.1%	-63.4%	-22.9%	-77.6%
FSU+EE	-11.2%	-42.9%	-12.2%	-42.9%	-50.7%	-56.6%	-45.4%	-71.6%
ASIA	-9.6%	-40.3%	-10.5%	-40.3%	-19.3%	-39.5%	-17.6%	-63.6%
DC	-14.5%	-36.9%	-14.9%	-36.9%	-37.4%	-47.3%	-35.9%	-66.4%
WORLD	-10.5%	-39.0%	-11.2%	-39.0%	-29.8%	-48.8%	-27.9%	-68.1%

Riahi and Roehrl (2000) also observe that carbon scrubbing is an important reduction option, because of the low cost assumptions but also because of the limited potential for structural changes, given the assumptions of the already high penetration of nuclear and renewable power plants in the A1B scenario. As regards sequestration, several remarks apply. First of all, the cumulative amount of CO_2 sequestered remains far from the total potential for sequestration (respectively 1.9% and 3.7%). Sequestration by forests and deep saline aquifer are the preferred sequestration options, because of their low costs. Their estimated potential and costs are critical parameters of the mitigation options chosen by the model.

One of the impacts of the availability of CO_2 sequestration options is *the role of coal* for satisfying primary energy needs and more specifically electricity generation (Figure 8.8). While coal use decreases in the first periods, its contribution to primary energy and electricity generation increases again later, while natural gas follows an inverse trajectory (increases in the first periods and decreases later, compared to base cases): gas CCGT with CO_2 capture progressively replaces conventional CCGT in the first decades; it is replaced later by the efficient and cheap coal SOFC with CO_2 capture when it becomes available (coal SOFC itself replaces pulverized coal plants selected in the base cases). Electricity generation by gas fuel cells remains in both base and mitigation cases, as it contributes to satisfy needs for decentralized electricity. Of course, conclusions are very dependent on the future cost of such advanced technologies, which is very uncertain. Other studies confirm the robustness of CCGT as it bridges the transition to more advanced fossil and zero-carbon technologies (Nakicenovic and Riahi, 2002). They also identify IGCC as one promising technology suitable for carbon sequestration. Of course, appropriate

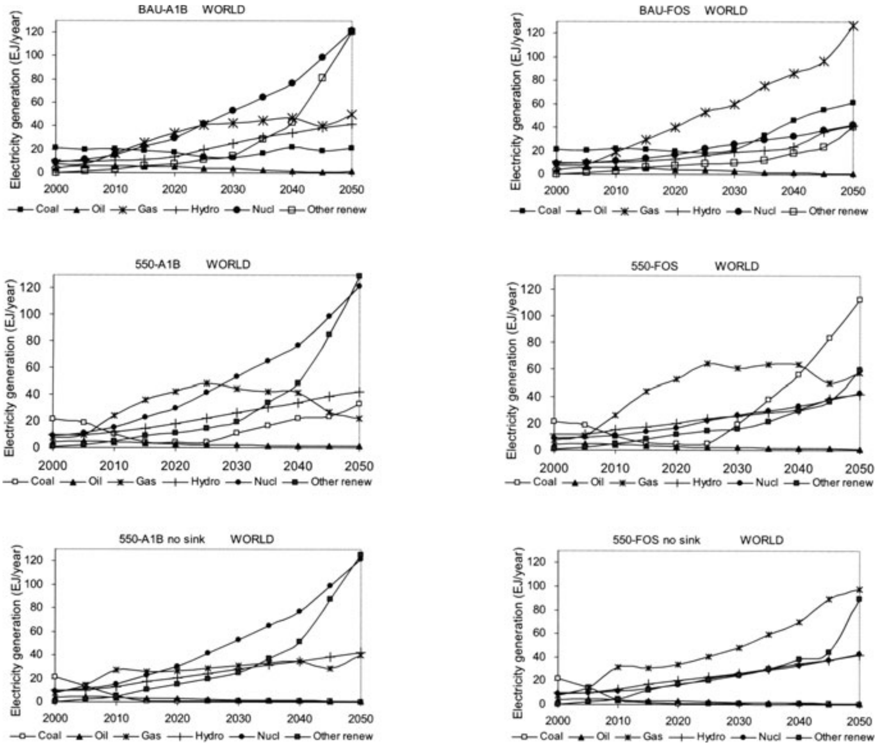

Figure 8.8. Electricity generation by fuel (base cases, 550 ppm scenarios, and sensitivity analysis on sinks)

changes in the assumptions related to investment and operation costs of SOFC in the MARKAL database could make this technology less competitive compared to other coal technologies like IGCC. Gielen (2003) also concludes that the electricity production by power plants with CO_2 capture is very sensitive to the feasibility of the IGCC-SOFC, which is speculative.

The role of renewable other than biomass in electricity generation increases in the 550-FOS scenario but not in the 550-A1B scenario, because of the limited remaining potential of renewable in the latter scenario. Finally, electricity from biomass plants and co-combustion of coal and biomass in coal power plants increase in both scenarios.

In both scenarios, *the substitution of oil by biomass in the transportation sector* increases, while the other alternative fuels (electricity, natural gas and hydrogen) remain unchanged compared to the respective base cases (Table 8.7). Investments in more efficient oil vehicles are also observed. Regional variations exist, reflecting the availability of biomass; for example, biomass represents more than 30% of transportation energy in AFR and CSA, these regions being biomass rich. The fact that hydrogen vehicles are not selected as a mitigation option can be explained by the cost of the technologies at both end-use level (vehicles) and transformation level, (production of hydrogen, more particularly technologies including carbon capture[19]); although the amount of hydrogen consumed does not increase in mitigation scenarios, its production method switches from gas reforming to gas reforming with CO_2 capture. This result is in agreement with other studies observing that biomass is an important fuel for transportation as a replacement of oil, while hydrogen starts playing an increasing role after the mid-century, when solar and nuclear hydrogen (truly zero-carbon options) become competitive and replace hydrogen produced from natural gas (Riahi and Roehrl, 2000).

In the other end-use sectors, the substitution of oil and coal by natural gas and electricity in industry, observed in the base cases, is strengthened, while no significant changes of the final fuel shares are observed in residential/commercial sectors (Table 8.7).

The price-induced reduction of elastic demands is rather small and contributes accordingly little to emission reductions. It is less than 3% in commercial and residential sectors except for demands depending on electricity only (residential lighting, residential electric appliances, commercial refrigeration, commercial electric office equipment and commercial other) that are reduced between 6 and 19%. The reduction of elastic demands is between 1 and 7% in industry, less than 2.1 % for road transportation, and reaches 14% for aviation.

Energy prices variations depend on regions, but the general trend is an increase of electricity price from 50 to 150% compared to base case and an increase of natural gas price up to 10%. No clear trend is observed for coal

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[19] As explained in Section 4.1, end-use consumption of hydrogen is emission-free but the production of hydrogen contributes to emissions either because it is produced from fossil fuels, or because it is energy consuming.

Table 8.7. Shares of final energy in end-use sectors (in percentage)

		BAU-A1B		550-A1B		BAU-FOS		550-FOS	
WORLD	%	2000	2050	2000	2050	2000	2050	2000	2050
Industry	Biomass	5.0	4.0	5.0	4.4	4.7	4.2	5.0	4.7
	Coal	20.4	8.5	20.6	7.5	19.2	8.6	20.6	6.9
	Gas	28.9	37.4	29.2	39.2	27.5	36.1	29.2	39.3
	Heat	0.5	0.6	0.5	1.5	0.4	0.6	0.5	1.1
	Oil	27.1	18.7	27.2	14.6	25.5	21.6	27.2	17.7
	Elc	17.4	29.8	16.8	31.8	21.9	27.9	16.8	29.3
	Other	0.7	0.9	0.7	0.9	0.7	1.0	0.7	1.0
Comm/Resi	Biomass	33.3	4.2	33.5	4.6	31.0	4.2	33.5	4.6
	Coal	5.1	9.8	5.2	9.3	4.8	9.7	5.2	9.8
	Gas	24.6	19.4	24.9	20.2	23.0	19.6	24.9	20.6
	Heat	5.7	2.3	5.7	2.4	5.3	2.3	5.7	2.4
	Oil	17.6	23.6	17.7	23.9	16.4	23.3	17.7	23.6
	Elc	13.3	39.7	12.8	37.9	19.2	39.7	12.8	37.2
	Other	0.2	1.0	0.2	1.6	0.2	1.2	0.2	1.8
Transport	Biomass	0.4	11.1	0.4	22.6	1.0	13.0	0.4	25.9
	Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Gas	1.0	12.2	1.0	12.3	0.3	8.2	1.0	12.3
	Hydrogen	0.0	12.2	0.0	12.3	2.3	14.3	0.0	12.3
	Oil	97.7	58.7	97.7	47.4	93.1	55.1	97.7	44.0
	Elc	0.9	5.7	0.9	5.5	3.4	9.4	0.9	5.5

prices, which vary between –10 to 43%. The increase of electricity price provokes a decrease in electricity consumption at world level in 2050 of 4.5% in 550-A1B scenario and 3.4% in 550-FOS scenario; the reduction of the electricity consumption is higher in the first periods when electricity is more expensive, reaching respectively 8.7% and 9.8% in 2010).

4.3.2 Cost analysis. The marginal price of CO_2 in the case of the stabilization of concentration at 550 ppm and assuming a world competitive market of CO_2, reaches 92.8 $US\$_{2000}$ / t CO_2 in 550-A1B scenario and 113.2 $US\$_{2000}$ / t CO_2 in 550-A1B scenario in 2050 (Table 8.8). The decrease of the marginal cost of CO_2in 2040 is explained by the penetration of more advanced wind technologies available in 2040 and later. We may note that the 2010 prices (30-35 $US\$_{2000}$ /tCO_2) appear to be in the high range of carbon prices estimated by other studies in the context of the Kyoto Protocol with a global trading of carbon permits (4-44 $US\$_{2000}$ /tCO_2) (Weyant, 2000). This can be explained by higher reductions of CO_2 in the MARKAL constrained scenarios than those required by the Kyoto Protocol in 2010. More interesting than absolute values, the comparison of carbon price and total cost of CO_2 reduction between scenarios, shows that the price-induced reduction of demands helps reduce the carbon price by 14% and 10% in 550-A1B and 550-FOS scenarios in 2050, while CO_2 sequestration reduces carbon price by a factor of more than 2.

The total costs relative to the respective Base cases are shown in Table 8.9. Clearly, sinks helps reduce the total cost by almost 50%. When annualized and expressed as a percentage of GDP in 2000, the cost increase represents respectively 0.8% and 1.2% in 550-A1B and 550-FOS scenarios when demands are elastic and sinks are included. Expressing the cost as a percentage of GDP does *not* mean that it represents the change in GDP, since MARKAL is not attempting to evaluate the GDP losses. Nevertheless, this result is close to the average GDP reduction obtained by other models for A1B stabilization scenarios (Hourcade and Shukla, 2001)[20].

4.3.3 Sensitivity analyses. Given the uncertainties related to CO_2 capture and sequestration, and because sequestration, being the cheapest mitigation options available, may hide the potential for "second best" strategies, it is interesting to observe the options computed by MARKAL when the possibility of*capture and sequestration is removed* (labelled "no sink").

(i) First, the switching from coal and oil to gas, biomass and electricity in end-use sectors is strengthened. For example, the share of biomass in transportation fuels reaches 29.6% in 550-A1B-no sink (+31% compared to the case with capture and sequestration) and 31.3% in 550-FOS-no sink (+21%). The share of biomass in transportation reaches the maximal bound (see Section 3.4) in AFR, CSA, ODA, where biomass potentials are high, in 550-A1B-no sink and 550-FOS-no sink.

(ii) The price-induced reduction of elastic demands is also increased (more than doubled in both cases), because the price of fossil fuels itself is higher: for example, the natural gas price increases up to 18% in 550-A1B-no sink compared to 550-A1B, and up to 42% 550-FOS-no sink compared to 550-FOS[21].

(iii) In the electricity sector, coal plants are completely replaced by gas power plants and renewable electricity plants (Figure 8.8): the increase of electricity generated by gas power plants is 81% in 550-A1B-no sink compared to 550-A1B and 70% in 550-FOS-no sink compared to 550-FOS; in the latter case, the increase of renewable is 50% (geothermal, solar and wind[22]). The role of CCGT as a transition to more advanced power plants (Gas fuel cells) is also strengthened.

(iv) Carbon price is increased by a factor of more than 2 after 2020 in both cases, reaching respectively 192 and 424 $US\$_{2000}$ / t CO_2 in 2050 in 550-A1B-

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[20] Comparison of costs must be treated with caution since the scenarios have not rigorously accounted for all the economic effects of climate policies (Hourcade and Shukla, 2001).

[21] The high increases of the price of natural gas are generally explained by investments in liquified natural gas infrastructures when gas demands are so high that the limits on natural gas imports by pipeline (gaseous) are reached. Of course, the user's decision to let the model invest in higher capacity of gas pipelines instead of liquified gas infrastructures would change the resulting price of natural gas.

[22] As explained in section 4.2, when the minimal level of renewable electricity is reduced (BAU-FOS), all the available hydroelectricity capacity still penetrates, being the cheapest renewable electricity sources. Consequently, the available renewable electricity potential is geothermal, wind and solar.

Table 8.8. Price of CO_2 reduction

US$2000/t CO2	2000	2010	2020	2030	2040	2050
550-A1B	0	32.4	60.4	62.6	54.1	92.8
550-A1B not elastic	0	45.3	68.5	71.6	54.0	105.7
550-A1B no sink	0	42.6	119.0	148.9	139.8	191.8
550-FOS	0	36.9	60.9	63.6	55.0	113.2
550-FOS not elastic	0	51.0	68.8	81.2	67.9	124.5
550-FOS no sink	0	47.8	139.3	194.1	209.6	423.5

no sink and 550-FOS-no sink (see Table 8.8). Total annualized cost of CO_2 reduction is increased by 70% in 550-A1B-no sink and it is more than double in 550-FOS-no sink compared to the base cases (see Table 8.9).

If the *price-elasticity of demands is assumed null*, the main effect is an increase in the electricity consumption and in the sequestration of CO_2. New electricity capacity relies on CCGT with CO_2 capture, and the amount of CO_2 sequestered increases by 13% and 7% in 2050 in 550-A1B-no elastic and 550-FOS-no elastic compared to respectively 550-A1B and 550-FOS. Carbon price is increased by 14% and 10% in 550-A1B-not elast and 550-FOS-not elast scenarios in 2050, reaching respectively 105.7 and 124.5 $US\$_{2000}$ / t CO_2 in 2050 (see Table 8.8). Total annualized cost of CO_2 reduction is increased by around 14% in both scenarios compared to the base cases (see Table 8.9).

Table 8.9. Total cost of CO_2 reduction (Net Present Value in 2000 in US$ Billion – horizon 2000-2050)

Billions	Reference scenario for cost calculation			
US$2000	BAU-A1B	550-A1B	BAU-FOS	550-FOS
550-A1B	4132	—	—	—
Not elast	4724	592	—	—
No sink	7115	2893	—	—
550-FOS	—	—	6389	—
Not elast	—	—	7339	950
No sink	—	—	12911	6522

If the *generation of electricity by coal plants remains limited* in the mitigation scenarios, coal power plants with CO_2 capture are replaced by CCGT with CO_2 capture and by biomass power plants.

Finally, if *no decentralized electricity is required*, gas fuel cells power plants are substituted by CCGT with CO_2 capture and, in a lesser extent, by CCGT without CO_2 capture and by biomass power plants.

5. Conclusion

A new version of the advanced multi-region World MARKAL model has been developed and calibrated to the A1B scenario provided by AIM over a 50-year time horizon. MARKAL can be considered as one of the very first world bottom-up optimization model with so high a level of detail in end-use and supply sectors. Several characteristics of World MARKAL contribute to reducing the gap between bottom-up and top-down models, and between optimization and simulation models: amongst them, the price-elasticity of end-use demands captures the impact of rising energy prices on economic output and *vice versa.* The multi-regional nature of the model renders possible the assessment of the impacts of energy-related decisions on trade. Finally, the availability of user-defined ad hoc constraints helps the model reflect non-economic decisions or reproduce certain behavioral characteristics of observed markets.

The analysis of the base and carbon constrained cases confirms and refines several conclusions observed by other models. First, the level of non-emitting electricity generation in the base case is a crucial assumption for defining future CO_2 emissions and reduction opportunities; given the impossibility to accurately predict future energy systems in the long term, multiple baseline scenarios are needed to guide the formulation of robust policies. Second, CO_2 capture and sequestration play a very important role in mitigation options as it competes directly with the other abatement options, such as renewable electricity generation; it also contributes to a major reduction in the marginal cost of CO_2, which is more than doubled if CO_2 sequestration is not allowed. The assumptions related to both the capture of CO_2 and the potential, costs and social acceptability of sinks are therefore crucial for the appropriate definition of climate policies. Moreover, the primary consumption of coal may increase in the long term when associated with the capture of flue gas CO_2 at power plants. CCGT‘s with and without CO_2 capture appear to be very robust technologies. In transportation, the substitution of oil by biomass is robust and much preferred to the other alternative technologies (electricity, natural gas and hydrogen). The price-induced reduction of elastic demands, which captures a great deal of the interaction between the energy system and the economy that was not previously accounted for in bottom-up energy models, also contributes to the emissions reduction, especially when CO_2 sequestration is not allowed, so that energy prices increase. The resulting annualized cost of CO_2 mitigation policies remains under 1% of the GDP for the stabilization of concentration at 550 ppmv in the A1B scenario.

The deeper analysis of hydrogen production and end-uses technologies, the availability and costs of CO_2 capture and sequestration, as well as the proper modelling and calibration of non-CO_2 greenhouse gases would deserve more attention. Finally, the assessment of energy and technology decisions for climate policies would benefit from the comparison of the global and regional economic costs computed by the World MARKAL for different environmental targets and different international cooperation frameworks. Future work will focus on these issues.

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Chapter 9

FLEXIBLE CARBON MITIGATION POLICIES: ANALYSIS WITH A GLOBAL MULTI-REGIONAL MARKAL MODEL

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Socrates Kypreos
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Abstract The Swiss National Centre of Competence in Research (NCCR-Climate) explores the predictability, variability and risks of climate change and the socio-economic response to it. The Paul Scherrer Institut (PSI) and the University of Geneva contribute to this programme by using models to simulate the impacts of policies for climate change mitigation. This study quantifies the benefits of several policies enhancing the flexibility of carbon dioxide (CO_2) mitigation, with emphasis placed on emissions trading, optimal timing paths and support for learning-by-doing (LBD) in the use of low-carbon technologies. We present illustrative results for a "Soft-landing" scenario, which imposes a CO_2-emission stabilization target that is consistent with stabilizing CO_2 concentration at 550 ppmv in the long run. This analysis has been conducted with the Global MARKAL Model (GMM), which is a multi-regional, "bottom-up", partial equilibrium energy-system model with endogenized technology learning (ETL). Incorporation of flexible CO_2 mitigation policies leads to significant reductions in energy-system costs and marginal costs of CO_2 abatement as well as increasing diffusion of advanced low-carbon technologies. In the future, an extended GMM model could be linked to a climate model (e.g., C-Goldstein, Marsh et al., 2002) to implement an Integrated Assessment Model (IAM) that would allow examining impacts of climate change.

1. Introduction

The *National Centre of Competence in Research on Climate* (*NCCR-Climate*), managed by the Swiss National Science Foundation, explores, with the help of quantitative methods, the climate vulnerability and risks, and investigates the market prospects of advanced, low-carbon technologies that are implemented

A. Haurie and L. Viguier (eds.), The Coupling of Climate and Economic Dynamics, 237–266.

under policies designed to stabilize atmospheric carbon (C) concentration at specified levels (NCCR, 2004). Within the context and scope of the NCCR-Climate research program, this paper explores the advantages of several policies that could enhance the flexibility of carbon dioxide (CO_2) mitigation. Among other reasons, flexible mitigation policies are required because of the large technological inertia of the global energy system, which causes structural transitions to span long periods of time, in addition to large institutional inertia and political obstacles that inhibit the rapid implementation of climate-change policies. For these reasons, we highlight the important role of spatial, temporal and technology-related *flexibility* in implementing CO_2-mitigation policies in the global energy system.

We concentrate on energy-related CO_2 emissions, which represent a substantial share of present-day greenhouse gas (GHG) emissions. Using the "bottom-up" global, multi-regional energy-system MARKAL model (hereon referred to as the GMM model), we examine a range of CO_2-reduction strategies and compare the resulting costs of CO_2 reduction across several scenarios. In addition, the impacts of endogenizing technology learning (ETL) in the electricity sector on technology choices and CO_2 abatement policies are analyzed. Specifically, we describe the induced changes in the primary-energy supply and electricity-generation technology mix, the modified rates of CO_2 emissions and the diffusion of advanced technologies in energy and end-use markets.

A first relevant aspect refers to the so-called "where" flexibility of CO_2 mitigation. Flexibility mechanisms, as defined by the Kyoto protocol, are basically methods of GHG emissions trading allowing a country to utilize the least-cost emissions reduction options. These flexible mechanisms are categorized as Joint Implementation (JI), the Clean Development Mechanism (CDM) and International Emissions Trading (IET), all of which are designed to allow industrialized countries with limited domestic low-cost emissions abatement possibilities to reduce mitigation costs by investing in emissions-reducing projects (or in carbon permits purchase) in other countries and thereby acquiring credits that equal the costs of avoided GHG emissions (Sager, 2003a). Taking advantage of the "where" flexibility of mitigation, these mechanisms can contribute to achieving cost-effective emissions reductions. For modelling purposes, this paper considers a generic carbon-emissions trading mechanism, that refers to all trade of emission permits and does not distinguish specifics of the IET, JI, and CDM categories considered under the Kyoto protocol. Hence, specific constraints associated with each of the Kyoto mechanisms are not considered here.

Another important kind of policy flexibility addressed herein is the "when" flexibility, which allows for an optimal trajectory of emissions reductions over a time horizon, and, therefore, is consistent with a long-term goal, such as the stabilization of atmospheric CO_2 concentration. In contrast with the imposition of stringent short-term reduction targets attendant to the "where" flexibility, allowing "when" flexibility could bring, among others, benefits related to avoiding the premature phase-out of capital-intensive energy technologies and related infrastructure and thereby reducing the cost of CO_2 abatement.

Related to these two aspects of policy flexibility is the role of technological change. Technology is recognized to play a key role in GHG mitigation strategies. Clearly, the technologies that would intervene in a mitigation strategy depend on, among other factors, the degree to which the "when" and "where" policy flexibilities are implemented, as well as the rates of technological progress through ETL. Stimulating the learning process of low-carbon, more efficient and clean energy technologies could provide significant benefits. Hence, the role of ETL has been highlighted in this study.

In summary, this study quantitatively elaborates on the following research questions using GMM:

- What are the economic and technology-mix implications of the "where" flexibility mechanism involving full trade of CO_2 emission permits at a world level?
- How will the effects of full emissions trading be affected by the introduction of "when" flexibility?
- How will the results of the previous two inquiries be changed if countries/regions were to support policies for technology diffusion and learning of low-carbon technologies?

This paper is organized as follows: Section 2 describes the global, multiregional MARKAL model (GMM). Sections 3 and 4 present the scenarios examined and the CO_2 emission reduction targets imposed on the global energy system. Section 5 discusses the GMM results at the global level, and stresses the role of the "where" and the "when" flexibility policy options, as well as the implications of policies designed to stimulate technology learning in a CO_2 mitigation strategy. Finally, Section 6 concludes with core findings and recommended future work.

2. Description of the modelling framework

The analysis presented in this paper has been carried out using the Global Multi-regional MARKAL Model (GMM) with endogenized technological learning (ETL). The GMM was originally developed by Barreto, 2001, and subsequently upgraded by the authors. The MARKAL (Market allocation) model (See Fishbone et al., 1981) is a dynamic linear programming, "bottom-up", energy-planning model that allows a detailed representation of energy technology options on both demand and supply side of the energy system.

Five world regions are considered in GMM, as defined in Figure 9.1. Two regions describe the industrialised countries of North America (NAME) and the other OECD countries (OOECD). One region covers transition-economies of Central & Eastern Europe and the Former Soviet Union (EEFSU). Two additional regions represent the developing world: the developing countries in Asia (ASIA) and Latin America, Africa and the Middle East (LAFM).

The Reference Energy System (RES, Resource → Refining → Conversion → Final Energy → End-Use Energy) that characterizes MARKAL (Fishbone et

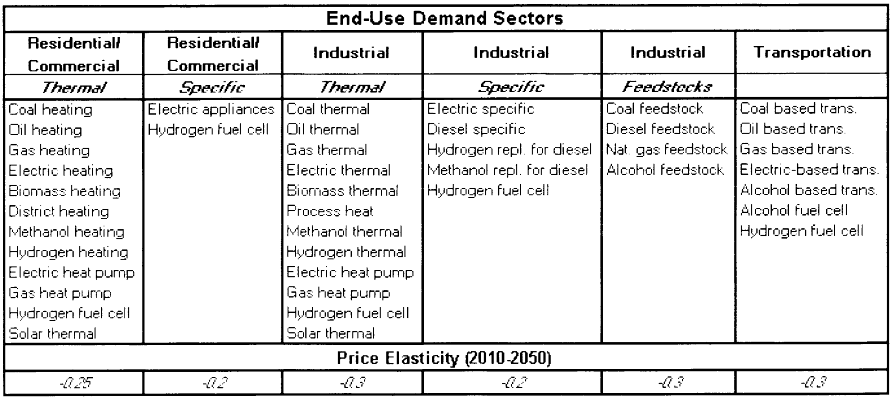
Figure 9.1. Definition of the world regions used in GMM

al., 1981), as described in Barreto, 2001, is applied to each of the five GMM regions. Six end-use demand sectors are used for each region in GMM, as elaborated in Table 9.1. The Industrial and the Residential/Commercial end-use sectors are divided into thermal and non-thermal (specific) uses. The Transportation sector merges together passenger and freight transport. Finally, the non-commercial use of biomass and non-energy feedstock is represented in the RES. In each of these demand sectors, a set of standard and advanced generic end-use devices (or technologies) is defined (e.g., coal-based heating in industry, oil-based transport, etc.). No explicit investment or fixed Operation and Maintenance (O&M) costs are considered for the generic end-use technologies specified in the model. Instead, "inconvenience costs" are introduced to reflect the fact that as the historical trend of shifting towards more flexible and cleaner energy carriers continues at the final-energy level, some technologies may be more difficult or much less attractive to introduce. Substitution at this level, therefore, is driven mainly by efficiencies and fuel costs. Future penetration of end-use technologies is controlled by the introduction of (exogenously controlled) annual growth and declination rates and by the exogenous enforcement of an absolute bound on specific technologies to allow competition in the end-use markets.

The energy-supply sector is represented in detail. Technologies for the production of electricity, heat and a variety of final fuels (e.g., oil products, alcohol, methanol, hydrogen, natural gas) from several fossil and non-fossil sources are included, as well as the corresponding transport and distribution (T&D) chains. Investment, fixed O&M and variable O&M costs are specified for all supply technologies considered.

The time horizon modelled by GMM is from 1990 to 2050, i.e., seven periods of ten-years duration each. A discount rate of 5%/year is used. The version of GMM used herein considers energy-related CO_2 emissions at regional and global level, as contributed by each of the five regions described in Figure 2.1;

Table 9.1. Generic end-use technologies applied in GMM; sector-specific price elasticities are indicated for each end-use demand category.



End-Use Demand Sectors					
Residential/ Commercial	**Residential/ Commercial**	**Industrial**	**Industrial**	**Industrial**	**Transportation**
Thermal	***Specific***	***Thermal***	***Specific***	***Feedstocks***	
Coal heating Oil heating Gas heating Electric heating Biomass heating District heating Methanol heating Hydrogen heating Electric heat pump Gas heat pump Hydrogen fuel cell Solar thermal	Electric appliances Hydrogen fuel cell	Coal thermal Oil thermal Gas thermal Electric thermal Biomass thermal Process heat Methanol thermal Hydrogen thermal Electric heat pump Gas heat pump Hydrogen fuel cell Solar thermal	Electric specific Diesel specific Hydrogen repl. for diesel Methanol repl. for diesel Hydrogen fuel cell	Coal feedstock Diesel feedstock Nat. gas feedstock Alcohol feedstock	Coal based trans. Oil based trans. Gas based trans. Electric-based trans. Alcohol based trans. Alcohol fuel cell Hydrogen fuel cell
Price Elasticity (2010-2050)					
-0.25	*-0.2*	*-0.3*	*-0.2*	*-0.3*	*-0.3*

other GHGs are not modelled. Sulphur dioxide (SO_2) and Nitrogen oxides (NO_x) emissions are represented only for the electricity generation sector.

An important feature of the GMM model is an ability to describe technology dynamics in energy-system development through the incorporation of learning curves for selected technologies. Endogenous Technological Learning (ETL) is one of the main mechanisms considered to model technological change in GMM. Cumulative, self-reinforcing learning processes play a key role in achieving performance improvements and cost reductions of specified technologies. Typical learning, or experience, curves are used to capture approximately the fact that the costs of technologies can decrease as operating experience with the specific technology is accumulated.

Endogenization of technological learning (ETL) enables the modeller to analyze how the specific investment cost of a "learning" technology declines with accumulated installed capacity of the respective technology (Messner, 1997). The detailed description and mathematical formulation of the learning-by-doing (LBD) modelling approach applied in the MARKAL model can be found in Barreto et al., 2002. The technological, cost, and learning specification of electricity generation technologies represented in the GMM model are given in Table 9.2.

The GMM model version used for this analysis applies the ETL option in combination with a partial-equilibrium algorithm, that adjusts the demand for energy services to the increased marginal cost of services that result from the imposition of a given policy constraint (Loulou et al., 1996) (e.g., meeting CO_2-emission reduction target). The MARKAL model with Elastic Demands (referred to as the MARKAL-ED) uses a procedure whereby the energy end-use demands are not fixed, but instead are elastic to their own prices, which are exogenously computed in the baseline and self-adjusted if modified scenario conditions affect the price. The model obtains equilibrium when the sum of producer and consumer surpluses is maximized. Consequently, the model ob-

Table 9.2. Specification of electric power technologies used in GMM. All costs are given in \$ (1998). Hydrogen fuel cells (H2FC) are specified as combined heat and power (CHP) producing technologies. The progress ratio (PR) is the rate at which the cost declines each time the cumulative capacity for a given technology doubles. The data presented derives from various sources and literature reviews. Characteristics of technologies with CO_2 removal are adopted from David et al., 2000; additional CO_2-storage cost (10 \$/t-CO_2 captured) is charged for these technologies.

Technology	Start year	Life time	Load factor (max.)		Efficiency		Investment cost	Fixed O&M cost	Variable O&M cost	Progress ratio
			start	2050	start	2050	\$/kW	\$/kW/yr	\$/GJ	
Fossil based power plants										
Coal conventional electric	1990	30	0.65	0.75	0.370	0.380	1050	38	0.72	
Coal conventional electric with DeSulf/DeNOx	2000	30	0.65	0.75	0.360	0.370	1150	48	1.22	
Coal conv. with DeSulf/DeNOx and CO2 seq.	2010	30	0.65	0.75	0.296	0.304	2090	80	1.53	
Coal cogeneration	1990	20	0.65	0.75	0.370	0.380	1155	49	1.5	
Coal advanced electric	1990	30	0.65	0.8	0.429	0.500	1584	47.5	0.75	0.94
Coal advanced electric with CO2 seq	2010	30	0.65	0.8	0.365	0.425	2060	90	1.13	0.93
Integrated coal gasification CC (IGCC)	2000	30	0.85	0.85	0.425	0.500	1401	40	0.88	0.94
Coal IGCC with CO2 sequestration	2010	30	0.85	0.85	0.361	0.425	1910	52	1.23	0.93
Gas combined cycle (NGCC)	1990	20	0.65	0.75	0.510	0.588	560	36.6	0.63	0.9
Gas combined cycle with CO2 sequestration	2010	20	0.65	0.75	0.459	0.529	1015	50	0.88	0.9
Gas turbine	1990	20	0.2	0.2	0.360	0.360	350	58.5	0.51	
Gas steam conventional	1990	20	0.65	0.65	0.386	0.410	987.7	50.6	0.56	
Cogenaration gas turbine	1990	20	0.4	0.46	0.370	0.370	750	51.6	0.63	
Gas fuel cell (GFC)	2000	20	0.65	0.65	0.599	0.649	2463	43.5	0.63	0.82
Hydrogen fuel cell (CHP) in industry	2010	20	0.85	0.9	0.4	0.6	3500	20	7.5	0.82
Hydrogen fuel cell (CHP) in res&com	2010	20	0.85	0.9	0.4	0.5	3500	20	5.8	0.82
Oil electric	1990	20	0.65	0.8	0.303	0.400	991	53.6	0.57	
Nuclear and renewable power plants										
Nuclear plant - Light water reactor (LWR)	1990	30	0.75	0.9	0.327	0.327	1800	80	0.19	
Advanced new nuclear power plant (NNU)	2010	30	0.85	0.9	0.345	0.345	1900	80	0.19	0.96
Hydro-electric plant	1990	50	0.42	0.46	0.385	0.471	2850	49.5	0.12	
Solar photovoltaics (SPV)	1990	20	0.2	0.25	0.400	0.400	5000	9	1.25	0.81
Solar thermal electric	2000	20	0.2	0.2	0.400	0.400	2900	9	1.25	
Wind turbine	1990	20	0.3	0.3	0.330	0.330	1150	13.5	0.83	0.9
Biomass power plant	1990	20	0.75	0.75	0.333	0.333	2650	47.8	0.92	
Geothermal electric	1990	20	0.75	0.75	0.381	0.381	2900	28	0.9	

jective function is comprised of two terms: the energy/technology production costs, and the loss of consumers' welfare associated with demand reduction (Kanudia et al., 1999).

The multi-regional feature of GMM allows simulation of bi-lateral and global trade of selected energy or environmental commodities (e.g., fuels, electricity, emission permits). Global trade of any given commodity must balance at each period (i.e., the sum of trade variables over all regions is equal to zero). The quantities as well as the unit cost (corresponding to the marginal price) of an endogenously traded commodity are model results. Shadow price of the commodity globally traded among regions reflects the cost the energy system has to pay for a unit of trade. A zero value of the shadow price implies that no cost is associated with producing and delivering the commodity, which is highly unlikely (EIA, 2003).

The trade variables transform the five regional modules of GMM into a single global energy model where actions taken in one region may affect all other regions. For instance, if regional carbon emission constraints are imposed on the energy system, CO_2-emission trading allows the reallocation of the carbon reduction targets within the trading regime and, therefore, creates incentives to deploy low-carbon technologies among the regions participating in the trading regime (Barreto et al., 2004). Again, the marginal costs of carbon emissions reduction (or a shadow price of carbon-emission permits globally traded), determined endogenously by the model, are equalized across the regions, and the revenue from exports received by the exporting region is exactly cancelled by the cost of imports incurred by the importing region. However, cost and revenues resulting from the permit trade for each region can be calculated *ex post.* Transaction costs and other additional charges possibly associated with trading of emission permits, however, are not accounted in this analysis.

3. Scenarios analysed

In the "Soft-landing" scenario, a carbon-constrained world is assumed, wherein global, but smooth, carbon-emission reduction commitments towards an emission target of 10 GtC/yr (Giga tonnes Carbon - 10^9 ton per year) by the year 2050 are specified (see Section 4 for further details). Each GMM region applies its specific CO_2 reduction entitlement, contributes to carbon reduction efforts and simultaneously trades carbon emission permits. In addition, global spillover of experience and knowledge transfer (including from North to South) are assumed to take place. The underlying storyline for the reference development refers to the SRES-IIASA B2 "dynamics-as-usual" case (IPCC, 2000; Riahi et al., 2000)[1], which is assumed to describe a plausible development of the energy system. The baseline end-use demands and renewable-energy potentials are directly taken from B2 scenario, and availability of fossil fuels is adopted from Rogner, 1997. However, no attempt has been undertaken to calibrate the baseline scenario to match the results of the SRES-B2 scenario. In this respect, the reference development corresponds to a PSI scenario, since the allocation of resources is based on an optimization performed under conditions of perfect foresight with LBD considerations.

Although the base year of GMM is 1990, the model is calibrated to reproduce energy statistics of the International Energy Agency for the year 2000 (IEA, 2002a; IEA, 2002b). Additional information sources were used for calibration of installed power-generation capacities in 2000 (IEA, 2002c; IEA, 2002d; EIA, 2003).

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[1] The B2 scenario of the Special Report on Emission Scenarios (SRES) is a "dynamics-as-usual" scenario where differences in the economic growth across regions are gradually reduced, and concerns for environmental and social sustainability at the local and regional levels rise along the time horizon. Population growth is consistent with the United Nations median projection increasing to 9.4 billion people in 2050, which is a continuation of historical trends. Economic growth is gradual, with world Gross Domestic Product (GDP, in 10^{12} \$/yr) increasing at an average rate of 2.8% per annum between 1990 and 2050. Income per capita grows at a global average of 1.8% per year for the same period, reaching an average value of 11,700 \$ (1990) per capita in the year 2050 (at market exchange rates) (IPCC, 2000; Riahi et al., 2000).

On the demand-side it is assumed that the historical shift from non-commercial to commercial fuels and towards more clean and flexible, grid-transported energy carriers at the final-energy level continue in the future. As for the non-energy feedstocks (mainly oil products and to a much lower extent natural gas and coal), it is assumed that they can be replaced by alcohol feedstocks after 2020. Conservation measures are not explicitly modelled.

Levels of power generation based on renewable- and nuclear-energy sources are controlled in GMM through the imposition of exogenous bounds and annual growth/declination-rate limits for each technology. Bounds applied for renewable resources reflect the regional technologically achievable potential of each type of source and is provided by Riahi et al., 2000; IEA, 2002c; UNDP, 2000. As indicated in Table 9.3, except for hydropower, only upper bounds are applied in 2050 for renewable power generation; the level of actual generation, therefore, is not forced, but is left free for determination through competition. In the case of nuclear power, the lower bound in 2050 corresponds to the present global level of generation. No limit is provided for the amount of CO_2 that can be stored in any type of reservoirs. The level of carbon sequestration, however, is controlled by annual growth rates of technologies being operated with CO_2 emissions removal.

To address the research questions posed in Section 1, three main and four supplementary global scenarios with different trade and learning modalities and constraints imposed on carbon emissions are investigated. Table 9.4 defines these scenarios and the naming conventions used.

In the present study, the most important scenarios are the BNNL, CFTL and CUTL scenarios. The BNNL scenario corresponds to the Baseline development with unconstrained carbon emissions but with endogenous technological learning (ETL). The CFTL and CUTL scenarios represent two alternative specifications of the "Soft-landing" scenario (see following Section 4). A group of four supplementary scenarios (CFNL, CFTN, CUNL, and CUTN) has been selected to contrast the main scenarios with the consequences of different policy actions (i.e., exclusion of emissions trade, exclusion of ETL). While not exhaustive, the scenario set depicted in Table 9.4 covers a broad range of possibilities.

4. CO_2 emission targets

The carbon emissions targets are set according to the "Soft-landing" scenario for each of the 5 world regions, as prescribed in Blanchard et al., 2001. In this scenario, CO_2 concentrations are stabilized in the long-term at about 550 ppmv of atmospheric CO_2, and all countries contribute to emission reduction. The 550 ppmv (Parts per million by volume) concentration target is frequently used as a precautionary, but attainable, level and represent the middle value of stabilization level identified by Wigley et al., 1996. The global emission trajectory of the "Soft-landing" scenario is similar to those presented in literature (Riahi et al., 2000; Wigley et al., 1996; IPCC, 2001). The allocation of emission entitlements takes into consideration the aspirations of less-developed countries for economic growth and distributes total emissions

Table 9.3. Assumptions for renewable and nuclear electricity sources applied in GMM. (*) Biomass potential refers to both electricity and heat production.

Bounds for renewable electricity sources in 2050 (EJ)						
Regions:	**NAME**	**OOECD**	**EEFSU**	**ASIA**	**LAFM**	**WORLD**
Hydro max	2.8	3.4	5.8	7.6	8.5	28.1
Hydro min	2.2	2	1.1	1.2	2.4	8.9
Wind max	9.4	12	9.3	9.9	9.8	50.4
Solar PV max	3.6	2.2	1.6	14.6	5.2	27.3
Biomass max*	8.4	3.3	10.8	53.5	112.4	188.4
Geothermal	1	0.8	2	5	2	10.8
Bounds for nuclear power in 2050 (EJ)						
Nuclear max	18	18	9.5	20	18	83.5
Nuclear min	2	2.9	0.9	1.5	0.1	7.4

Table 9.4. Scenarios specifications and description.

Scenario ID	**Scenario specification**
Main scenarios	
BNNL	**B**aseline case, **N**o-Carbon constraint, **N**o-Trade of emissions permits, with ET**L**
CFTL	**C**arbon **F**ixed annual constraint, Partial equilibrium, **T**rade of emissions permits, ET**L**
CUTL	**Cu**mulative Carbon constraint, Partial equilibrium, **T**rade of emissions permits, ET**L**
Supplementary scenarios	
CFNL	**C**arbon **F**ixed annual constraint, Partial equilibrium, **N**o-Trade of emissions permits, ET**L**
CFTN	**C**arbon **F**ixed annual constraint, Partial equilibrium, **T**rade of emissions permits, **N**o-ETL
CUNL	**Cu**mulative Carbon constraint, Partial equilibrium, **N**o-Trade of emissions permits, ET**L**
CUTN	**Cu**mulative Carbon constraint, Partial equilibrium, **T**rade of emissions permits, **N**o-ETL

such that a smooth trajectory to 10 GtC/yr will be obtained prior to 2050, with a decline subsequently (ACROPOLIS, 2003)[2]. For defining regional CO_2 reduction entitlements, certain rules apply. With regard to differences in energy and economic dynamics across the world regions, a differentiation is maintained in the "Soft-landing" scenario between industrialized countries and developing countries, as introduced by the Kyoto protocol. For the Annex B countries, the emission reduction rate is the same as established in the Kyoto protocol for the first commitment period 1990-2010. For example, if the reduction target for the EU in 2010 is 8 % below 1990, its emissions in 2030 should not exceed 0.92*0.92 times its emission levels in 1990. This rule does not apply for setting carbon constraints to developing countries, however. For the non-Annex

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[2] The timing of imposed carbon constraint follows the Intergovernmental Panel on Climate Change (IPCC) emission pathway, which implies the maximum energy related CO_2 emissions of 10 GtC/yr by around 2030 (excluding about 2 GtC/yr from agriculture sector) (IPCC, 2001).

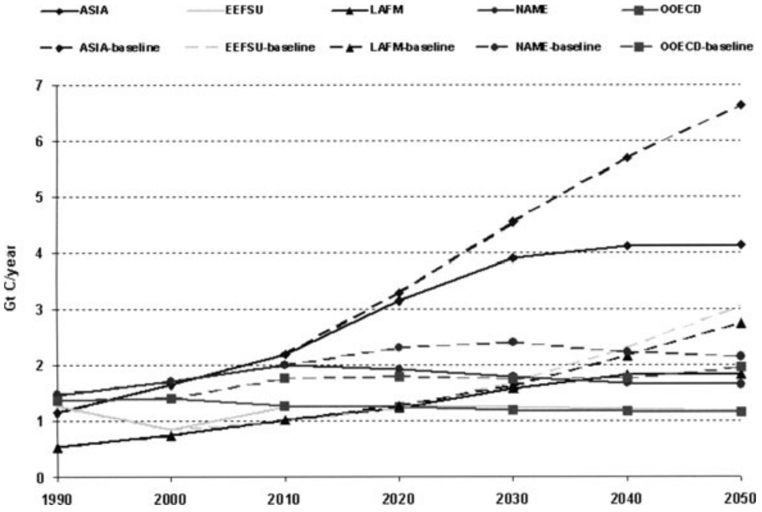

Figure 9.2. Regional CO_2 emissions rates under constraints applied for the "Soft-landing" scenario

B countries, stabilization targets are based on 2010 emissions, the GDP per capita and projections of the population growth (for details see Blanchard et al., 2001). It is assumed that by around 2030 the increase in emissions from developing regions must be at most equal to the reduction of the Annex B countries. To achieve a stabilization of carbon concentrations, the emissions of the non-Annex B countries should in the longer term stabilize and eventually decrease.

The regionalized CO_2 emissions rates under conditions imposed for the "Soft-landing" scenarios are shown in Figure 9.2. These emission rates follow the implementation of regional CO_2 reduction policies, and allow for the overall emissions stabilization.

Moderate growth rates in CO_2 emissions of 0.9% and 1.4% are allowed in ASIA and LAFM regions between the years 2020 and 2050 to account for expected economic and population growth in these regions. On the contrary, emissions in other (industrialized) world regions are forced to decline from 2020 onward, with annual declination rate of –0.2% in EEFSU, -0.3% in OOECD, and –0.5% in NAME region. It is assumed that the OOECD and EEFSU regions fulfil their emission-reduction obligations given by the Kyoto protocol (UNFCC, 1999).

The scenario presented in this analysis is one of many possible scenarios integrating developing countries into the emission-reduction process aiming at the 550-ppmv stabilization targets on the global level. An example of different emission reduction targets for the same atmospheric CO_2 concentration level can be found in Labriet et al., 2004, where, for example, the short-term

'Kyoto-like' carbon mitigation policies are exceeded by imposing higher global emissions reduction rates between 2010-2020.

Alternative approaches in setting CO_2 targets are examined herein by using a cumulative constraint (CUTL scenario). Instead of setting annually fixed emissions limits for each time period, a cumulative CO_2 constraint for the whole commitment period is specified equal to the integral of the annual bounds of the "Soft-landing" scenario. Simultaneously, trade of carbon permits between regions is allowed. Optimizing under these conditions allows for the aforementioned "when" and "where" flexibility options in carbon mitigation policy to be examined, which promise the maximum possible efficiency in meeting carbon constraint specifications. Based on the results of the cumulative constraint, it would be possible to evaluate and compare the technological and economic implications and to verify how 'optimal' the "Soft-landing" carbon emissions targets are (see Sections 5.5 and 5.7 for further details).

The "Soft-landing" scenario assumes late participation of USA in the CO_2 reduction policy (i.e., the US implements only domestic policies up to 2010 and joins the global emission permit trade in 2020). After 2010, all regions trade carbon permits as long as they accept emission reduction obligations, and, therefore, CDM projects are not explicitly modelled. In the period around 2010, where the Kyoto protocol applies, only 50% of the Former Soviet Union and Eastern Europe's "hot air" availability (Sager, 2003b) can be traded with other Annex B countries, while the other half is assumed to be lost, since no banking of any kind is considered (see the following Section 4.1).

4.1 "Hot Air"

The origin of so-called "hot air" in the countries of the Former Soviet Union and Eastern Europe (EEFSU) was the dramatic economic loss and the associated strong decrease in energy use in this region in the last decade of the 20^{th} century. Consequently, a 30% drop in carbon emissions took place between the years 1990 and 2000 (IEA, 2002e). According to the emission-reduction objectives proposed by the Kyoto protocol, the CO_2 emissions of these regions should remain at the same level as in 1990. Therefore, the economies-in-transition within the EEFSU region (Annex B group members) could in principle sell the full amount of "hot air" permits to countries that face binding Kyoto constraints without undertaking any further reduction in their own current emissions.

However, some studies (Sager, 2003b; Eyckmans et al., 2001; Den Elzen et al., 2001) indicate that, for the sake of their own profit-maximization, EEFSU countries should instead impose certain restriction on their "hot air" availability for trade. To reflect this argument, EEFSU countries are allowed in the GMM runs to trade only 50% of their "hot air" emissions in 2010. The expected amount of "hot air" available for trade in the first commitment period certainly depends on the economic growth in the EEFSU regions. Literature sources estimate this amount to be within the range of 0.15 to 0.5 GtC/yr in 2010 (Haurie et al., 2003). Based on the estimated level of emissions in the baseline scenario, the amount of "hot air" adopted in GMM is 0.26 GtC/yr.

4.2 Specification of emissions trade

Trade of CO_2-emission permits is specified in two main (CFTL, CUTL) and two supplementary (CFTN, CUTN) scenarios, according to the current climate policy as defined in the Kyoto protocol and the recent Marrakech agreement. "Hot air" can be traded only in the period around 2010, but at the same time an upper bound of 50% of the total "hot air" availability is imposed. Trade takes place in 2010 only between OOECD countries and the EEFSU region (both in the group of Annex B); the NAME region is excluded from trade in this time period. Afterwards, all world regions trade emissions permits. The total amount of traded permits and the respective time development under the "Soft-landing" scenario is discussed in Section 5.5.

5. Results

The following section describes the main results of GMM and reports on outcomes of different scenarios relative to the baseline case and the implications of trade and learning modalities for the CO_2 emission reduction policies studied. Although the energy system of five world regions is modelled, results presented here emphasize the global developments of primary and final energy consumption, the structural changes in power generation (e.g., fuel mix, choice of technologies), and the overall system costs. Impacts of the "Soft-landing" endowments in CO_2 emissions are reported in the form of regional trade of emissions permits and the respective marginal costs. Additionally, global indicators (e.g., energy and carbon intensity) are used to describe the behavior of the energy system under selected scenarios.

5.1 Primary energy consumption

The global primary-energy consumption decreases for the carbon-constrained scenarios. In the year 2050, a 3.4% (i.e., in scenario CFTL) and 5.7% (i.e., in scenario CUTL) reductions relative to the baseline are observed. In both scenarios, a significant increase in the contribution of carbon-free nuclear energy and renewables is reported over the timeframe 1990-2050. Although in relative terms nuclear energy shows maximum gains, in absolute terms renewable-electricity sources (particular for hydropower), renewable heat, and nuclear energy have similar contributions to primary-energy production. Consequently, the share of coal is reduced, as is that for oil and natural gas, although reductions for the latter occurs to a lower extent.[3]

Figure 9.3 presents relative shares and absolute levels of the primary-energy sources in the year 2050 for the three main scenarios. The share of coal consumption is reduced relative to the baseline scenario by 45% in the CFTL

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[3] The fossil equivalent value corresponds to the reciprocal of the average efficiency of the fossil fuel power plants, and is used for reporting the primary-energy equivalent of renewable and nuclear energy production of electricity. A fossil equivalent of 3.033 is used in GMM.

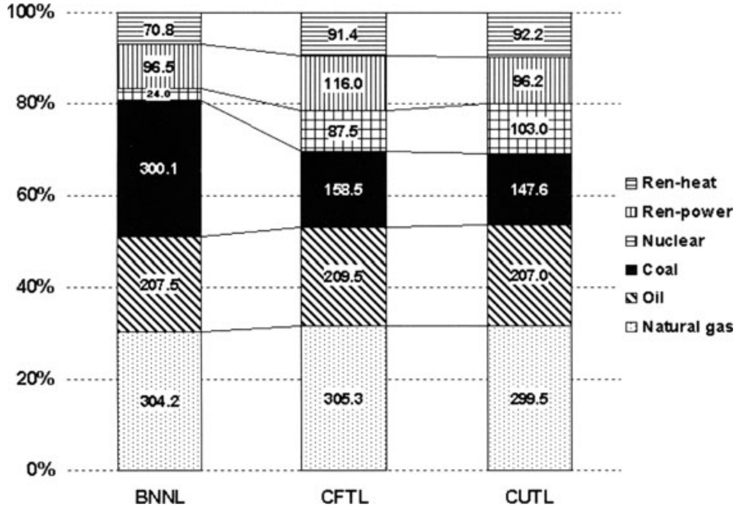

Figure 9.3. Relative fuel shares in the total primary energy consumption in the year 2050 and for selected scenarios. The absolute levels in primary energy use are also shown in EJ/yr units.

scenario and by 48% in the CUTL scenario. Natural gas, therefore, becomes the most important primary-energy source, with a share of more than 31% in both carbon-constrained scenarios (CFTL, CUTL), although in absolute terms the use of gas and oil is almost constant. Nuclear energy increases significantly in relative and absolute contributions (i.e., from 2.4% in the baseline scenario to 9% in the CFTL scenario and is further increased to almost 11% in the CUTL scenario). The share of power generation based on renewable-energy sources in the CFTL scenario, therefore, reaches 12%, but is reduced to 10.2% in the CUTL scenario. Generally, renewable energy becomes the largest carbon-free primary energy source and plays a major role in carbon mitigation. The difference in the shares of renewable heat for the two carbon-constrained scenarios is marginal, however.

5.2 Electricity production

The electricity generation in the baseline scenario (BNNL) is dominated by systems fueled with coal. Different kinds of coal-fired power plants contribute 50% to the total global power generation at the end of the time horizon (2050). From the year 2030 onward, the conventional coal plants are replaced by advanced coal systems (i.e., supercritical plants, Pressurized Fluidized-Bed Combustion - PFBC), and Integrated Coal Gasification Combined Cycle (IGCC) technologies. Natural Gas Combined Cycle (NGCC) gains the second largest market share by the year 2050 and contributes more than 31% of total power production. Approximately 20% of the electric power for the baseline scenario

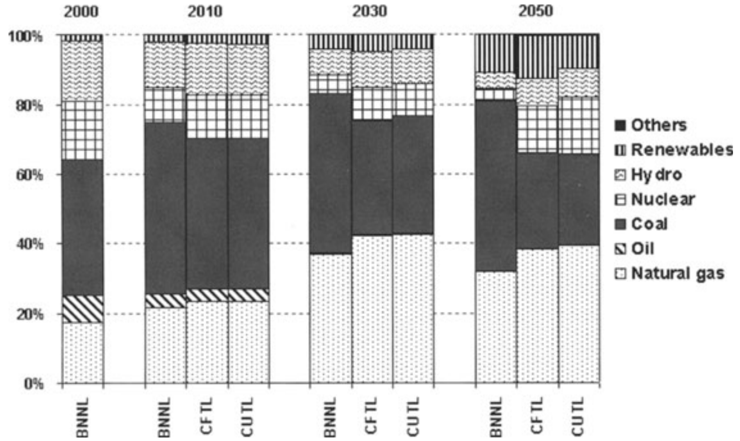

Figure 9.4. Development in the electricity production by fuel type in selected scenarios (relative shares).

is supplied by the carbon-free nuclear and renewable energy sources in the year 2050.

The imposed carbon-emission reduction target decreases the overall power generation in 2050 by 5.4% for scenario CFTL and by 7.9% for scenario CUTL, relative to the baseline, since the production cost of electricity (and, therefore, the price) increases. Figure 9.4 shows similar developments in the power-generation mix in both carbon-constrained cases. The carbon constraint results in a strong reduction of coal use for power generation (a decrease by 47%- 49% over baseline in the final year 2050). The only coal-based technology that undergoes significant increase compared to the BNNL baseline scenario is the IGCC with carbon capturing; this technology supplies nearly 9% of total power generation in 2050. Instead of coal, carbon-free nuclear and renewable electricity sources are chosen, and their combined share reaches 34%. Non-biomass renewable electricity-generation potential in 2050, as presented in Table 9.3, is exploited to the extent of 38% and 33% in the CFTL and CUTL scenarios, respectively. Power production from natural gas is primarily based on NGCC. Natural gas becomes the dominant fuel for electricity production in 2050 and provides 39% of the total annual generation.

Figure 9.5 compares electricity generation by technology in the year 2050 for the three main scenarios (BNNL, CTFL, CUFL) and allows a better presentation of the technological spectrum under different policy settings. Under the carbon constraint, both conventional and advanced-coal generation (including IGCC) are significantly reduced compared to the baseline development. On the other hand, IGCC systems with carbon capturing increase the market share considerably, and play an important role in achieving the "Soft-landing" emissions-reduction target. A decrease in electricity produced from wind turbines relative to the baseline in 2050 is explained by the presence of an addi-

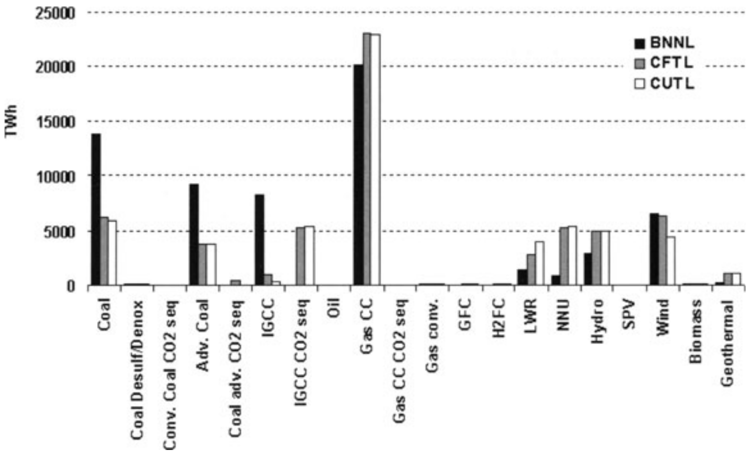

Figure 9.5. Electricity generation profile in 2050 in selected scenarios.

tional constraint applied to intermittent technologies.[4] Finally, a substantial increase in production from hydropower and geothermal sources is reported in the year 2050 for both carbons-constrained cases (CTFL, CUFL).

Figure 9.6 elucidates which technologies contribute to global power generation in the carbon-constrained scenario (CFTL), for the years 2030 to 2050, with and without ETL. The outcomes of technology penetration depend on a number of key factors, such as bounds applied, market penetration rates and the learning-by-doing elasticity. These results illustrate that the differences in power-generation mix are not large, and, as expected, the structural changes caused by incorporation of ETL are more significant in 2050 as compared to 2030. In 2030, the most pronounced shift is the more rapid substitution of coal-based power generation with the NGCC systems. In the CFTL scenario, the additional demand for less carbon-emitting electricity sources in 2050 is met predominately by a higher penetration of 'learning' technologies such as NGCC, advanced nuclear plants, wind turbines, and systems incorporating CO_2 sequestration, as compared to the scenario without ETL. In scenarios where ETL is active, fuel cells based on natural gas and hydrogen penetrate the market by the end of time horizon. On the other hand, the IGCC systems without carbon removal, geothermal energy and conventional nuclear plants penetrate at higher levels when ETL is not included. Total electricity production in 2050 is higher by 3% in the CFTL scenario compared to the case without ETL, since ETL reduces the electricity generation costs and consumption thereby increases.

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[4] This constraint does not allow a group of intermittent technologies (wind turbines, SPV) to exceed certain share of overall power generation (in this case 25%). Since the total power generation in carbon-constrained scenarios decreases, the share of "allowed" generation from e.g., wind turbines is also lowered.

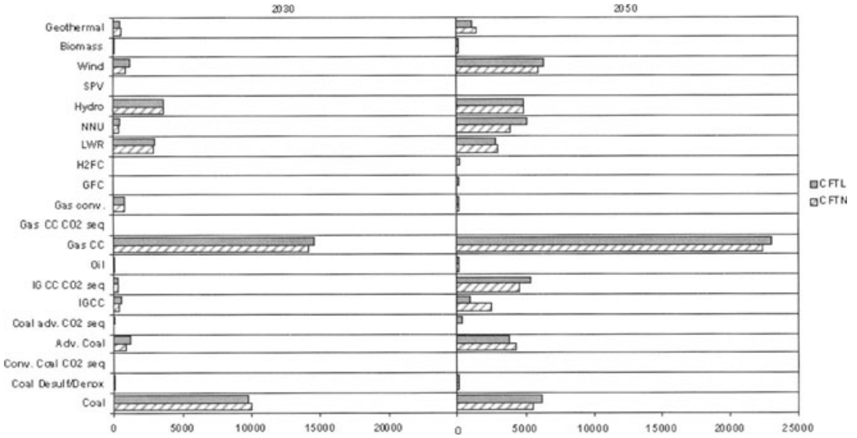

Figure 9.6. Comparison of electricity generation (TWh) in 2030 and 2050 in scenario with and without ETL.

5.3 Final energy demand

Since the carbon constraint causes an increase in the marginal cost of energy, the global final-energy demand is reduced relative to the baseline. The reduction is between 5.3% and 7.2% in the carbon-constrained cases. Figure 9.7 illustrates that the most significant change observed in the final-energy markets is the reduced relative importance of fossil fuels other than oil products. The relative shares of final demand for electricity and biomass remain almost unchanged. At the same time, networks of district heating systems and the other energy carriers (e.g., hydrogen, non-biomass renewable sources) increase market shares under the carbon-constrained scenarios.

5.4 Global CO_2 emissions

Total global carbon emission rates in the baseline scenario increase continuously throughout the modelled time horizon, giving an annual rate of 1.8%/yr and reaching a level of 16.5 GtC/yr by the year 2050. Under the "Soft-landing" constraint active, emission growth culminates in 2020, while a stabilization trajectory begins after 2030 to reach the level below 10 GtC/yr by 2050. The relative global carbon emissions decrease over the baseline scenario is 40% for the CFTL scenario in 2050 and represents an absolute reduction of 6.6 GtC/yr.

The cumulative carbon emission reduction over the reference development for the periods 2010 to 2050 is 24.5% under both CFTL and CUTL scenarios. However, the carbon emission trajectories, as shown in Figure 9.8, indicate minor differences between the two respective scenarios (CFTL, CUTL). In the CFTL scenario, regional emission bounds force smooth stabilization after 2030. On the other hand, the CUTL scenario with flexible timing of imposing the CO_2

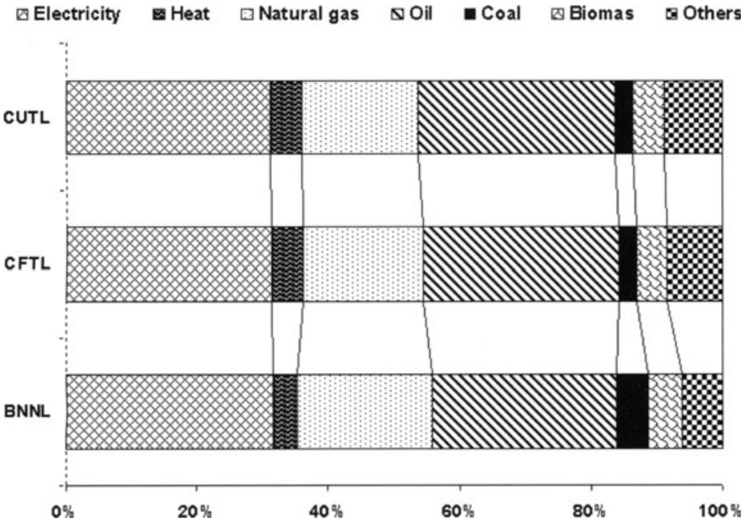

Figure 9.7. Relative fuel shares in total final energy demand in 2050 in selected scenarios.

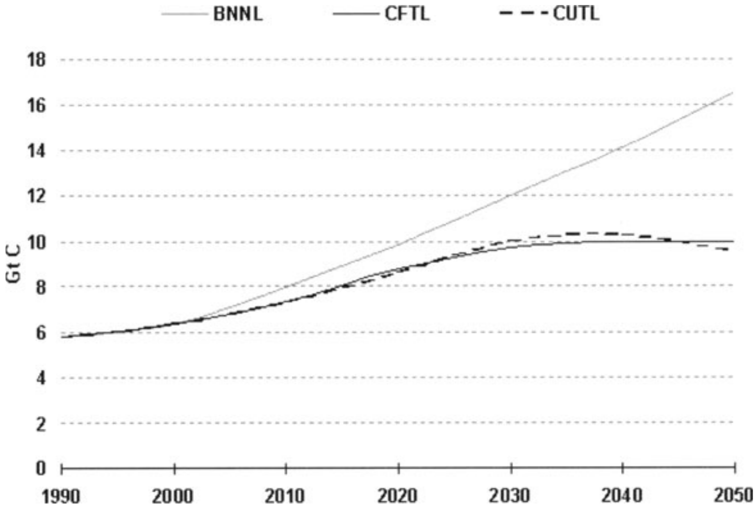

Figure 9.8. Development of total global CO_2 emissions under the baseline and carbon-constrained scenarios.

reduction target projects a stronger reduction in the period of 2050, but allows more emissions in earlier years.

The decarbonization effect can be illustrated by allocating carbon mitigation to different reduction components (Kypreos, 1990), as shown in Figure 9.9.

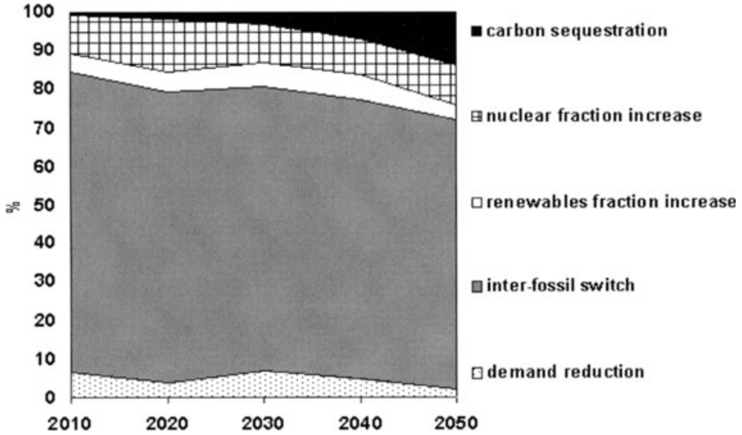

Figure 9.9. Break-down of CO_2 reduction components under CFTL scenario.

Five carbon reducing components were considered: a) inter-fossil switching (i.e., from coal to natural gas); b) reduction of fossil fuel fraction resulting from increases in nuclear energy use; c) reduction of fossil-fuel fraction in favor of renewables; d) carbon sequestration; and finally, e) the reduction of end-use demand as a result of price changes (partial equilibrium). It should be noticed that most of energy conservation measures are included in the exogenous reduction of the energy intensity underlying the B2 baseline case. Over the entire time horizon, the inter-fossil-fuel switching plays a dominant role in carbon mitigation (78% and 69% of CO_2 reduction in 2010 and 2050). Carbon-free primary-energy sources also play an important role in the CO_2 emissions abatement for the CFTL scenario, wherein nuclear energy contributes 10-14% and renewables contribute 4-6% to the total reduction. Reduction in end-use demand contributes to carbon mitigation by 6.8% in 2030, and declines in 2050. Carbon removal and sequestration from fossil fuel combustion starts to play a significant role in the second part of the time horizon. Its share in overall CO_2 reduction in 2050 corresponds to 14%. Although the total potential for carbon sequestration is not bounded in GMM, the cumulative amount of carbon removal and storage in the CFTL scenario (13 GtC/yr during the period 2010-2050) represents only 2.4% of a cumulative potential derived from 'conservative' estimates presented in literature (UNDP, 2000). Considerable variances in total contribution of CO_2 reduction components, in particular the carbon sequestration, can be identified in other studies (e.g., Labriet et al., 2004). They are determined by differences in baselines, emission reduction levels, assumptions of cost and availability of new technologies, resources availability, and price elasticities.

The analysis of economic and policy implication on trade with CO_2 emissions credits is one of a key purposes of this modelling exercise; assumptions related

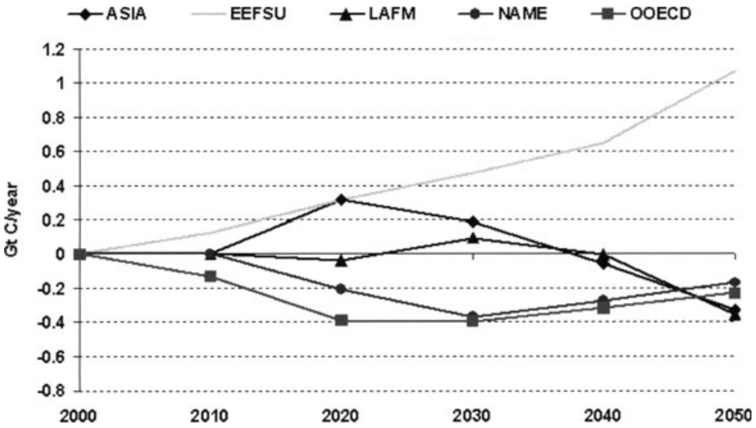

Figure 9.10. Trade of CO_2 emissions permits under CFTL scenario.

to trade specification under the "Soft-landing" scenario are described in Section 4.1.

Figure 9.10 illustrates the development of carbon-emission permits trade within the five GMM regions under the CFTL scenario conditions. The amount of carbon permits globally traded among regions increase from 0.63 GtC/yr in 2020 to 1.07 GtC/yr in 2050. The dominant suppliers of carbon credits are, despite the "hot air" restriction in the first phase, the EEFSU region (cumulative carbon permits supply of 26.4 GtC) and ASIA (over 5 GtC). The main buyer of carbon credits is the OOECD region, with resulting cumulative purchase of 14.5 GtC, followed by the NAME region (10.2 GtC) and LAMF. Towards the end of the time horizon, a switching from a selling to buying position is projected for the developing regions of ASIA and LAFM. This shift can be explained by the strong growth of energy demand based on fossil fuels in the 2030-2050 periods, and by the allocation of CO_2 emission reduction quotas.

The introduction of a cumulative constraint (for the CUTL scenario) raises an important policy question concerning the proper timing of imposing the carbon reduction targets. Recall that, in the CUTL scenario, instead of imposing emission limits for each time period, a cumulative CO_2 constraint is set up for the whole commitment period. The regional emission endowments are as specified for the "Soft-landing" constraint. Trade of CO_2 permits is allowed among the regions, as under the CFTL scenario. As shown in Figure 9.11, the NAME and OOECD regions remain major buyers of the CO_2 permits also in the CUTL scenario, whereas EEFSU region becomes a sole permits supplier. However, the results reveal that the global trade occurs mainly in the periods 2030-2040 which suggests that the regional "Soft-landing" emission targets of CFTL scenario coincide well with the allocation of emission reduction by region and time under the cumulative constraint (CUTL).

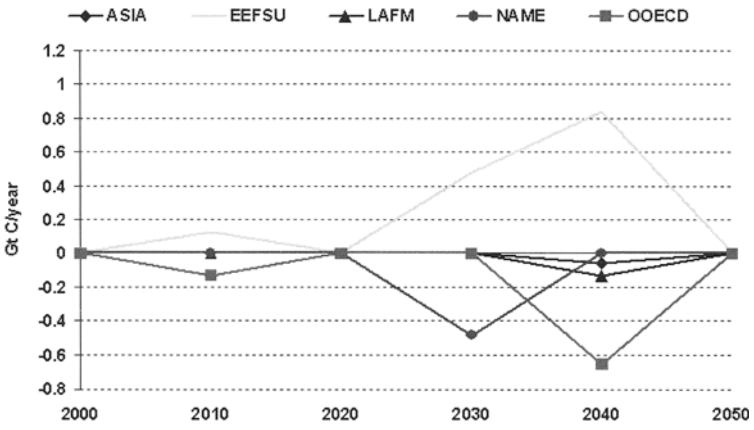

Figure 9.11. Trade of CO_2 emissions permits under CUTL scenario.

5.5 Global indicators

A set of additional indicators has been developed to analysze behavior of the RES for the "Soft-landing" carbon-constrained scenarios. First, the energy intensity (both the primary-energy consumption and the final-energy demand per unit of GDP) is plotted versus time in Figure 9.12. The three main scenarios show similar stronger reduction by the year 2010, followed by a period of slower reduction; annual declination rates of -1.0%/yr for primary-energy intensity and -1.2%/yr for the final-energy intensity are observed for the second phase. The total reduction over baseline in final-energy intensity by the year 2050 is 5.3% for the CFTL case, and 7.2% for the CUTL scenario; these reductions are stronger than for the primary-energy intensity.

In Figure 9.13, the carbon intensity for the global RES is shown that presents the amount of CO_2 emitted per GJ of primary energy consumption for the baseline and the carbon-constrained scenarios. The global carbon intensity for the baseline scenario increases slightly until the year 2030, and subsequently stabilizes as less carbon-emitting sources gain market shares. On the other hand, the decarbonization effects under the CFTL and CUTL scenarios start from the beginning of the time horizon. The carbon intensity follows similar trends in both constrained cases, with the annual declination rate of -0.8%/yr.

Figure 9.14 illustrates, how the carbon reduction specified for the "Soft-landing" scenario target is achieved under different policies by plotting baseline-normalized carbon intensity versus energy intensity based on primary energy, all expressed as a function of time. All carbon-reduction scenarios tend to achieve the target by reduction in carbon intensity; however, projections of how the reference energy system reacts to meet emission reduction targets vary somewhat across scenarios. In scenarios with cumulative constraint (CUTL, CUTN), the reduction in energy intensity grows towards the end of time hori-

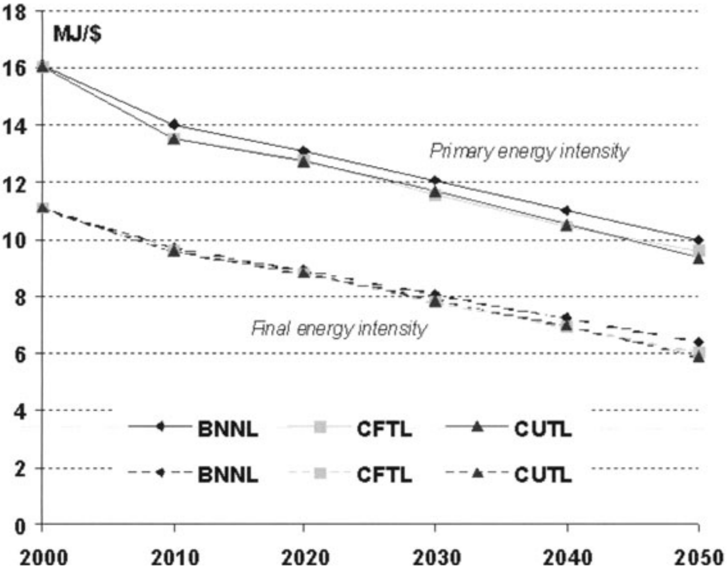

Figure 9.12. Development in primary- and final-energy intensity under baseline and carbon-constrained scenarios.

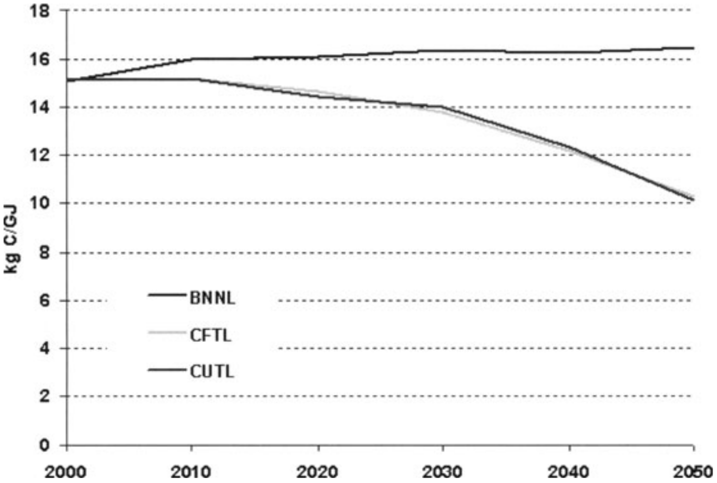

Figure 9.13. Development in the carbon intensity under baseline and carbon-constrained scenarios.

zon, while for the CFTL scenario the contribution of energy intensity reduction in 2050 is decreased. The decrease in energy intensity is the most pronounced

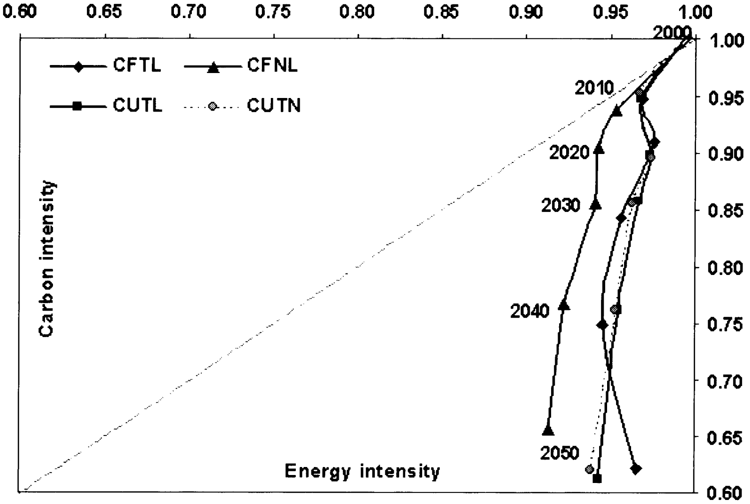

Figure 9.14. Projection of relative changes in energy and carbon intensity for selected scenarios.

in CFNL scenario, where the absence of trade of carbon-emission permits leads to the strongest demand reduction.

Regional comparisons of CO_2 emissions per capita under the CFTL scenario (Figure 9.15) show the highest value of this indicator for the NAME region all over the studied period despite considerable emission-cuts in the last periods resulting from active carbon reduction policies. The values of this indicator for the OOECD region steadily sink after 2000, but at lower values. On the other hand, the EEFSU region experiences an increase up to the year 2020 (see also discussion in Section 4.2) and subsequently declines with a rate -0.08%/yr over the remainder of the time horizon because of the projected changes in the RES and the trade modalities.

5.6 Costs of carbon-mitigation policy scenario

Marginal carbon-abatement costs (equal to carbon emission permit prices) are presented for four selected scenarios in Figure 9.16. Carbon permit prices vary across scenarios and over time. Differences are determined by the level of severity of carbon constraint relative to the baseline scenario, the dynamics of technology change (ETL), and the trade specifications.

In all scenarios, carbon prices increase over the time horizon, without any abrupt changes. Under the CFTL scenario the carbon permit price culminates in 2040 at a value of 110 \$/tC, and is reduced by 30% by the end of time horizon. This reduction is a consequence of LBD. When the ETL option is not active, as in scenario CFTN, the carbon price in 2050 is 29% higher relative to the CFTL scenario. The induced increase in the price of permits in the case

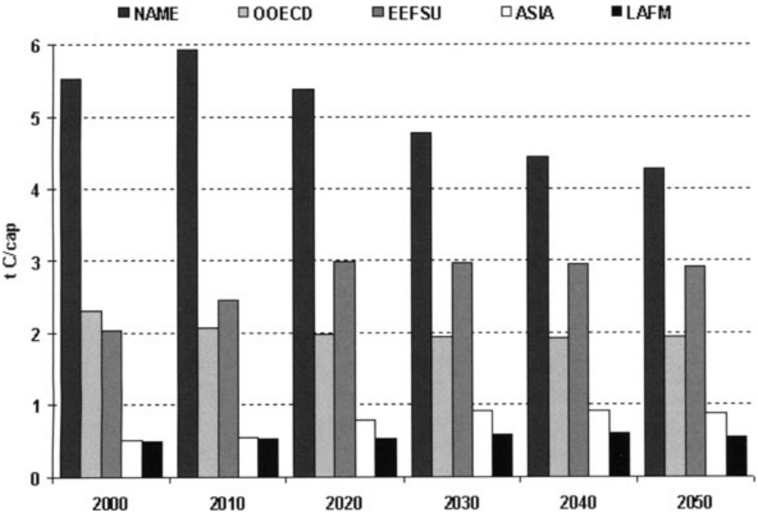

Figure 9.15. Development of regional CO_2 emissions per Capita under CFTL scenario.

without learning (i.e., the CUTN scenario) varies between 31.9% in 2010 and 3.7% in 2050. Figure 9.16 also shows marginal costs of carbon reduction in the CUNL scenario, where inter-regional trade of carbon permits is not allowed. The range of marginal cost in 2050 varies from 41 \$/tC for the EEFSU region to 682 \$/tC for the OOECD region and reflects regional differences in emission reduction potential and severity of emission reduction targets imposed.

Figure 9.17 documents the relative changes of the discounted energy system costs for all the scenarios analyzed as compared to the baseline scenario. The discounted energy system cost together with the welfare loss (sum of consumers and producers surpluses) is increased by 0.46% in the "Soft-landing" scenario when the partial-equilibrium option is applied together with the carbon constraint while the CO_2 permits are traded (CFTL). It rapidly increases further to 1.71% when the global trade in CO_2 permits is excluded (CFNL). On the contrary, in the case of a cumulative carbon constraint with active ETL and trade options (CUTL), the discounted energy system cost is increased by only 0.43%. This result indicates the benefits of less-stringent timing of achieving the carbon-mitigation burden. Finally, if ETL is inactive, as in the CUTN scenario, the energy system costs is increased relative to the BNNL by 0.98%. Changes in the energy system costs and marginal costs of carbon reduction indicated in this section are within the cost range reported by comparable studies (Labriet et al., 2004). Similar findings concerning the effect of LBD are also reported in the literature (Manne et al., 2002). Finally, to give a sense of magnitudes involved, the total discounted system cost is 64.1 T\$ for the baseline BNNL scenario.

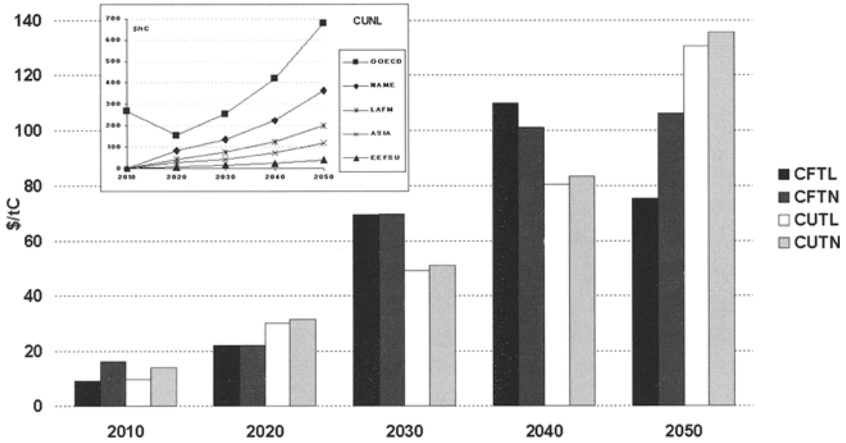

Figure 9.16. Marginal cost of carbon emission permits reported for selected scenarios versus time. Inset: marginal cost of carbon reduction by regions in scenario with absence of inter-regional trade of carbon permits (CUNL).

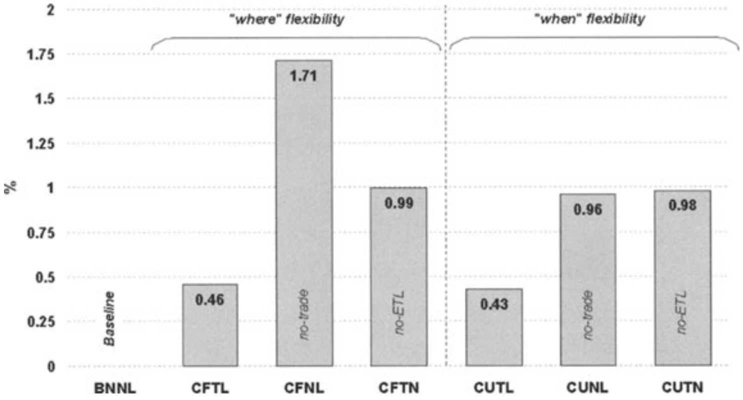

Figure 9.17. Relative change in the cumulative discounted energy system cost over the baseline scenario.

6. Conclusions

This study investigates the implications of the so-called "Soft-landing" scenario for reduction of CO_2 emissions under different policies and quantifies the corresponding structural changes and technology dynamics in the global energy system using the five-region Global MARKAL Model.

The "Soft-landing" scenario has been used to illustrate the important role of spatial, temporal and technology-related flexibility in CO_2 mitigation within the global energy system. Generally, "flexibility" reflects the ability of the global energy system to effect a transition towards a low-carbon, more sustainable form in the long term, while accommodating large technological, social and economic uncertainties. The long-lived infrastructures and technological regimes that typify the global energy system lead to large inertia. Therefore, policies are necessary that facilitate such transition while minimizing associated costs. In this paper, we examined how the emission reduction targets of the "Soft-landing" scenario could be achieved if international emissions trading, alternative timing of CO_2 targets and policies that support technology learning in emerging low-carbon technologies are implemented.

The study quantifies the maximum costs of CO_2mitigation policies that stabilize global CO_2emissions to levels below 10 GtC/yr, to vary between 75 and 135 U\$/tC. Also, differences in the discounted cumulative energy system costs of carbon control, including the associated welfare losses (but excluding the benefits accrued from the mitigation of atmospheric carbon) are low for a range of scenarios. The costs are bounded below 0.43% of the baseline energy-system cost if efficient policies are followed. Otherwise, non-efficient policies (e.g., absence of global carbon permits trade) could increase the cumulative costs to more than 1.7%. Clearly, these results depend on the particular baseline scenario used, as well as specific assumptions about energy-technology dynamics, but the magnitude of these differences illustrate the benefits that flexible mitigation strategies might offer. The cost-related findings presented in this paper are in agreement with results from similar studies analyzing the effects of imposing a target to stabilize CO_2 concentration in the atmosphere at 550 ppmv (e.g., Labriet et al., 2004 also in this volume).

Three types of policies that would increase the flexibility of global CO_2 mitigation and reduce associated costs are identified as follows:

- *Trade of emissions permits or the "where" flexibility:* International trading of emission permits benefits from efficient CO_2 abatement options across the world and contributes to a significant reduction in control cost. However, implementing international co-operation agreements to achieve climate-policy goals appears as a challenging task. Specifically, the participation of developing countries, where a number of development concerns other than climate change have priority in the policy-making agenda, appears to be difficult. For instance, bringing developing regions that rely on cheap coal resources (e.g., China and India) to accept emission reduction obligations will never be an easy policy task. Additionally, it becomes necessary to identify and quantify the synergies that could exist between climate change policies and sustainable-development policies in the developing world (Beg et al., 2002). Furthermore, carbon-mitigation targets imposed on the developing regions have to be defined carefully, while respecting regional social and economic conditions. Assigning generous CO_2 emission quotas to these countries may alleviate the attendant costs of emission reduction, by allowing the sales of emissions permits. It remains as a future scope for the analysis to identify which strategies and international coalitions could be more effective and to explore the ancillary benefits of policies that reduce the risk of climate change.

- *Optimal timing or the "when" flexibility:* For the illustrative "Soft-landing" scenario, allowing for a cost-optimal timing path in selecting CO_2reduction targets can produce additional gains of 7.7% in the cumulative discounted energy system cost as compared to the "where" flexibility scenario. Although the gains resulting from this simulation are relatively low, since the CO_2 targets imposed by the "Soft-landing" scenario and the optimal path in emission reduction estimated by the cumulative constraint are similar, the results of the analysis reported herein illustrate the need to search for optimal timing paths in reducing global CO_2 emissions. Optimal CO_2 mitigation paths should allow for a smooth and cost-effective transition to a low-carbon global energy system, such that an adequate balance is cast between: a) the gradual phase-out of carbon-intensive technologies and, b) the necessary improvement of technical and economic performance of low-carbon emerging technologies and their introduction into the marketplace.

- *Demonstration and deployment of new, low-carbon technologies:* The results reported herein indicate that endogenized technology learning substantially reduces the overall cost of CO_2 mitigation required by the "Soft-landing" scenario; reduction of up to approximately 57% are indicated. However, although models with perfect foresight may indicate that low-carbon energy technologies with promising learning potential would become competitive in the long term, this expectation is probably unrealistic for "real-world" markets. Emerging low-emission technologies (e.g., photovoltaic and fuel-cell systems) at the present stage of development are expensive when compared to conventional fossil-based systems. Furthermore, because knowledge cannot be fully appropriated, short-term-oriented markets are likely to under-invest in those technologies. Market experience, however, is an important factor driving cost and performance improvements of new technologies. Moreover, technological progress requires a substantial amount of time. The introduction of policies to support the demonstration and deployment of low-carbon technologies (e.g., learning investments and niche markets), therefore, is a prerequisite to stimulate their learning process and their successful introduction to the marketplace (PCAST, 1999).

The GMM results presented herein could be extended to consider other greenhouse gases (for studying the "what" flexibility) to define the emission trajectories for climate models and study, for example, changes in CO_2 concentrations, temperature change and sea-level rise induced by different policy instruments. For such purpose, future work could be oriented towards linking GMM with a climate model (e.g., C-Goldstein, Marsh et al., 2002) via the analytical cutting plane algorithm (Beltran et al., 2004) and to coupling

GMM with a simplified macro-economic model (Kypreos, 1996). Doing so, an Integrated Assessment Model (IAM) could result that couples a bottom-up representation of the energy-system linked with a general circulation model in a way that takes into account macro-economic feedbacks. Such an IAM would enable studying the effects of policy actions related to energy and the environment on climate change and the corresponding economic impacts in the context of the NCCR-Climate project.

To make GMM suitable for linkage to a climate model, several enhancements are required, such as the extension of the time horizon to 2100 or beyond, and incorporation of non-CO_2 GHGs either using marginal abatement cost curves (MACs) (e.g., Manne et al., 2001; Hyman et al., 2003) or by endogenizing technologies for control of these other GHGs within the model. Finally, to avoid possible underestimation of ETL effects in non-electric sectors, future work should focus on extending endogenized technology learning to other non-electric sectors (e.g., transportation and fuel production).

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Chapter 10

AIR POLLUTION HEALTH EFFECTS: TOWARD AN INTEGRATED ASSESSMENT

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Abstract In this paper we develop a methodology for integrating the health effects from exposure to air pollution into the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium model of the economy that has been widely used to study climate change policy. The approach incorporates market and non-market effects of air pollution on human health, and is readily applicable to other environmental damages including those from climate change. The estimate of economic damages depends, of course, on the validity of the underlying epidemiological relationships and direct estimates of the consequences of health effects such as lost work and non-work time and increased medical expenses. We apply the model to the US for the historical period ranging from 1970 to 2000, and reevaluate estimates of the benefits of US air pollution regulations originally made by the US Environmental Protection Agency. We also estimate the economic burden of uncontrolled levels of air pollution over that period. Our estimated benefits of regulation are somewhat lower than the original EPA estimates, and we trace that result to our development of a stock model of pollutant exposure that predicts that the benefits from reduced chronic air pollution exposure will only be gradually realized. As modelled, only population cohorts born under lower air pollution levels fully realize the benefits. While other assumptions about the nature of health effects of chronic exposure are possible, some version of a stock model of this type is needed to accurately estimate the timing of benefits of reduced pollution.

1. Introduction

Scientists and policy makers have become increasingly aware of the need to jointly study climate change and air pollution because of the interactions among policy measures and in the atmospheric chemistry that creates the con-

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stituents of smog and affect the lifetimes of important greenhouse gases such as methane. Tropospheric ozone and aerosols, recognized constituents of air pollution, have important effects on the radiative balance of the atmosphere. Existing methods for estimating the economic implications of environmental damage do not provide an immediate approach to assess the economic and policy interactions. Most economic analyses of environmental damages are aimed solely at valuation, often using current values of critical economic data such as wages or medical expenses.

Integrated assessment seeks to understand the feedbacks and interactions among complex systems. For integrated assessment of global environmental change we are interested in impacts in different regions of the world and over long time horizons. Estimates of economic impact of environmental damage, where the value of key economic variables often are drawn mostly from a few countries circa the 1990's, are unlikely to be constant over time or across regions. These values may be difficult to predict with accuracy but models that estimate mitigation costs have not shied away from making estimates. When comparing an estimate of the benefits of avoided environmental damage with the cost of mitigation one would like to use similar assumptions about key economic variables on both the benefit and cost side of the equation. A reason for integrating these effects is thus simply a consistency of valuing them with mitigation costs.

The ultimate goal is a fully integrated model of anthropogenic emissions and mitigation costs, the relevant earth system responses to these forcings, and the feedback on the economy of environmental effects with potential implications for economic activity and emissions. Thus, we are concerned not just with the valuation of impacts, but on how climate or air pollution affect the economy, and thus potentially the emissions of pollutants. As a first step toward that end, we develop a methodology for integrating the health effects from exposure to air pollution into the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium economic model of the economy that has been widely used to study climate change policy (Babiker, et al., 2001; Paltsev, et al., 2003, 2004). In that regard, the EPPA model is representative of a large number of economic models that provide a detailed representation of economic activity that contributes to emissions of polluting substances. We are focused here on the largely neglected part of the problem: how to provide an equally detailed and consistent representation of the economic impact of environmental damage within such a modelling framework. To identify this new version of the model, we refer to it as EPPA-HE (EPPA-Health Effects).

The approach we develop incorporates market and non-market effects of air pollution on human health, and is readily applicable to other environmental damages including those from climate change. We begin with the basic data that supports CGE models, the Social Accounting Matrix (SAM) that includes the input-output tables of an economy, the use and supply of factors, and the disposition of goods in final consumption. We identify where environmental damage appears in these accounts, estimate the physical loss, and value the loss within this accounting structure.

Our approach is first and foremost an exercise in environmental accounting, augmenting the standard national income and product accounts to include environmental damage. Our estimate of economic damages stemming from the health effects of urban air pollution depends, of course, on the validity of the underlying epidemiological relationships and direct estimates of the consequences of these health endpoints such as lost work and non-work time, and increased medical expenses. For this purpose we have used estimated relationships drawn from a large body of work on the epidemiological effects of air pollution and economic valuation of them. We make no claim of creating better estimates of these relationships that in the end are crucial to any economic analysis. Our contribution is to introduce these relationships in a dynamic economic model so that economic valuation of damage over time is consistent with the projected economy.

We apply the model to the US for the historical period ranging from 1970 to 2000. To do this, we simulate the economy with air pollution damages we estimate to have occurred due to the existing level of air pollution during that period. This is an effort in benchmarking the economic model so that the macroeconomic performance of the economy matches the actual historical performance. Once we have the model benchmarked in this manner, we are then able to re-simulate it over the period (or into the future) with other levels of air pollution.

We evaluate estimates of the benefits of US air pollution regulations in the US and compare them to a set of benefit estimates originally made by the US Environmental Protection Agency (US EPA, 1989, 1999). For this purpose, we use the counterfactual level of air pollution (what it would have been without regulation) estimated by the US EPA in their study. This allows us to focus more specifically on how our endogenous valuation approach compares with the more traditional method used by the US EPA. We also estimate the economic burden of uncontrolled levels of air pollution over that period. Here we simulate the counterfactual case of what the economy would have been like if pollution levels had been at their background or 'natural' levels, without any contribution from human activity. This, we argue, is the environmental accounting exercise—comparing the actual economic performance over the period to what it might have been without the high and changing levels of air pollution.

We begin with a description of the EPPA-HE model, identifying the additions we made to the standard EPPA. We next turn to the problem of developing the basic data needed for the model. We then provide the estimates of benefit and burden of air pollution in the US from 1970-2000. We finally offer some conclusions.

2. MIT EPPA-HE

The MIT EPPA-HE model is built on the standard EPPA 4 model extended to include health effects. The EPPA model is a recursive-dynamic multi-regional general equilibrium model of the world economy, which is built on the GTAP dataset (Hertel, 1997; Dimaranan and McDougall, 2002) and additional data for greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and urban gas emissions (Mayer, et al., 2000). The version of EPPA used here (EPPA 4) has been updated in a number of ways from the model described in Babiker et al. (2001). Most of the updates are presented in Paltsev et al. (2003, 2004). The various versions of the EPPA model have been used in a wide variety of policy applications (e.g., Jacoby et al., 1997; Jacoby and Sue Wing, 1999; Reilly et al., 1999; Paltsev et al., 2003). EPPA 4 includes (1) greater regional and sectoral disaggregation, (2) the addition of new advanced technology options, (3) updating of the base data to the GTAP 5 data set (Dimaranan and McDougall, 2002) including newly updated input-output tables for Japan, the US, and the EU countries and rebasing of the data to 1997, and (4) a general revision of projected economic growth and inventories of non-CO_2 greenhouse gases and urban pollutants (Table 10.1).

The base year for the EPPA 4 model is 1997. From 2000 onward, it is solved recursively at 5-year intervals. All production sectors and final consumption are modelled using nested Constant Elasticity of Substitution (CES) production functions (or Cobb-Douglas and Leontief forms, which are special cases of the CES). The model is written in the GAMS software system and solved using the MPSGE modelling language.

Extending the model to include health effects involves valuation of non-wage time (leisure) and inclusion of a household production of health services, which we represent in a simplified diagram of Social Accounting Matrix (SAM) as shown in Figure 10.1. The extensions of the model are highlighted in italic bold. This simplified SAM ignores government, investment, and exports and imports as they are not directly affected by the extensions for EPPA-HE (but are part of the model, and are indirectly affected in simulations). The basic SAM includes the inter-industry flows (input-output tables) of intermediate goods and services among industries, delivery of goods and services to final consumption, and the use of factors (capital, labor and resources) in production. EPPA 4 contains a household production sector for personal transportation that delivers transportation services to final consumption (Paltsev, et al, 2004).

For EPPA-HE we add a household production sector that provides a 'pollution health service' to final consumption to capture economic effects of morbidity and mortality from acute exposure. This household production sector is shown as 'household mitigation of pollution health effects.' It uses 'health services' (i.e. hospital care and physician services) from the SERV sector of EPPA and household labor to produce a health service. The household labor is drawn from labor and leisure and thus reduces the amount available for other uses; i.e. an illness results in purchase of medical services and/or patient time to recover when they cannot work or participate in other household activities. We use data from traditional valuation work to estimate the amount of each of these inputs for each health endpoint as discussed in the following sections. Changed pollution levels are modelled as a Hick's neutral technical

Table 10.1. Countries, Regions, and Sectors in the EPPA Model.

Country or Region	Sectors
Annex B	**Non-Energy**
United States (USA)	Agriculture (AGRI)
Canada (CAN)	Services (SERV)
Japan (JPN)	Energy Intensive products (EINT)
European Union+[a](EUR)	Other Industries products (OTHR)
Australia/New Zealand (ANZ)	Transportation (TRAN)
Former Soviet Union[b](FSU)	**Energy**
Eastern Europe[c](EET)	Coal (COAL)
Non-Annex B	Crude Oil (OIL)
India (IND)	Refined Oil (ROIL)
China (CHN)	Natural Gas (GAS)
Indonesia (IDZ)	Electric: Fossil (ELEC)
Higher Income East Asia[d](ASI)	Electric: Hydro (HYDR)
Mexico (MEX)	Electric: Nuclear (NUCL)
Central and South America (LAM)	Electric: Solar and Wind (SOLW)
Middle East (MES)	Electric: Biomass (BIOM)
Africa (AFR)	Electric: Natural Gas Comb.Cycle (NGCC)
Rest of World[e] (ROW)	Electric: NGCC w/ Sequestration (NGCCS)
	Electric: Integrated Coal Gasification w/ Combined Cycle and Sequestration (IGCC)
	Oil from Shale (SYNO)
	Synthetic Gas from Coal (SYNG)
	Household
	Own-Supplied Transport (OTS)
	Purchased Transport Supply (PTS)

[a] The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).

[b] Russia and Ukraine, Latvia, Lithuania and Estonia (which are included in Annex B) and Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan which are not. The total carbon-equivalent emissions of these excluded regions were about 20% of those of the FSU in 1995. At COP-7 Kazakhstan, which makes up 5-10% of the FSU total joined Annex I and indicated its intention to assume an Annex B target.

[c] Hungary, Poland, Bulgaria, Czech Republic, Romania, Slovakia, Slovenia.

[d] South Korea, Malaysia, Phillipines, Singapore, Taiwan, Thailand.

[e] All countries not included elsewhere: Turkey, and mostly Asian countries.

	Production Sectors	***Household Production***	Final Consumption
Production Sectors	Input/Output ***Medical Services for Air Pollution***	Household Transportation ***Household Mitigation of Pollution Health Effects***	Goods and services ***Pollution Health Service*** ***Leisure***
Factors	Labor, Capital, Resources	***Household labor***	***Total Consumption =Total Factor Income***

Figure 10.1. Expanded Social Accounts Matrix for EPPA-HE. Newly added components in bold italics.

change: higher pollution levels requires proportionally more of all inputs to deliver the same level of health service, or lower levels require proportionally less[1]. Figure 10.2 shows the household production structure with the added components for EPPA-HE in bold italics. The key new additions are (1) leisure as a component of consumption and (2) the Household Healthcare (HH) sector that includes separate production relationships for health effects of each pollutant. The elasticity, σ_L, is parameterized to represent a labor own-price supply elasticity typical of the literature, as discussed in more detail later. The HH sector is Leontief in relationship to other goods and services and among pollutant health endpoints. Mortality effects simply result in a loss of labor and leisure, and thus are equivalent to a negative labor productivity shock.

3. Data and Stock-Flow Accounting

Impacts on health are usually estimated to be the largest air pollution effects when measured in economic terms using conventional valuation approaches, dominating other losses such as damage to physical infrastructure,

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[1] Modeled here as a negative technical change, greater expenditure *due to more pollution* draws resources from other uses and thus reduces consumption of other goods and leisure—more pollution is thus bad. The increased expenditures combat the pollution effects, and do not increase consumption and welfare. Of course, greater expenditure for *a fixed level of pollution* will generate more health benefits.

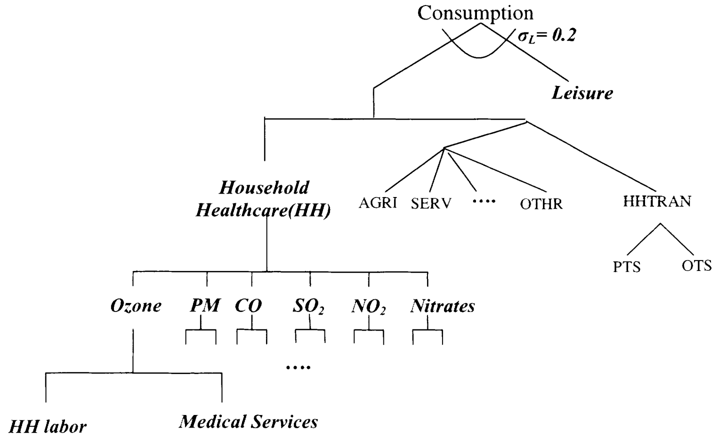

Figure 10.2. Household and Consumption Structure for EPPA-HE.

crops, ecosystems and loss of visibility (e.g. US Environmental Protection Agency, 1999). The health effects of air pollution present themselves as both a loss of current well-being (an illness brought on by acute exposure to air pollution that results in temporary hospitalization or restricted activity) and as an effect that lasts through many periods (years of exposure that eventually lead to illness, and deaths where losses to society and the economy extend from the point of premature death forward until that person would have died of other causes had they not been exposed to pollution.) Thus, we are faced with accounting both for stocks and flows of labor endowment in the economy and the population's exposure to pollution. Health effects also present themselves as both market and non-market effects. Death or illness of someone in the labor force means that person's income is no longer part of the economy, clearly a market effect. Illness also often involves expenditure on medical services, counted as part of the market economy. Death and illness also involve loss of non-paid work time, a non-market impact. This likely involves a loss of time for household chores or a loss of time spent on leisure activities. The health effects area thus is both a large component of total air pollution damages and provides an opportunity to develop methods to handle a variety of issues faced in valuing changes in environmental conditions[2].

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[2] Health effects raise other issues as well, such as non-use value, and interdependency of welfare among individuals, that we do not attempt to address here.

3.1 Epidemiological Relationships

Epidemiological relationships have been estimated for many pollutants, as they relate to a variety of health impacts. The work has been focused on a set of substances often referred to as 'criteria pollutants,' so-called because the U.S. EPA developed health-based *criteria* as the basis for setting permissible levels. These same pollutants are regulated in many countries.

Tables 10.2 and 10.3 are adapted from the Holland et al. (1998) in an extensive study for the European Commission. The reported relationships summarize the known health effects of exposure to these pollutants, building on a data compilation originally started in the US. Table 10.2 contains relationships estimated for a general healthy population, and reflects the fact that some of the relationships differ for children or the elderly as compared with the general adult population. Table 10.3 contains estimated relationships for the population of asthmatics, a group that is more vulnerable to air pollution. Holland et al. (1998) also include a set of estimates for effects they considered less certain. These relationships between health and air pollution have been found to be statistically significant in some studies. However, these were studies of small populations or the relationships have been found statistically insignificant in other studies. We did not include these, but Yang (2004) conducted a sensitivity analysis where he included them. He found these could be quite important, doubling estimates of the damage. Most of his results come from a suspected relationship between elevated CO and mortality.

All of the relationships including those in Tables 10.2 and 10.3 are, of course, subject to uncertainty as to the magnitude of the relationship. The relationships reported in these tables are linear, but there remains considerable debate about whether the relationships may be non-linear in some way. One aspect of this is whether there is a threshold below which pollution has no effect. Another is whether the effects are independent as these simple relationships imply, or instead whether exposure to multiple pollutants might be more or less harmful than the sum of each independent effect. There is not strong evidence supporting a particularly non-linear relationship, although this should be probably understood as just that: absence of evidence for non-linearity rather than evidence that the relationship is linear. An aspect of these estimated relationships in Tables 10.2-10.3 is that they cover the entire population. Any relationship thus reflects to some degree both individual response to varying dose levels and varying vulnerability within the population.

The effects in Tables 10.2 and 10.3 range from hospital admissions due to respiratory problems and restricted activity days (the normal activities of individuals are impaired but no medical care is required) to death due to acute or chronic exposure. The pollutants include tropospheric ozone (O_3), nitrates, SO_2, CO, and particulate matter (PM 10, PM 2.5). The Holland, et al. (1998) study does not identify PM as among the highly uncertain relationships, but subsequent to their review controversy developed around the relationship of mortality and chronic exposure to PM. An earlier study by Pope et al. (1995) cited in the Holland et al. (1998) review was found to suffer from an error introduced by statistical package used to produce the estimates. We have included in Table 10.2 a revised study (Pope et al., 2002) that corrected that error.

The PM relationship has been the subject of contentious debate in the United States as the US EPA moved to strengthen regulations governing fine particulates. Particulate matter, unlike other substances such as CO or O_3, is not a chemically well-defined substance.

It is dust or soot, and is variously composed of organic carbon, black or elemental carbon, and other materials such as sulfur or nitrogen compounds and heavy metals. Thus, while the widely used work by Pope and colleagues finds a relationship between chronic exposure to PM and death rates, particular constituents of PM may be the real culprit. In any case, whereas a pollutant such as carbon monoxide is clearly toxic at high enough levels and has measurable physiological effects at lower levels, clearly establishing the physiological effects of PM on the human body has been more difficult. Since the composition of PM can vary widely, a statistical relationship estimated across different locations with different PM composition may then not hold if one changes the level of PM in a particular location, if one changes PM levels, or if one tries to use the relationship for other locations not in the original sample.

We have not tried in any way to resolve these uncertainties in the epidemiological relationships, but simply use the set reported in Tables 10.2 and 10.3, noting that this is the basis for evaluation of air pollution benefits in Europe and similar assessments by the US EPA draw on these same studies. We separate effects by pollutant and the mortality effects of exposure to PM, to help understand which uncertainties are potentially important for the results.

3.2 Accounting for Health Effects in the SAM

The next step is to turn the impact categories (which are called "health endpoints" in epidemiological literature) into units relevant to our economic model. An economy's SAM, constructed from national income and product accounts and input-output tables, is the base data for a computable general equilibrium model such as EPPA. The data in these tables are interpreted as physical quantities of the goods or factors in the economy. As economic aggregates, however, they must be reported in common units, and currency units (i.e. US dollars) are used in these aggregations. For example, national economic accounting values labor contributions at the wage rate. Thus, the labor force contribution of a high-wage individual working 40 hours per week will be a bigger than a low-wage individual working the same number of hours. Similarly, agricultural output or output of the steel industry is simply the total value of sales of the industry rather than in tons of output. This weights products by their value rather than tonnage or some other unit that would obviously make comparison of computer chips and cement, or haircuts and surgery problematic.

In a similar way, we make use of the traditional economic valuation literature to interpret the components of value as a measure of the quantity of labor or leisure lost, or of the quantity of medical services required to treat the

Table 10.2. Health Effects of Air Pollutants on the General Population. Morbidity units are in [cases/(yr-person-ug/m^3)]. Mortality are in [%Δ annual mortality rate/ug/m^3]. Adapted from Table 8.1 in Holland et al. (1998).

Receptor	Impact Category	Pollutant	E-R fct	Reference
Entire Population	Respiratory hospital admissions	PM 10	2.07E-06	Dab et al 1996, Ponce de Leon 1996
		Nitrates	2.07E-06	
		PM2.5	3.46E-06	
		SO_2	2.04E-06	
		O_3	7.09E-06	
	Cerebrovascular hospital admissions	PM 10	5.04E-06	Wordley et al 1997
		Nitrates	5.04E-06	
		PM 2.5	8.42E-06	
	Symptoms days	O_3	3.30E-02	Krupnick et al 1990
	Acute Mortality	PM 10	0.040%	Spix and Wichmann 1996, Verhoeff et al 1996, Anderson et al 1996, Touloumi et al 1996, Sunyer et al 1996
		Nitrates	0.040%	
		PM2.5	0.068%	
		SO_2	0.072%	
		O_3	0.059%	
	Chronic Mortality	PM 2.5	0.40%	Pope et al 2002
Children	Chronic Bronchitis	PM 10	1.61E-03	Dockery et al 1989
		Nitrates	1.61E-03	
	Chronic Cough	PM 10	2.07E-03	Dockery et al 1989
		Nitrates	2.07E-03	
		PM 2.5	3.46E-03	
Adults	Restricted activity day	PM 10	2.50E-02	Ostro, 1987
		Nitrates	2.50E-02	
		PM 2.5	4.20E-02	
	Minor restricted activity day	O_3	9.76E-03	Ostro and Rothschild, 1989
	Chronic bronchitis	PM 10	4.90E-05	Abbey et al, 1995
		Nitrates	4.90E-05	
		PM 2.5	7.80E-05	
Elderly 65+	Congestive heart failure	PM 10	1.85E-05	Schwartz and Morris, 1995
		Nitrates	1.85E-05	
		PM 2.5	3.09E-05	

health effect. Often this literature constructs the valuation estimates in exactly this manner, identifying a hospitalization day as the medical service and then valuing it at the average cost of a day in the hospital to treat the endpoint, or identifying lost work time, and valuing it at the average wage rate. Other valuation estimates have tried to estimate the total value of the health endpoint

Table 10.3. Air Pollution Health Effects on Asthmatics. Morbidity units are in [cases/(yr-person-ug/m^3)]. Mortality are in [%Δ annual mortality rate/ug/m^3]. Adapted from Table 8.1 in Holland et al. (1998).

Receptor	Impact Category	Pollutant	E-R fct	Reference
All	Asthma attacks	O_3	4.29E-03	Whittemore and Korn 1980
Adults	Bronchodilator usage	PM 10	1.63E-01	Dusseldrop et al 1995
		Nitrates	1.63E-01	
		PM 2.5	2.72E-01	
	Cough	PM 10	1.68E-01	Dusseldrop et al 1995
		Nitrates	1.68E-01	
		PM 2.5	2.80E-01	
	Lower respiratory symptoms (wheeze)	PM 10	6.10E-02	Dusseldrop et al 1995
		Nitrates	6.10E-02	
		PM 2.5	1.01E-01	
Children	Bronchodilator usage	PM 10	7.80E-02	Dusseldrop et al 1995
		Nitrates	7.80E-02	
		PM 2.5	1.29E-01	
	Cough	PM 10	1.33E-01	Dusseldrop et al 1995
		Nitrates	1.33E-01	
		PM 2.5	2.23E-01	
	Lower respiratory symptoms (wheeze)	PM 10	1.03E-01	Dusseldrop et al 1995
		Nitrates	1.30E-01	
		PM 2.5	1.72E-01	
Elderly	Ischaemic heart disease	PM 10	1.75E-05	Schwartz and Morris, 1995
		Nitrates	2.92E-05	
		PM 2.5	4.17E-07	
		CO		

including 'non-market' effects. These are based on methods such as contingent value surveys, asking people their willingness to pay to avoid the health endpoint. Normally, one would expect this to include market effects (lost wages or expenditures on health care) plus some valuation of the non-market effects of illness—pain and suffering and associated loss of enjoyment or attention to household activities because of the illness. We have exploited the components of these valuation estimates: costs related to hospital costs we treat as a demand for medical services, lost work time we treat as a reduction in the labor force (in dollar equivalents), and damages beyond these market effects we treat as a loss of leisure.

Valuation estimates we use are also from the Holland et al. (1998) survey of the literature, and the estimates, converted to US dollars are shown in Table 10.4. For each endpoint related to each pollutant (e.g. respiratory hospital visit due to exposure to ozone), we allocated a share of the total cost to demand for medical service, lost labor, or lost leisure. Not all pollutants are associated with

Table 10.4. Morbidity Valuation Estimates. From Table 12.9 in Holland et al. (1998) converted to 2000 dollars.

Health impacts	Costs in US dollars 2000
Restricted Activity Day	\$106
Respiratory Hospital Admissions	\$11,115
Cerebrovascular Hospital Admissions	\$11,115
Symptoms Days	\$11
Chronic Bronchitis Adults	\$148,296
Chronic Bronchitis Children	\$318
Chronic Cough for Children	\$318
Congestive Heart Failure	\$11,115
Asthma attacks	\$52
Cough	\$318
Lower Respiratory Symptoms (wheeze)	\$11
Ischaemic Heart Disease	\$11,115
Minor Restricted Activity Day	\$11
Emergency Room Visit	\$315
Acute Mortality	\$30,225

all endpoints, but we end up with 50 separate combinations. Based on Yang (2004) and Holland et al. (1998), the allocations for morbidity endpoints are 50 to 85 % for the costs of medical services, 10 to 15% for lost leisure, and the remaining for lost labor. That is, the bulk of morbidity costs are market costs. See Yang (2004) for the complete list, and allocation for each combination. We assume mortality is only lost labor and leisure, the proportion depending on the age at death, and our accounting of leisure time for those in the work force. We discuss the approach for representing these costs in the SAM, and for inclusion of leisure time in greater detail in the following sections.

3.3 Leisure

The two critical questions regarding leisure are: (1) how much, and (2) what is its value? These are intertwined as the relevant quantity for CGE modelling is a total endowment in value terms. How much non-work time to explicitly account is somewhat arbitrary. In much traditional CGE work that includes non-work time, the goal is to represent a labor supply response. An intuitive basis for an expanded accounting of non-work time in that case is an estimate of the maximum potential labor force one could imagine for a given population. For example, Babiker, Metcalf, and Reilly (2003) assumed a value of an additional potential labor force of 25 % of the recorded payments to labor endowment. The estimate is arbitrary to a large degree because the 'known' parameter is the own-price supply elasticity of labor (ε), and from it with the initial non-working share (α) of the labor force one can determine elasticity of substitution between labor and leisure (σ), the critical CGE model variable, via the following relationship:

$$\varepsilon = \frac{\alpha}{1-\alpha}\sigma \tag{1}$$

For a given estimate of ε which we take to be representative of the econometric literature studying price responsiveness of labor supply, a higher estimated α, will simply lead to a lower benchmark value of σ. If benchmarked in this way, to a first order the supply of labor in response to a change in wages will be the same regardless of the potential labor force estimate. Here, we are interested in accounting for loss of labor and leisure time, not only of the existing and potential workforce, but also of children and elderly who are not part of the workforce. We thus estimate non-work time to include all waking non-work time of the current workforce and of children and elderly. We assume the workforce values its leisure at the margin at the wage rate, however, we note (Figure 10.3) that the wage profile for the US rises with age, peaking in the 50-54 age group, and then falls. Based on this wage profile we value loss of children's time at 1/3 the average adult wage rate, and the loss of the elderly's time at 2/3 that of the average adult wage. Aggregating the value of time of children, elderly, non-working, and the non-work time of those in the labor force, we estimate α at 0.55, and based on central estimates the current labor price elasticity of 0.25, we arrive at a value of σ=0.2 as shown in Figure 10.2 [3].

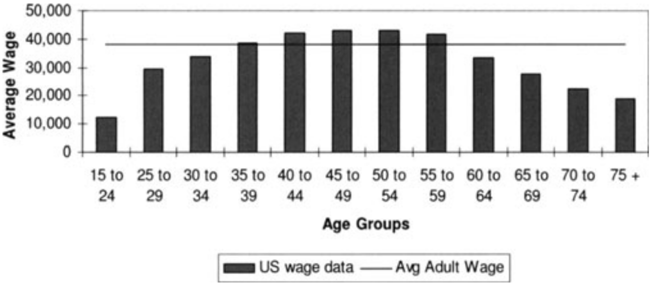

Figure 10.3. US Wage Distribution, Annual Wages. From US Dept. of Labor, 2004.

3.4 Mortality and Chronic Exposure

Air pollution deaths may result from exposure to high levels of pollution experienced during a particularly bad air pollution event (acute exposure), or from exposure over many years from low levels of pollutants (chronic exposure).

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[3] It is not essential that we value all waking non-work time. We could instead have created an estimate of the maximum potential loss from air pollution damages, but the intuition is clearer if we simply include all non-work time. It also automatically facilitates a further expansion of the accounting of non-work time for other household uses or damages.

Death from acute exposure normally only affects those that are close to death from other causes and the commonly accepted loss of time is 0.25 to 0.5 years (Pope et al., 1995, 2002; Holland et al., 1998). We assumed the loss was 0.5 years, and for our purposes this loss can be treated purely as a loss in the current period—a flow accounting of less labor in that period. Deaths due to chronic exposure require more complex accounting. The nature of the epidemiological results is that a reduction in exposure to a given concentration level of pollution should be interpreted as a reduction by that level each year over the lifetime of the individual, i.e. a proportional reduction in cumulative exposure. Since we have a model that we wish to simulate through time, with different levels of the pollutant in each period, we need to (1) explicitly calculate the cumulative exposure over time and how the annual average cumulative exposure is changed because of each year's change in concentrations, and (2) track the change in deaths as they occur over time. The chronic exposure deaths are from PM.

For these purposes, we construct a simple age cohort population model. Mean annual cumulative exposure of cohort n at time t, $\bar{C}_{t,n}$, is the sum of average annual exposure from the birth year, a_n, of the cohort.

$$\bar{C}_{t,n} = \sum_{i=a_n}^{t} \frac{c_i}{t - a_n}, n = 1, \ldots, 8 \tag{2}$$

Cohort age groups are: 1-4, 5-14, 15-29, 30-44, 45-59, 60-69, 70-79, and 80+. The specific formulation is used to be consistent with the underlying epidemiological relationships, as in Pope et al. (2002), that relate the percentage increase in the probability of death (%Δ pr(d)) to mean annual exposure:

$$\%\Delta pr(d) = ERfct * \bar{C} \tag{3}$$

where ERfct is the variable as defined in Table 10.2. And note that mean $\bar{C}$ is not defined by cohort and is simply the average over the entire time period in these studies. Chronic exposure deaths are assumed in this literature to occur only to those over 30, even though exposure accumulates from birth as in equation 2. The epidemiological work does not further resolve the age distribution of death. We were concerned, however, that ERfct may vary with age cohort. Since the estimated change is the increase in the probability of death from all causes, the predicted increase due to PM will depend on the death rate from all causes for each age group. Deaths due to causes such as accidents, crime, childbirth, or infectious diseases, for example, are likely unrelated to PM exposure. Instead we expect deaths from chronic exposure to PM to be from causes like cardiopulmonary disease or disease of the lungs such as emphysema or cancer because such deaths might occur as a result of breathing PM over many years. We thus make the ERfct age-cohort specific by conditioning it on the age distribution of deaths due to cardiopulmonary and lung diseases (cpl) relative to all deaths:

$$ERfct_n = ERfct_T * \frac{\Pr(d : cpl)_n / \Pr(d)_n}{\Pr(d : cpl)_T / \Pr(d)_T} \tag{4}$$

Here Pr (d: cpl) and Pr(d) are, respectively, the annual probability of death from cpl and from all causes, and the n and T subscripts are, respectively, for cohort n and the total over-30 population as whole. For the US, this conditioning ratio rises from about .75 for 30-44 to .9 for 45-60 age cohorts, and then to about 1.25 for cohorts 60-69 and 70-79. It then drops to about 1.15 for the 80+ cohort, apparently as death from 'natural causes' becomes a bigger fraction of all deaths. Conditioning the ERfct in this way thus has the effect of distributing the PM deaths toward the older age groups. This adjustment more gradually phases in the rate of death, rather than assume the risk is zero at age less than 30 and then a proportional increase in the death rate for all age cohorts over 30.

A death at an early age has a continuing effect on accounting of potential labor supply over the period of the remaining expected life of the individual. We assumed those who died in an age cohort were at the midpoint age for the cohort, and that the expected age of death absent chronic exposure was 75. For cohorts over 75 we assume one year of life was lost[4]. To investigate this approach we conducted a model experiment to estimate a 'value of remaining life' that we could compare to more conventional estimates. The model experiment involved running EPPA-HE from 2000 to 2100, assuming 1,000,000 deaths in 2000. The deaths were distributed across age cohorts as if they were due to chronic exposure to PM as we have modelled it (i.e., using equation 4). By 2045, given an assumed lifetime of 75 and no deaths below 30, all of these individuals would have died from other causes. Economic effects continue, however, because with a lower overall level of the economy through 2045, the capital stock is lower in 2045 than it otherwise would have been. We simulate the model through 2100. We are then able to calculate the consumption plus leisure difference between this scenario and a reference without the deaths, calculate the present discounted value of the difference, and divide the result by 1,000,000 to obtain our implicit estimate of the value of a life lost to chronic PM exposure, taking into account remaining average years of life lost. Previous cost-benefit studies use such a value directly, calculating it from studies of the value of life, and assumptions regarding the remaining years of life lost. The net present value through 2100 we obtained was \$0.69 million (3% discount rate) and \$0.67 million (5%) discount rate.

In comparison, Holland et al. (1998) had values ranging from \$0.42 million (3% discount rate) to \$0.38 million (5% discount rate) for the EU. The Holland et al. (1998) study is most directly comparable to ours in that it attempted to

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[4] 75 is an approximate mean of the life expectancy at birth for the period 1970-2000. Life expectancy, given that one has survived to certain age, e.g. 65, is considerably more than 75. For example, on average those who were 65 in 2000 had a life expectancy of 83 in the US according the Center for Disease Control (2004). We used the average life expectancy on the basis that those who suffer death due to chronic exposure are likely more vulnerable to these types of diseases and in the absence of PM exposure were also more likely to have developed these chronic diseases from other environmental factors. The best assumption here is not obvious to us, and more investigation is needed.

explicitly account for the years of life lost. They assumed an average of 5 years of life lost for PM exposure. Our method results in an average of 3 years, but it obviously depends on the specific pattern of exposure—in our model, higher concentrations would lead to earlier death, and more years of lost life, whereas lower concentrations would reduce the number deaths and also result in shifting out the age at death, and so result in fewer years of lost life. Our approach is more structural, and richer in that sense, but in extending the structure in this way the various uncertainties in any such estimate are more apparent: at what age do people die from chronic exposure and how does it depend on cumulative exposure?

The more traditional approach is that of the US EPA (1999), who used a value of $4.8 million per PM mortality. Kunzli et al. (2000) in a study of externalities of transportation in the EU used $1.4 million per PM mortality. US EPA (1999) and Kunzli et al. (2000) use the value of a statistical life based on literature estimates. These are constructed in various ways. Implicitly these may reflect a personal (but unknown) discount rate. These estimates also do not directly consider the years of remaining life lost; i.e. whether the death occurred at 30 or 75 years of age. EPA (1999) identified an alternative calculation where they assumed the average years of life lost from PM was 14, considerably higher then either our estimate or that of Holland et al (1998) but the valuation estimate they used for their primary study was simply that of statistical life, and so was unrelated to this estimate of years lost.

There are of course various methods of valuing life ranging from contingent valuation and wage-risk studies to estimates of lifetime earnings. Our approach is more similar to the latter where we are not claiming to value life, but simply estimating the economic impact of a loss of someone at a particular age, including the lost leisure (household time) valued at the wage rate, assuming individuals are making this tradeoff at the margin.

4. Economic Impacts of Air Pollution: The Case of the US 1970-2000

4.1 Benchmarking EPPA-HE with Historical Pollution Levels

To test EPPA-HE we apply it to the US for the historical period from 1970 to 2000. This allows us to compare our estimates of economic damage from air pollution with estimates from a major US EPA study (US EPA, 1999). The first step in this analysis is to benchmark EPPA-HE to data for the US economy in 1970, with air pollution levels as they existed in 1970, and then reproduce the growth of the economy from 1970 to 2000 given the changing levels of pollution and how we estimate them to affect the economy. Given our parameterization of pollution damage functions in EPPA-HE, and given historical pollution levels, there are damages over the period. The observed economic trends (e.g. GDP, macroeconomic consumption) occurred with those

Table 10.5. US urban air pollution levels, 1970-2000: Actual and Projected Without Control Policies. Concentrations in ppm, except PM10 in μg-m^{-3}. Historical data and projected No-Control Emissions are from US EPA, 1988, 1999, 2003.

	1970	1975	1980	1985	1990	1995	2000
CO-Actual	12.8	11.8	8.8	7.4	6.1	4.8	3.4
CO-No Controls	12.8	12.9	11.1	11.22	10.5	9.19	7.24
NO_2-Actual	0.0231	0.0260	0.0275	0.0246	0.0231	0.0215	0.0195
NO_2-No Controls	0.0231	0.0311	0.0382	0.0383	0.0391	0.0394	0.0391
SO_2-Actual	0.0161	0.0150	0.0150	0.0100	0.0088	0.0060	0.0053
SO_2-No Controls	0.0161	0.0179	0.0219	0.0144	0.0134	0.0094	0.0084
Ozone-Actual	0.153	0.153	0.143	0.125	0.117	0.116	0.103
Ozone-No Controls	0.153	0.168	0.172	0.169	0.175	0.191	0.185
PM10-Actual	79.0	51.3	42.8	28.9	27.0	26.6	25.0
PM10-No Controls	79.0	54.3	55.3	40.9	41.3	44.7	45.6

damages. In this benchmarking step we match projected market GDP growth and returns to labor to the actual historical growth and returns.

Table 10.6. PM10 Concentrations (μg-m^{-3}). From Mintz, 2003.

1923	94.1
1940	105.3
1945	108.6
1950	110.5
1951	111.8
1955	105.9
1960	102.0
1965	92.1
1968	85.5

Because many of the damages involve lost labor, returns to labor is a key variable in our damage estimate[5]. For the economic data we use the Council of Economic Advisors (2003) data. This includes estimates of real GDP growth and the total of wage, salary disbursements, and other labor income

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[5] We have not attempted to rebenchmark the economy sector-by-sector, or use earlier input-output tables and predict the transition from one year's I-O tables to a later set of observed I-O relationships.

as a measure of total returns to labor. We adjusted labor productivity growth and capital accumulation to match these variables at 5-year increments, the standard EPPA resolution, starting in 1970. We used average urban pollution levels (tables 10.5 and 10.6), obtained from the US EPA (1989, 1999, 2003) and assumed the entire urban metropolitan population of the US was exposed to these average levels. Data on the urban population is from US Census Database (2004). Because deaths due to chronic exposure to PM are a function of accumulated exposure over the lifetime of individuals, we constructed an estimate of cumulative exposure of the 1970 population, using data on PM going back to 1923, the longest series we could obtain. For age cohorts alive in 1970, who were born before 1923 we assumed exposure in earlier years was at the 1923 level.

4.2 Counterfactual Simulations—Benefits and Burdens

With this revised benchmark we are then able to evaluate counterfactual scenarios with different levels of pollution. We considered two counterfactual scenarios for the period 1970-2000. One scenario simulated the US economy as if there had been no air pollution regulations over the period. The second scenario simulated the US economy with pollution at background (natural) levels. We then compared these counterfactual cases to the simulation with emissions at their actual historical levels. In the first case, we obtain an estimate of the benefits of air pollution regulations, the benefit side of a cost benefit analysis of these policies. In the second case, we are able to assess the burden on the economy of the air pollution that existed. It is an exercise in environmental accounting—what was the effect of air pollution on the economy in each year and how was growth over the period affected by changing pollution levels. For the benefit analysis we used US EPA (1989, 1999) estimates of what pollutant concentrations would have been without regulations, as summarized in Table 10.5. Seinfeld and Pandis (1998) report background (natural) pollution levels in ppm of CO, 0.05; Ozone, 0.01; NO_2, 0.00002; SO_2, 0.00002, and in μm^{-3} of PM10, 0.001. We have assumed background levels at 1 percent of the 1970 average US urban levels.

4.3 Results

The benefits from air pollution regulation rose steadily from 1975 to 2000 by our estimate (Figure 10.4). The rise results from reductions in emissions that were particularly large between 1975 and 1985, especially for ozone and PM. These pollutants are by far the largest sources of damage/benefit, as discussed further below. This reflects the relatively serious and numerous health effects due to exposure to these two pollutants based on existing epidemiological estimates. The EPA projected emissions do show some reduction over the period even in the absence of pollution regulations. The main sources of these pollutants are the combustion of fuels which were generally increasing.

The reduction therefore reflects a general improvement of technology and other factors, such as change in fuel mix, regulations, etc. If it had been assumed that emissions coefficients per unit of fuel burned would have remained at their 1970 levels without pollution control regulations, then emissions of all substances would have increased over the period and the estimated benefits would have been much larger.

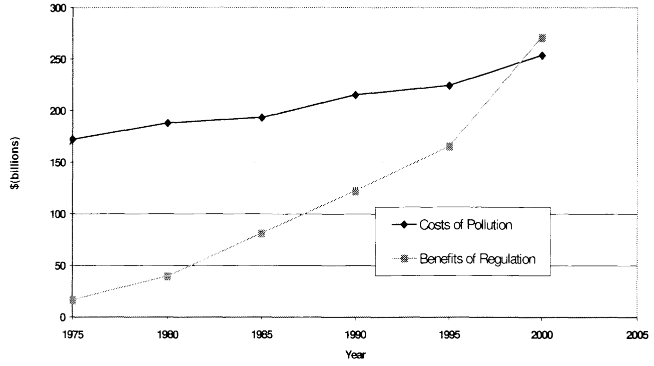


Figure 10.4. Remaining Costs of Pollution; Benefits of Air Pollution Regulation.

Benefits in terms of *additional market consumption* rise to about 3.3% of *total market consumption* by 2000. *Additional market consumption + leisure* rise only to about 2.1% of *total consumption + leisure* value in 2000, but of course both the numerator and denominator are larger than the market consumption estimate alone. How much of leisure time to include in the expanded accounting of the economy is somewhat arbitrary, as noted previously, and so a better comparison of percentage loss may be *additional market consumption + leisure* as a percent of *market consumption* only: this rises to 5% by 2000. One aspect of the expanded accounting worth noting is how it affects the income constraint in a willingness to pay sense. A true willingness to pay estimate of benefits should be income constrained. In our approach, benefits are not necessarily constrained by market income but by the total resources available to the household including market income plus the value of leisure. This is entirely reasonable in our judgment. Faced with illness or death to a member, households will use their non-market resources as well as income to combat the disease, and thus exhibit a willingness to pay (or use) these resources.

The remaining costs of pollution over the period are less dependent on a projection of a counter-factual case. Essentially background levels of pollution are so low that little damage occurs—slightly different assumptions about background levels would thus have little effect on our estimates. In this case, we move to background pollution levels beginning in 1975, and so we see (Figure 10.4) high costs of pollution in 1975. Because the actual pollution levels are falling over time, due to regulations, exposure to pollution per person is falling.

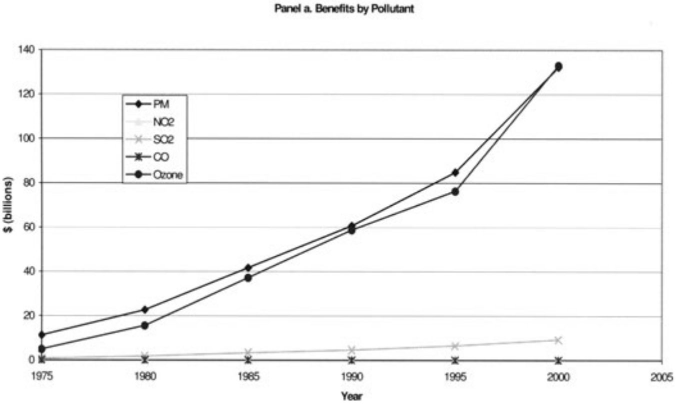
This alone would reduce pollution costs over time. The urban population is growing slowly, but the more important factor is that the economy and wage rates are growing over the period. As the value of lost work and leisure rise over time, the absolute economic cost of pollution actually rises slightly over the entire period, despite a substantial decrease in the level of pollution.

Falling pollution levels are reflected in the percentage losses. Damages in terms of *lost market consumption* are about 3.3% of *total market consumption* in 1975 and this falls to 2.5% by 2000. *Lost market consumption + leisure* rise as a percentage of *total consumption + leisure* is somewhat lower (2.7% in 1975 falling to 2.0% in 2000). *Lost market consumption + leisure* as a percent of *market consumption* only falls from 6.9% in 1975 to 4.7% in 2000. Since the total consumption and total consumption+ leisure also reflect growing population and income, we see the percentage loss decreasing even though the absolute loss is rising over time.

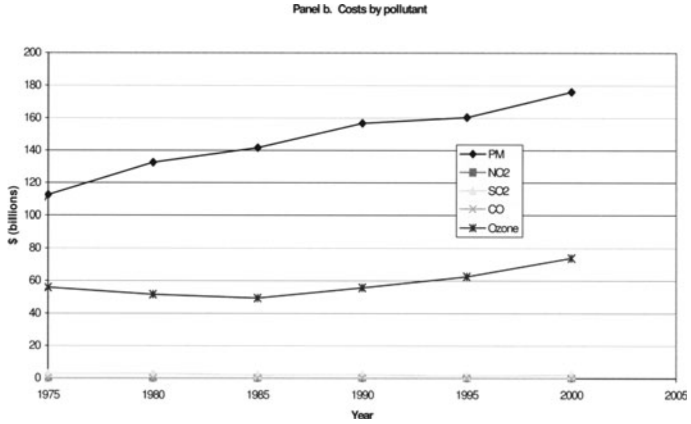
One aspect of the pollution calculation is worth noting with regard to chronic mortality effects in the air pollution cost burden estimate. We assumed mortality fell to 0.01% of what it was in 1970 under actual historical levels of PM. This implicitly assumes that the entire population alive in the 1970-2000 period had been exposed to "background" levels of PM their entire lives—including the pre-1970 period. This captures much of the cumulative effect of earlier exposure. In reality, accumulated mortalities from circa 1900 to 1975 would have been avoided as well if there had been much lower PM, and so the economy would have been larger still in 1975 than in our counterfactual case. To make such a calculation would require extending our demographic model and EPPA-HE back to that much earlier date, and data limits prevented us from doing that.

Figure 10.5 shows the benefits and costs by pollutant. We made this calculation by running the historical case, setting each of the pollutant levels in turn to their "no control" or "background" level. Since there is the possibility of interaction effects within the economy, these separate calculations do not necessarily have to add up to the total estimates when all pollutant levels are changed at the same time. In fact, the sum of the separately calculated pollutants add up to within at most 1.2% of the estimate when all pollutants are changed at the same time, and so the effects are nearly linear and this decomposition method is quite accurate. As noted earlier, PM and ozone give by far the largest effects. In the benefits calculation ozone and PM benefits are very similar. In the costs case, however, the remaining costs of PM are higher than the remaining costs of ozone by a factor of about 2. NO_2 and SO_2 costs are so low relative to PM and ozone that the plots are indistinguishable from zero and lie nearly atop one another.

Mortality due to chronic exposure to PM remains particularly controversial. We estimated these effects separately by running the PM-only scenarios, with and without the chronic mortality effects. In the benefits calculation, mortality due to chronic exposure to PM starts out in 1975 as 5% of PM benefits and rises to just over 50% in 2000. The effects rise rapidly over the period because of the



(a) Benefits by Pollutant



(b) Costs by Pollutant

Figure 10.5. Benefits and Costs by Pollutant.

stock nature of accumulating exposure. The small initial reductions, with substantial accumulated historical exposure, only slightly reduces the deaths due to chronic exposure. The reductions accumulate as people are exposed to lower PM levels over an increasing number of years and the benefits grow rapidly. The PM pollution costs for mortality exhibit a very different pattern, because we assume mortality drops to 0.01% of what it would have been, thereby implicitly assuming that these low levels of PM had existed over the entire lives of those alive in 1975. As already noted, if we were able to consider the current (1970-2000) economic effects of mortality in the pre-1970 period, the mortality costs would be larger.

4.4 Comparison to EPA Benefit Study

This method of estimating benefits and costs is relatively novel. EPA cost-benefit studies of air pollution regulations (US EPA, 1989; 1999) used a more conventional benefit valuation method. For the same set of pollutants, they estimated total benefits in 2000 dollars of $27.6 trillion over the 30-year period, 1970-2000. That compares to our estimate of $3.5 trillion, which we get by summing and multiplying our estimate by 5 (to interpolate for years in between our 5 year model runs). Two important factors in the difference between our estimates and EPA's are that we have (1) taken into account the gradual effects on mortality of lower levels of PM, and (2) accounted for the value of the loss of life in terms of annual loss of labor and leisure. In terms of a policy benefit calculation to be compared with costs borne in the period, our approach undercounts the total benefit of the pollution reductions, but the EPA's approach may overcount them.

Our undercounting stems from the fact that the remaining value of a saved life should be counted as part of the benefit of the policy in that period, even that part of the flow of benefits that extends beyond the accounting period. If a building or other asset is destroyed, its value is lost immediately, and a death is analogous to that situation. The number of lives saved in the period may, however, be overcounted by EPA's approach because the death rate falls as if everyone had been exposed to the new lower levels all of their lives. We track the gradual improvement over time. The $3.5 trillion was the result, however, of a model run only to the year 2000, and so it does not include the post-2000 benefits.

To get a more complete estimate of the future (post-2000) benefits of lower pollutant levels during the 1970-2000 period related to chronic exposure, we simulated the model forward to the year 2070 under the following conditions. We assumed that post-2000 pollution levels were the same in both 'actual' and the 'no control' cases. All we observe as a result is the remaining flow of benefits from the different levels of pollution in these two cases in the historical (pre-2000) time period. The result is an additional, undiscounted, sum of $17.1 trillion for a total undiscounted cost of $20.6 trillion. This is very similar to the US EPA estimate. It is somewhat lower, and this is not surprising given that our 'average' undiscounted mortality loss was valued at $0.72 million whereas EPA valued a mortality loss at $4.8 million. We previously reported the 3% and 5% discounted value; our estimate of $0.72 is taken from that simulation, but without discounting.

While the EPA life value estimate may include an implicit discount rate, the value of lives implicitly saved years in the future should be discounted. EPA's long run equilibrium calculation does not allow that to be considered, whereas with our stock-flow accounting we identify deaths by age cohort, and when in time they occur (and would be avoided or delayed by a pollution policy). Thus, we discount the \$20.6 trillion at 3% and 5%. The discounted benefit is \$6.5 and \$3.9 trillion, respectively. If our estimate of years of life lost is in the right range, discounting has little affect on the value per life saved because the value is only discounted 3 years on average. Thus, this big difference mainly reflects the fact that many of the lives apparently saved in EPA analysis during the 1970-2000 period would only be saved in the fairly distant future. Their benefit is that accumulated lower chronic exposure means they are less likely to develop diseases like heart and lung disease late in their lives. These values should be discounted in a proper cost benefit analysis. We also would argue that it is more appropriate to use the explicit accounting of years of lost life, rather than simply using the value of statistical life. That said, there are a number of caveats that must accompany our estimates. The years of remaining life estimate we arrive at may be low, and we had to make a variety of assumptions to generate a profile of deaths by age cohort that go beyond the underlying epidemiological estimates. Our valuation approach is not necessarily as inclusive as a contingent valuation measure that may include other 'non-use' values. Our goal was not to estimate the value of a statistical life, but instead to estimate the economic impacts of saving a life, expanded to include a value of non-work time saved. But, the difference between our results and EPA's appears less due to the fundamental value one places on saving a life, and more the result of our stock flow accounting and explicitly counting years of life saved (however valued) rather than simply a life, with no discrimination as to whether that involved saving 50 or 5 years of life.

5. Summary

We developed a method for endogenously calculating the economic impacts of the effects of air pollution on human health. This involved expanding the underlying economic accounts to include leisure, including a household health sector that used medical services and household labor to mitigate the health effect of air pollution. We also developed a simple age cohort model to track cumulative exposure to particulate matter because the epidemiological literature finds increased death rates due to chronic exposure. The explicit accounting for cumulative exposure turns out to be quite important in valuing the benefits of air pollution regulation because it affects when those benefits would be realized. It also allows us to estimate how deaths in different age cohorts would change, and thus the number of years of life saved by a pollution policy. The approach was implemented in a version of the MIT EPPA model, EPPA-HE.

The ability to endogenously calculate benefits and impacts of environmental change has great promise, only partially realized in this initial exploration. Ultimately extended to other regions, it automatically values changes consistent with the economic variables for different countries and as those values change in the future under different assumptions of economic growth and policies. There are also feedbacks on emissions and other economic variables that may be important for some problems such as climate change. The methodology thus has a richer set of applications, and can assure greater consistency in economic modelling scenarios, than traditional benefit estimation.

We applied the model to the US for the period 1970-2000. This involved first re-benchmarking the model to replicate the macroeconomic performance of the economy with the air pollution health effects. We were then able to simulate counter-factual cases. One involved a "no emissions control" case—what emissions would have been had the air pollution regulations of the Clean Air Act never been put in place. A second counter-factual case involved the assumption that the urban population experienced only background levels of the pollutants that would exist if there were no emissions from industrial sources. The first scenario allowed us to estimate a benefit of air pollution regulations. We found that the benefit rose to over $250 billion per year by 2000, and equaled about 5% of total macroeconomic consumption in the year 2000. The total benefits realized over the period equaled $3.5 trillion, a large benefit but much less than the US EPA estimate of $27.6 trillion. To our estimate we must add a present value estimate of the benefits from reduced cumulative exposure during 1970-2000 that will only be realized after 2000. If we do not discount this amount, our total estimate is comparable in magnitude the US EPA estimate, but discounted at 3% our total benefit is $10 trillion, and at 5% is $7.4 trillion.

The case of pollution levels at background levels allows us to estimate the remaining burden of air pollution. In absolute dollar terms this has been high and gradually rising over the entire period (from about $175 to $250 billion per year from 1975 to 2000). It has fallen as a percentage of the economy (from 6.9 to 4.7% between 1975 and 2000), however, mostly because pollution levels have fallen due to regulation. It continues to rise in absolute terms because the wage rate and the urban population are rising and so more people are exposed and the value of lost time has risen. Properly accounting for the stock nature of chronic exposure would require us to re-simulate the economy from circa 1900, and data did not allow that. The estimate of burden to the economy during the 1970 to 2000 period does not, therefore, include an estimate of effects due to mortality that occurred prior to 1975, but would have had continuing economic effect into the study period.

In terms of both benefits and remaining burden, the effects of tropopsheric ozone and particulate matter are the most important in terms of our estimate of economic impact. CO, NO_2, and SO_2 effects were quite small in comparison. Mortality due to chronic exposure to PM is an important component of the costs, and this is one of the more controversial health effects of pollution. In the benefits calculation, much of this occurs after 2000 but it has become an important component even by 2000. In the burden calculation mortality is important over the whole period.

There remain a number of caveats that must accompany these results. We have not investigated in detail the underlying epidemiological estimates, and there remain uncertainties and controversies surrounding these. Our estimates are only as accurate as these underlying relationships. Never-the-less, our estimates are comparable to existing benefit estimates, and the differences are mostly the result of key improvements we have made in accounting for chronic exposure effects.

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Chapter 11

CARBON TAX AND INTERNATIONAL EMISSIONS TRADING: A SWISS PERSPECTIVE*

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Abstract. This paper assesses the economic impacts of the Swiss climate policy formulated under the Kyoto Protocol; the impacts on the carbon price, the welfare cost, and trade effects are examined. Our analysis is based on a multi-sectoral and multi-regional, computable general equilibrium (CGE) model of the world economy (GEMINI-E3) which includes a representation of the Swiss economy. The model is used to evaluate the economic costs incurred in reaching the Swiss emission target through a CO_2 tax, and/or by joining a EU-wide emission trading regime.

1. Introduction

Having ratified the Protocol on 9 July 2003, Switzerland is now committed to reducing greenhouse gases (GHG) emissions by 8 per cent from 1990 levels between 2008 and 2012. To comply with its commitment, a new Federal law on CO_2 was approved by the parliament on October 8th 1999, and put into force on May 1st 2000. According to the CO_2 federal law, which contains a "legally binding" target of 10 per cent reduction in CO_2 emissions by 2010 compared to 1990, the reduction targets are to be achieved by a policy mix that combines different instruments: CO_2 relevant measures taken in other policy sectors (e.g. distance and weight dependent heavy vehicles fee HVF, Energy Law, "SwissEnergy" programme); voluntary measures by the business community; subsidiary CO_2 tax introduced as of 2004 earliest allowing for companies to exempt themselves by signing a reduction commitment; and flexible mechanism

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provided in the Kyoto Protocol. The implementation of emissions trading for CO_2 emissions might take place at the Swiss level or within a EU-wide emissions trading regime.

In this paper, we assess the economic impacts of alternative climate change policies to comply with the Kyoto commitment in Switzerland. We address in particular the following questions: 1) What would be the cost of the Kyoto commitment if Switzerland does not participate in the flexibility mechanisms of the Kyoto Protocol? 2) Since Switzerland will be impacted by decisions both at home and abroad, what would be the economic effects of implementing an international emissions trading system in the European Union? 3) What would be the effects of joining the EU market for tradable emissions permits? 4) Finally, is the Swiss CO_2 law consistent with the Kyoto target?

Various models have been developed to assess climate change policies in Switzerland. Using a bottom-up model of the energy system, the Swiss Markal model, Bahn et al., 1998 have estimated the cost of curbing CO_2 emissions in Switzerland by 10 percent in 2010 through a carbon tax. According to the authors, the carbon price might be around 182 Swiss francs per tonne of CO_2 (CHF/tCO_2). Using a dynamic-recursive Computable General Equilibrium (CGE) model for Switzerland (GEM-E3 Switzerland), Bahn and Frei, 2000 have estimated that the carbon tax associated with a 10 percent reduction of CO_2 emissions by 2010 might range from 83 to 103 CHF/tCO_2 in 2010. Kumbaroğlu and Madlener, 2003 have developed a hybrid model combining a detailed bottom-up representation of the electricity sector with a CGE model (SCREEN) for Swiss climate policy analysis. In this study, the tax required to achieve the 10 percent emissions target comes close to the cap of 210 CHF/tCO_2.

None of these models is able to represent an international market for tradable emissions permits, and to capture the international trade effects of climate change policy choices. Since GEM-E3 Switzerland and SCREEN are "stand-alone" models with all foreign countries included in a single "Rest of the World" region, the international carbon price has to be set exogenously without representing international emissions trading. Moreover, the different models represent Switzerland as a small open economy having negligible impacts on world prices. Consequently, these models do not take into account the trade effects on foreign and domestic climate policies. It has been shown elsewhere, however, that carbon policies may have a significant impact on welfare through changes in the terms of trade (Babiker et al., 2003; Bernard and Vielle, 2003; Viguier et al., 2003; Babiker et al., 2004). The cost of the Kyoto target will not only depend on policy choices in Switzerland but also in other Annex B countries, in particular in the European Union. To represent these climate policy interactions, we have opted for another modeling framework that includes a detailed representation of the Swiss economy in a multi-regional CGE model of the world economy.

We begin by describing our modeling approach to assess Swiss impacts of the Kyoto Protocol agreement, and to compare the carbon prices and welfare costs of the different policy scenarios. We then review some of the assumptions made to calibrate the GEMINI-E3 model and to define the baseline scenario created to examine the economics of CO_2 emissions for Switzerland. Finally, we present and discuss the simulation results, including the impact of policy choices on efforts to reduce emissions, carbon price, welfare cost, and terms of trade.

2. The GEMINI-E3 Model

In this section, we provide some information about the model, the data needed to build and calibrate the GEMINI-E3. We also present the baseline scenario, where CO_2 emissions are not limited.

2.1 Modeling Framework

The name of GEMINI-E3 was first used for a Computable General Equilibrium Model developed jointly by the French Ministry of Equipment and the French Atomic Energy Agency (CEA) under the supervision of Alain Bernard (Bernard and Vielle, 1998). The GEMINI-E3 is a multi-country, multi-sector, dynamic-recursive CGE Model that incorporates a highly detailed representation of indirect taxation. This version of GEMINI-E3 is formulated as a Mixed Complementarity Problem (MCP) using GAMS with the PATH solver (Ferris and Pang, 1997; Ferris and Munson, 2000). A detailed description of the model is provided in Appendix A.

For purposes of appraising energy policies directly involving the electric sector (e.g. implementation of nuclear programs), the model incorporates a technological sub-model of power generation that is better suited for comparing investments in different kinds of plants. It is the third GEMINI-E3 version in this succession that has been especially designed to calculate the social marginal abatement costs (MAC, i.e. the welfare loss of a unit increase in pollution abatement), and then to simulate tradable emission permits markets based either on market prices (carbon tax) or on social marginal costs.

The original version of GEMINI is fully described by Bernard and Vielle, 1998. Updated versions of the model have been used to analyze the implementation of economic instruments for GHG emissions in a second-best setting by Bernard and Vielle, 1999, to assess the economic impact of the US withdrawal from the Kyoto Protocol by Bernard and Vielle, 2002, and to analyze the behavior of Russia in the Kyoto Protocol by Bernard et al., 2002; Bernard et al., 2003. Table 11.1 gives an overall description and the main characteristics of the model. Beside a comprehensive description of indirect taxation, the uniqueness of the model is to simulate all relevant markets: e.g. commodities (through relative prices), labor (through wages), and domestic and international savings (through rates of interest and exchange rates). Terms of trade (i.e. transfers of real income between countries resulting from variations of relative prices of imports and exports), and then "real" exchange rates can then be accurately modeled.

Table 11.1. Dimensions of the GEMINI-E3 Model

Countries or Regions		**Sectors**
Annex B		***Energy***
Germany	DEU	01 Coal
France	FRA	02 Crude Oil
United Kingdom	GBR	03 Natural Gas
Italy	ITA	04 Refined Petroleum
Spain	ESP	05 Electricity
Netherlands	NLD	***Non-Energy***
Belgium	BEL	06 Agriculture
Rest of EU-15	OEU	07 Mineral products
Switzerland	CHE	08 Chemical Rubber Plastic
United States	USA	09 Metal and metal products
Japan	JAP	10 Paper Products Publishing
Eastern Europe[a]	CEA	11 Transport n.e.c. (road and railway)
Canada, Australia, and New Zealand	CAZ	12 Sea Transport
Former Soviet Union	FSU	13 Air Transport
Non-Annex B		14 Other Goods and services
China	CHI	
Brazil	BRA	***Household Sector***
India	IND	
Middle East and Turkey	MID	***Primary Factors***
Asia	ASI	Labor
Latin America and Mexico	LAT	Capital
Rest of World[b]	ROW	Energy
		Fixed Factor (for sectors 01-03)
		Other inputs

[a] Includes Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, and Slovenia.
[b] All countries not included elsewhere (mostly Africa).

The household demand function is described by a linear Expenditure System (LES) derived from the Stone-Geary direct utility function (Stone, 1983). The model employs a convention that is widely used in modeling international trade: the Armington assumption (Armington, 1969). Under this convention a domestically produced good is treated as different commodity from an imported good produced in the same industry. Indirect taxation and social contribution rates are differentiated by commodity (taxes on production, on imports), by sector (social contributions, subsidies), by sector × commodity (intermediate consumption), by commodity × institutional sector (final demand), and by commodity × sector × IS (investment, savings).

Time periods are linked in the model through endogenous real rates of interest determined by the equilibrium between savings and investment. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses.

The main outputs from the GEMINI-E3 model, by country, annually are: carbon taxes, marginal abatement cost and price of tradable permits when relevant - effective abatement of CO_2 emissions, net sales of tradable permits (when relevant), total net welfare loss and components (net loss from terms

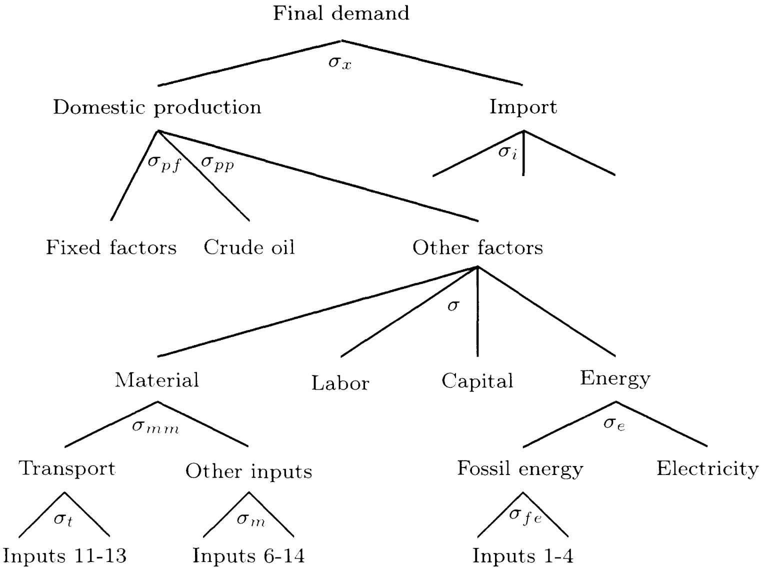

Figure 11.1. Structure of the Production Sector in GEMINI-E3

of trade, pure deadweight loss of taxation, net purchases of tradable permits when relevant), macroeconomic aggregates (e.g. production, imports and final demand), real exchange rates and real interest rates, and industry data (e.g. change in production and factors of production).

2.2 Calibration

The new version of GEMINI used in this paper is built on a comprehensive energy-economy data set, the GTAP-5 database (Hertel, 1997), that expresses a consistent representation of energy markets in physical units as well as a detailed Social Accounting Matrix (SAM) for a large set of countries or regions and bilateral trade flows.

Figure 11.1 represents the structure of the production sector in the model. Production technologies are described using nested CES functions. The default values for elasticity parameters are reported in Table 11.2.

2.3 Reference Case

The reference case for the different regions, with the exception of Switzerland, were closely calibrated against projections of CO_2 emissions, energy consumption, GDP, and population, as provided by the Energy Information Administration, 2003, the International Energy Agency, 2002a and 2002b, the World Bank and the United Nations.

Table 11.2. GEMINI-E3 Default Parameters

Parameter	Sector	Value	Parameter	Sector	Value
σ	All	0.30	σ_t	All	0.60
σ_{pf}	All	0.20	σ_m	All	0.20
σ_{pp}	All	0.10	σ_x	01	2.00
σ_e	All	0.40		02	10.00
σ_{ef}				03	2.00
	01 to 04	0.10		4, and 06 to 10	3.00
	03	0.10		05	0.50
	04	0.10		11 to 13	0.10
	05	1.50		14	1.50
	06 to 08, 10, and 14	0.90	σ_{mm}	All	0.20
	09, and 11 to 13	0.30	σ_{ai}	2	10
σ_{mm} All	0.20			1, 3-14	2

In the case of Switzerland, we have defined a baseline scenario that includes existing laws and regulations that have an impact on future CO_2 emissions in Switzerland. This baseline is fully consistent with population, GDP, energy consumption, and CO_2 emissions growth projected by the Swiss government in a scenario "with measures implemented" (Bundesamt fur Energie, 2001; United Nations Framework Convention on Climate Change, 2002). Our baseline scenario, which is based on this "official scenario" including existing laws and regulations that are likely to have an effect on energy consumption and carbon emissions, is built on three essential assumptions (United Nations Framework Convention on Climate Change, 2002):

- The economic and demographic framework develops as expected; the annual average GDP growth rate is expected to be 2.1% from 2001 to 2010, and 1.6% from 2010 to 2025.
- Energy efficiency increases gradually in response to energy legislations and energy efficiency programmes (e.g. the Federal programme entitled "Energy Switzerland").
- Nuclear power capacity is maintained at present level until existing nuclear plants reach the end of life, and electricity purchasing agreement are renewed (e.g. imports from France), so that the penetration of modern gas-fired power stations or combined heat and power installations can be limited.

As shown in table 11.3 and figure 11.2, this baseline scenario is characterized by a medium GDP growth rate combined with low energy consumption and CO_2 emissions. It means that we assume a relatively high increase of energy efficiency but limited changes in the fuel mix for the reference case. In this baseline case, it is assumed that Switzerland will not be able to reach its Kyoto target on the basis of existing trends (United Nations Framework Convention on Climate Change, 2002). This reference case is close to the "high growth" variant

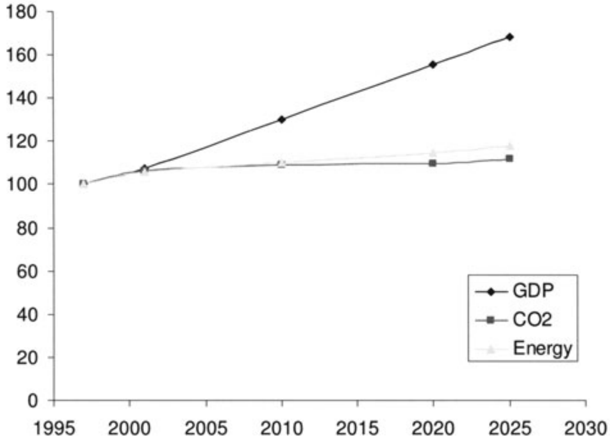

Figure 11.2. Projected GDP, CO_2 Emissions, and Energy Consumption Growth in Switzerland, 1997-2025 (1997 = 100)

Table 11.3. Projected Average Annual Growth in GDP, CO_2 Emissions, and Primary Energy Consumption from 2001 to 2010 in the GEMINI-E3 Reference Case (Selected Regions)

	GDP	CO_2 Emissions	Primary Energy Consumption
DEU	2.3%	0.2%	0.4%
FRA	2.4%	0.5%	0.9%
GBR	2.5%	0.6%	0.9%
ITA	2.2%	0.9%	1.1%
ESP	2.5%	0.3%	0.6%
NLD	2.3%	0.7%	1.0%
BEL	2.5%	0.4%	0.5%
CHE	2.1%	0.3%	0.5%
OEU	2.5%	0.5%	0.8%
USA	3.2%	1.6%	1.7%
JAP	1.9%	0.5%	0.8%
CAZ	3.2%	2.0%	2.1%
CEA	4.1%	0.7%	1.6%
FSU	4.3%	2.3%	2.6%

of the GEM-E3 baseline (Bahn and Frei, 2000), but it is largely different from the baseline of the SCREEN model, where carbon emissions are projected to rise by around 46 percent by 2020 compared to 2000 (Kumbaroğlu and Madlener, 2003). Indeed, the authors of the study have assumed that the growth in electricity demand and the widening gap in generation capacity because of the decommissioning of nuclear power stations towards 2020 is met by domestically generated electricity from gas-fired power stations.

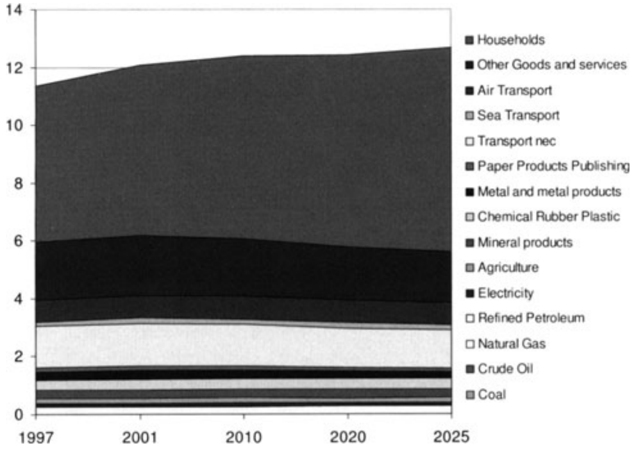

Figure 11.3. Baseline CO_2 Emissions by Sector in Switzerland, 1997-2025 (in MtC per year)

Figure 11.3 depicts the structure of baseline CO_2 emissions in Switzerland from 1997 to 2025. In 2001 the Swiss economy was characterized by a low share of energy-intensive industries in the carbon balance. The electricity sector represented only 1 per cent of total CO_2 emissions. The biggest carbon emitter from these industries, namely the chemical industry accounted for almost 3 percent. Almost 50 percent of total emissions comes from the household sector, and 20 percent comes from the transportation sector. According to our model, the share of household emissions is likely to increase in the future if nothing is done to depart from the baseline scenario. The emissions from the household sector may increase by 1.2 MtC from 2001 to 2025, whereas the emissions from the other sectors may be reduced by around 0.6 MtC.

As shown in figure 11.4, this reference case assumes a limited growth in final energy consumption. The 0.5 percent increase per year from 2001 to 2025 in final energy consumption is largely explained by higher electricity and gas consumption (+1.1 and +0.6 percent per year, respectively).

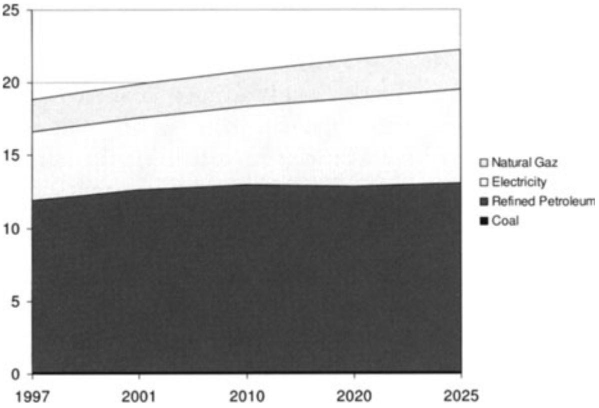

Figure 11.4. Change in Energy Consumption in Switzerland, 1997-2025 (in Mtep)

3. Scenarios and Results

In this section, we present and comment on simulation results obtained from GEMINI-E3. The reference case is compared with three "stylized" climate policy scenarios.

3.1 Policy Scenarios

Switzerland considers a complex climate policy that mixes different instruments that would be implemented on different timescales. The CO_2 Law is based on a voluntary approach in the first phase (Art. 4): big emitters, groups of companies, and energy intensive industries are willing to take voluntary action to limit energy consumption and CO_2 emissions. If voluntary and other CO_2 relevant measures are found to be insufficient to achieve the reduction targets, then a CO_2 tax will be introduced (Art. 6-13). Whereas the CO_2 Law concentrates on the reduction of emissions domestically, it is also considered to implement the flexible mechanisms, namely the Clean Development Mechanism (CDM), Joint Implementation (JI) and International Emissions Trading (IET) as set out by the Kyoto Protocol.

Considering uncertainty in the future design of the Swiss climate policy, it is useful to assess and compare contrasted policy scenarios that could inform policy-makers on the economic impact of policy choices such as the implementation of a tax CO_2 and/or participation in international emissions trading. In this context, we consider three policy scenarios:
(i) Kyoto without trading (**No Trading**): we assume that the Kyoto Protocol target is met through a CO_2 tax that is implemented uniformly in the different

economic sectors of Switzerland, but also in the other Annex B regions (except the USA); no international emissions trading takes place in this scenario.

(ii) Kyoto with EU-wide trading (**EU Trading**): In the process of pushing forward the implementation of emissions trading at the EU level, the European Commission has just published a new directive on EU-wide emissions trading (European Commission, 2003). The directive states that only selected sectors will have the opportunity to participate in the CO_2 permits market in the first period (2005-2008). The permits market will probably be extended in the next periods to other GHG emissions and other sectors. Our scenario does not correspond exactly to the EC directive but applies to a full trading regime that includes all economic sectors in Europe. In this scenario, however, Switzerland does not join the EU-wide emissions trading regime, but instead implements a uniform CO_2 tax.

(iii) Kyoto with emissions trading (**EU+CH Trading**): In this scenario, it is assumed that Swiss firms can participate in the European carbon market without restrictions.

3.2 Kyoto Without Emissions Trading

The reduction of carbon emissions to be realized by 2010 will depend on the emissions targets and on the projected emissions baselines. As shown in table 11.4, the effort in carbon reduction could vary from one Annex B country to another. The Kyoto target is unconstraining for the former Soviet Union, that could play a "hot air game" (Bernard et al., 2002; Bernard et al., 2003). For the EU countries, the carbon reduction efforts are based on the political agreement, namely on the "Burden Sharing Agreement" (BSA), that was reached at the environmental Council meeting on June 1998 to allocate the aggregated EU target (-8%) among the Member States. Viguier et al., 2003 have shown, using the EPPA-EU model, that Denmark, Finland and the Netherlands would make the highest effort and that the burden imposed on Germany, France, the United Kingdom, and Italy would be limited. Our estimates are consistent with the EPPA-EU results, except for Italy. The carbon emission reduction is rather low for Germany because the unification process leads to the withdrawal of many inefficient fossil fuel industrial plants. In the UK, the switch from coal to gas in the electricity sector has led to emissions reductions in the first half of the 1990s. Since it is assumed that the increase of carbon emissions will be relatively limited in the reference case, the carbon emission reduction of Switzerland is closed to the average for the EU countries (15 percent).

Table 11.4 shows the "shadow price" associated with the No Trading scenario. The shadow price corresponds to the marginal value of the constraint, an equivalent to the carbon tax rate needed to achieve the reduction assuming that tax revenues are distributed in a lump sum. As explained by Viguier et al., 2003, the differences in carbon prices estimates come from: 1) the estimates of required abatement levels and; 2) from differences in marginal abatement cost (MAC) curves slopes. As said before, difference in abatement levels result from targets and baseline emissions. Differences in MAC curves are explained

Table 11.4. Emissions reduction and carbon price in 2010 associated with Kyoto Protocol Specifications

	Emissions reduction (in %)	Carbon price (in \$/tC)
DEU	-9.4%	60
FRA	-14.7%	198
GBR	-15.6%	101
ITA	-20.1%	267
ESP	-21.2%	203
NLD	-31.9%	434
BEL	-28.7%	407
CHE	-15.0%	313
OEU	-15.2%	126
JAP	-19.3%	248
CAZ	-25.7%	177
CEA	-4.6%	13
FSU	1.5%	0

by the differences in abatement opportunities, depending on the structural and technological characteristics of each economy.

Given the burden sharing agreement (BSA), carbon prices vary greatly across EU countries. In general, a correlation is found between CO_2 reduction rates and carbon prices, except for the United Kingdom. According to GEMINI-E3, the carbon price might be closed to 313 dollars per tonne of carbon (\$/tC), or roughly 117 Swiss francs per tonne of CO_2, in Switzerland. This price is high compared to the reduction rate of 15 percent. Indeed, the carbon intensity of the Swiss economy is already low because of the characteristics of the electricity sector (mainly hydroelectricity and nuclear), the structure of industry, and of the reduced share of fossil fuels in the energy balance.

An important and direct response to climate change concerns is the new Federal Law on the reduction of CO_2 emissions. If the reduction target is not likely to be met through voluntary measured, a CO_2 tax not exceeding 210 Swiss francs per tonne of CO_2, will be levied in a second phase after 2004, when the Parliament will approve the tax rates fixed by the Federal Council. This maximum tax rate envisioned by the Swiss CO_2 Law, which corresponds to roughly 560 \$/tC, is far above the estimated carbon tax obtained in this model to meet the target reduction; hence, the emissions target could be reached through the existing CO_2 Law.

Figure 11.5 provides detailed information about carbon emissions reduction by sector in Switzerland under a uniform CO_2 tax regime. As expected, even if most of the reductions would come from the transportation and households sectors in absolute terms, the reduction effort would be higher in the energy-intensive industries and the electricity sector. Indeed, efficient climate policy would require more abatement in sectors with low-abatement costs without taking into account concerns related to distribution.

Welfare cost is a useful indicator to measure the economic impact of climate policies on the economy (Weyant, 1999). In this study, welfare change is esti-

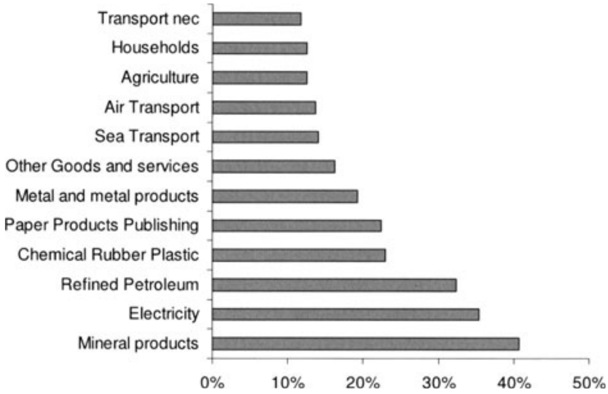

Figure 11.5. CO_2 Emissions Reduction by Sector in Switzerland With A Uniform Carbon Tax, 2010 (in % Change)

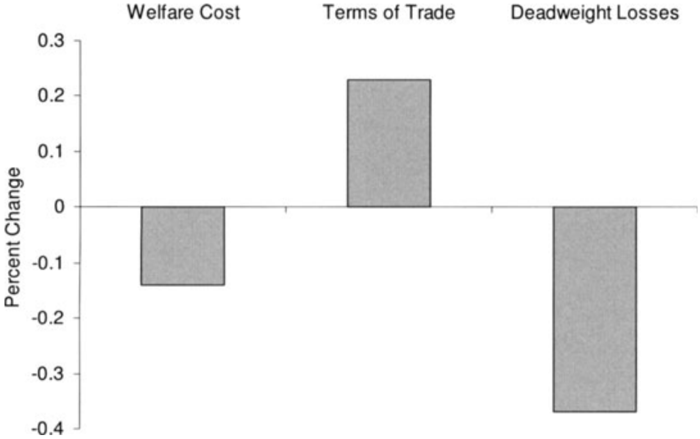

Figure 11.6. CO_2 Decomposition of the Welfare Effect of Kyoto in the Uniform Carbon Tax Scenario in Switzerland, 2010 (in EV % Change)

Table 11.5. Emissions Reduction for Different Policies in 2010 (in % Change)

	No Trading	EU Trading	EU+CH Trading
DEU	-9.4%	-18.7%	-18.7%
FRA	-14.7%	-11.8%	-11.8%
GBR	-15.6%	-20.0%	-20.1%
ITA	-20.1%	-13.4%	-13.5%
ESP	-21.2%	-17.3%	-17.4%
NLD	-31.9%	-15.6%	-15.7%
BEL	-28.7%	-15.3%	-15.4%
CHE	-15.0%	-15.0%	-8.3%
OEU	-15.2%	-16.6%	-16.7%
USA	1.1%	1.1%	1.1%
JAP	-19.3%	-19.3%	-19.3%
CAZ	-25.7%	-25.7%	-25.7%
CEA	-4.6%	-4.6%	-4.6%
FSU	1.5%	1.5%	1.5%

mated in equivalent variation. The equivalent variation measures the amount of extra income (at current prices) that consumers would need to be compensated for the losses in income caused by the policy change (Varian, 1992). As shown in (Bernard and Vielle, 2001; Babiker et al., 2003; Viguier et al., 2003; Babiker et al., 2004), the welfare cost of climate policies can be decomposed in two main effects: the income effect and the terms of trade effect.

The decomposition of the economic effects of meeting the emissions target in Switzerland is presented in figure 11.6. The welfare cost of achieving the Kyoto target is projected to be around -0.14 percent per year with a uniform carbon tax (No Trading scenario). Income losses are much higher (-0.37 %) but they are partially compensated by terms of trade improvement (+0.23 %). This positive terms of trade effect of the climate policy is observed in most of Annex B countries (Viguier et al., 2003): the export prices of Annex B countries tend to increase relative to the price of their imports, especially for fossil fuels.

3.3 Kyoto With EU-Wide Emissions Trading

Since we observe that marginal abatement costs vary greatly across Annex B countries, one might expect a significant cost reduction through international emission trading. This is particularly true for Switzerland, which has a relatively high carbon price compared to the countries.

As shown in table 11.5, international emission trading (IET) tends to bring emissions rates closer for the countries considered. The implementation of IET can thus be viewed as a way to correct inconsistencies in the initial allocation of emissions rights. Germany and the United Kingdom are the main exporters of emission permits, whereas Belgium, Italy, and the Netherlands are the main importers. When permits can be freely traded within Europe, the emissions reductions of Germany is twice as much as the emission reduction required to meet the target domestically.

As expected, the participation of Switzerland in the IET regime does not have a significant impact on the emissions market itself. A total of 31 MtC of carbon is traded within Europe when Switzerland joins the EU-wide trading system (figure 11.7). Switzerland is a net importer of emissions permits, a total of 0.8 MtC, which corresponds to less than 3 % of total exchanges. But it represents almost fifty percent of the required reduction in Switzerland.

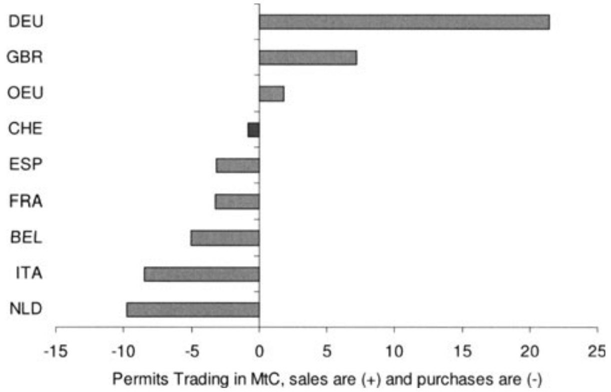

Figure 11.7. CO_2 Permit Purchases Under the EU+CH Emissions Trading Regime in 2010 (in MtC over the period)

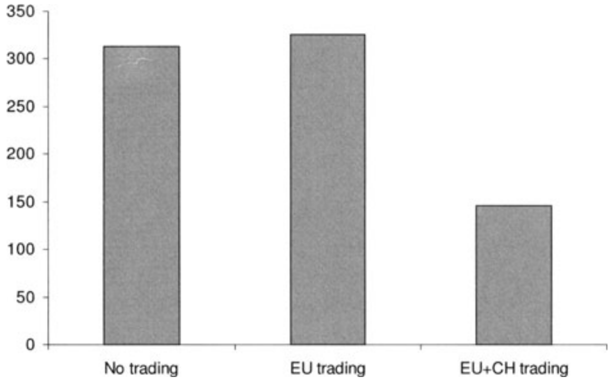

Figure 11.8. Carbon Price in Switzerland in 2010 (in US$/tC)

This opportunity to import emission permits from the European Union has a significant impact on the costs of reaching the target in Switzerland; the carbon price might fall from 313 \$/tC to 146 \$/tC in 2010 (figure 11.8). As shown in figure 11.9, Switzerland might gain from the implementation of a EU-wide trading regime even if it does not decide to join. Indeed, the Swiss economy is highly connected to European economies via international trade. Hence, European decisions about climate policy design can have an impact on a small opened economy like Switzerland. In particular, implementing a IET system within Europe has the effect of reducing prices in Europe relative to prices in Switzerland. This change in relative prices has a positive effect on terms of trade and related consumption in Switzerland. As a result, welfare in Switzerland is improved in the EU Trading scenario compared to the No Trading scenario (see figure 11.9).

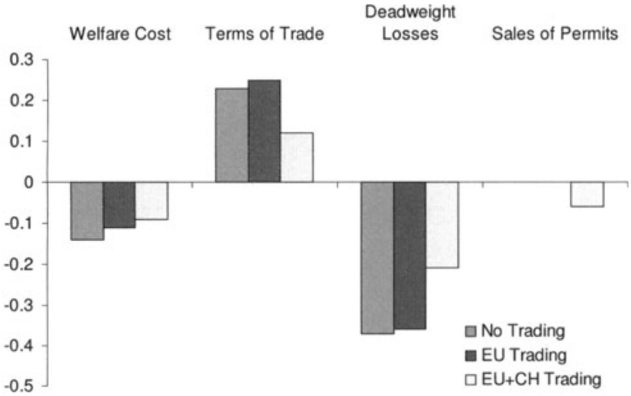

Figure 11.9. Decomposition of the Welfare Costs of Kyoto for Different Policies in Switzerland in 2010 (in % Change)

Swiss participation in IET has also a positive welfare effect. Joining the EU-wide trading system has a negative terms of trade effect, since domestic prices tend to decrease. But this adverse effect of the Swiss participation is outweighed by the positive income effect associated with the reduction of the abatement costs. One can note that half of the positive welfare effect of international emissions trading is not a result of the participation of the country but of the implementation of a permits market within the European Union (see figure 11.9).

To conclude, joining a EU-wide trading might help Switzerland in complying with its emissions target. The compliance costs of the Kyoto agreement might be greatly reduced by implementing a hybrid system that would combine a carbon tax with emissions trading (McKibbin and Wilcoxen, 1997). This hybrid policy, consisting of domestic emissions trading programmes coupled with a tax, would increase certainty about the likely costs of the carbon policy. The domestic carbon tax would correspond to a "trigger price" or a "safety valve", at which countries would sell additional permits domestically (Jacoby and Ellerman, 2002).

3.4 Sensitivity analysis

In order to determine the robustness of the results and conclusions, we conducted a sensitivity analysis. Alternative assumptions have been made with regards to the baseline emission profile of Switzerland.

As shown in figure 11.2, we assumed a small increase of energy consumption compared to the GDP growth, and therefore a decoupling between GDP and energy consumption ensues. The energy intensity in Switzerland, as measured with purchasing power parities, is among the lowest of all OECD countries. This low level of energy intensity is mostly due to the structure of the industry sector, which is comprised mainly of low energy-consuming industries. According to an IEA study (International Energy Agency, 1999), energy intensity of Switzerland has fluctuated over time, but has been quite stable from 1973 to 1997. On average, the energy intensity of Switzerland has declined by almost 0.5 percent from 1997 to 2001. Using energy and GDP forecast from Bundesamt fur Energie, 2001, it is supposed in the original baseline ($\mathbf{BaU}_1$) that the energy intensity will decline from 1.4 to 1.6 percent per year from 2001 to 2020. This projection would certainly represent a change from previous trends.

The alternative baseline ($\mathbf{BaU}_2$) assumes a 1 percent per year reduction of the energy intensity per year from 2001 to 2010, which leads to a 19.5 percent increase of CO_2 emissions in 2010 relative to the 1990 level compared to 15 percent in the original reference case. The Swiss carbon price was projected under these conditions to be around 117 CHF/tCO_2 (313 \$/tC) for the No Trading scenario. The price of carbon reduction is currently projected to be close to 175 CHF/tCO_2 (468 \$/tC) with the alternative baseline scenario ($\mathbf{BaU}_2$). Figure 11.10 shows that baseline assumptions can have a significant impact on welfare. In the No Trading scenario, welfare losses can increase by more than 70 percent when we assume that the Swiss economy might be more energy-intensive. Sensitivity analysis shows that our conclusions regarding the economic impact of international emission trading remain valid. It becomes even more beneficial for Switzerland to join the IET system when energy consumption grows more rapidly: the reduction in welfare cost resulting from the participation in IET is higher for the alternative baseline ($\mathbf{BaU}_2$).

To conclude, this sensitivity analysis emphasizes the importance of exogenous assumptions in evaluating the impacts of the carbon policy on the Swiss economy.

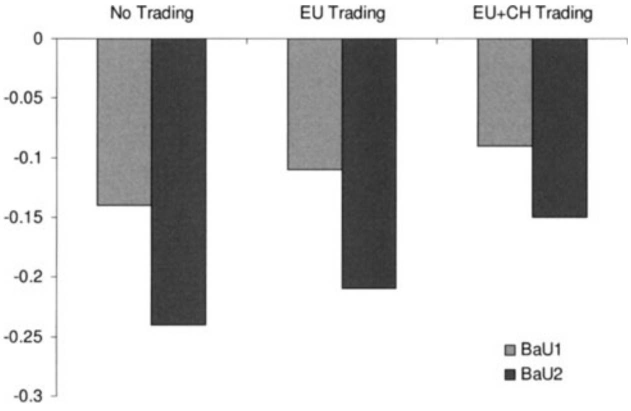

Figure 11.10. Welfare Costs of Climate Policies in Switzerland Under Alternative Baseline cases (in % Change)

4. Conclusion

In this paper, we have presented results from a new version of a CGE model of the world economy, GEMINI-E3, which has been specifically designed to assess the economic and carbon reduction impacts of a range of climate change policies. Including a representation of the Swiss economy, this model can be used to analyze the economic impacts of alternative climate change policies designed to comply with the Kyoto commitment in Switzerland.

According to the GEMINI-E3 model, the emissions reduction of Switzerland is comparable to most of the EU countries (-15 % of 1990 values in 2010). The carbon price, however, might be 117 CHF/tCO_2 (313 \$/tC) if Switzerland were to meet its emissions target by implementing a uniform carbon tax. Under these policy conditions, Switzerland ranks in the upper-bracket of domestic carbon prices in Annex B countries. This result is explained by the characteristics of the Swiss economy, with the limited potential for low-cost abatement in the electricity sector and in the industry being primary causes.

Given this level of domestic carbon price, Switzerland might gain from joining a EU-wide emissions trading regime. In our simulations, Switzerland would meet its emissions target by importing half of the required emissions reductions at 55 CHF/tCO_2 (146 \$/tC). The creation of a market for tradable emissions permits would lower significantly the welfare costs of the carbon constraint. Additionally, Switzerland would benefit from an efficient climate policy abroad and from joining the system with much delay.

This model-based analysis shows that the existing Swiss CO_2 law provides an appropriate institutional framework with which to comply with the Kyoto agreement. The Swiss government would not have to set the carbon tax at the maximum carbon tax rate foreseen by the law, particularly if Switzerland decided to join the EU emissions trading system. Under a hybrid system that combines a carbon tax with international emissions trading, the tax could serve as a "safety valve" that would reduce the uncertainty on costs and competitiveness impacts of the climate policy. The trigger required to achieve the Kyoto targets should not be set under 55 Swiss francs per tonne of CO_2.

Sensitivity analysis shows that the conclusions regarding the costs of Kyoto Protocol kind of policies in Switzerland are sensitive to baseline projections. Carbon price and welfare costs might increase significantly if lower rates of energy intensity improvement in the "Business-as-Usual" scenario are assumed. The gains from joining the EU trading system are then increased.

One must be cautious in interpreting the results and using them for policy recommendations since we have analyzed and compared very "stylized" and fully efficient climate policies. In practice, the environmental integrity and the economic cost of the Swiss climate policy will depend on the design of the tax scheme (e.g. tax exemptions and tax recycling) and on the implementation of other instruments (e.g. voluntary measures, programme SwissEnergy, heavy vehicles fee, etc). Further research is needed to evaluate the Swiss CO_2 law: the potential of emissions reduction through voluntary agreements; the possibility to import emissions rights through the Clean Development Mechanism (CDM) and Joint Implementation (JI); and climate policies combining different instruments and including the other greenhouses gases.

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Appendix A

Production and Trade

For each sector the model computes the demand on the basis of final demand[1] (Y_{ir}) that includes household consumption (HC_{ir}), government consumption (GC_{ir}), exports (EX_{ir}), investment (IV_{ir}), and intermediate uses (IC_{ikr}):

$$Y_{ir} = HC_{ir} + GC_{ir} + EX_{ir} + IV_{ir} + \sum_k IC_{ikr} \tag{1}$$

where i, r, and k stand for sectors, regions, and products respectively.

Total demand is then divided between domestic production (X_{ir}) and imports (M_{ir}):

$$X_{ir} = Y_{ir} \cdot \lambda^x_{ir} \cdot \alpha^x_{ir} \cdot \left[\frac{PY_{ir}}{\lambda^x_{ir} \cdot PD_{ir}}\right]^{\sigma^x_{ir}} \tag{2}$$

$$M_{ir} = Y_{ir} \cdot \lambda^x_{ir} \cdot (1 - \alpha^x_{ir}) \cdot \left[\frac{PY_{ir}}{\lambda^x_{ir} \cdot PI_{ir} \cdot \left(1 + \kappa^i_{ir}\right)}\right]^{\sigma^x_{ir}} \tag{3}$$

where PY_{ir} represent the price of production, PD_{ir} is the price of domestic production; σ^x_{ir}, α^x_{ir} and λ^x_{ir} represent the CES parameters; respectively, the elasticity of substitution, the share parameter and the technology shifter.

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[1] Unless specified otherwise all variables are indexed over time t. However for the sake of simplifying the notations tis time index is not shown.

Production is realized with four aggregated inputs: capital (K_{ir}), labor (L_{ir}), energy (E_{ir}), and material (MA_{ir})[2]:

$$K_{ir} \cdot \theta_{ir}^{k\ t} = X_{ir} \cdot \lambda_{ir} \cdot \alpha_{ir}^{k} \cdot \left[\frac{PD_{ir}}{PK_{ir} \cdot \lambda_{ir} \cdot \theta_{ir}^{k\ -t}}\right]^{\sigma_{ir}} \tag{4}$$

$$L_{ir} \cdot \theta_{ir}^{l\ t} = X_{ir} \cdot \lambda_{ir} \cdot \alpha_{ir}^{l} \cdot \left[\frac{PD_{ir}}{PL_{ir} \cdot \lambda_{ir} \cdot \theta_{ir}^{l\ -t}}\right]^{\sigma_{ir}} \tag{5}$$

$$E_{ir} \cdot \theta_{ir}^{e\ t} = X_{ir} \cdot \lambda_{ir} \cdot \alpha_{ir}^{e} \cdot \left[\frac{PD_{ir}}{PE_{ir} \cdot \lambda_{ir} \cdot \theta_{ir}^{e\ -t}}\right]^{\sigma_{ir}} \tag{6}$$

$$MA_{ir} \cdot \theta_{ir}^{mt} = X_{ir} \cdot \lambda_{ir} \cdot (1 - \alpha_{ir}^{k} - \alpha_{ir}^{l} - \alpha_{ir}^{e}) \cdot \left[\frac{PD_{ir}}{PM_{ir} \cdot \lambda_{ir} \cdot \theta_{ir}^{m-t}}\right]^{\sigma_{ir}} \tag{7}$$

where PK_{ir}, PL_{ir}, PE_{ir}, PM_{ir} represent the price of capital, labor, energy, and material; and where θ_{ir}^{k}, θ_{ir}^{l}, θ_{ir}^{e} and θ_{ir}^{m} represent the technical progress incorporated respectively in capital, labor, energy and material.

Individual inputs (i.e. inputs in coal, crude oil, ..., agriculture, electricity, ..., other goods and service) are computed through the nested CES as shown in figure 11.1.

Imports are computed by origins (MR_{irh}) with a CES function:

$$MR_{irh} = M_{ir} \cdot \lambda_{ir}^{i} \cdot \alpha_{irh}^{i} \cdot \left[\frac{PI_{ir}}{\lambda_{ir}^{i} \cdot PX_{ih} \cdot (e_h/e_r)}\right]^{\sigma_{ir}^{ai}} \tag{8}$$

where PI_{ir} and PX_{ir} represent the price of imports and exports; and where h stand for the place of import origin, and e_h and e_r are exchange rates.

Final Demand

Households consumption Household behavior consists of three interdependent decisions: 1) labor supply; 2) savings; and 3) consumption of the different goods and services. It is assumed that each household maximizes a Stone-Geary utility function subject to a consumption expenditure constraint. The resulting first-order conditions are referred to as LES (linear expenditure system) functions, since spending on individual commodities is a linear function of total consumption spending. The consumer demand function is described by the following:

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[2] In Sector 01, 02, and 03, the model takes into account a fix factor as in figure 1; Sector 04 includes a crude oil input.

$$HC_{ir} = \phi_{ir} + \frac{\beta_{ir}}{PC_{ir}} \cdot \left[HCT_r - \sum_k (PC_{kr} \cdot \phi_{kr}) \right] \qquad (9)$$

where HCT_r is the total household consumption, PC_{ir} is the price of consumption, ϕ_{ir} represents the minimum necessary purchases of good i, and β_{ir} corresponds to the marginal budget share of good i.

Government consumption Total government consumption (GCT_r) is exogenously fixed and is mainly driven by growth rates. The model splits total consumption between goods (GC_{ir}) on the basis of budget share β^g_{ir}:

$$GC_{ir} = \beta^g_{ir} \cdot GCT_r \qquad (10)$$

Investment Investment by products (IV_{ir}) are derived from investment by sector (I_{kr}) through a transfer matrix Φ_{ikr}:

$$IV_{ir} = \sum_k \Phi_{ikr} \cdot I_{kr} \qquad (11)$$

Exports Exports (EX_{ir}) are computed on the basis of imports (MR_{irh}):

$$EX_{ir} = \sum_h MR_{irh} \qquad (12)$$

Price system

The equations for price of the composite goods (PY_i^r) is:

$$PY_i^r = \lambda^x_{ir} \cdot \left[\alpha^x_{ir} \cdot PD_{ir}^{1-\sigma^x_{ir}} + (1 - \alpha^x_{ir}) \cdot \left(PI_{ir} \cdot \left(1 + \kappa^i_{ir}\right)\right)^{1-\sigma^x_{ir}} \right]^{\frac{1}{1-\sigma^x_{ir}}} \qquad (13)$$

with the price of domestic production (PD_{ir}) equal to

$$PD_{ir} = \lambda_{ir} \cdot \left[\alpha^x_{ir} \cdot \left(\frac{PK_{ir}}{\theta^k_{ir}} \right)^{1-\sigma_{ir}} + \alpha^l_{ir} \cdot \left(\frac{PL_{ir}}{\theta^l_{ir}} \right)^{1-\sigma_{ir}} + \right.$$
$$\left. \alpha^e_{ir} \cdot \left(\frac{PE_{ir}}{\theta^e_{ir}} \right)^{1-\sigma_{ir}} + (1 - \alpha^k_{ir} - \alpha^l_{ir} - \alpha^e_{ir}) \cdot \left(\frac{PM_{ir}}{\theta^m_{ir}} \right)^{1-\sigma_{ir}} \right]^{\frac{1}{1-\sigma_{ir}}} \qquad (14)$$

The equations for base price (PB_{ir}) including tax on production, price of consumption (PC_{ir}), government consumption (PG_{ir}), intermediate consumption (PIC_{ir}), investment (PV_{ir}), labor (PL_{ir}), exports (PX_{ir}), and imports (PI_{ir}) are:

$$PB_{ir} = \frac{PY_{ir}}{\left(1 - \kappa_{ir}^{b}\right)} \tag{15}$$

$$PC_{ir} = PB_{ir} \cdot \left(1 + \kappa_{ir}^{h}\right) + \tau_{ir}^{h} \cdot TCO2_r \tag{16}$$

$$PG_{ir} = PB_{ir} \cdot (1 + \kappa_{ir}^{g}) + \tau_{ir}^{g} \cdot TCO2_r \tag{17}$$

$$PIC_{ikr} = PB_{ir} \cdot \left(1 + \kappa_{ikr}^{i}\right) + \tau_{ikr}^{i} \cdot TCO2_r \tag{18}$$

$$PV_{ir} = \sum_{k} \left(PB_{kr} \cdot \Phi_{kir} \cdot (1 + \kappa_{kir}^{v})\right) \tag{19}$$

$$PL_{ir} = W_r \cdot (1 + \kappa_{ir}^{w}) \tag{20}$$

$$PX_{ir} = PB_{ir} \cdot (1 + \kappa_{ir}^{x}) \tag{21}$$

$$PI_{ir} = \lambda_{ir}^{i} \cdot \left[\sum_{h} \alpha_{ihr}^{i} \cdot \left[PX_{ih} \cdot (e_h/e_r)\right]^{1-\sigma_{ir}^{ai}}\right]^{\frac{1}{1-\sigma_{ir}^{ai}}} \tag{22}$$

where κ_{ir}^{b} is the tax rate applied to production; κ_{ir}^{h}, κ_{ir}^{g}, κ_{ikr}^{i}, κ_{ir}^{v} are Value Added Tax (VAT) rates[3] applied, respectively, on household consumption, government consumption, investment and intermediate consumption; κ_{ir}^{w} is a tax rate linked to wages (mainly social contribution, W_r), κ_{ir}^{i} reflects import duties rate; and κ_{ir}^{x} models export subsidies rate. The parameters τ_{ir}^{h}, τ_{ir}^{g}, τ_{ikr}^{i} are the carbon content of one unit of household consumption, government consumption and intermediate consumption, respectively, and $TCO2_r$ is the carbon tax.

Capital accumulation

The supply of capital by sector (KC_{ir}) is determined by the following accumulation relationship:

$$KC_{ir} = (1 - \delta_{ir}) \cdot KC_{ir}^{t-1} + I_{ir}^{t-1} \tag{23}$$

where δ_{ir} is the depreciation rate of capital, and investment by sector is determined on the basis of anticipated capital demand, as follows:

$$I_{ir} = KA_{ir} - (1 - \delta_{ir}) \cdot KC_{ir} \tag{24}$$

where the anticipated capital (KA_{ir}) is equal to:

$$KA_{ir} = (1 - \chi_{ir}) \cdot KO_{ir} + \chi_{ir} \cdot \left(\frac{KC_{ir}^{2}}{KC_{ir}^{t-1}}\right) \tag{25}$$

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[3] Or tax on sales with different tax rates, depending on fiscal system of the regions.

and where the optimal capital (KO_{ir}) is computed on the basis of the CES function, anticipated prices (PDA_{ir}, PVA_{ir}) and domestic production $(XA_{ir})^4$:

$$KO_{ir} \cdot {\theta_{ir}^{k}}^{t+1} = XA_{ir} \cdot \lambda_{ir} \cdot \alpha_{ir}^{k} \cdot \left(\frac{PDA_{ir}}{PVA_{ir} \cdot (R_r + \delta_{ir}) \cdot {\theta_{ir}^{k}}^{-t-1}} \right)^{\sigma_{ir}} \tag{26}$$

with R_r the interest rate.

The demand for capital $((K_{ir}))$ is derived through the CES function (see equation [4]). The demand of capital is equal to supply (KC_{ir}) through the rental price of capital (PK_{ir}) (see equation [33]).

Government budget

The government budget balances revenues derived from (indirect and direct) taxation and expenditures equal to government consumption and transfers to households (mainly through the distribution of social benefits, SB_r). The equation for government revenue is:

$$\begin{aligned} SG_r = {} & \sum_i Y_{ir} \cdot \frac{\kappa_{ir}^{b} \cdot PY_{ir}}{\left(1 - \kappa_{ir}^{b}\right)} + \sum_i PB_{ir} \cdot \kappa_{ir}^{h} \cdot HC_{ir} + \sum_i PB_{ir} \cdot \kappa_{ir}^{g} \cdot GC_{ir} + \\ & \sum_i PI_{ir} \cdot \kappa_{ir}^{i} \cdot M_{ir} + \sum_i PB_{ir} \cdot \kappa_{ir}^{x} \cdot EX_{ir} + \sum_i W_r \cdot \kappa_{ir}^{w} \cdot L_{ir} + \\ & \sum_i PB_{ir} \cdot \sum_k \Phi_{ikr} \cdot \kappa_{kir}^{v} \cdot I_{kr} + \sum_k PB_{kr} \cdot \sum_i IC_{kir} \cdot \kappa_{kir}^{i} + \\ & \sum_{i=1,4} HC_{ir} \cdot \tau_{ir}^{h} \cdot TCO2_r + \sum_{i=1,4} GC_{ir} \cdot \tau_{ir}^{g} \cdot TCO2_r + \\ & \sum_k \sum_{i=1,4} IC_{ikr} \cdot \tau_{ikr}^{i} \cdot TCO2_r + \kappa_r^{r} \cdot REV_r - \sum_i (GC_{ir} \cdot PG_{ir}) - SB_r \end{aligned} \tag{27}$$

where κ_r^r represents the rate of direct taxation.

Households budget

Households saving is computed on the basis of household revenue REV_r with an exogenous saving rate ζ_r:

$$REV_r = W_r \cdot \sum_i L_{ir} + \sum_i K_{ir} \cdot PK_{ir} + \sum_i FF_{ir} \cdot PF_{ir} + SB_r \tag{28}$$

$$SH_r = REV_r \cdot (1 - \kappa_r^r) \cdot \zeta_r \tag{29}$$

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[4] In dynamic-recursive models expectations regarding investment expenditures are based on static or backward-looking expectations.

The equation for households consumption is:

$$HCT_r = REV_r \cdot (1 - \kappa_{ir}^r) - SH_r \tag{30}$$

Carbon Emissions

Carbon emissions by region are computed on the basis of energy consumption:

$$CO2_r = \sum_{i=1,4} \sum_{k} IC_{ikr} \cdot \tau_{ikr}^i + \sum_{i=1,4} HC_{ir} \cdot \tau_{ikr}^h + \sum_{i=1,4} GC_{ir} \cdot \tau_{ikr}^g \tag{31}$$

General equilibrium conditions

We give the market clearing equations for labor, capital, fix factor, government budget, trade, carbon emission and investment. Variables in brackets are used to clear the market:

$$LS_r = \sum_i L_{ir} \qquad (R_r) \qquad \forall r \tag{32}$$

where LS_r is the supply of labor by households (fixed exogenously).

$$K_{ir} = KC_{ir} \qquad (PK_{ir}) \qquad \forall i \quad \forall r \tag{33}$$

$$FF_{ir} = FS_{ir} \qquad (PF_{ir}) \qquad \forall i = 1,2,3 \quad \forall r \tag{34}$$

where FS_{ir} is the supply of fix factor (fixed exogenously).

$$\varepsilon_r = SG_r \qquad (\kappa_r^r) \qquad \forall r \tag{35}$$

we supposed that government surplus or deficit is fix and equal to ε_r.

$$\sum_i M_{ir} \cdot PI_{ir} = \sum_i EX_{ir} \cdot PX_{ir} \qquad (e_r) \qquad \forall r = 1, ..., 20 \tag{36}$$

Of course, if $n-1$ trade balances are cleared ,the trade balance for region 21 is balanced,

$$CO2_r = CO2Q_r \qquad (TCO2_r) \qquad \forall r \tag{37}$$

where $CO2Q_r$ is the emission constraint.

The last equilibrium condition is computed through the Walras law:

$$SH_{ir} + SG_{ir} = \sum_i IV_{ir} \cdot PV_{ir} \qquad \forall r \tag{38}$$

Chapter 12

AN OVERVIEW OF EXTREME CLIMATIC EVENTS IN SWITZERLAND: IMPLICATIONS FOR ASSESSING ECONOMIC DAMAGES AND COSTS

Martin Beniston

Abstract This paper provides an overview of extreme climatic events that are a feature of current and future climate that require full understanding if they are to be assessed in terms of social and economic costs. A review will be made of the type of events that can be important in mid-latitudes, with examples taken from heat waves, floods, droughts, and wind-storms that have affected Switzerland during the course of the 20^{th} century. New regional climate model results are also presented for the IPCC A-2 scenario conducted over Europe, to highlight the likely shifts in extremes that may result from warmer global temperatures. The paper will then address some of the issues that need to be considered when attempting to use climate model results for the assessment of economic costs related to extreme climate events.

1. Introduction

As climate continues to warm during the course of the 21^{st} century, it can be expected that extreme events will also increase, because the thermal energy that drives many atmospheric processes will be enhanced. Although this intuitive reasoning also has a physical basis, it is for the moment still difficult to demonstrate that extremes have increased conjointly with the rise in mean global temperatures over the last 100-150 years, simply because they are rare events that cannot be related in a statistically-meaningful manner to changes in mean climatic conditions, as was shown for example by Frei and Schaer (2001).

There is no single definition of what constitutes an extreme event. Extremes can be quantified *inter alia* on the basis of:

- how rare they are, which involves notions of frequency of occurrence; this is the definition that the Intergovernmental Panel on Climate Change has

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adopted (IPCC, 2001), whereby an extreme is referred to as occurring below the 10th percentile or above the 90th percentile of a particular statistical distribution of temperature, precipitation, pressure, etc.;

- how intense they are, which involves notions of threshold exceedance; the intensity of an event can often have a direct bearing on the associated human and economic damage costs, and can be related to heat waves, excessive wind velocities, or to both ends of the "precipitation spectrum" that can lead to droughts on the one hand and floods on the other;
- the impacts that may emerge from a particular event or set of events, that will also determine the costs for socio-economic and environmental sectors that are related to extremes; impacts-based definitions of extremes are complex because in many instances, many damaging natural hazards can be triggered in the absence of an intense or rare climatic event.

Public awareness to extreme weather hazards has risen sharply in recent years, in part because of instant media attention that serves to emphasize the catastrophic nature of floods, droughts, storms, and heat waves or cold spells. There is also a general perception that the number of extreme events has increased in the past few decades, based on statistics from the insurance sector as shown in Figure 12.1 (from Munich Re, 2002). These insurance statistics highlight the fact that, with the exception of earthquakes, climate-related hazards are those that take the heaviest toll on human life and exert among the highest damage costs. In the second half of the 20th century, there have been 71 "billion-dollar events" resulting from earthquakes, but more than 170 events with similar costs related to climatic extremes, in particular wind-storms (tropical cyclones and mid-latitude winter storms), floods, droughts and heat-waves.

There is thus an obvious incentive for the research community as well as the public and private sectors to focus on research related to extreme climatic events and the possible shifts in their frequency and intensity as climate changes in the course of the 21st century. However, closer interpretation of the elements of Figure 12.1 suggests that most of the increase in damage costs resulting from extreme climatic events is related to higher population densities in risk-prone areas than in past decades and a corresponding rise in insured infrastructure, rather than to an increase in the number of events themselves (Swiss Re, 2003).

It is thus clear that none of these definitions on their own are entirely satisfactory, however, and each definition corresponds to a particular situation but cannot necessarily be applied in a universal context.

Understanding the mechanisms underlying various forms of climatic extremes is of interest to assess of the manner in which they may evolve in the future, under changing climatic conditions. A better understanding can in turn allow improvements in the ability to quantify the costs associated with natural climate-related hazards and thereby provide the basis for strategies to adapt to climatic change from an economic point of view.

This paper will thus provide an overview of climatic extremes, using examples from the alpine region, and the manner in which they can be investigated;

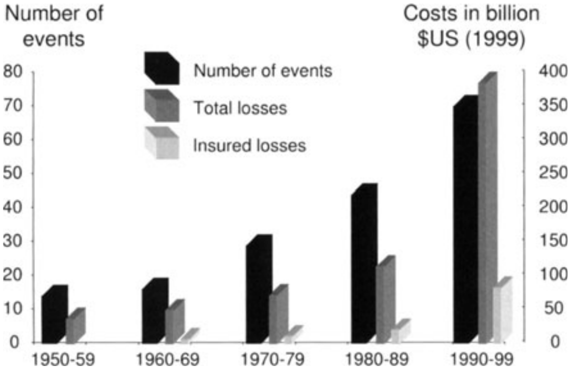

Figure 12.1. Number of extreme climate-related events, death toll, and associated damage costs as a percentage of all natural hazards in the second half of the 20th century (from Munich Re, 2002).

some thought will be devoted to the approaches that can be applied to enable an interface with economic models, thus providing a deterministic framework for assessing the economic and social costs of future extreme events.

2. Observations of Certain Climatic Extremes in the 20th Century in Switzerland

The alpine climate is one that has undergone significant change over the past 100–150 years; temperatures have risen by up to 2°C in many parts of Switzerland between 1901 and 2000 (e.g., Jungo and Beniston, 2001), which is well above the global-average 20th century warming of about 0.6°C reported by Jones and Moberg (2003). It is thus of interest to determine some of the causal mechanisms that are responsible for the rapid rise in temperatures in Switzerland over the course of the 20th century and whether this has had a bearing on the extremes of climate

One of the most significant sources of decadal-scale climatic fluctuations in the alpine region is related to the North Atlantic Oscillation (NAO). The NAO is a large-scale alternation of atmospheric pressure fields (i.e., atmospheric mass), whose centers of action are near the Icelandic Low and the Azores High. One mode of the NAO is when sea-level pressure is lower than normal in the Icelandic low pressure center, it is higher than normal near the Azores, and vice-versa, hence the notion of an oscillatory behavior of the system. Another mode is that pressures may also rise or fall simultaneously in both cells, but then the NAO signal is not quite as well-defined. The NAO index is a normalized pressure difference between the Azores (an alternate location is Lisbon, Portugal) and Iceland; it is a measure of the intensity of zonal flow across the North Atlantic and the associated position of storm tracks and regions of strongest storm intensity. This flow is itself driven by the temperature (and hence pressure) contrasts between polar and tropical latitudes.

The NAO represents one of the most important modes of decadal-scale variability of the climate system after ENSO (El Niño/Southern Oscillation) in terms of its influence on hemispheric or global effects, and accounts for up to 50% of sea-level pressure variability on both sides of the Atlantic (Hurrel, 1995). It is observed to strongly influence precipitation and temperature patterns on both the eastern third of North America and western half of Europe particularly during winter months. It has been shown in recent years (Beniston, 1997; Hurrel, 1995; Serreze et al. 1997) that a significant fraction of climatic anomalies observed on either side of the Atlantic are driven by the behavior of the NAO. For example, Figure 12.2 illustrates the time series of the NAO index and minimum temperature at a high alpine site (Säntis) in the 20th century; the synchronous behavior between temperature and the NAO is particularly striking in the second half of the 20th Century, as compared to the earlier part of the century. This is partly related to the fact that in the first half of the 20th century, atmospheric circulations in the alpine region were less dominated by Atlantic influences, and hence the oscillatory behavior of the NAO, than they have been in more recent decades. The variance of temperature that can be accounted for by NAO fluctuations during the last 40-50 years exceeds 72%.

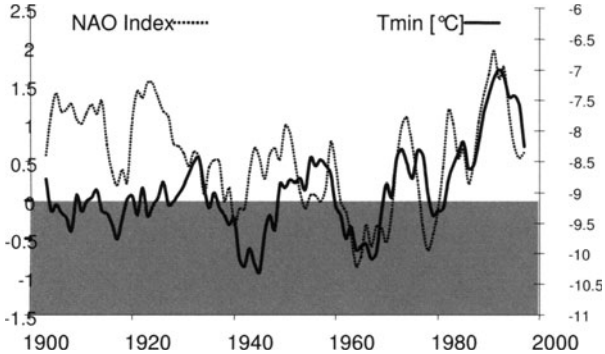

Figure 12.2. Time series of the North Atlantic Oscillation index and average winter minimum temperatures at Säntis (eastern Switzerland, 2,500 m above sea-level).

A particular feature of the positive phase of the NAO index is that it is invariably coupled to anomalously low precipitation and milder than average temperatures, particularly from late fall to early spring, in southern and central Europe (including the Alps and the Carpathians), while the reverse is true for periods when the NAO index is negative. As a result, extremes of temperature can and have occurred in the past in relation to particular modes of the NAO. In order to highlight the possible influences of such NAO modes on extremes of pressure, temperature and moisture, the lower and upper 10 quantiles of the NAO index probability density function (i.e., extremes in the sense of the IPCC definition) during the 20th century winters have been used. These thresholds are representative of two highly contrasting synoptic regimes affecting the Alps, namely above-average pressure and associated positive temperature and negative moisture anomalies when the threshold is above the 90% level, and lower than average pressure and its controls on temperature and humidity when the index is lower than the 10% level (Beniston and Jungo, 2002).

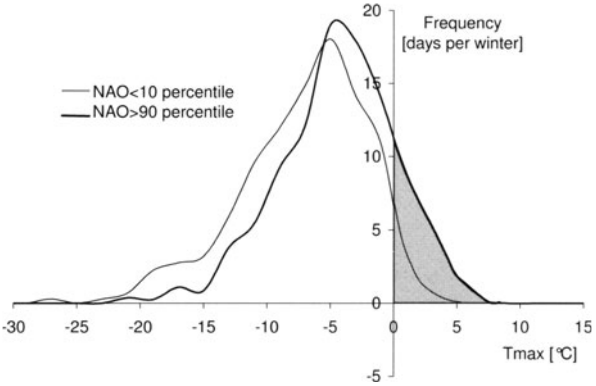

Figure 12.3. Shifts in the probability density function (PDF) of mean winter maximum temperatures at Säntis for periods when the North Atlantic Oscillation index is lower than the 10th quantile or above the 90th quantile.

One illustrative example is the comparison of the probability density function (PDF) of maximum winter temperature at Säntis for periods when the NAO index exceeds the 90th quantile and when it is below the 10th quantile given in Figure 12.3. A distinct shift towards warmer temperatures is observed in both the means and the extremes, with a doubling of the number of days that exceed the freezing point when the NAO index is above the 90th quantile compared to when it is below the 10th quantile. In general terms, the influence of the persistently high values of the NAO since the early 1970s has been to increase the upper tails of the temperature and pressure PDFs to a significant degree, and to reduce the relative humidity and precipitation amounts at most locations in Switzerland, which is a logical consequence of the presence of above-normal pressure in the region. Because of the controls that the NAO can exert over much of the winter season, the combination of higher temperatures and lower moisture can have a number of impacts on the natural environment. In particular, the fact that at high elevations such as Säntis (2,500 m asl), the number of days where diurnal temperatures exceed the freezing point can increase by as much as two weeks during the winter season inevitably has implications for the timing of snow-melt and the amount of snow which remains on the ground throughout the winter. Earlier snowmelt in turn feeds into the hydrological systems, by increasing river discharge earlier in the season compared to "normal" or negative NAO values. Warmer temperatures are also associated with precipitation falling more as rain than as snow even at higher elevations. When combined with early snowmelt runoff, this can lead to critical hydrological situations, particularly downstream of the mountains, as was experienced for example in early 1995, when the Rhine River overflowed its banks in Germany and The Netherlands as a result of heavy rains in the lowlands and early snowmelt in the Alps.

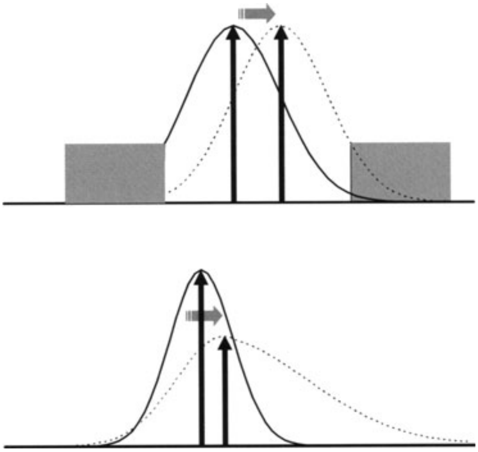

Figure 12.4. Illustrative examples of possible shifts in the probability density function of an atmospheric variable such as temperature. Upper: a symmetrical shift in the entire distribution; lower: an asymmetric shift with a change in both the skewness and the kurtosis of the distribution.

Heat waves are generally believed to increase when average temperatures are on the rise. This is because if there is a rise in the mean of temperature as given by the vertical arrows in Figure 12.4 (adapted from IPCC, 2001), there can be a symmetrical shift in the PDF of temperature, with the same increase of extreme temperatures at the high end of the distribution (that could be taken as "heat waves") as there is a decrease at the low end of the PDF (that could be considered as "cold spells"), as indicated by the shaded areas. However, the change in mean temperature can also be accompanied by a shift in the skewness and/or the kurtosis of the distribution, yielding a profile that is seen in the lower part of Figure 12.4. In this lower figure, the shift in means is in fact less than in the upper graph, but the asymmetry of the curve yields a disproportionate increase in the extremes of warm temperatures.

Over the course of the 20th century, observations suggest that there has been a shift in the PDFs of both minimum and maximum temperatures, between the coldest part of the century (1901–1910) and the warmest part (1991–2000), as exemplified in Figure 12.5 for Basel, at 317 m above sea level. The increase in average winter minimum temperatures is 2.2°C between the two periods, from -2.6°C to -0.4°C. The number of days below freezing has decreased by half, from 26% to 13% of the winter season, while the number of warm winter nights (above 10°C) has increased by a factor of 3, from 2.5 to 8 days per winter.

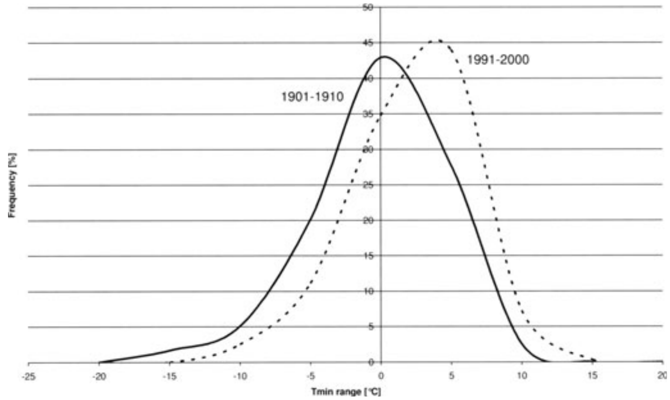

Figure 12.5. Shifts in the probability density function (PDF) of mean annual maximum temperatures at Basel between the coldest (1901–1910) and warmest (1991–2000) periods of the 20th century.

When analyzing threshold exceedance such as the number of days with maximum temperatures above 30°C in Basel, there is a correlation of 0.65 between mean annual maximum temperatures and threshold exceedance; this correlation rises to 0.90 when comparing the number of days exceeding 30°C with mean *summer* maximum temperatures (June, July, and August averages). This is logical in the sense that heat waves will generally occur during the summer, whereas on an annual basis, a cold winter may well be followed by a very warm summer, leading to a moderate annual temperatures and thus a more tenuous link with threshold exceedance. Similar conclusions can be reached for most measurement sites at low elevations in Switzerland.

Other forms of extremes that cause considerable economic damage and, in some cases, loss of life include heavy precipitation events and winter storms. Heavy precipitation shows trends that are statistically significant in the last quarter of the 20th century (although the trends cannot be directly related to the rate of warming over the same period), while winter storms of the intensity of the December, 1999 *Lothar* event are still extremely rare events that cannot be linked in any statistically-meaningful manner to long-term global warming.

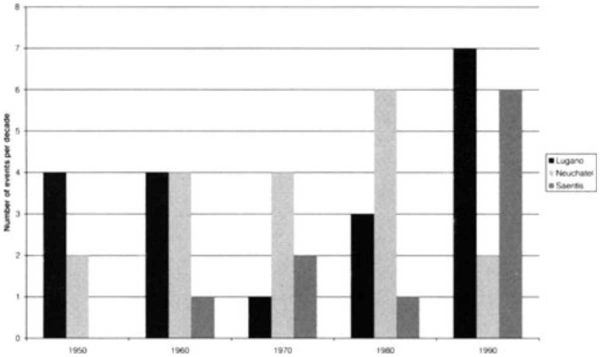

Figure 12.6. Number of extreme precipitation events exceeding thresholds of 100 mm/day in Lugano and Säntis, and 50 mm/day in Neuchâtel for the last 5 decades of the 20th century.

Figure 12.6 shows the behavior of extreme precipitation events based on selected thresholds in Lugano (south of the Alps), Neuchâtel (north of the Alps), and Säntis (within the alpine domain at high altitude). The thresholds for Lugano and Säntis are 100 mm/day, and for Neuchâtel 50 mm/day. The graph shows that the number of events reached its maximum in Neuchâtel in the 1980s, and at Lugano and Säntis in the 1990s; the sharpest increase is at Säntis where the threshold is exceeded 6 times in the 1990s compared to two or less occurrences per decade prior to the 1990s. In terms of the total amount of precipitation associated with these extremes, Figure 12.7 confirms the trends already seen in the number of events (Figure 12.6), where a three-fold increase in cumulated water amounts from the 1980s to the 1990s for the sites in the Alps and south of the Alps can be observed; Neuchâtel on the other hand shows a decrease in total precipitation that is linked to the decrease in events. At and above 100 mm/day, the potential for flooding and enhanced erosion is high, especially in exposed mountain terrain, as has been reflected in the high costs associated with the Brig catastrophe (September, 1993), the floods of Lake Maggiore in the falls of 1993 and 2000, and the devastating landslides and mudslides in the vicinity of the Simplon (Gondo, October 2000), for example. Attempting to link these events to average warming trends, either on an annual basis or on the basis of the temperatures that prevail during the specific extreme precipitation event, is difficult because there is not necessarily any direct relationship between a given level of temperature at a particular location, and complex physical processes that are an aggregate of numerous mechanisms occurring at various spatial scales.

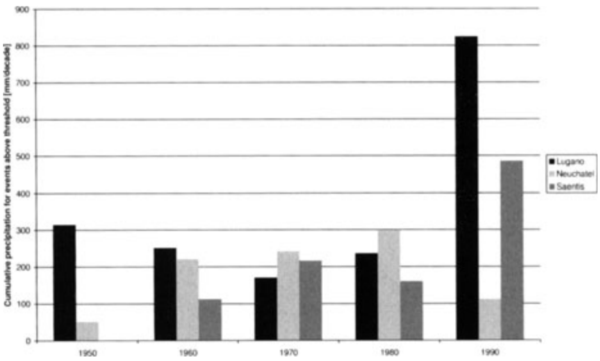

Figure 12.7. Cumulative precipitation for extreme events beyond the 100 mm/day threshold at Lugano and Säntis, and 50 mm/day in Neuchâtel for the last 5 decades of the 20th century.

It is currently impossible to establish direct relationships between severe wind storms and warming trends, at least in the alpine region, because of the rare nature of these events. Strong storms are generated either over the Atlantic, or are associated with föhn-type flows over the Alps, and as such have very little to do with local climatic conditions over the Alpine domain. As shown in Figure 12.8, during the last 30 years of the 20th century, there are no trends apparent in terms of peak wind velocities recorded during each year at La Dôle, a summit of the Jura Mountains exceeding 1600 m elevation close to Geneva that tends to intercept westerly flows with little interference from topography upstream in France. The record is rather short but nevertheless highlights the fact that there is no significant increase in extreme wind velocities in relation to the increase of close to 2°C in mean annual temperatures that were recorded at La Dôle during this period.

Loss of life and economic damage resulting from strong wind storms, that generally occur during the winter in western Europe and the alpine area, can be significant (e.g., Ulbrich et al., 2000). The December 1999 *Lothar* storm resulted in uprooted or damaged trees equivalent to more than 4 times the annual felling rate in certain Swiss cantons (BUWAL, 2000), and damage to infrastructure that exceeded USD 1 billion in Switzerland alone and over USD 20 billion in the countries affected by the winter storm from France to central Europe, according to SwissRe (2003). Current 20-year return periods of wind velocities associated with winter storms are in the range 30-75 m/s, according to the altitude and the latitude of the site (Goyette, 2003, personal communication).

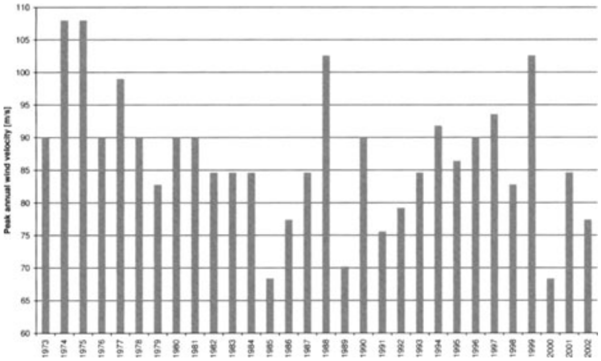

Figure 12.8. Annual peak wind velocities measured at La Dôle (western Switzerland, 1,690 m above sea-level) for the period 1973-2002.

3. Modeling Future Climate and Climatic Extremes

A crucial question when assessing climatic change resulting from increased levels of greenhouse gases in the atmosphere is related to the manner in which extremes of climate as discussed in the former section may change in intensity and/or frequency as conditions become warmer. Although additional heat in the atmosphere may be a necessary condition, it is by no means a sufficient condition for generating extreme events. In order to investigate the future behavior of a non-linear system such as climate, it is necessary to use 3-D numerical modeling systems applied to the global and regional scales.

Climate models are essentially weather-forecasting models that operate at lower spatial resolution in order to allow longer-term integrations. They attempt to incorporate as many elements of the climate system as possible, i.e., the oceans, the cryosphere, and the biosphere in addition to the atmosphere itself. Such models typically solve large sets of equations on several hundred thousand grid-points distributed in three dimensions around the globe; these computations are repeated 50 or more times per simulated day in order to adequately represent the temporal evolution of the system. Computer time and space requirements are thus extremely large, and climate simulations make full use of the resources of advanced supercomputers. Global and regional climate models are based on the physical dynamic and thermodynamic laws governing the atmosphere. These describe the redistribution of heat, momentum, and moisture resulting from atmospheric motion, radiative transfer and thermodynamics associated with phase changes of water. The governing equations are non-linear partial differential equations that require appropriate numerical methods for their solution (e.g., Henderson-Sellers and McGuffie, 1987; Trenberth, 1991).

The complexity and mutual inter-dependency of mountain environmental and socio-economic systems pose significant problems for climate impacts studies (Beniston et al., 1997), particularly when dealing with extreme weather events. The current spatial resolution of General Circulation Models (GCMs) is generally too low to adequately represent the orographic detail of most mountain regions when investigating current and future trends in regional climate. On the other hand, most impacts research requires information at fine spatial definition, where the regional details of topography or land-cover are important determinants in the response of natural and managed systems to climatic change. Since the mid-1990s, the scaling problem related to complex orography has been addressed through regional modeling techniques, pioneered by Giorgi and Mearns (1991), and through statistical-dynamical downscaling techniques (e.g., Zorita and von Storch, 1999).

So-called "nested" approaches to regional climate simulations, whereby large-scale data or GCM outputs are used as boundary and initial conditions for regional climate model (RCM) simulations, have been applied to scenario computations for climatic change in the 21^{st} century (Giorgi and Mearns, 1999). The technique is applied to specific periods in time ("time slices" or "time windows") for which high-resolution simulations are undertaken. GCM results for a given period include the long-term evolution of climate prior to the particular time horizon, based on an incremental increase of greenhouse gases. The RCM focuses on a high-resolution simulation for a limited time span over a given geographical area. The nested modeling approach represents a trade-off between decadal- or century-scale, high resolution simulations that are impossible, even with current high-performance computers, and relying only on coarse resolution results provided by long-term GCM integrations. Although the method has a number of drawbacks, in particular the fact that the nesting is "one-way" (i.e., the climatic forcing occurs only from the larger to the finer scales and not vice-versa), RCMs in general improve the regional detail of climate processes. This can be an advantage in areas of complex topography, where orographic precipitation may represent a significant fraction of annual or seasonal rainfall in various mountain regions. Such improvements are related to the fact that RCM simulations capture the regional detail of such forcing elements as topography or large lakes, and the local forcing by these features on regional climate processes better than GCMs (Beniston, 2000).

Over time, the increase in spatial resolution of RCMs has allowed an improvement in the understanding of regional climate processes and the assessment of the future evolution of regional weather patterns influenced by a changing global climate. Marinucci et al. (1995) tested the nested GCM-RCM technique at a 20-km resolution to assess its adequacy in reproducing the salient features of contemporary climate in the European Alps, while Rotach et al. (1997) repeated the numerical experiments for a scenario of enhanced greenhouse-gas forcing. RCM spatial resolution has continually increased since the beginning of the 1990s, partially as a response to the needs of the impacts community. Currently, simulations with 5 km or even 1 km grids are used to investigate the details of precipitation in relation to surface runoff, infiltration, and evaporation (e.g., Arnell, 1999; Bergström et al., 2001), extreme events such as precipitation (Frei et al., 1998), and damaging wind storms (Goyette et al., 2001; Goyette et al., 2003).

When applied to climate change scenarios, global and regional models are powerful tools that allow an insight into the possible climate futures in response to various levels of greenhouse gas emissions and concentrations. Figure 12.9 shows the probable global warming rate in response to a number of emission scenarios developed by the IPCC (2001). According to the scenario, the response of climate ranges from an increase in global mean temperatures of 1.°C to 5.8°C. The scenarios are based on pathways of economic and population growth, hypotheses related to technological advances, the rapidity with which the energy sector may reduce its dependency on fossil fuels, and other socio-economic projections related to deforestation and land-use changes, for example. Socio-economic futures are of course fraught with uncertainty, hence the range of scenarios that the IPCC has developed in order to have a range of climatic responses to future global social, demographic, and economic trends.

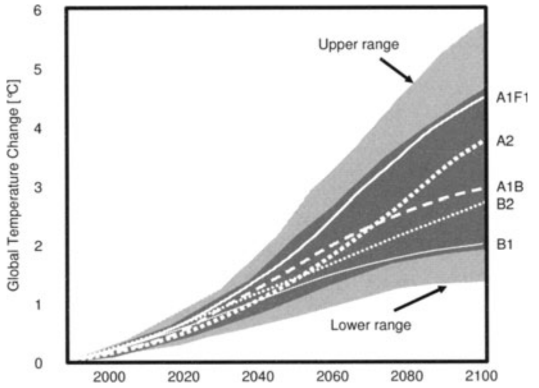

Figure 12.9. Global warming futures according to various greenhouse gas emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC, 2001).

At the regional scale, RCM simulations at high spatial and temporal resolution have been undertaken over Europe by a network of European research groups working in the context of the "PRUDENCE" project (Christensen et al., 2002). Preliminary results from the HIRHAM model (Christensen et al., 1998) indicate that on average, Europe is likely to experience a rise in average temperatures by about 4°C in the period 2071-2100 compared to the reference period 1961–1990, when using the IPCC Scenario A-2 for greenhouse gas emissions; this scenario represents an upper range of possible futures illustrated in Figure 12.9, in order to assess the response of the climate system to strong greenhouse-gas forcing. The distribution of changes in summer maximum tem-

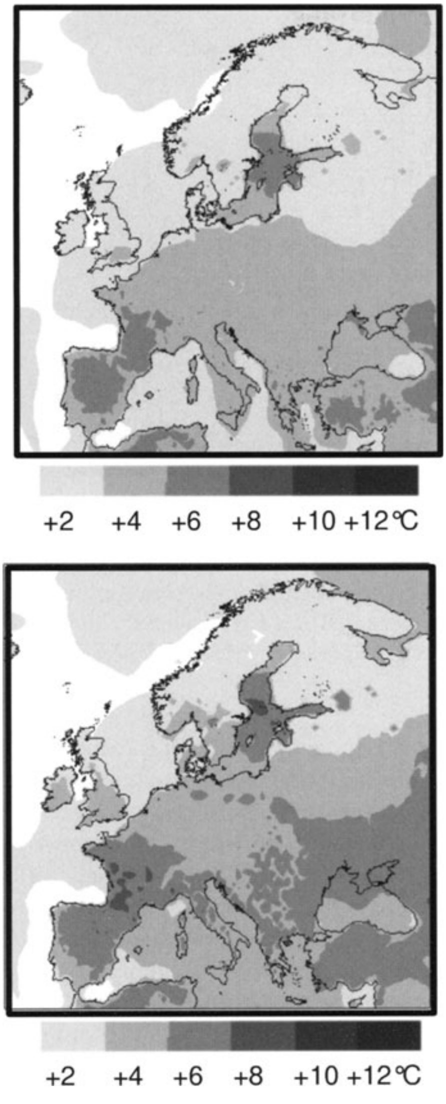

Figure 12.10. Upper: shifts in mean summer (June, July and August) maximum temperatures in Europe between current climate (1961–1990 average) and future climate (2071–2100 average) for IPCC Scenario A-2; lower: shifts in extreme summer temperatures above the 90th quantile between current and future climates(Figure: Courtesy B. Koffi, University of Fribourg).

peratures is given in Figure 12.10 (upper), where a general northward migration of climatic zones leads to warming that exceeds 6°C from the Iberian Peninsula to SW France and in the Baltic Sea region, for reasons related to changing hydrological and soil moisture regimes. The changes in the 90th quantile of

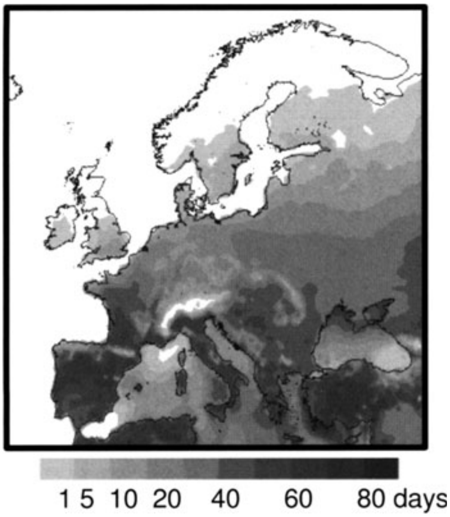

Figure 12.11. Changes in the number of days where maximum diurnal temperatures (Tmax) exceed the 30°C threshold in Europe between current (1961–1990) and future (2071–2100) climates based on HIRHAM4 regional climate model simulations for the IPCC Scenario A-2 (Figure: Courtesy B. Koffi, University of Fribourg).

maximum temperature (Figure 12.10, lower), exhibit an asymmetric increase, i.e., the shifts in the upper extremes of summer temperatures are generally more marked than the changes in means, and can exceed 8°C in some parts of western and southern Europe. The change in mean summer maxima is thus accompanied almost everywhere by disproportional shifts in the extremes; this has significant repercussions for hydrology, ecosystems, and agriculture, where extreme temperatures exert stronger controls on evaporation or desiccation, heat and water stress on plants than mean temperatures.

Another manner of viewing the changes in extreme temperatures is illustrated in Figure 12.11, where the change in the number of days where changes in the maximum daily temperatures (Tmax) that exceed 30°C between the reference period 1961–1990 and the end of the 21^{st} century (2071–2100) have been mapped for Europe. The northward shift of the climatic zones by 400-600 km is well visible, with climate by the end of the 21^{st} century in southern France resembling the current conditions of southern Spain, and the summers of the alpine region tending towards those of southern France within the same time-frame.

The analysis of the PDF of maximum daily temperatures, illustrated in Figure 12.12 for Neuchâtel (based on RCM data for the closest grid-point to Neuchâtel), emphasizes the strong shift in temperature extremes between the 1961–1990 reference period, and the future period. The number of days where maximum temperatures remain below the freezing point drop sharply to only 3 days as compared to 16 days per year on average currently, while the 30°C threshold is exceeded on average 70 years per year in the future compared to a range of 15–25 days under contemporary climatic conditions, i.e., a three- to five-fold increase in the warm extreme range of temperature. Maximum annual temperatures are seen to exceed 45°C in some years of the 2071–2100 period, as opposed to about 33-36°C currently (the absolute maximum temperature record for Switzerland just exceeded 40°C in Aarau in August 2003).

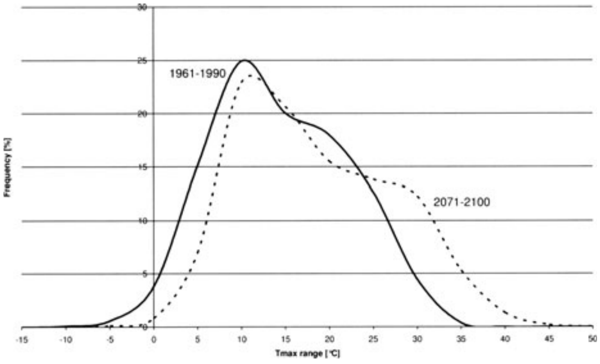

Figure 12.12. Shift in the maximum temperature PDF as computed by the HIRHAM regional climate model for current (1961–1990) and future (2071–2100) climatic conditions at Neuchâtel.

Future precipitation trends, while more problematic to simulate in climate models than temperature, nevertheless shows a dual trend, i.e., a general reduction in *average* annual precipitation, and an increase in *extreme* precipitation events. This has already been shown to be the probable case for much of Europe by Christensen and Christensen (2003), where as a result of much warmer summer temperatures, precipitation tends to decrease on average. On the other hand, the energy supplied by the higher temperatures is capable of triggering short-lived but very severe convective rainfall events, which in some parts of the Alps could increase by as much as 30% for a 2°C warming according to Frei et al. (1998).

Simulations of daily precipitation over the Swiss Plateau suggest that both ends of the precipitation "spectrum", i.e, very dry conditions or those associated with strong precipitation events, are likely to increase. Although *average* precipitation changes little between the current and future reference periods, episodes with little or no rainfall in the HIRHAM model are seen to increase by about 33% in the future, while the number of days with precipitation exceeding 25 mm/day or more may increase by 25%. The tendency of a dual simultaneous increase of low and high precipitation extremes in the mid-latitudes in a warmer climate has been reported elsewhere, notably for North America (e.g., IPCC, 2001; Trenberth, 1999) and for Europe (e.g., Christensen and Christensen, 2003).

Very preliminary results from modeling studies of extreme winter storms, based on model studies of events such as the 1990 *Vivian* storm (Goyette et al., 2001) or the 1999 *Lothar* storm (Goyette et al., 2003), suggest an increase in the frequency of strong winds originating in the Atlantic at the expense of föhn-type storms related to southerly flow across the Alps. There is a strong probability that the alpine region will experience at least one event with similar intensity to the 1999 *Lothar* "storm-of-the-century" by 2020. While this may not appear to be significant, it should be borne in mind that the insured infrastructure is likely to increase over the next decades, thus leading to a strong rise in damage costs in the event of such a wind storm affecting the region.

4. Using Climate Simulations to Assess Damage Costs

The preceding sections have provided a brief overview of the types of climatic extremes that have occurred in the past and those that may be experienced in a future warmer climate. Climate and atmospheric modeling has made considerable progress in recent years, to the extent that the simulation of extreme climatic events at high spatial and temporal resolution is now possible within the general limits of accuracy and uncertainty associated with such models.

The link to economic models, enabling an assessment of damage costs related to extreme events in a future climate, poses numerous problems, however. There is no universal manner of coupling two types of model whose concepts, structure, and objectives are very different from one another. It is illusory to aim for an integrated model structure, by which the estimates of economic costs related to extreme events could be provided by one single modeling system. Rather, the link between climatology and economics needs to be carried out in a progressive manner, with a strong focus on dialog between the experts in all domains concerned. The key to interdisciplinary research is primarily a question of opening up to other domains, and to understand the functioning, limits, and strengths of methodologies and models used by other communities.

Problems that require careful attention, when attempting to use climate information for impacts purposes, and in particular economic impacts related to events, include the type of data needed for the impacts assessment, a model's capability in delivering such data, and the spatial and temporal scales of the event under consideration.

Table 12.1 provides a brief insight into the types of questions that need to be reviewed when using climatic data for economic impacts assessments.

Spatial and temporal scales of weather events are elements that will determine the course of an economic impact assessment and the manner in which the data from a climate model can be applied to the evaluation of damage costs. Table 12.2 emphasizes the problems of scale that need to be addressed and explains why a unique methodology cannot be applied to the problem of damage costs for all types of events. There is also the added complexity of compatibility

Table 12.1. The type of data that needs to be considered and its implications for economic impacts assessments.

Type of model data	**Implications for economic impact assessments**
Mean temperature, precipitation?	Of interest because a few impacts can be triggered in the absence of a climatic extreme.
Extremes of heat, moisture, wind?	It is necessary to pre-determine for each variable what constitutes an extreme: threshold exceedance, frequency, etc.
Frequency (PDF) of events?	According to the type of event, the percentile level (e.g., 5, 95, 10, or 90) needs to be defined.
Return period of events?	This is another manner of viewing frequencies often used by insurance companies for establishing their statistics and hence their premium rates.
Threshold (intensity) of events?	This may provide a more direct relationship between a particular event and its economic impacts, e.g, some insurance companies will automatically reimburse damage to infrastructure when wind velocities are measured at more than 75 km/h.
Pre-established relationships?	A number of known links can be used to assess damage under changing climatic conditions, e.g., wind velocity and damage to buildings; cold spells and costs of road maintenance; snow duration and revenue for ski resorts; extreme precipitation and flood damage; etc.

of scales between those that a climate model can realistically deliver, and those associated with damage to infrastructure that are often at very local scales such as individual buildings, for example. In this case, gridded model data can be provided for a range of relevant variables, but it is necessary to bear in mind that many of the impacts themselves may be restricted to scales that may be orders of magnitude smaller than the resolution of the models. These problems need to be addressed through appropriate downscaling techniques that allow a coherent transfer of information from the grid-resolved scales to the impacts levels.

5. Concluding Remarks

While changes in the long-term mean state of climate will have many important consequences on numerous environmental, social, and economic sectors, the most significant impacts of climatic change are likely to come about from shifts in the intensity and frequency of extreme weather events. Indeed, insurance costs resulting from extreme weather events have been steadily rising since the 1970s, essentially in response to increases in population pressures in regions that are at risk, but also in part because of recent changes in the frequency and severity of certain forms of extremes. Regions now safe from catastrophic

Table 12.2. Typical spatial and temporal scales of extreme climatic events, illustrating the difficulty of defining a unique strategy for using climate data in economic impacts assessments.

Type of extreme	**Typical spatial scale of event**	**Typical spatial scale of impact**	**Typical time scale of event**	**Typical time scale of impact**
Winter wind storms	System: 1000 km Track: > 1000 km	Individual buildings to large areas along storm track	1 day	A few seconds (response to gusts)
Heat waves, cold spells	100 km^2 – >1000000 km^2	From persons to large areas	> 3 days	Comparable to the duration of the event
Extreme precipitation	1 km^2 – 10000 km^2	Individual buildings to large areas	Minutes to hours	A few minutes to a few hours
Floods	1 km^2 – > 10000 km^2	Individual buildings to large areas	Minutes to months	A few minutes (flash floods) to several weeks after the event
Hail	1 km^2 – 10 km^2	Cars, buildings, to large agricultural surfaces	Minutes	A few seconds (damage by hail)
Drought	100 km^2 – >1000000 km^2	Comparable to the scale of the event	Several days to several months	A few days to several weeks after the event

wind storms, heat waves, and floods could suddenly become vulnerable in the future. Under such circumstances, the associated damage costs could be extremely high. It seems appropriate, therefore, considering the environmental, human and economic costs exerted by extreme climatic events, to address the problem of whether there may be significant shifts in extremes both from a physical and an economic point of view, in order to attempt an assessment of the potential damage costs that could befall a particular region, thereby providing a conceptual basis for the establishment of appropriate response strategies.

This paper has given a brief overview of certain types of weather extremes as they have affected the alpine region, and as they may continue to do so in the future, under changing global climate. It has been emphasized throughout that there are no simple links between the behavior of extremes in relation to changes in mean climatic conditions, which adds complexity when attempting to understand and to simulate extreme events in mid-latitude mountain regions. It has also been stressed that there are no easy solutions to coupling economic and climatic models, because of numerous problems related to spatial and temporal scales of the weather elements and the impacted infrastructure, the very different conceptual approaches used in the different types of model, and a lack of long-term experience in the dialog between the two research communities.

It is through this latter factor, namely the improvement in the mutual understanding of two vastly different disciplines by the research communities involved, that progress will be achieved in addressing the important and complex issues related to the impacts of climatic change and weather extremes on infrastructure and human systems.

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Chapter 13

SWISS AGRICULTURE IN A CHANGING CLIMATE: GRASSLAND PRODUCTION AND ITS ECONOMIC VALUE

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Jürg Fuhrer

Abstract The impact of increasing atmospheric CO_2 concentrations and climate change on the grassland production in Switzerland is investigated with the help of a simple model of grass growth. The model operates at the seasonal scale. The range of future climatic conditions is represented by three scenarios, one of which mimics the conditions of the heat wave of the summer of 2003. The model results indicate that during the 21st century grassland production could potentially increase by about 50 %. However, less favourable water conditions could offset the beneficial impact of elevated CO_2 and higher temperatures. According to the model predictions, shortage of water during the growing season would follow from a decrease in precipitation and, in one of the scenarios, an increase in potential evapotranspiration. It is argued that production levels close to the potential limit could actually be achieved through irrigation. This measure could be realized at reasonable costs, but its implementation would eventually depend on the competition for water among the different economic actors.

1. Introduction

The value of the agricultural production of Switzerland for the year 2000 was estimated by the Swiss Farmers' Union (2001) at 7.6 billion Swiss francs (sfr). This value includes all sales of agricultural products to other economic sectors, both at home and abroad, but does not account for the monetary value related to fluxes of goods within the agricultural sector (Swiss Farmers' Union, 2001, p. 191). In this scheme, the value associated with animal production was of 5.2 billion sfr, or 68 % of the total, with shares of 2.6, 1.1 and 1.0 billion sfr from dairy products, cattle and pork meat, respectively. For these three categories

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of products, the contribution of the domestic production to the total demand was of 94, 85 and 91%.

Animal husbandry substantially depends on the energy output of grasslands. Of the 65'000 terajoules (TJ) of convertible energy needed in 2000 for animal feeding, 49'000 TJ or 75 % were supplied by the domestic forage production. Assuming that this percentage can be used to scale the value of the animal production, and excluding the intrinsic value of grasslands and forages, we end up with 3.5 to 4.0 billion sfr associated with grassland production. This represents a significant fraction of the total.

Presently, the area allocated to productive grasslands and pastures is of 745'000 ha or 70 % of the total agricultural acreage (Swiss Farmers' Union, 2001). The productivity of these areas depends on the type and intensity of management, but also on geographic and climatic factors. On the average the annual dry matter production is of the order of 1 kg m^{-2} or 10 t ha^{-1}.

According to the Intergovernmental Panel on Climate Change (IPCC, 2001), the 21st century will be characterized by an overall increase in atmospheric CO_2 concentrations and temperature. In the IPCC scenarios, CO_2 concentrations are projected to increase by more than a factor of 2 by the end of the century, whereas the most likely temperature rise is settled in a range between 1.5 and 5 °C. For the alpine region the temperature is expected to increase slightly more rapidly than on the global scale.

The aim of the present paper is to quantify the impact of climate change on grassland production and to discuss the most obvious economic implications. The analysis is based on a simple description of the dynamics of cut grassland ecosystems. In essence, this description is consistent with the formulation of grassland dynamics in more complex models such as the Hurley Pasture Model (Thornley, 1998) and the Pasture Simulation Model (Riedo et al., 1998). Given that the emphasis of the paper is on physical and biological principles, the discussion of the economic aspects is kept at a very basic level. A more thorough analysis of the economic impact of climate change on agriculture at the local, regional and global scale can be found in Flückiger and Rieder (1997).

2. Grassland production: the model

In the present context, by grassland production or grassland yield we understand the production of aboveground biomass, expressed as dry matter (DM) per unit area. Units are [kg DM m^{-2}], and 1 kg DM $m^{-2} \equiv 10$ t DM ha^{-1}. We distinguish between potential and actual production. The potential production is defined as the production obtained at given radiation, temperature and CO_2 levels under unlimited supply of water and nutrients. By actual production we mean the water-limited production, always assuming a sufficient availability of nutrients.

With reference to Thornley (1998), the growth of aboveground biomass or shoot dry matter, W_{sh} [kg DM m^{-2}], can be described by the following first-order differential equation:

$$\frac{dW_{sh}}{dt} = G_{sh} - k\,W_{sh} \quad , \tag{1}$$

where G_{sh} [kg DM m^{-2} d^{-1}] is the shoot growth rate and k [d^{-1}] a turnover rate accounting for the ageing process. The two parameters G_{sh} and k vary in time depending on the actual environmental conditions. For simplicity, however, we assume that these are constant and equal to their seasonal mean values over the entire vegetation period. This allows equation (1) to be solved analytically. With the initial condition $W_{sh}(0) = 0$ the solution reads:

$$W_{sh}(t) = \frac{G_{sh}}{k}\left(1 - e^{-kt}\right) \quad , \tag{2}$$

with an equilibrium limit given by:

$$W_{sh} \longrightarrow \frac{G_{sh}}{k} \quad \text{as} \quad t \longrightarrow \infty \quad . \tag{3}$$

To a first approximation, this asymptote represents the total production per growth cycle. To estimate the annual dry matter yield, Y [kg DM m^{-2}], we need the number of growth cycles per year. For cut grasslands, this is equivalent to the number of cuts per year, n_{cut}. It follows that:

$$Y \approx n_{cut}\,\frac{G_{sh}}{k} \quad . \tag{4}$$

The number of cuts rests on the length of the vegetation period, τ_{veg}, and of each cutting cycle. The criteria defining the latter are not easily translated into a simple mathematical expression. For this reason we assume that the length of a typical growth phase is constant and set $\tau_{cut} = 40$ days. Hence:

$$n_{cut} = \frac{\tau_{veg}}{\tau_{cut}} \quad . \tag{5}$$

The drawback of the above premise is that n_{cut} is not necessarily an integer, but this is acceptable within the overall framework of the model.

With reference to the free-air CO_2 enrichment (FACE) experiment carried out at Eschlikon, Switzerland (see review by Kimball et al., 2002, and references therein) the vegetation period is specified as the time of the year for which the temperature exceeds a given base, T_b. Its start and end are thus given by the condition $T(D_{start}) = T(D_{end}) = T_b$. Here we set $T_b = 5\ ^oC$, in accordance with the threshold mentioned in Kimball et al. (2002) and also in the study conducted by Menzi (1988).

If, in common with other impact studies (e.g. Thornley and Cannell, 1997), we approximate the annual march of T by a sinusoidal function:

$$T = M_T + A_T \sin(\omega D - \varphi_T) \quad , \tag{6}$$

with M_T being the annual mean temperature, A_T and φ_T the amplitude and phase of the annual cycle, $\omega = 2\pi/365$ and D the day of year, then:

$$D_{start} = \frac{1}{\omega}\left\{\arcsin\left(\frac{T_b - M_T}{A_T}\right) + \varphi_T\right\} \quad , \tag{7}$$

$$D_{end} = D_{start} + \tau_{veg} \quad , \tag{8}$$

and

$$\tau_{veg} = \frac{1}{\omega}\left\{\pi - 2\arcsin\left(\frac{T_b - M_T}{A_T}\right)\right\} \quad . \tag{9}$$

These equations are valid provided that:

$$\left|\frac{T_b - M_T}{A_T}\right| \leq 1 \quad . \tag{10}$$

Let us now examine the environmental conditions affecting G_{sh} and k. As pointed out by Monteith (1981), the potential growth rate, $G_{sh,pot}$, is nearly a constant fraction of the net amount of CO_2 assimilated (gross photosynthesis minus respiration). From the molecular weights of CH_2O and CO_2 this ratio is $30/44 \sim 3/4$. Furthermore, experimental evidence suggests that the amount of CO_2 respired is also a constant fraction of the gross photosynthesis, usually between 35 and 45 % (Yamaguchi, 1978). Therefore, the growth rate is expected to be:

$$G_{sh,pot} \approx 0.4\,P_{can,pot} \quad , \tag{11}$$

where $P_{can,pot}$ [kg C m^{-2} d^{-1}] is the potential value of the gross photosynthetic rate of the canopy. The validity of (11) is confirmed for a wide range of environmental conditions by calculations carried out with the mechanistic Pasture Simulation Model (Riedo et al., 1998).

The details of the evaluation of $P_{can,pot}$ can be found in Thornley and Johnson (1990) and Thornley (1998) and are not reproduced here. Briefly, $P_{can,pot}$ depends on incident radiation, temperature, CO_2 concentrations, and the leaf-area index, LAI [m^2 m^{-2}]. The latter determines the amount of radiation absorbed by the canopy. To keep the model at a basic level, we assume that the effective LAI is proportional to $G_{sh,pot}$ and that under present-day conditions LAI = 3 m^2 m^{-2}. (Strictly speaking, the effective LAI is proportional to G_{sh} but this would imply an iterative solution).

Having established $G_{sh,pot}$, the actual growth rate, G_{sh} [kg DM m^{-2} d^{-1}], is calculated as (Thornley, 1998):

$$G_{sh} = G_{sh,pot}\,W \quad , \tag{12}$$

where W [-] is a measure of the effects of water limitation on growth satisfying the relation $0 \leq W \leq 1$. In many agricultural applications (e.g. Doorenbos and Kassam, 1979) this factor is represented by the so-called wetness index, which is the ratio of actual and potential evapotranspiration, ET_{act}/ET_{pot}.

The minimalist probabilistic description of root zone soil water proposed by Milly (1993, 2001) suggests that:

$$W = r \left\{ \frac{e^{[\alpha(1-r)]} - 1}{e^{[\alpha(1-r)]} - r} \right\} , \tag{13}$$

where $r = RR/ET_{pot}$ is the ratio of precipitation, RR [mm d^{-1}], and potential evapotranspiration, and the parameter α depends on soil type and mean rainfall depth, h [mm], according to:

$$\alpha = \frac{Z_r\ (\theta_f - \theta_w)}{h} . \tag{14}$$

Here, $\theta_f = 0.20$ $\mathrm{m}^3\ \mathrm{m}^{-3}$ and $\theta_w = 0.13$ $\mathrm{m}^3\ \mathrm{m}^{-3}$ are the volumetric soil water contents at field capacity and permanent wilting point, respectively, and $Z_r = 0.5$ m is the depth of the rooting zone. The values for θ_f and θ_w are those of a sandy loam, chosen for this study as the representative soil type. In general, θ_f and θ_w can be found in tables or inferred from soil texture using procedures outlined in Shirazi and Boersma (1984) and Campbell (1985).

In (13) the potential evapotranspiration, ET_{pot}, is evaluated using the Penman-Monteith relation (Monteith and Unsworth, 1990). The aerodynamic resistance is computed using the standard micrometeorological formulation for neutral conditions (Garratt 1992), with values for the wind speed, roughness length and zero-plane displacement of 2 m s^{-1}, 0.05 m and 0.2 m, respectively. As in Riedo et al. (1998), the canopy resistance is described following the model of Ball et al. (1987), which includes the effects of LAI, relative humidity, RH, $P_{can,pot}$, and CO_2 concentrations. This model predicts an almost linear increase of the canopy resistance with increasing CO_2 concentrations, consistently with current understanding of the effects of CO_2 on leaf and canopy conductance (Kimball et al., 2002; Polley, 2002).

As seen from (4), the other determinant of the total yield is the turnover rate, k [d^{-1}]. For its potential value Thornley (1998) proposes $k_{pot} = 0.08$ d^{-1}. However, his model keeps track of four age categories, whereas a single age category is considered here. In our case realistic results are obtained with $k_{pot} = 0.02$ d^{-1}. This value must be modified to account for the acceleration of the ageing process under water stress. In line with Thornley (1998) we assume:

$$k = \frac{k_{pot}}{W} . \tag{15}$$

From (4), (12) and (15) it finally follows that:

$$Y \approx Y_{pot} W^2 , \tag{16}$$

where

$$Y_{pot} \approx n_{cut} \frac{G_{sh,pot}}{k_{pot}} \tag{17}$$

is the potential yield in units of [kg DM m^{-2}].

3. The climate scenarios

For the present analysis we define a small set of climate scenarios relying on information from a number of sources. The scenarios span the whole 21st century and are valid for the summer season and for low elevations.

For the evolution of CO_2 concentrations, we refer to the A2 scenario of IPCC (2001). The A2 scenario yields atmospheric CO_2 levels of about 370, 530 and 860 ppm by 2000, 2050 and 2100, respectively. It envisions population growth to 15 billion by the end of the 21st century and a rather slow economic and technological development. It projects slightly lower greenhouse gases emissions than the earlier IS92a scenario, but also slightly lower aerosol loadings, giving a faster rise in CO_2 concentrations than in the IS92a and B2 scenarios.

For temperature and precipitation we propose a minimum (least absolute change) and a maximum (largest absolute change) scenario. In both cases we assume a linear evolution in time, quantified according to a compilation of global climate scenarios available from the IPCC data centre (IPCC, 2001), a corresponding set of regional climate scenarios derived by statistical downscaling (Jasper et al., 2004), and historical weather data for the period 1901-2000 (Bantle, 1989).

In addition, we specify a so-called extreme scenario by referring to the meteorological conditions of the summer of 2003. In Switzerland, this summer was rather unique, with a temperature departure from the long-term average of the order of +5 °C and precipitation amounts clearly below the long-term mean (Schär et al., 2004). The extreme scenario is implemented with the intention of providing a possible lower limit for grassland production in individual, not necessarily consecutive years.

Since the length of the growing season is variable, equation (9), for temperature we first prescribe scenarios for the annual mean, M_T. With y denoting the year, the minimum (MIN), maximum (MAX) and extreme (EXT) scenarios read:

$$M_T(y) = \begin{cases} 8 + 0.015\,(y-2000) & {}^o\mathrm{C} & \mathrm{MIN} \\ 8 + 0.060\,(y-2000) & {}^o\mathrm{C} & \mathrm{MAX} \\ 13 & {}^o\mathrm{C} & \mathrm{EXT} \end{cases} . \tag{18}$$

We further fix amplitude and phase of the annual cycle at $A_T = 11\ {}^o\mathrm{C}$ and $\varphi_T = 2.2$. Although this value for A_T is somewhat larger than the corresponding figure inferred from the historical data, it ensures that equation (10) is always satisfied. We then find the average temperature of the growing season, $< T >$, by integration of (6), with (7), (8) and (9), as

$$< T > = M_T - \frac{1}{\tau_{veg}} \frac{A_T}{\omega} \{\cos(\omega\, D_{end} - \varphi_T) - \cos(\omega\, D_{start} - \varphi_T)\} . \tag{19}$$

For the average precipitation of the growing season we propose:

$$< RR > (y) = \begin{cases} 4 - 0.004\,(y-2000) & \mathrm{mm\ d^{-1}} & \mathrm{MIN} \\ 4 - 0.016\,(y-2000) & \mathrm{mm\ d^{-1}} & \mathrm{MAX} \\ 2 & \mathrm{mm\ d^{-1}} & \mathrm{EXT} \end{cases} . \tag{20}$$

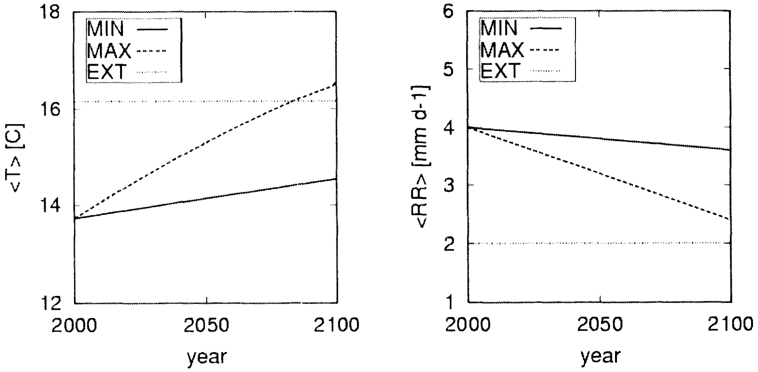

Figure 13.1. Minimum (MIN), maximum (MAX) and extreme (EXT) scenarios for the mean temperature (<T>, left panel) and precipitation ($<RR>$, right panel) of the growing season.

We further assume that the mean rainfall depth is constant and take $< h >=$ 10 mm.

The scenarios for $< T >$ and $<RR>$ are shown in Fig. 13.1. The increase in $< T >$ in the MIN and MAX scenarios is less than the corresponding increase in M_T because the frequency distribution of temperature is, relatively speaking, shifted toward lower values as the growing season becomes longer. The same reasoning applies to the mean temperature of the vegetation period in the EXT scenario, which is only about 3.5 ^{o}C higher than the corresponding present-day mean temperature in the MIN and MAX scenarios, instead of the 5 ^{o}C assumed for the annual mean temperature.

Estimates of the mean net radiation, $<NR>$ [W m^{-2}], and mean relative humidity, $<RH>$ [%], needed for computing $<ET_{pot}>$, are derived from $< T >$ and $<RR>$ as follows:

$$< NR > \; = \; -10 + 15 \; < Gl > \quad , \tag{21}$$

with

$$< Gl > \; = \; 250 \; - \; 10 \; < RR > \tag{22}$$

being the mean global radiation [W m^{-2}], and:

$$< RH > \; = \; 80 \; - \; 3 \; (< T > \; - 8) \quad . \tag{23}$$

These or similar relations can be drawn from a statistical analysis of the historical weather records (Bantle, 1989). In particular, (22) can be explained noting that changes in precipitation are associated with changes of the same sign in cloudiness and therefore changes of the opposite sign in global radiation.

4. Growth and production scenarios

Inspection of equations (16) and (17) shows that in the model the impact of climate change on grassland production is a combination of alterations in: 1) the potential growth rate; 2) the number of cuts; and 3) the wetness index. In all three scenarios the potential growth rate positively responds to the rise in CO_2 levels in the way defined by the model of Thornley (1998) (Fig. 13.2). Differences among the scenarios reflect the specific radiation and temperature conditions.

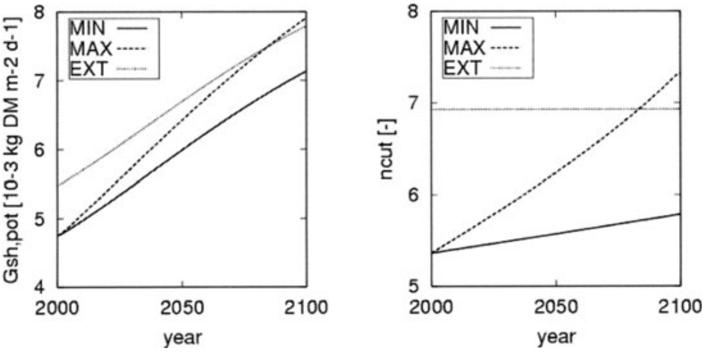

Figure 13.2. Minimum (MIN), maximum (MAX) and extreme (EXT) scenarios for potential growth rate ($G_{sh,pot}$, left panel) and number of cuts per year (n_{cut}, right panel).

The number of cuts (Fig. 13.2) closely follows the evolution of the annual mean temperature, M_T, because to first order:

$$\begin{aligned} n_{cut} &= \frac{T_{veg}}{T_{cut}} = \frac{1}{T_{cut}\,\omega}\left\{\pi - 2\arcsin\left(\frac{T_b - M_T}{A_T}\right)\right\} \\ &\sim \frac{1}{T_{cut}\,\omega}\left\{\pi - 2\left(\frac{T_b - M_T}{A_T}\right)\right\} \qquad (24) \\ &\propto M_T\ , \end{aligned}$$

all other terms in this equation being constant.

The wetness index, as defined by equation (13), accounts for both the changes in precipitation (Fig. 13.1) and potential evapotranspiration (Fig. 13.3). In the MIN scenario a slight diminution of the mean precipitation and moderate values of the potential evapotranspiration ensures that $(<RR>/<ET_{pot}>) > 1$ and $<W> \sim 1$ in all years. In the EXT scenario, $W << 1$ because $(<RR>/<ET_{pot}>) << 1$. In the MAX scenario, $<RR>$ and $<ET_{pot}>$ display opposite tendencies, with $<RR>$ decreasing and $<ET_{pot}>$ increasing with time. This results in a pronounced reduction of $(<RR>/<ET_{pot}>)$ and consequently W. Elevated CO_2 concentrations improve the water use

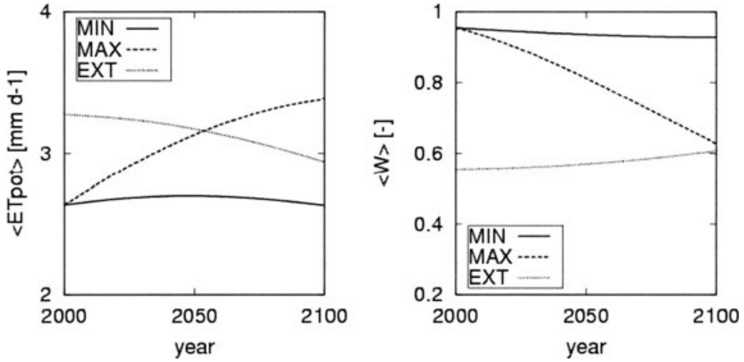

Figure 13.3. Minimum (MIN), maximum (MAX) and extreme (EXT) scenarios for the mean potential evapotranspiration ($<ET_{pot}>$, left panel) and the mean wetness index ($<W>$, right panel) of the vegetation period.

efficiency in all scenarios by raising the canopy resistance, but a decrease in $<ET_{pot}>$ is actually observed only in the EXT scenarios. In the MIN scenario, $<ET_{pot}>$ remains nearly constant, while in the MAX scenario $<ET_{pot}>$ becomes substantially larger. The relative increase of the order of 30 % in the latter scenario is in line with the results of an earlier analysis carried out with the Pasture Simulation Model by Riedo et al. (2001).

Does this finding contradict the experimental evidence collected by Kimball et al. (2002)? We do not think so because: 1) as in other modelling studies (Thornley and Cannell, 1997; Riedo et al., 2001), elevated CO_2 concentrations favour growth and are therefore accompanied (limiting factors remaining unchanged) by higher values of the LAI (see also Lockwood, 1999). In the model of Ball et al. (1987) this partially or completely counterbalances the CO_2 effect on canopy resistance; 2) as the temperature raises and the relative humidity drops, the water vapour pressure deficit becomes larger and so does the aerodynamic (or adiabatic) term in the Penman-Monteith relation (cf. Lockwood, 1999); and 3) the decrease in precipitation in both scenarios implies an upward trend in global and net radiation. This positively contributes to the energy (or diabatic) term in the Penman-Monteith relation.

The combined effects of the environmental factors on the evolution of potential and actual production is shown in Fig. 13.4. As expected, the potential production increases in all scenarios, by about 60 % in the MIN, by more than a factor of 2 in the MAX, and by 40 % in EXT scenario. These figures are striking, but obviously do not equally apply to the actual production. In the MIN and MAX scenario this latter is of the order of 1.2 kg DM m^{-2} under present climatic conditions, in good agreement with the average production for the year 2000 found in the statistics of the Swiss Farmers' Union (2001) (see Introduction). By the year 2100, the actual yield increases to about 1.8 kg DM m^{-2} in the MIN scenario, but remains of the same order as in 2000 in the

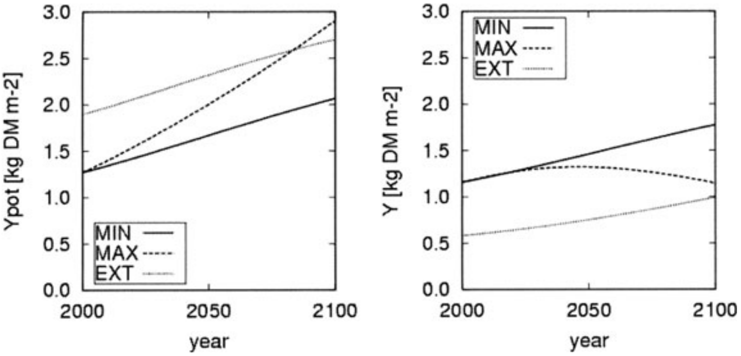

Figure 13.4. Minimum (MIN), maximum (MAX) and extreme (EXT) scenarios for potential (Y_{pot}, left panel) and actual yield (Y, right panel).

MAX scenario. In relative terms, the results of the MIN scenario are comparable to those obtained by Riedo et al. (2000). In this scenario the effects of water stress are secondary, but the decrease in the wetness index largely offsets the doubling of the potential production in the MAX scenario. In the EXT scenario, the present production is of 0.6 kg DM m^{-2}. This figure may appear unrealistically low. However, observations carried out at the experimental site of Oensingen demonstrate that under the extreme conditions of the summer of 2003 grass growth is effectively reduced to negligible levels (Fig. 13.5).

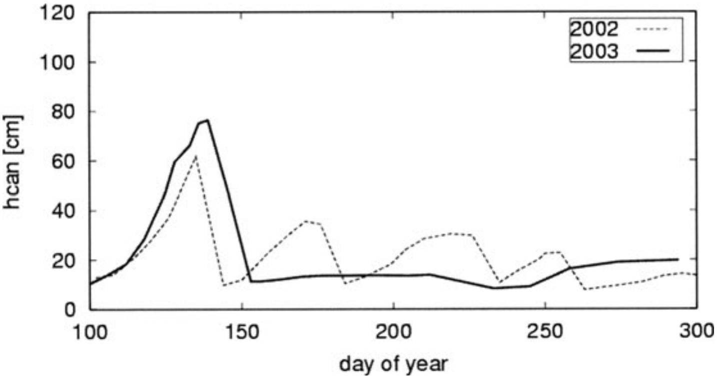

Figure 13.5. Measurements of the canopy height, h_{can} [cm], in an intensively managed grassland at the experimental site of Oensingen (7° 44' E, 47° 17' N, 450 m.a.s.l.) during 2002 (dashed line) and 2003 (continuous line). The conditions assumed for the extreme scenario are those observed after day 150 of the year 2003.

By the year 2100 the total production in the EXT scenario increases to about 1.0 kg DM m^{-2}. Although precipitation and temperature do not change in this scenario, so does the potential evapotranspiration. This is sufficient for reducing the water stress imposed on grass growth.

5. Discussion and conclusions

Our simulations suggest that during the course of the 21st century grassland production in Switzerland could potentially benefit from elevated atmospheric CO_2 concentrations and more favourable temperature and radiation conditions (see also Fuhrer, 2003, and references therein). An increase in the total grassland production of about 50 % appears realistic in the case of moderate warming and associated changes in the hydrological cycle. If changes in the thermal and hydrological conditions were more pronounced, grassland production could increasingly become water-limited. Then, an obvious strategy for sustaining a more vigorous production would be to meet the water requirements with the help of irrigation facilities. What would be the cost of such a measure at the national scale?

Approximate expenses for fixed irrigation systems can be inferred from data supplied by the Swiss Federal Office for Agriculture (2003). The data refer to a program for the improvement of soil productivity in the Valais during the decade 1993-2002. The data give effective costs per unit area in the order of 20'000 sfr ha^{-1}, not taking into account the charges for water and maintenance. If we extrapolate this value to the 745'000 ha of productive grasslands and pastures and assume a realization time of 50 years, we obtain structural costs in the order of 0.3 billion sfr annually. This is a non-negligible but still reasonable amount if compared to the present value of the grassland production (see Introduction). The question remains whether the necessary water would be available to agriculture at reasonable costs for the whole of the 21st century or competition among different economic sectors could rise the price of this primary good.

In general, the costs of adaptation represent a key issue for the economical development of the agricultural sector, in particular if summers such as the one of 2003 turn out to be more frequent. This is not improbable, as pointed out in the last assessment report of the IPCC (2001) and more recent studies based on regional climate models (Beniston, 2004; Schär et al., 2004). Actually, the findings of Beniston (2004) and Schär et al. (2004) even suggest that the conditions expressed by the extreme scenario could become rather typical during the second half of the 21st century.

Experimental evidence indicates that the response of vegetation to elevated CO_2 concentrations varies depending on whether nutrients are limiting or not (Kimball et al., 2002) and on the type of management (Flückiger and Rieder, 1997). For our analysis we have assumed unlimited supply of nutrients at all times, but aspects related to soil fertility must be taken into account for refining the present results.

In summary, productive grasslands represent the backbone of the agriculture of Switzerland. They significantly contribute, directly or indirectly, to the economy of the primary sector. The fate of agriculture in a changing climate is therefore conditional on the future of grassland production.

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Chapter 14

MODELLING CLIMATE CHANGE IMPACTS AND VULNERABILITY IN SWITZERLAND

Ana Priceputu
Hubert Greppin

Abstract

This paper explores the methodological background in climate change impact assessment, focusing on the coupling and co-action between the climate system, the biosphere, and human activities. The aim of this study is to shape a methodological framework to assess regional sensitivity/vulnerability to climate change, by introducing the ombrothermic diagram technique as a basis for analysis. Some aspects of the possible outcome for Switzerland depending on the future climate evolution have been analysed within this framework.

1. Introduction

The Swiss territory (41295 km^2: 0,027% of the world emerged surface and 0,4% of the European one) is situated between 193 and 500 m altitude for 15% of the territory, between 500 and 1000 m for 32%, 29% ranges between 1000 and 2000 m, and 24% exceeds this last limit. The local biomass corresponds to $\sim$ 0,018% of the world biomass and the net photosynthetic production pro year (NPP) to $\sim$ 0,027% of the world NPP (human population: 0,11% of the world population, producing 0,2% of the world CO_2 emission by fossil energy consumption). The extension of this local emission rate to the world level (6.10^9 H) would give $\sim$ 16 Gt atmospheric CO_2/y (600 ppm CO_2; +3°C). The actual Swiss biomass corresponds to $\sim$ 40% of the wilderness situation (potential biomass formation if Switzerland was devoid of human presence and activities) (Flüeler et al., 1976; Greppin et al., 2000, 2002).

This territory is constituted by the trilogy: Alps ($\sim$ 60% surface, maximum altitude: 4634 m; $\sim$ 1/8 population), Plateau ($\sim$30% surface, between 400 – 500 m; $\sim$ 3/4 population), and Jura mountains ($\sim$ 10% surface, maximum alti-

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tude: 1680 m, ~1/8 population). This country, located in the heart of Europe, is highly compartmented, with important altitudinal gradients and local mosaic structure. The consequence, at an average level, is a mean climatic position (semi-continental type), yet incorporating great variations in local precipitation and temperature, which generates substantial difficulties in modelling. These particularities are reinforced by the fact that Switzerland is under the influence of four climatic European spaces (west: oceanic type; east: continental; north: boreal; south: mediterranean). The oceanic character is preponderant, and Switzerland is a water-works in Europe (annual water flux: 1,219 10^6 t/km^2). All these specificities induce a high plant biodiversity, which is very representative of the European flora, in spite of its reduced national territory (Flüeler et al., 1976; Pfister and Messerli, 1990; Racine and Raffestin, 1990; Lauber and Wagner, 1998; Beniston and Verstraete, 2001).

The Swiss territory is under the effects and control of the articulation between three functioning logics that have appeared successively during the earth history: the climatic (physics, chemistry) and geologic one (~ 4,6 10^9 y), the biologic and ecologic one (3,8 10^9 y), and the human, economic and cultural one (~ 2 10^5 y), this last with a progressive and important environmental impact since the 19^{th} century. Sustainability therefore depends on the interactions and coupling between these three independent logics that define a physical, chemical and biological envelope of viability (dead or alive for biomass and species, as well as for human populations and activities). The viability of both biosphere and anthroposphere, in co-action with each other as well as with the climate system, is a prerequisite for sustainable development (see fig. 14.1 and 14.2). Viability indicators and sentinel variables permit one to follow the evolution towards sustainability and to determine the way to maximize human activity and expression with the optimum biosphere viability (Greppin, 1978; Greppin et al., 1998, 2000, 2002, 2003). Living cells and ecosystems are very sensitive to temperature and its variation (metabolic reactions, protein denaturation, ecosystems biodiversity and biomass modification). The thermic phase space analysis (Greppin et al., 2003) is a global way to observe climate change and estimate future trend (world: +2,2°C in 2100; Switzerland: +5,3°C; Swiss Alps: +5,5°C).

Humans have already changed their environment in a significant manner throughout their history. Global climate change poses a different type of threat because of the complexity of the systems involved and related uncertainties. The average global surface temperature of the planet is projected to increase by 1,4 to 5,8°C over the period 1990 to 2100, and the CO_2 atmospheric concentrations from 360 ppm to 540-970 ppm (IPCC, 2001). The question addressed in this study is what would be the resulting damages and eventual benefits of such future for Switzerland and how would these impacts be distributed across the country? An assessment of region/sector-specific climate sensitivity is therefore necessary in order to identify key vulnerabilities of interacting human-environment systems to the main climatic stimuli. We develop an ombrothermic approach to climate change impact assessment, focusing on key

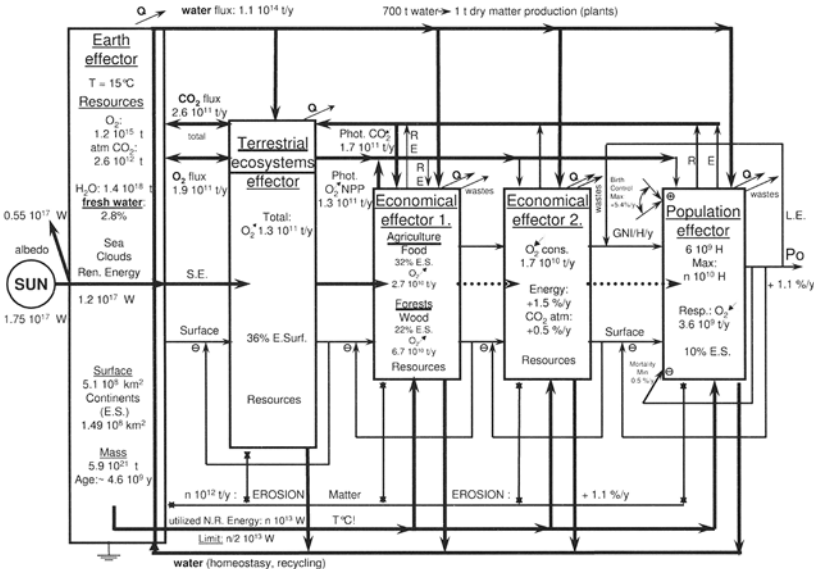

Figure 14.1. Viability Envelopes. Resp: respiration; E: energy; NR: non-renewable.

relationships between the two most limiting climatic factors, i.e., temperature and precipitation.

Some of the current methodologies for impact/vulnerability assessment are discussed in Section 2. Section 3 gives a general overview of our own methodological approach. Regional distribution of climate change impacts on natural, semi-natural and managed system in Switzerland as depicted from our ombrothermic analysis is detailed in Section 4. Section 5 focuses on the regional pattern of agricultural vulnerability. Tourism (i.e., winter tourism) and associated vulnerability is discussed in section 6; section 7 investigates some aspects of regional sensitivity to climatic extremes. Finally, section 8 presents conclusions and strategic considerations.

2. Frameworks for Impact and Vulnerability Assessment

The concepts of impact, sensitivity, vulnerability and adaptability and the relationships among them are increasingly invoked in the current literature on the possible outcomes of future climatic changes. The methodology used in their assessment gradually evolved from equilibrium to dynamic impact evaluation, and finally to vulnerability and adaptation policy assessments (Füssel and Klein, 2002).

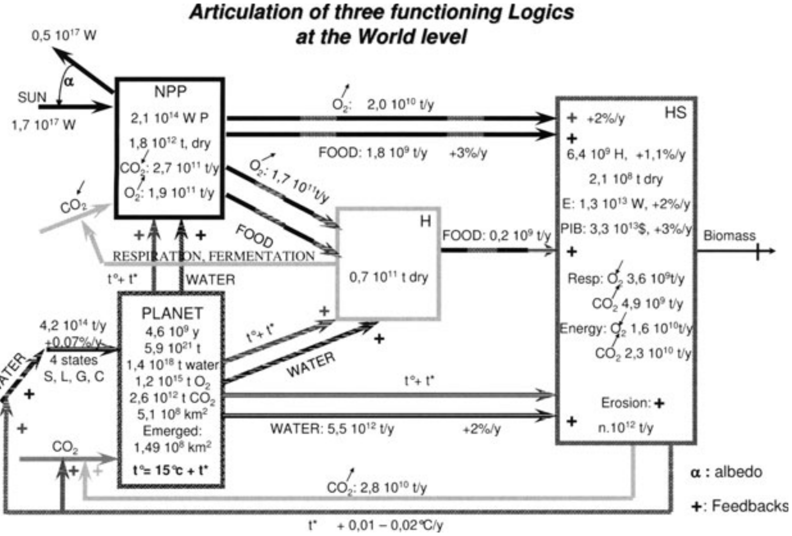

Figure 14.2. Articulation of the three functioning logics. P: photosynthesis; S, L, G, C: solid, liquid, gazeous, clouds.

Various approaches have been used to represent aggregated impacts in *Integrated Assessment Models* of climate change. The first step in damage assessment is the *equilibrium analysis* of a $2xCO_2$ scenario – a static evaluation of the monetary impacts associated with a doubling of atmospheric CO_2 concentration on *present* economy, which is also assumed to be in equilibrium. Two comprehensive analyses are particularly relevant: Nordhaus (1998) and Tol (2002a). In a second step, this evaluation is used to interpolate the trajectory of the monetized damages as a *function of the global mean temperature* (e.g., Nordhaus, 1994b; Tol, 1996; Tol and Fankhauser, 1998). The shape of the *damage function* used to represent impacts within an *Integrated Assessment Modelling* framework, determines the damage before and beyond benchmark climatic change, as well as the impact of aerosol cooling. Usually, expert knowledge and/or sensitivity analysis are used to asses this shape (e.g., Nordhaus, 1994a; Tol 2002b). Additional methodological limits include the choice of the impact driving variable(s)[1], metrics and valuation methods, treatment of non-market damages and indirect effects, discounting, etc. (Tol, 1996; Tol and Fankhauser, 1998). All in all, first generation damage functions are very sim-

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[1] The damage profile over time was shown to depend in a significant manner on whether level or rate in climate change is used (Tol, 1996).

plified relationships that fail to account for important factors determining the real magnitude of damages.

Vulnerability[2] is a broader concept than potential impact, although the two are closely related. Vulnerability is an important impact determinant, and impacts also change the degree of vulnerability. From another standpoint, impacts can be precisely described (e.g., expressed as changes in biophysical indicators such as ecosystem primary productivity, or in economic ones, such as sector monetary output); vulnerability has no agreed metric, and it cannot be measured in predefined terms (Füssel and Klein, 2002). Furthermore, vulnerability of human systems to climatic events depends to a large extent on number of other factors such as basic environmental conditions, technical and financial capability, demographic, socio-economic and cultural constraints, society organization and their future evolution. From this perspective, time-dependent damage functional forms should be described in terms of changing climate, socio-economic circumstances, vulnerability, degree of adaptation and adaptability limits (Tol and Fankhauser, 1998).

Tol (2002b) uses this vulnerability-based approach to represent climate change impacts within an *Integrated Assessment Modelling* framework. He estimates a series of impact functions that take into account the dynamics of both climate change and the impact sectors. The model uses statistical methods to combine and extrapolate results of different studies over different climates and different degrees of vulnerability to climate change. Vulnerability is measured only by socio-economic indicators, such as per capita income, population above 65, and economic structure. Nordhaus and Boyer (2000) also develop a set of regionally and sectorally disaggregated impact functions based on a willingness to pay approach. Their estimation includes for the first time a catastrophic impact category, associated with major geophysical calamities. The resulting impact functions indicate the fraction of annual income that a region is willing to pay in order to avoid the effects of incremental climate change for a given sector. Both Nordhaus and Tol express monetary impacts as a function of temperature increase and both assume future socio-economic vulnerability decaying as a function of increasing incomes.

Toth et al. (2000) and Füssel et al. (2003) use a particular approach to model climate change impacts within the same integrated assessment framework. The main new aspects are the use of non-monetary aggregated indicators (i.e., impacts are expressed in biophysical units) and the inclusion of spatial/seasonal details of climate change and climate variability. The approach is used to derive specific *climate impact response functions* (CIRFs) for different types of natural vegetation. The main indicator used to quantify the impacts of climate change on vegetation is the percentage of an area where the current biome is no

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[2] Vulnerability in the human sciences is typically identified in terms of three elements: system exposure to crises, stresses, and shocks; inadequate system capacities to cope; and severe consequences and attendant risks of slow system recovery.

longer viable[3], which is derived by the application of a geographically explicit impact model (i.e., BIOME1 is used to compute changes in the global distribution of biomes for a given climate and CO_2 concentration.). The 3-dimensional *response surface diagram* represents the relationship between two input variables of the CIRF (i.e., global annual temperature change and CO_2 atmospheric concentration) on the horizontal axes and the chosen impact indicator on the vertical axis. Thus, in contrast to earlier examples of point estimates or impact functions interpolated from a few points, the CIRFs describe systems' responses across a larger extent of future climate change patterns. However, their complete focus on biophysical impacts and the lack of integration with socio-economic drivers of vulnerability provide only a partial "ecocentric" assessment.

Reilly's work (e.g., Reilly and Schimmelpfennig, 1999; Reilly et al., 2003) addresses more specifically the issue of agricultural impact and vulnerability assessment. Two basic approaches are used to evaluate crop and farmer response to climate change: *structural modelling* and *spatial analogue techniques.* The first method needs detailed input on specific crops and crop varieties response to different climatic conditions, usually determined by means of field/controlled experiments, and furthermore, on farm management practices and their implications for farm costs and revenues. These approaches usually model a single representative crop or farm. The second approach is based on statistical analysis of regional long time-series data in order to separate climate from other factors (e.g., soil conditions, technological inputs, etc.). Even though the results of such analyses reflect more precisely how farmers operate under real commercial conditions, they lack accuracy in deducing the effect of increasing CO_2 concentrations on plant growth.

These are only a few examples amongst various conceptual frameworks and methodologies that are currently applied to vulnerability/impact assessment. One can easily see that most of them are particularly useful in characterizing human vulnerability, or on the contrary, focus mainly on the ecological one, but they all mask the complexity of the components, states, and interactions that determine the real extent of system vulnerability. For example, impacts on one system can modify impacts on others, through both biophysical and socio-economic processes. On the other hand, climate change is not occurring and will not occur in isolation, but in conjunction with many other forms of both environmental and non-environmental changes. Linked human activities and natural processes are simultaneously altering the global cycles of water, carbon, nitrogen, phosphorus, and sulfur, the radiative properties and chemical composition of the atmosphere, the physical structure of land cover over large scales, the chemistry and biology of freshwaters and oceans, etc. (Vitousek et al., 1997). These multiple stresses interact in complex ways, in both their biophysical aspects and their linkages to human impacts and responses. Some

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[3] Additional impact indicators are: % stable biome area, total potential biome area, % stable forest area, total forest area, protected area with biome change, etc.

systems' responses to climate may interact so strongly with nonclimatic stresses that an assessment of the climatic response alone may be highly problematic (IPCC, 2001).

To sum up, potential consequences of climate change differ in several fundamental ways from changes for which well-developed methods for evaluation and decision making are available. Climate change will simultaneously affect (either positively or negatively) many resources and many diverse aspects of the natural, social, and economic environment, of which some are directly or indirectly represented in markets and others are not. The expected changes will extend decades or centuries into the future, and will consequently be experienced by people whose choices, perceptions, and values may strongly differ from ours. And more importantly, these changes will not necessarily be marginal and gradual, but may be large and in some cases sudden: in the response of ecological and societal systems to climate change and other stresses, as in the climate system itself (Broecker 1995, 1997), rapid or discontinuous responses are possible when stresses exceed some threshold; such responses are important to understand because they may be associated with acute vulnerabilities and are likely to pose strong challenges for adaptation (Schneider et al., 2000; Downing et al., 2001).

3. Methods and Tools

We use a GIS approach to model sector sensitivity/vulnerability to climate change, in an attempt to link potential vulnerability of natural, semi-natural and managed systems to the complex climatic spatial relationships between temperature, precipitation and runoff formation, following the idea that impacts are not driven by changes in mean annual temperature and/or precipitation regime, but by site-specific monthly relationships between the two.

The outputs of two major atmosphere-ocean General Circulation Models, which were downscaled to the Swiss regional level (an overview of the downscaling method is given in Gyalistras, 2002), were used as inputs for this study. Only two climate scenarios were retained, considering the extent of climate change predictions and focusing on the extreme cases. Table 14.1 lists the scenarios used and the assumptions behind them.

Baseline temperature and precipitation data were taken from historical climatological data (1951-2000). We used a 5 km gridded temperature and precipitation data set, which was constructed for the topographically complex region of Switzerland (Gyalistras, 2003). Temperature measurements came from 136 climate stations and precipitation data from 515 stations.

The 5 km gridded data set for the monthly mean Swiss temperature and precipitation was analysed by means of GIS. Four major regions were identified within the country ranges (Plateau, Prealps, Alps and Jura mountains), for which ombrothermic diagrams were constructed. This method, originally developed by Gaussen and Bagnouls (1954), gives a precise climatic classification, based on the specific combination of the two most limiting climatic factors: temperature and rainfall. The method plots mean monthly temper-

Scenario	**CO_2 emissions (GtC)**			**CO_2 atmospheric concentration (ppmv)**		
	2000	**2030**	**2100**	**2000**	**2030**	**2100**
CCC IS92a	7.97	13.08	20.28	368.01	439.48	705.67
CSIRO SRES A2	7.97	14.72	29.08	368.01	448.16	840.69

Table 14.1. Scenarios used in the analysis.

ature (^{o}C) and monthly precipitation (mm) on the same axis, with the scale of the precipitation data at twice that of the temperature data. Both data sets are plotted against an axis of time. The resulting ombrothermic diagram shows general monthly trends and identifies months with unfavourable conditions for plant growth. Water deficiency conditions exist during months when the precipitation curve drops below the temperature data curve. Plants are under temperature stress when the temperature curve drops below the freezing mark (0^{o}C).

An aridity/humidity index[4] may therefore be constructed (i.e., Bagnouls-Gaussen aridity index, which is defined in the way as the dry, or arid month, corresponds to the month having the ratio between precipitation (P) and temperature (T) less than two), in order to summarize relevant climatic information: drought related phenomena are indicated by positive BGI values, hydrological stress due to excessive amounts of rainfall by monthly values $<$ -400. The index gives a regional approximate of the potential ecosystem exposure to water stress related conditions during significant plant growth stages.

Vulnerability of winter tourism to future snow conditions in the Alps and in the Jura mountains was modelled using a similar spatial approach. Site suitability for winter sport practice is considered to indicate potential regional vulnerability to changes in seasonal solid precipitation regime. Ski suitable areas are computed from elevation data[5], slope and terrain orientation, and snow reliability conditions, by using the weighted overlay procedure within ArcView GIS. Some of the outputs of our analysis are discussed in the following sections.

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[4] The aridity/humidity index can be estimated by the Bagnouls-Gaussen index (BGI) using the following equation:

$$BGI = \Sigma_{i=1}^{n} (2Ti - Pi) * k$$

where: Ti is the mean air temperature for month i in ^{o}C, Pi is the total precipitation for month i in mm, k represents the proportion of month during which 2Ti - Pi >0.

[5] Federal Office of Topography, MNT100.

4. Regional vulnerability of natural, semi-natural and managed ecosystems in Switzerland

The three most ecologically important environmental factors affecting plant growth are light, temperature, and water (precipitation/runoff). Plant growth and development are controlled by internal regulators that are modified according to environmental conditions. Length of daylight, temperature, precipitation, seasonal precipitation pattern, soil moisture, and evaporation are the environmental factors that affect plant growth in a region. Native vegetation and naturalized plants function as meteorologic instruments capable of measuring all these integrated climatic factors.

Precipitation and temperature are generally considered the most limiting factors affecting the physiological and ecological plant status[6]. The biological situation of a plant at any time is determined by the balance between rainfall and potential evapotranspiration. The higher the temperature, the greater the rate of evapotranspiration and the greater the need for rainfall to maintain homeostasis. When the amount of rainfall is less than potential evapotranspiration demand, a water deficiency exists and plant water stress develops. The ombrothermic graph technique is intended to identify the monthly periods in which water deficiency conditions exist and assumes that most plants experience some level of water stress during water deficiency periods. This technique is not sensitive enough to identify the degree of water stress experienced by plants or the level of long-term damage and it cannot identify periods shorter than one month because most temperature and precipitation data are summarized on a monthly basis. This characteristic in the data set forces a default assumption that water deficiency conditions shorter than a month do not cause long-lasting negative effects and that short-term water stress causes minimal damage from which the plants recover. It also assumes that stored soil water is adequate to compensate for plant transpiration losses during periods of water deficiency shorter than a month.

The ombrothermic relationships for the four major regions in Switzerland were analysed under present and future (2030, 2100) climate condition (Fig. 14.3a-i, 14.4a-i). Table 14.2 summarizes the main conclusions resulting from this analysis.

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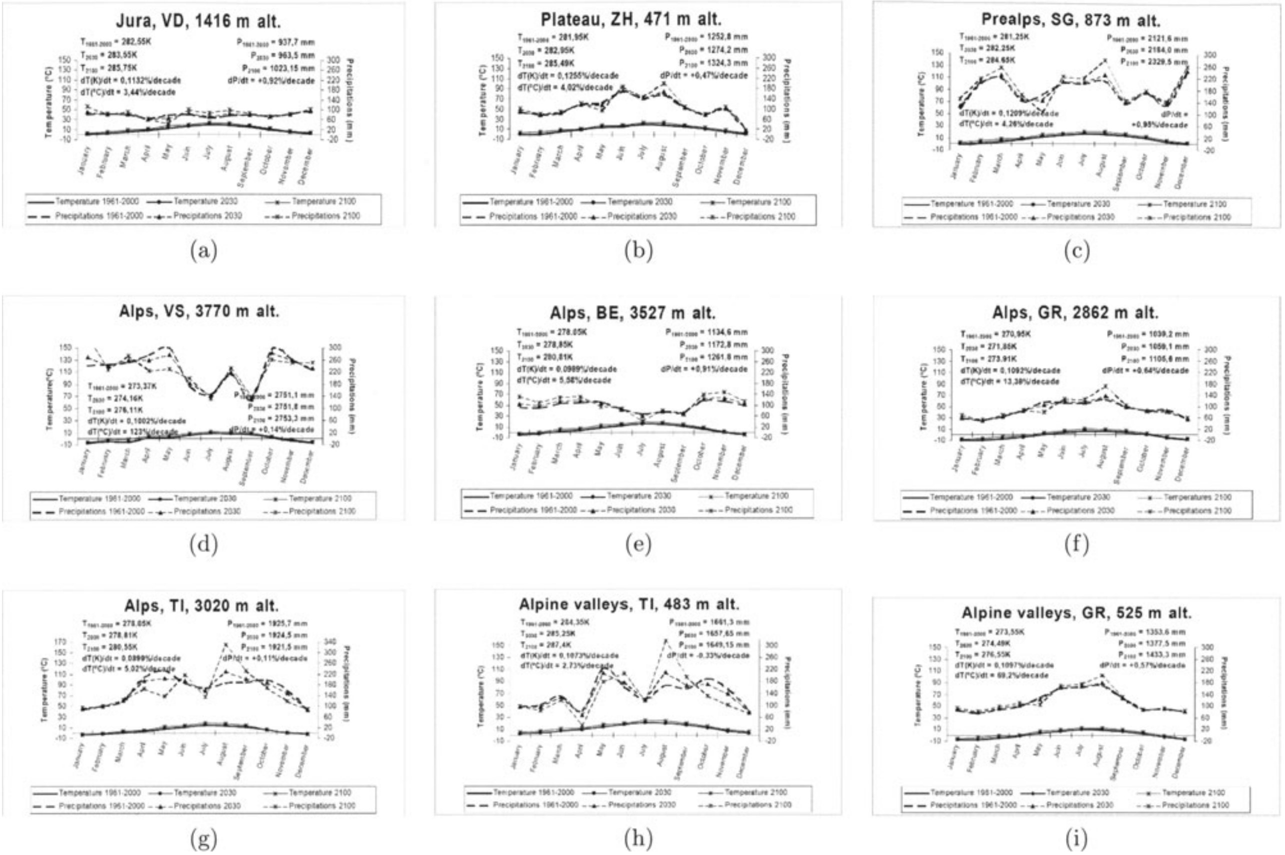
[6] According to Liebig's "Law of the Minimum" (Liebig, 1855).

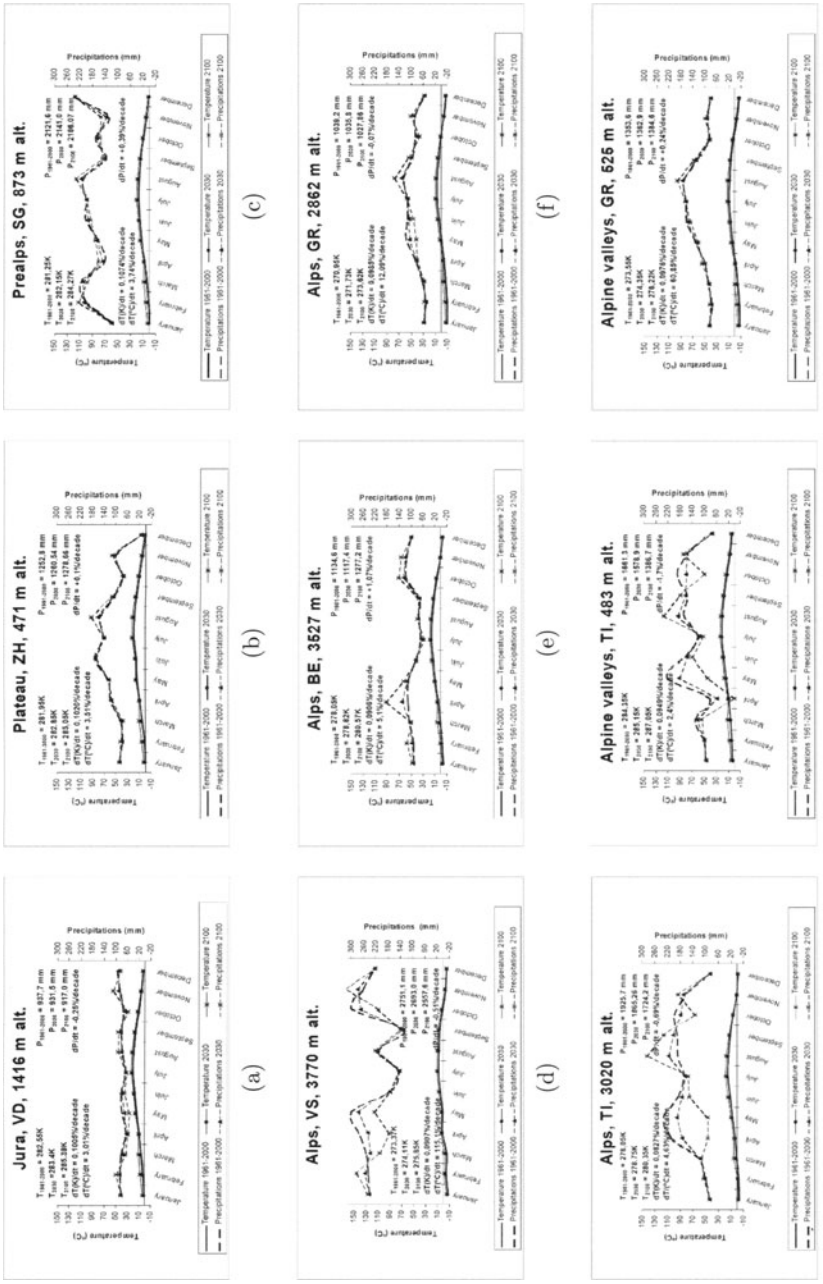


(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 14.3. Ombrothermic diagrams for the Jura mountains, Plateau, Prealps and Alps under CCC IS92a scenario



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Figure 14.4. Ombrothermic diagrams for the Jura mountains, Plateau, Prealps and Alps under CSIRO SRES A2 scenario.

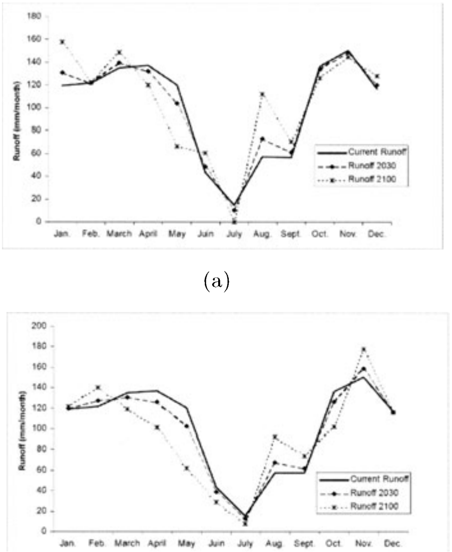
Table 14.2. Regional climate change in Switzerland and anticipated impacts.

Region/ Scenario	**Jura**	**Plateau**	**Prealps**	**Alps and alpine valleys**
CCC_GG IS92a	**Mean annual temperature increase:** 0,33^{o}C/decade; (dT(^{o}C)/dt = 3,73%/decade; dT(K)/dt = 0,1170%/decade). **Precipitation:** -4,2%/decade in May, +3,3%/decade in August; (mean annual change: +0,83%/decade).	**Mean annual temperature increase:** 0,35^{o}C/decade; (dT(^{o}C)/dt = 4,12%/decade; dT(K)/dt = 0.1225%/decade). **Precipitation**: -2,9%/decade in May, +3,3%/decade in August; (mean annual change: +0,48%/decade).	**Mean annual temperature increase:** 0,33^{o}C/decade; (dT(^{o}C)/dt = 6,22%/decade; dT(K)/dt = 0.1150%/decade). **Precipitation:** -3,7%/decade in May, +3,3-3,4%/decade in August; (mean annual change: +0.74%/decade).	**Mean annual temperature increase:** 0,27^{o}C/decade; (dT(^{o}C)/dt = 13,39%/decade; dT(K)/dt = 0,1092%/decade). **Precipitation:** VS: -2%/decade in April; GR: -2,9%/decade in May and $\sim$ +3% in August; TI: -4,1%/decade in May and +7,7-+9%/decade in August.
	Possible dry period during May with adjacent consequences for agriculture/pastures.	*General positive effects on agriculture and forestry due to mean precipitation and runoff increase, and diminishing low-temperature stress period.* *Enhanced plant water stress during May.* *Modifications in parasite's development cycles, incidence of new pathogens, parasites, competitors.* *Changes in the precipitation/runoff monthly pattern may affect flood frequency and duration.*	*Positive effects on grassland and forest ecosystems.* *Altitudinal shifts of forest and grassland ecosystems.* *Arable land expansion in bioclimatic suitable regions of the Prealps.*	*Plant water stress conditions during April and May in Southern Ticino → difficult plant growing period with consequences for biomass accumulation.* *Important increase in the flooding risk for valley regions in Ticino due to dramatic changes in precipitation and runoff formation during the months of August and September.* *Greater forest fire risks in Southern Ticino, higher pest incidence affecting forest health.* *Decrease in slope stability at high altitudes due to permafrost melting.*
CSIRO SRES A2	**Mean annual temperature increase:** 0.28^{o}C/decade; (dT(^{o}C)/dt = 3.17%/decade; dT(K)/dt = 0,1041%/decade). **Precipitation:** -2 to –3%/decade in May, -2%/decade in October; up to +2%/decade in August; (mean annual change: -0.12%/decade).	**Mean annual temperature increase:** 0.3^{o}C/decade; (dT(^{o}C)/dt = 3.17%/decade; dT(K)/dt = 0.1041%/decade). **Precipitation:** Increase in August monthly precipitation up to 1.8 – 1.9%/decade; (mean annual change: +0,1%/decade).	**Mean annual temperature increase:** 0.28^{o}C/decade; (dT(^{o}C)/dt = up to 11,27%/decade for dT(K)/dt = 0.1073%/decade). +1,8 - +2,1%/decade increase in monthly August **precipitation**: (mean annual change: +0,22%/decade).	**Mean annual temperature increase**: 0,25^{o}C/decade; (dT(^{o}C)/dt = 12,09%/decade; dT(K)/dt = 0,0985%/decade). Decrease in mean monthly **precipitation** from April to July (-2 - -6%/decade) and important increase from July to October in the southern part of the Alps (up to +4,3%/decade).
	Predicted changes do not lead to significant consequences in this region.		*Precipitation and runoff changes in the Prealps will have repercussions on the Plateau regions (e.g., positive agricultural effects, changes in flood magnitude and frequency).*	*Severe water deficiency conditions during April in the Southern Ticino Alps and alpine valleys, which will favour sclerophyllous vegetation.* *Very high flood risk in autumn (Ticino).* *Forest fire risk ↑ in Southern Alps, forest pest incidence ↑.* *Landslide risk ↑ at high altitudes.* *Glaciers retreat → flood frequency and irrigation systems in Valais*

The long-term ombrothermic graph for the present situation shows that near water deficiency conditions hardly exist for the regions analysed. Water stress periods become evident in Ticino valleys and, to a larger extent, on the entire southern side of the Alps, under both IS92a and SRES A2 scenarios (-60 to -107 mm/year in 2030, -200 to -357 mm/year in 2100, depending on the scenario) (Fig. 14.3h,i and 14.4h,i). The IS92a generates more dry extremes: near water stress conditions can be identified even in some regions situated in the Jura mountains (-10 to -32 mm/month in May), and in the Bern's Alps (-8 to -26 mm/month in July) (Fig. 14.3a,e). This indicates that plants generally may have a difficult time growing and accumulating biomass during the stressful months (May-July), and since most of the plant growth occurs in May, June, and July, primary production could be significantly altered. Favourable water relations occur during the months of June, July, and August on the Plateau and in the Prealps, indicating that plant primary productivity and biomass would beneficiate during these 3 months (Fig. 14.3b,c; 14.4b,c). A dryer May period is predicted for these regions, but within plant tolerance limits. Nevertheless, subliminal water stress is most likely to occur if we consider additional negative effects of runoff changes from April to July. On the other hand, changes in the precipitation and temperature pattern occur gradually on the Plateau, a reinforcement tendency being observed from west to east, and the period during which plants are submitted to low-temperature stress diminishes considerably in the central and western part of this orographic unit.

Generally, ombrothermic analyses indicate that plant water stress conditions are likely to develop during the month of May in the Prealps, on the Plateau and in the Jura region. Swiss Alps show a more diverse monthly pattern: potential hydrologic stress related to water deficiency situations is identified during July in the Bernese Alps and during April and May in their southern part (Ticino). Valais and Grisons are apparently exempted of such critical water relationships, exception made for some low altitude valleys located within their cantonal limits.

Extreme precipitation and runoff increases in the Alps during August and September may enhance negative effects. Along with direct damage from floods, which are extreme events with localized effects, excess soil moisture associated with heavy rainfalls tends to reduce plant productivity. Hydrologic stress due to too much water in the soil increases the risk of plant diseases and insect infestation and deteriorates root system physiological processes. This kind of negative influence on plant productivity and growth is easily identifiable on the ombrothermic graphs. The August-September conditions in Ticino (Fig. 14.3h,i; 14.4h,i) and in the Prealps (Fig. 14.3c) become critical for ecosystem's primary productivity in 2100. In Valais, even tough projected changes are not as drastic as in other alpine regions (Fig. 14.3d, 14.4d), hydrologic stress related to too much precipitation remains a possible threat for biomass formation during late spring (April-May) and late autumn (October-November). These stresses are more or less attenuated in 2100 under the CCC SRES A2 scenario (Fig. 14.4d): rainfall peaks shift from October to November-December and important reductions in monthly precipitation amounts are shown during the April-May period. These changes will ease hydrologic pressure on vegetation, favouring plant physiological processes and more generally ecosystem's primary productivity.



(a)

(b)

Figure 14.5. Estimated runoff changes in the Swiss Alps under IS92a (a) and SRES A2 (b) scenarios.

Furthermore, changes in runoff formation and potential evapotranspiration rate are likely to interfere with the primary productivity and plant biomass. Figures 14.5a and 14.5b show estimated runoff changes in the Alps under the two scenarios. Annual runoff generally increases by 1,2% in 2030 and by 4% in 2100 under the IS92a scenario, but more importantly, the monthly pattern shows serious perturbations: important decreases are anticipated during April, May and July, affecting biomass accumulation in lower regions such as the Prealps and the Plateau. The SRES A2 scenario produces a 1,6% decrease in annual runoff by 2030 and -5,45% by 2100, with a progressive reduction between March and July (up to -47 - -48% during May and July 2100). Thus, vulnerable period for plant growth ranges from spring to mid-summer, during which unfavourable water relations will negatively affect the process of biomass formation for both grassland and forest ecosystems. Agricultural systems should be less impacted by these changes in mean monthly precipitation and runoff formation, since crop sensitivity to water stress may be attenuated through increased irrigation.

Nevertheless, direct and indirect effects of atmospheric CO_2 concentrations on plant physiological mechanisms may attenuate the negative effects listed above. Long-term exposure of plants to elevated CO_2 leads to a number of growth and physiological effects, many of which are interpreted in the context of ameliorating the negative impacts of drought (e.g., enhanced water-use efficiency and higher drought tolerance, reductions in stomatal conductance and impacts on leaf water potential, osmotic adjustments and leaf dehydration tolerance, etc.). Most importantly, CO_2 physiological effects are correlated with enhanced rates of photosynthesis and biomass production, which will ameliorate the productivity of both natural and managed ecosystems (Kramer, 1981; Keeling et al., 1996).

5. Agriculture Vulnerability to Climate Change

Swiss agriculture is mainly differentiated between the plains, hills and mountains. The cropping pattern is therefore region specific, i.e. function of bioclimatic conditions. Some of the crops are rarely, or not at all cultivated in the hills or in the mountain regions, and yields are generally lower than those obtained in the plain. For example, wheat yield in the hills represents only 90% of the mean yield in the plain, and potato also has lower yield potential in the hills (16,75% less than in the plain). Swiss mountain agriculture is strongly focused on landscape maintenance: grasslands and pastures in the Alps represent the main type of agricultural landuse. Mountain regions are primarily used to make hay and raise grazing animals, particularly at high altitude. Wooded land covers between 40% and 70% of the alpine areas considered. The percentage of arable land is rather low and tends to be declining. On the other hand, mountain farm income is strongly dependent on adjacent activities such as winter tourism, and thus becoming more vulnerable to changes in climate.

Nevertheless, Swiss farmers are one of the most highly protected and subsidized producer group in the world. OECD estimates show that Switzerland is subsidizing more than 70% of its agriculture, compared to 35% in the EU.

5.1 Vulnerability of Mountain Agriculture to Climate Change

The alpine environment, its relief (altitude, slope) and climatic particularities (cold and humid) influence in a sustainable manner the environmental quality of mountain regions by strictly limiting human activities, particularly in the case of farming. The soil is often poor, produces little and is very sensitive to erosion. Because of these physical conditions, farming in mountain areas is more difficult and less profitable than at lower altitudes. Mean 1999/2001 farming income per capita in the Swiss alpine area is 43,33% lower than the one in the plain, and continues to decrease in 2002 (-15,8% compared to the 2001 level).

Over long periods of time, mountain farming has proved its great capacity to integrate the constraints imposed by an inhospitable environment (sloping land, soil often not very productive, high altitude land, harsh climate). In the course of this adaptation process, specific farming practices have been developed (e.g., grazing at high altitude, permanent crops on sloping land or in terraces, etc.). These mountain farming practices are aimed at preserving the environment, because of the particularly fragile and unstable balance between human activities and alpine environment. Natural resources can be easily overutilised, due to the lack of suitable agricultural land, the search for profitability (e.g., intensification), poor management of grasslands, etc. However, one of the primary threats to the mountainous environment is total or partial underfarming. The abandoning of agriculture lands causes acute environmental deterioration: soil erosion, pauperisation of the landscape and biodiversity, etc. The Swiss subsidizing policy, which was shown to be one of the strongest in Europe, is meant to avoid this kind of negative effects on the alpine regions by protecting farm income.

Depending on the region, farmers rely to a variable degree on off-farm income. In the Alps, an important number of farmers depend on winter tourism[7]. This is an important factor affecting future farm revenues because subsidizing policies may change in the future regardless of climate change, along with additional income reduction from activities in other sectors. Therefore. direct impacts of climate change on the tourism industry may have serious indirect effects on agriculture, because of the strong link between these two sectors in the entire alpine region.

Thus, mountain farms remain more vulnerable to climatic changes than those located in the hills/plain: their size and gross operating margins are very often below the national averages; the rate of pluriactivity and income dependence on additional activities is often very high in the mountains (e.g., winter tourism), becoming a major factor of weakness; the low income of mountain farmers is probably one of the primary factors of vulnerability, since it considerably diminishes the adaptation capital.

5.2 Agricultural Vulnerability in the Plateau Region

The Swiss "Mitteland", located between the Jura and the Alps, is the planest area in the country. It is only Seeland, the area of the Three Lakes (Morat, Neuchâtel, and Bienne Lake), which truly constitutes a plane; the remainder is represented by hills. The main cropping activity in Switzerland is concentrated on the Plateau, due to favourable bioclimatic conditions. The main crops cultivated in this area are wheat (~21% of total cultivated land), barley (~13%), maize (~7%) and potato (4%).

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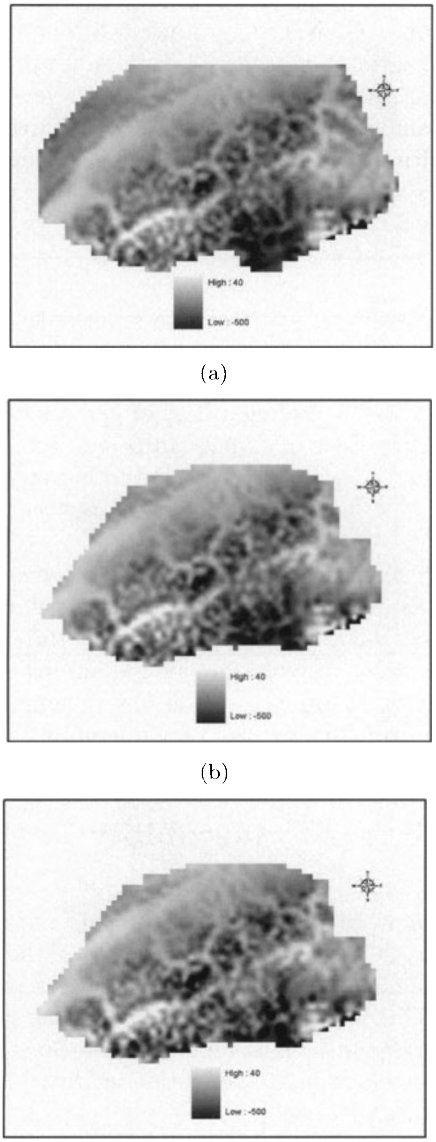
[7] In the Central Grisons, tourism's share of the gross domestic product rises up to approximately 70%. In this same area, agriculture represents only 7% of the total GDP.



(a)

(b)

(c)

Figure 14.6. Bagnouls-Gaussen May index for the present situation (a), and for future climate conditions (b: CCC IS92a 2030, c: CCC IS92a 2100).

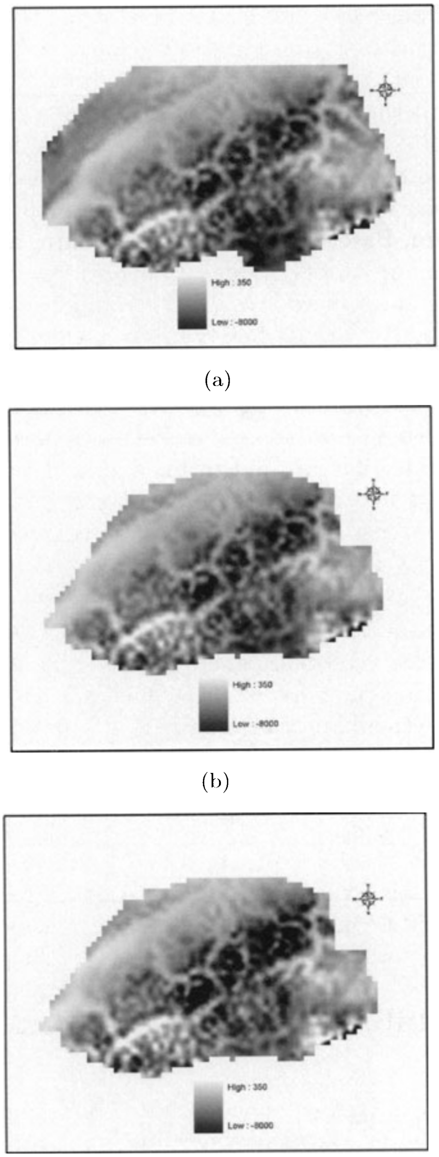


Figure 14.7. Bagnouls-Gaussen April-July index for the current Swiss climate (a), and for future conditions (b: 2030; c: 2100) under the IS92a scenario.

The ombrothermic analysis of the Plateau region mainly identified the month of May as the most critical period for plant growth and development. Figure 14.6 details the BGI spatial pattern during this interval. An important increase in the extent of its critical values (> 0) is shown over the entire Swiss plane during the period 2030-2100. The most affected regions are mainly localized in the west part (the canton of Vaud appears particularly subjected to improper plant water conditions which are projected to develop by 2100) and in the north (Neuchâtel, Jura, Basel-land, Aargau, Solothurn, and the northern part of Bern canton). The largest BGI values corresponding to severe hydrological conditions are mainly localized in low altitude alpine valleys (Southern Ticino and Valais) and gradually expand by the year 2100. Figure 14.7 depicts the ombrothermic trend during the entire critical period April-July. It shows an important increase in potential drought risks (corresponding to positive values of BGI) in Valais, Ticino, in the west and in the north part of the Swiss Plateau, as well as increased water flux in the Prealps and in the Central Mitteland.

Future spatial shifts of (un)suitable ombrothermic conditions as depicted from figure 14.7 suggest consequent altitudinal expansion of both agroforestry and pasture activities. Vineyards regions in Valais are an interesting example. The present water deficit in this region (only 400 mm per year) is actually compensated by an audacious irrigation system which channels water from the glaciers to the vineyards. As future climate change will modify both soil water availability (through enhanced hydrologic deficit; Fig.14.7b,c) and irrigation sources (i.e., glaciers retreat), new bioclimatic suitable areas will be cultivated with vines on higher altitude southern slopes.

Severe water stress conditions (affecting plant growth and development during more than two consecutive months) and resulting consequences for agricultural production on the Plateau (if no additional application of irrigation measures is planned) are expected to become a real threat only after the year 2100. These effects will be most likely enhanced by increased frequency in the occurrence and in the spatial extent of extreme drought phenomena.

6. Vulnerability of Alpine Tourism to Climate Change

The Swiss economy is highly dependent on domestic and international tourism, which both represent ~5,3% of the total GDP. Of a total revenue of 21.9 billion Swiss francs in 2002, 9.7 billion (43%) came from domestic tourism. Expenditure by foreign visitors in Switzerland added some 12.2 billion Swiss francs (3% of the Gross Domestic Product). Tourism revenue is extremely dependent on natural factors such as landscape, water, snow and weather/climate. Climatic changes will thus be more quickly reflected on tourism than on other economic sectors: projected changes in the alpine snow cover are generally showing significant reduction in a future warmer climate (Beniston et al., 1996; Beniston, 2000), which will eventually endanger the tourism industry.

Today, ~85% of Switzerland's 230 ski resorts can be regarded as snow-reliable (the critical altitudinal limit is currently considered to be 1200 m).

Number of ski resorts located in the Prealps cannot provide secure snow cover even under present climatic conditions (Abegg, 1996; Buerki, 2000).

Ski resort site suitability was modelled under two possible scenarios concerning the future evolution of the snow reliability line (300 m and 500 m altitudinal shift respectively in 2030-2050, as projected by Abegg, 1996). Ski adapted area is calculated from elevation data, derived slope and terrain aspect, and snow reliability conditions. Figure 14.8 shows modelled changes in potential ski resort site suitability. If the line of snow-reliability were to rise to 1500 m, ~ 30% of the potential ski resort suitable area would be lost, especially in the Jura region, in the Prealps, and on the southern side of the Alps (Fig. 14.8b). A more drastic snow pack evolution scenario produces up to 60% reduction of potential ski suitable area, which will further affect winter tourism regions, such as Grisons and Valais (Fig 14.8c).

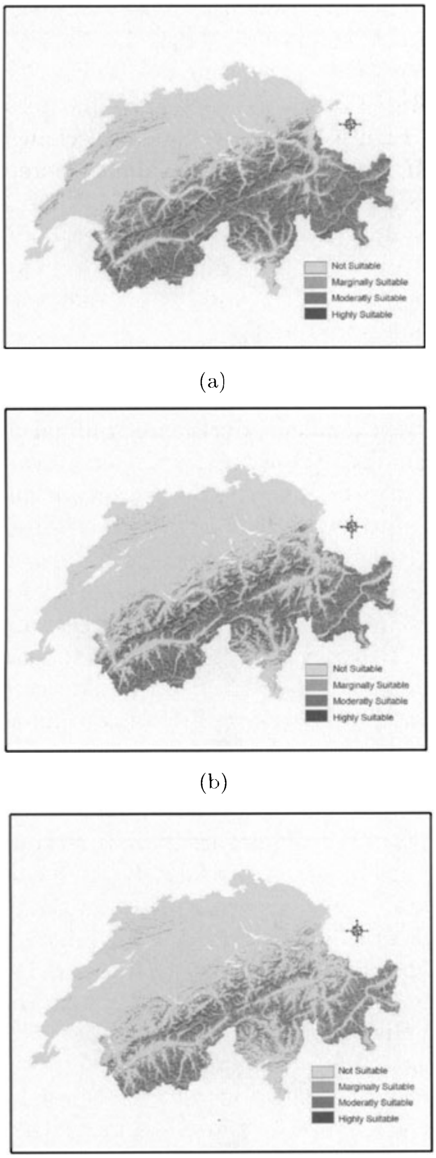
Climate change will thus produce new development trends in the alpine area: high-altitude areas will be favoured by projected changes in the alpine climate and will experience greater demand. Further altitudinal expansion of the winter tourism industry is therefore projected for the cantons of Valais and Grisons (Abegg, 1996, Buerki, 2000). However, these economically advantaged regions will be subjected to higher environmental pressure. Most affected low-altitude regions will be those situated in the Jura mountains, in the Prealps, in the lower Alps (e.g., Vaud, Fribourg, Bern) and on their southern side (Ticino). As the indirect impacts of future tourism spatial pattern will mainly reflect on mountain agriculture, it should be expected that the same mountain regions will experience higher agricultural vulnerability. Altogether, the lower part of the Alps may be very seriously impacted by future climatic changes.

7. Climate Extremes

The climate system is highly nonlinear: there is no simple proportional relationship between cause and effect, and relatively small changes in some aspects of the system can have a dramatic overall effect on the entire system (chaos). Very complex feedbacks and interactions between antroposphere and natural spheres determine this nonlinear/chaotic behaviour, and the subtle balance between them may lead to instability, forcing the system to a runaway condition (Broecker, 1995, 1997; Rial et al., 2003).

It is interesting to notice how nonlinear responses of the climate system to internal or external forcing manifest at different spatial and temporal scales. At one extreme, the orbital (10^4-10^5 years; Milankovitch cycles) and millennial global scales, abrupt climate change appears as rapid warming events followed by periods of slow cooling. At the other, decadal/annual regional scale, complexity in climate response to imperfect feedback balance increases, and nonlinear behaviour takes various behaviours: extreme precipitation, floods and droughts, heat/cold waves, wind storms, etc.

The risks associated with some of these forms of expression may be analysed by means of ombrothermic diagrams, particularly those directly related to changes in the temperature/precipitation pattern (e.g., droughts, floods, forest

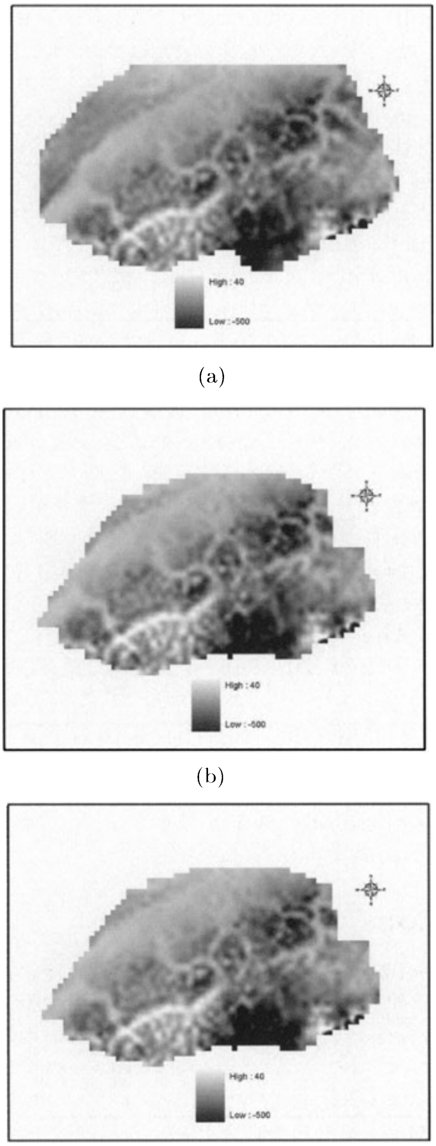


(a)

(b)

(c)

Figure 14.8. Climate change impacts on potential ski resort site suitability in Switzerland. (a) Current suitability map. (b) Suitability map for a 300 m rise of the snow reliability limit. (c) Suitability map for a 500 m rise of the snow reliability line.



(a)

(b)

(c)

Figure 14.9. Bagnouls-Gaussen September index for the present situation (a), and for CCC IS92a 2030 (b) and 2100 (c).

fire risks). Table 14.2 lists the extreme climatic situations identified for Switzerland. Ticino appears particularly sensitive to both flooding events and drought related phenomena (Fig. 14.3h,i; 14.4h,i). Ombrothermic relationships identified during April 2100 for the CCC SRES A2 scenario (Fig. 14.4i) may be associated with very high forest fire risks on the southern alpine slopes. Flooding hazard is shown to increase during the months of August and September under both scenarios, as well as drought related phenomena during the month of April. Figure 14.9 depicts the BGI September pattern under the present climatic situation, and for the future conditions (2030, 2100) predicted under the IS92a scenario. Black areas, corresponding to low BGI values, indicate potential flooding risk (depending on the region's orographic characteristics). It clearly identifies Ticino as highly subjected to extreme precipitation phenomena during September, and anticipates an expanding spatial pattern of this extreme situation by 2030 (Fig. 14.9b) and even more by the year 2100 (Fig. 14.9c).

This is just an example of how ombrothermic analyses may be useful at identifying spatial shifts of specific regional risks. On a larger scale, the entire alpine area appears more subjected to high climatic instability and exhibits higher sensitivity to extreme climatic manifestations than any other region in Switzerland (e.g., landslide frequency increase because of higher slope instability, flooding of alpine valleys due to precipitation and runoff increase at higher altitudes, forest fires in the southern alpine region, etc.). Positive feedbacks are strongest in the Swiss Alps (e.g., snow cover reduction, glacier and permafrost melting), and will be furthermore enhanced by future global warming. This situation will eventually lead to a proliferation of extreme climate events in this region, with dramatic consequences for mountain communities (Beniston, et al., 1996; Beniston, 2000). The conjunction between these additional stresses and already cited impacts on ecosystems, agriculture and tourism will result in severe changes over the entire alpine chain and its proximities, which will require well-planned adaptation strategies.

8. Conclusions

This paper addressed the complex issue of regional/sectoral climatic vulnerability in Switzerland. Defining a vulnerable area/sector is not a prediction of negative consequences *per se*, nor does it give a value for each type of impact. It is an indication that under a certain range of changes in the local climate, there would be climatic situations leading to more serious regional effects than in other areas. This may be due to greater system sensitivity to the climatic stimuli, and/or to reduced natural and human coping ability. Since vulnerability cannot be directly measured or observed, suitable indicators are needed to approximate its extent.

The ombrothermic diagram technique offers the possibility to highlight gradual shifts that occur in the seasons' pattern, their relative lengthening/contracting, as well as corresponding seasonal drought conditions and/or precipitation abundance. Thus, analyses using this method make it possible to assess the regional extent of natural risks (e.g., forest fires, flooding events, landslides, ecosystem evolution, incidence of parasites, etc.). Water and temperature, CO_2 (if its atmospheric concentration increases considerably), are key limiting factors for plant growth and development (forests, grasslands, agriculture). The ombrothermic technique identifies plant stress periods by considering the complex relationship between these elements. Our results for Switzerland show that physiological stress will be mostly enhanced by changes in climate during the months of major plant growth and biomass accumulation, which will seriously alter ecosystems' primary productivity on the one hand, and on the other ancillary functions/resources that they provide to the human sphere.

The geographic particularities of Switzerland and its quadruple external climatic influence will make the effects of climate change very diversified according to regions. Ticino and low alpine valleys, as well as the Swiss Plateau are most vulnerable to flooding events.

The evolution of the temperature/precipitation relationship in the Southern Alps may increase forest fire risk during mid-spring dry season. Higher slope instability caused by glacier retreat and permafrost melting will reflect on the future frequency of landslide and mudslide phenomena at high altitudes. Generally, the Swiss alpine region experiences the most unstable climate, due to prevailing positive feedback actions. As global warming will further enhance their destabilizing influences, a reinforcement tendency in the future manifestation of extreme climate situations should be expected.

Adaptation processes, autonomous and/or planned, may attenuate these negative consequences of climatic changes by augmenting systems' coping capacity. Nevertheless, sector adaptability to future climate change is unequal. The swiss legislation on forests and agriculture being very complex (commune, canton, confederation), sectoral adaptation to climate change will be primarily determined by political processes and less driven by direct environmental considerations. The problem of vulnerability to extreme climate events which represent one of the major impact categories on a large portion of the Swiss territory, could be essentially solved by reconsidering urban and regional planning, by promoting sustainable development, and by prioritising the degression of already existent and future environmental threats. It is the only efficient strategy that will allow human survival within regional environmental limits and global biosphere boundaries (Greppin et al., 2000). Vulnerability, meaning the potential to be harmed, is directly related to sustainability, which in many of its meanings denotes the capacity to persist, i.e., that a society has the ability to withstand harm, specifically the harm of depleted environmental resources (Brundtland Report). Thus, both vulnerability and sustainability imply long-term risks that must be addressed. Societies have choices to make in the present and in the future, choices that will have an echo on ulterior vulnerability, promoting or inhibiting sustainability and coping capacity. Their future evolution will be mainly the result of cultural and political processes.

Thus, understanding the complex interactions between the climate system, the biosphere, and human activities, identifying the most important regulatory functions which intervene in coupled systems' dynamics are the only means to progress towards an adequate "reality representation" within assessment models.

The approach we propose is a purely biophysical one, and further integration with socio-economic models of vulnerability should be considered in order to provide a full picture of climatic vulnerability. Finally, the role of endogenous drivers that can reinforce/reduce system's ability to cope with external perturbations (e.g., cultural and political structures) should also be taken into account. Only such integration of the biophysical, socio-economic, cultural and political complex interactions of a system would provide a complete vulnerability assessment of synergetic human-environment systems.

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