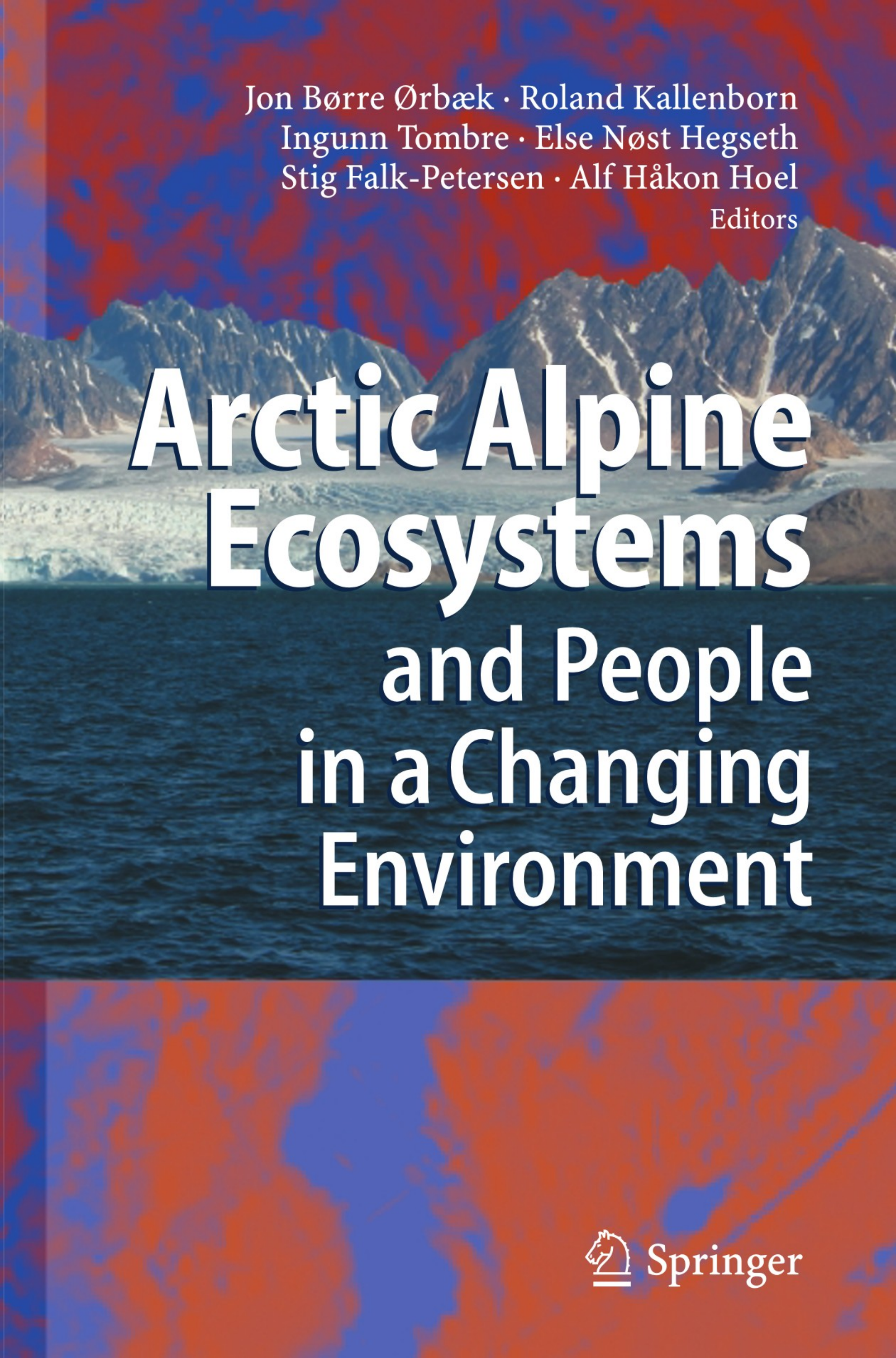

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Arctic Alpine Ecosystems and People in a Changing Environment

with 86 Figures and 10 Tables

Springer

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Preface

This book addresses the significant environmental changes experienced by high latitude and high altitude ecosystems at the beginning of the 21st century. Increased temperatures and precipitation, reduction in sea ice and glacier ice, the increased levels of UV-radiation and the long-range transported contaminants in arctic and alpine regions are stress factors that challenge terrestrial and aquatic ecosystems. The large natural variation in the physical parameters of these extreme environments is a key factor in structuring the biodiversity and biotic productivity, and the effect of the new stress factors can be critical for the population structures and the interaction between species. These changes may also have socio-economic effects if the changes affect the bio-production, which form the basis for the marine and terrestrial food chains.

The book is uniquely multidisciplinary and provides examples of various aspects of contemporary environmental change in arctic and alpine regions. The 21 chapters of the book are organised under the fields of •Climate change and ecosystem response, •Long range transport of pollutants and ecological impacts, and •UV radiation and biological effects, each also including aspects of the •Socio-economic effects of environmental change. The introductory chapter presents and explains the internal connection and integration of all chapters. The added value of these reviews and review-like manuscripts from different disciplines hopefully yields new information about the integrated aspects of environmental change.

The chapters are written on the basis of manuscripts presented at the international conference on “Arctic Alpine Ecosystems and People in a Changing Environment”, organized in Tromsø, Norway in February 2003. The conference was multidisciplinary in scope, aiming at creating new links and understandings across disciplinary boundaries and among researchers and research infrastructures, inviting the international marine, terrestrial and atmospheric environmental change research communities to meet and exchange recent research and monitoring results. The emphasis was on the European arctic and alpine environments. The conference was organized as a EURO-CONFERENCE supported by the European Commission. It also served as the final conference of the European Network for Arctic-Alpine Multidisciplinary Environmental Research (ENVINET), the final conference of the Nordic Arctic Research Programme (NARP), the last user meeting of the Ny-Ålesund Large Scale Facility, the first conference of the Arctic Seas Consortium and the final workshop of the EU-project UVAC (The influence of UV-radiation and climate conditions on fish stocks).

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The editors wish to thank all authors and co-authors for their valuable set of complementary and multidisciplinary chapters, which together hopefully will add value to the reflection of the integrated scientific questions and environmental challenges faced by arctic-alpine environments. We would also like to thank the many reviewers that have provided valuable comments and advice to all manuscripts, as well as Mrs. Ingrid Storhaug for her very competent assistance in editing this volume.

Tromsø 2005, on behalf of the editors
Jon Børre Ørbæk, Norwegian Polar Institute

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Abbreviations

AARI	Arctic and Antarctic Research Institute
ACIA	Arctic Climate Impact Assessment
Ah	Aryl hydrocarbon receptor
AHDR	Arctic Human Development Report
Alt	Altitude (in meters above sea level - a.s.l.)
AMAP	Arctic Monitoring and Assessment Programme
AMOC	Atlantic meridional overturning circulation
AMOUR	Assessment Model for UV-radiation and Risks
AO	Arctic Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
a.s.l.	Above sea level
AVHRR	Advanced Very High Resolution Radiometer
AW	Atlantic Water
BCC	Basal Cell Carcinoma
BFR	Brominated flame retardant
BP	Before present
BWF	Biological weighting factor which expresses the relative damage incurred by exposure to UV radiation
CACAR	NCPs Canadian Arctic Contaminants Assessment Report
CAFF	Conservation of Arctic Flora and Fauna
CDOM	Colored dissolved organic matter
CFC	Chlorofluorocarbons
CFC's	Chloroflurocarbons, major ozone depleting substances
CHL	Chlordanes
Chl	Chlorophyll
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon dioxide
CPD	Cyclobutane-pyrimidine dimers
CYP	Cytochrome P450
D_1-protein	Reaction center protein of PS II
3-D	Three-dimensional
DDD	1,1-dichloro-2,2-bis ethane
DDE	1,1-dichloro-2,2-bis ethylene
DDT	1,1,1-trichloro-2,2-bis(p-chlorophenyl)ethane

DEM	Digital elevation model
DF	Digital Filtration
DHA	Docosahexaenoic acid
DKr.	Danish Kroner
DNA	Desoxyribo Nucleic Acid
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
dw	Dry weight
EANET	Acid Deposition Monitoring Network in East Asia
EC_{50}	Effective concentration causing a response in 50 % of the treated organisms
EC AQFD	European Commissions Air Quality Framework Directive
ECHAM	Atmospheric general circulation model developed partly at the European Centre for Medium-range Weather Forecast and partly at the Max-Plank Institute for Meteorology in Hamburg
EGC	East Greenland Current
EIONET	European Environment Information and Observation Network
ENSO	El Niño-Southern Oscillation
ENVINET	European Network for Environmental Research
EPA	Eicosapentaeneoic acid
EROD	7-ethoxyresorufin-*O*-deethylase
ESOP	European Sub-Polar Ocean Programme
FCT method	Flux-Corrected Transport method
FS	Fram Strait
fT3	Free triiodothyronine
fT4	Free tetraiodothyronine
GAW	Global Atmospheric Watch
GEM	Gaseous Elemental Mercury
GIMMS	Global Inventory Modeling and Mapping Studies
GMES	Global Monitoring for Environment and Security
GMES-GATO	GMES-Global Atmospheric Observations
GSI	Global Solar Irradiiance
HadCM	The Hadley Centre coupled climate model
IABP	International Arctic Buoy Programme
HCA	Hydroxycinnamic acid
HBCD	Hexabromocyclododecane
HCB	Hexachlorobenzene
HCH	Hexachlorocyclohexane
HIV	Human Immunodeficiency Virus

IESA	Inside ellipse -species absent
IESP	Inside ellipse -species present
IgG	Immunoglobulin G
IgM	Immunoglobulin M
ind	Number of individuals
IPCC	Intergovernmental Panel on Climate Change
ISMO	Ice Statistical Model
K_{OA}	Octanol-air partition coefficient
KNMI	Royal Netherlands Meteorological Institute, de Bilt, the Netherlands
Lat	Latitude (in degrees North)
LHC	Light-harvesting complex
LHS	Left-hand side
LOAEL	Lowest observed adverse effect level
LOEL	Lowest observed effect level
LPJC	Lund-Potsdam-Jena dynamic global vegetation model
LRTAP-EMEP	Convention on Long-range Transboundary Air Pollution, European Monitoring and Evaluation Programme
lw	Lipid weight
MAA	Mycosporine-like amino acid
MeO	Methoxylated
$MeSO_4$	Methylsulfonyl
mRNA	Messenger ribonucleic acid
MTCLIM	Montane regional climate model
N	North (latitude)
N maps	The area actually occupied by a species as compared with the distribution as represented by a calculated ellipse
NAC	North Atlantic Current
NAMMCO	North Atlantic Marine Mammal Commission
NAO	North Atlantic Oscillation
NARP	Nordic Arctic Research Programme
NASA	National Aeronautics and Space Administration, USA
NCP	Indian and Northern Affair’s, Northern Contaminants Program
NDVI	Normalised Difference Vegetation Index
NERI	National Environmental Research Institute (Denmark)
NIP	National Implementation Plans

NMSC	Non-Melanoma Skin Cancer
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No-observed adverse effect levels
NODC	National Oceanographic Data Centre
NOEL	No-observed effect levels
NPI	Norwegian Polar Institute
NwAC	Norwegian Atlantic Current
NwCC	Norwegian Coastal Current
OESA	Outside ellipse -species absent
OESP	Outside ellipse -species present
OH	Hydroxylated
OSPAR/CAMP	Oslo-Paris Commissions Comprehensive Atmospheric Monitoring Programme
OWSM	Ocean weather station
P maps	Maps showing bands of increasing probability of specified winter and summer temperature combinations being suitable for the survival of the species under discussion
PAH	Polynuclear aromatic hydrocarbons
PAR	Photosynthetically active radiation or visible light, 400-700 nm
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenyl ethers
PCB	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzo-p-dioxins
PCDF	Polychlorinated dibenzofurans
PCN	Polychlorinated napthalene
PFAS	Perfluorinated alkyl substances
PFOS	Perfluorooctane sulfonate
PNA	Pacific North American pattern
POP	Persistent organic pollutants
PS I	Photosystem I
PS II	Photosystem II
psbA	Gene sequence encoding for the D_1-protein
Q_A	Plastquinon A, primary electron acceptor of PS II
Q_B	Plastquinon B, secondary electron acceptor of PS II
RAF	Radiation Amplification Factor, percent increase in effective UV for a one percent decrease in the atmospheric ozone column
rbcL	Gene sequence encoding for large subunit of

	RubisCO
RHS	Right-hand side
RIVM	The National Institute for Public Health and the Environment, Bilthoven, the Netherlands
ROS	Reactive oxygen species
RubisCO	Ribulose-1,5-bisphosphate carboxylase/oxygenase
SAT	Surface Air Temperature
SCC	Squamous Cell Carcinoma
SCUP-h	Skin Cancer Utrecht Philadelphia, biological action spectrum for skin cancer development in humans (de Gruijl and van der Leun, 1994)
SCUP-m	Skin Cancer Utrecht Philadelphia, murine biological action spectrum for skin cancer development derived from experiments in hairless mice (de Gruijl et al., 1993)
SLP	Sea level pressure
SOD	Superoxide dismutase
SST	Sea surface temperature
SZA	Solar zenith angle
T*	Weighted transparency. An index that expresses the UV-spectral effects of stratospheric ozone depletion and water column optical characteristics on a biologically relevant scale
T3	Triiodothyronine
T4	Thyroxin
T_a	Air temperature
T_e	Operative environmental temperature
TBT	Tri-butyl-tin
TCDD	2,3,7,8-tetrachlorodibenzo-p-dioxin
TEQ	Dioxin equivalency quotient
Tmax	Maximum temperature (in degrees Celsius)
TOC	Total organic carbon
TOMS	Total Ozone Mapping Spectrometer
TS	Temperature and salinity
TT	Travel time
tT3	Total triiodothyronine
tT4	Tetraiodothyronine
UNEP	United Nation’s Environment Programme
US-EPA	United States – Environmental Protection Agency
UV	Ultraviolet
UVA	Ultraviolet A, wavelengths in the range: 315-400 nm
UVB	Ultraviolet B, wavelengths in the range: 280-315 nm

UVR	Ultraviolet radiation
VEINS	Variability of Exchanges in the Northern Seas
VEMAP	Vegetation/Ecosystem Modelling and Analysis Project
WMO	World Meteorological Organisation, Geneva, Switzerland
ww	Wet weight
WWII	World War II
XP	Xeroderma Pigmentosum, genetic skin disorder with extreme UV-sensitivity
Zmax	Max depth (in meters)

Arctic-Alpine Ecosystems and People in a Changing Environment - Introduction

1 Integrated aspects of environmental change: Climate change, UV radiation and long range transport of pollutants

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1.1 Introduction

Global warming, changes in climate variability, long-range transport of pollutants, and reduced stratospheric ozone, represent increasing challenges to the arctic and alpine ecosystems. Forced by natural and anthropogenic variability, these key environmental factors are amplified in polar (high latitude) and alpine (high altitude) environments. Climate change and ecosystem impact studies involve a number of different and related forcing factors and interaction processes in the atmospheric, terrestrial and marine environments. They represent multiple stress factors that add to harsh environments with large natural variability, and the changes are also connected through natural links and feedback processes.

The integrated physical and biological effects and interactions on marine and terrestrial ecosystems are complex to understand. UV radiation and its ecosystem effects are shaped by a number of physical parameters in the atmospheric, terrestrial and marine environments which contribute to its total biological impact. And so is true also for the long range transported pollutants. Their transport into the physical and biological environments, involve a number of pathways as well as physical, chemical and biochemical transformation processes. Their impact on ecosystems and humans are complex and cannot be treated in isolation. This introductory chapter provides a framework for the integration of the individual chapters of this book.

1.2 Climate change and ecosystem response

The arctic and alpine areas of Northwest Europe are especially sensitive to climate perturbations, due to the strong influence by the North Atlantic oceanic and atmospheric heat advection processes. As discussed by Furevik et al. (Chap. 8), abrupt climate changes with ~10°C temperature variations over just a few decades occurred during the period of the last glacial maximum, with the termination of the Younger Dryas 11 600 years ago (Dansgaard et al., 1989) representing the last major climate perturbation in the region. They argue that observational evidence suggests that such abrupt changes in climate may be explained by sudden switches in the strength or positioning of the warm and saline Atlantic waters (AW) flowing into the Nordic Seas, forced by increased freshwater discharges making the surface waters fresh enough to inhibit the deepwater formation (Clark et al., 2001). It is therefore not unlikely that the current global warming trends, with enhanced melting of glacier ice and a general intensified hydrological cycle, may in a similar way influence the thermohaline circulation in the North Atlantic and contribute to a destabilization of the stable climate experienced since the last glacial period.

Scientific scenarios suggest that the Arctic temperatures increase almost twice as fast as average global warming (ACIA 2004). Increased summer temperatures leads to more effective ablation. While European alpine glaciers are receding quickly (Beniston et al. 2003), the mass balance of Arctic glaciers show a larger regional variation and variable response (Arendt et al., 2002; Lefeauconnier et al., 1999). The extent of summer melt of the Greenland ice sheet has significantly increased during the past 20 years or so (Steffen et al., 2002). Seasonal snow cover is reduced with increasing length of growing seasons (Høgda et al., Chap. 5), and the continued melt may induce large regional shifts in animal and plant distribution (Crawford and Jeffree, Chap. 6). According to Nuttall (Chap. 2), the results of scientific research and the observations from indigenous peoples suggest that the current climate changes are more pronounced in the Arctic than in any other region of the world (ACIA 2004).

Hansen-Bauer (Chap. 3) provides a review of the climate trends in the European Arctic during the 20th century and provides scenarios of future change. Large changes are seen in the climate records, of which the annual mean precipitation is the most pronounced with significant increase in large parts of the European Arctic. A positive warming trend in temperature is also evident but less significant, due to the large natural variability in this region. According to Hansen-Bauer (Chap. 3), the recent warming

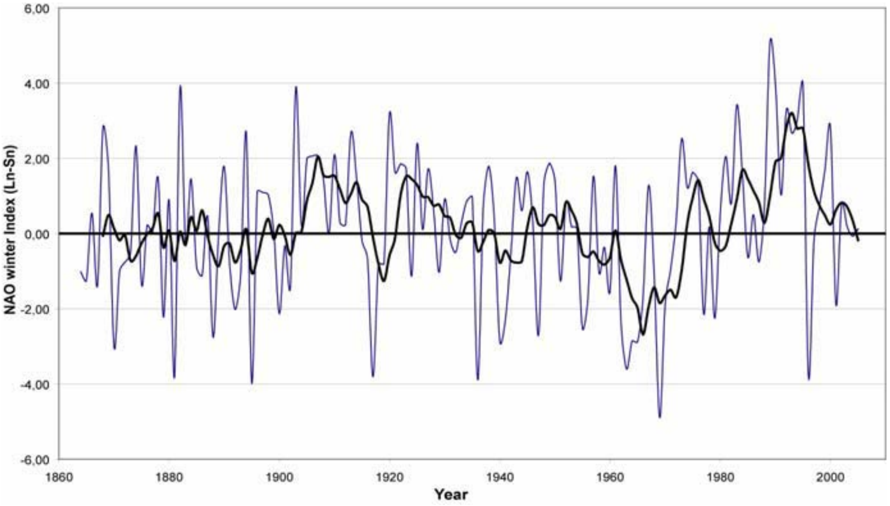

Fig. 1.1. North Atlantic Oscillation (NAO) Winter Index 1864-2003. Data provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (1995).

trend is associated with a positive North Atlantic Oscillation index (NAO, Hurrell 1995) and is evident during the last decades of the 20th century (see Fig. 1.1). This is especially emphasised in central and especially in eastern parts of the European Arctic, probably at least partly triggered by antropogenic forcing of the climate system.

According to Hansen-Bauer (Chap. 3), the Global Climate Models (AOGCMs) show rather different results for the projected changes in atmospheric circulation patterns and do not in general show the observed positive trend in the NAO. However, they project larger warming and precipitation increase in the Arctic than for the global average, with large projected reduction in summer sea-ice during for the 21st century. These projected changes are mainly in conformity with observed changes in temperature and sea-ice concentration during the last decades (Johannessen et al. 2004).

Arctic and alpine lake communities are well suited for studying ecological impacts of climate change, due to their simple structure, sensitivity to variation in ice and snow cover, and the availability of paleolimnological records. According to Primicerio et al. (Chap. 4), the ice phenology is an important driver of a number of ecological parameters for lake biota. Longer ice-free productive periods, induced by climate warming (Magnuson et al. 2000), prolong the seasonal activity of community members with expected increase in production. They claim that the seasonal dynamics of plankton and benthos is likely to change, leading to compositional and structural changes in plankton and benthos as well as the population and community structure of fish.

As for ice and aquatic environments, regional climate change impacts on snow melt and its distribution also significantly affects the length of the growing season. Høgda et al. (Chap. 5) have used the NOAA AVHRR GIMMS NDVI satellite dataset for the last two decades, producing maps for Fennoscandia that define the start and end of the growing season. Their results show that the estimated onset of spring is closely correlation with ground data on the onset of leafing of birch, with high regional differences. In the southern part of Fennoscandia, and on the oceanic west coast of Norway, the earlier spring fits with the pattern for western and central Europe. However, for the mountaineous areas in southern Norway and in the continental parts of northern Fennoscandia, the results indicate a stable or even a slightly delayed trend. Combined with the autumn trends, they find that the growing season is prolonged for the whole area, except the northern continental parts of Fennoscandia.

The tolerance of Arctic and alpine ecosystems to such climate changes can be studied by looking at the geographical limits of plant survival. Crawford et al. (Chap. 6) combine a map-modelling system that is sensitive to changing meteorological data, with comprehensive knowledge of the many interactions between physiology and environment, in their interpretation of plant distribution maps and the relating changing climates to species occurrence. They demonstrate that many species of woody plants of northern distribution have not only northern and southern limits to their distribution, but are restricted also in their east-west dispersal. Their probability models suggest that for some species, the migration patterns are also sensitive to existing temperature *seasonality,* and that the seasonality gradients may present barriers to the migration notwithstanding overall warming.

As plant distribution maps may connect large scale climate variability trends with ecosystem effects, similar variability can also be found on much smaller scales. Topography and the potentially large variability in the physical environmental parameters create a mosaic of microclimatic conditions at landscape scales. According to Armbruster et al. (Chap. 7), the variability in physical conditions, surface inhomogenities and radiation loads are important because all terrestrial biotic response to climate change is mediated by the local microclimate experienced by the organism. They argue that on the scale of meters, the spatial variability in temperature can be of the same order ($>2^{o}$C) as the estimate of the global warming expected to result from a future doubling of atmospheric CO2 (Houghton et al., 2001), or comparable to moving more than 400 m in elevation or 450 km in latitude. Classical physical climate parameters may therefore not be representative in topographically complex areas and in the high Arctic, where spatial rearrangements of indigenous species with different thermal requirements may in fact be a more prominent biotic response to climate warming than immigration of new species from other regions.

Marine related climate processes significantly force what happens in the atmosphere. Furevik et al. (Chap. 8) focus on the inflow of Atlantic Water (AW) to the Nordic Seas, its pathways and transformation within the Nordic Seas and the Arctic Ocean. These waters are of vital importance for the marine climate, water mass transformation and biomass production in the Nordic Seas. Together with the north-eastward heat flow transport with the numerous North Atlantic cyclones, this heat flow associated with the AW is responsible for the mild and favourable climate of northwest Europe.

The Nordic Seas are also a key area for the conversion of light surface water to dense deep waters, representing the Atlantic meridional overturning circulation (AMOC), or the Atlantic part of the "great conveyor belt" (Broecker, 1991). According to Furevik et al. (Chap. 8), most AOGCMs participating in the third assessment report of the Intergovernmental Panel of Climate Change suggested a 30-40% reduction in the strength of the AMOC during this century (Houghton et al., 2001).

Such dynamical patterns in the inflow of AW to the Arctic are of fundamental importance for Arctic primary production. Falk-Petersen et al. (Chap. 9) postulate that a warmer climate with reduced ice cover will shift zooplankton community structures towards a smaller size spectrum and with lower energy content per individual. This will also lower the potential for seasonal accumulation of lipid stores in their predators such as specialised seabirds. They claim that these effects are based on the very specialized process where carbon fixed photosynthetically in algal blooms is converted into high-energy lipid (oil) reserves by the major Arctic herbivores, a process which varies on all time scales during the Arctic summer, from days to decades and longer due to the variability in sea ice conditions. This lipid-based energy flux, increasing the lipid level from 10-20% of dry mass in phytoplankton to 50 to 70% in herbivorous zooplankton and ice-associated fauna, is probably one of the most fundamental specialisations in Arctic bioproduction (Falk-Petersen et al., 1990). It is therefore also the primary reason for the large stocks of fish and mammals in Polar waters and a key factor in the structuring the biodiversity of Arctic ecosystems.

Such changes in the marine environment and its exploitable resources can have a large impact on social systems. Drawing on recent research from the Arctic Climate Impact Assessment (ACIA 2004) in particular, Nuttall (Chap. 2) provides a brief assessment of climate change impacts on the local livelihoods and traditional resource use practices of arctic indigenous peoples. Rasmussen et al. (Chap. 10) discuss how social changes in Greenland have been heavily influenced by the environmental conditions, and how the social transformations reflect the interaction between different responses to the variations in the natural resource base. Such studies are important for our total understanding of living conditions for people and ecosystems in a changing environment.

1.3 UV radiation and biological effects

Atmospheric UV radiation has potential harmful effects on humans and ecosystems. The depletion of stratospheric ozone observed over the last two decades in the Arctic (Müller et al. 1997; Rex et al. 1997), as well as over parts of Europe (WMO 2003), is of serious concern, since this may lead to an increase in ambient UV radiation. Surface UVB radiation (280-315nm) may induce a wide range of harmful effects on humans (skin cancer, cataracts, suppression of the immune system) and on ecosystems by decreasing biomass and crop yields, growth conditions and algal distribution patterns in unique marine ecosystems ((UNEP 1999, Wiencke et al. 2000). The Vienna Convention (1985) and the Montreal protocol (1987) have successfully led to reduced production and emissions of ozone depleting substances, leading to an expected slow recovery of the ozone layer over the next century (UNEP 2003).

The link between atmospheric ozone and UV radiation is often referred to by Radiation Amplification Factors (Blumthaler et al., 1995), showing that the erythemally weighted UV radiation increases by about 1.1% when ozone decrease by 1%. However, due to its major dependence on other atmospheric and surface related parameters that are also highly variable, trends and future UV levels are difficult to identify. According to Blumthaler (Chap. 11), long term measurements of UVB radiation show a slight increase of a few percent per decade in the 80's and early 90's, most pronounced at high northern latitudes during spring. However, from their 20 years of measurements at a high alpine station, where the variability of UV irradiance under cloudless conditions is dominated by ozone and albedo variations, no significant increase was found.

Surface UV radiation is determined mainly by cloud cover, solar zenith angle, ozone and aerosols. In arctic and alpine environments, altitude and surface albedo are also significant. Blumthaler (Chap. 11) has derived quantitative relations between these parameters and the levels of UV radiation, showing that cloud cover, solar zenith angle, aerosols, altitude, and surface albedo significantly alter the surface UV radiation by the same order of magnitudes as can be the result of ozone variations.

These complex interaction patterns between atmospheric and surface parameters responsible for shaping the surface UV spectrum are important when assessing its ecosystem effects. Plants are expected to be vulnerable to UVB radiation, and according to Nybakken (Chap. 12), a large number of studies has been carried out at all levels of effects, from cellular investigations to large projects concerning the effects on entire ecosystems. Focussing on the possible negative effects of increased UVB radiation and the UV absorbing pigments of plants of both arctic and alpine origin, she contributes to this under-investigated field with only a few previous UVB response studies carried out on plants from arctic and alpine areas, as well as studies conducted in the field or with plants growing in their natural ecosystems (Caldwell et al. 1998). The analysis of screening pigments in a number of arctic and alpine plants agrees well with numerous field and growth chamber studies that show that the increased concentration of phenolic compounds in higher plants is a common response to UVB radiation (Searles et al. 2001).

The arctic and alpine environments also contain a range of waterbodies. In addition to the atmospheric parameters, a number of physiochemical and biological parameters are responsible for shaping the underwater UV spectrum (Ørbæk et al., 2002). Hessen (Chap. 13) focuses on observed and potential effects of UV radiation for the inhabitants of arctic and alpine freshwater ecosystems, as well as the various abiotic challenges that may be superimposed on the UV stress. He claims that the numerous small, shallow and transparent tundra ponds in high arctic localities may support a substantial benthic production, despite a scarcity or absence of benthic macrophytes and fish, with often dense populations of large-sized species of crustaceans. On the other hand, the few deeper (>3m) and larger lakes in the Arctic, which resembles the typically deep and oligotrophic alpine lakes, do not freeze to the bottom and may house populations of fish. In these ecosystems, short wave solar radiation may negatively affect both primary and secondary production. Whereas UV radiation is considered the most harmful part of the spectrum, visible photosynthetic active radiation (PAR) may also cause a suite of cellular damages (Hessen Chap. 13).

Vincent et al. (Chap. 14) show that arctic, antarctic and alpine aquatic ecosystems are particularly vulnerable to climate-induced shifts in underwater UV radiation, and that the controlling effect of snow, ice cover and coloured dissolved organic matter (CDOM) on the biological UV exposure under water, may be larger than those caused by moderate ozone depletion. Although UV radiation may be strongly attenuated in coastal waters by CDOM released from terrestrial ecosystems, the importance of snow and ice cover and the sparse catchment vegetation zones in the arctic typically result in low CDOM concentrations. Based on their paleo-ecological studies of fossil diatoms and UV-screening pigments preserved in lake sediments, a strong landscape influence on the underwater spectral light regime of high latitude and alpine lakes is indicated, in the past and present.

Hanelt et al. (Chap. 15) give a well documented presentation of the recent investigations on biological effects of UV radiation on marine ecosystems in the Arctic. In recent years they have carried out several studies on the distribution, physiology and UV radiation effects on several algal species like seaweeds growing in the Arctic environment (Hanelt et al. 1997a; Bischof et al. 1998). They point out that although the UV radiation is more intense in temperate zones, the polar algae are more sensitive to UV as compared to their temperate relatives. Potential negative effects on primary plant productivity may occur especially in spring, low temperatures and clear water conditions allowing harmful UV wavelengths to penetrate several meters into the marine water column. Hanelt et al. (Chap. 15) also point out that the summer discharge of turbid fresh water into the coastal waters overlays the more dense sea water, causing a stratification in the optical features, salinity and temperature of the water body that strongly attenuate solar radiation in the first meter of the water column. This effect is increased during warm summers with rainfall and intensified runoff from melting snow and ice covers. Organisms in deeper waters are thus more protected against harmful UVB radiation.

Ozone depletion and the induced increased UV radiation levels also have consequences in terms of health risks such as for example skin cancer. In their Assessment Model for UV Radiation and Risks (AMOUR), Slaper et al. (Chap. 16) evaluate the full source-risk chain from production and emission of halocarbons, the resulting stratospheric ozone depletion with changes in ambient effective UV doses, and the corresponding skin cancer risks. Updating his previous analysis of the kind (Slaper et al. 1996), the new model also takes into account the role of climate and ozone interactions in the arctic region on the future risks at mid-latitudes in densely populated areas in Europe. Their analysis predicts that a slow recovery of the ozone layer will occur with a return to ‘normal’ (1980) levels around 2050, and that skin cancer risks are expected to rise until 2050-2070.

1.4 Ecological impacts of long range pollutants transport

Contaminants are transported from industrialized source areas by ocean currents, sea ice and large scale wind patterns (Fig. 1.2). After entering these transport pathways, the contaminants reach the soils, snow and ice, biota and water of the remote environments in a number of different forms and phases. The soluble and particulate phases as well as the precipitation and scavenging processes involved are highly influenced by changing circulation patterns and other forms of climate change (AMAP 2003). As an example, arctic and alpine regions are especially vulnerable to temperature rise due to potential increased melting of snow and ice, and this phase change to water influence the redistribution and transfer of contaminants from the physical environment to the biota.

MacDonald (Chap. 17) describes thoroughly the processes involved in the long range transport of contaminants as well as the environmental systems that control the further metamorphosis of the pollutants after being deposited and brought into the biological systems. Climate change and variability strongly affect both pathways and the stationary phases (MacDonald et al. 2005), involving complex interaction with temperature, winds, precipitation, runoff patterns, snow and ice, organic carbon cycling, ocean circulation, and human activities.

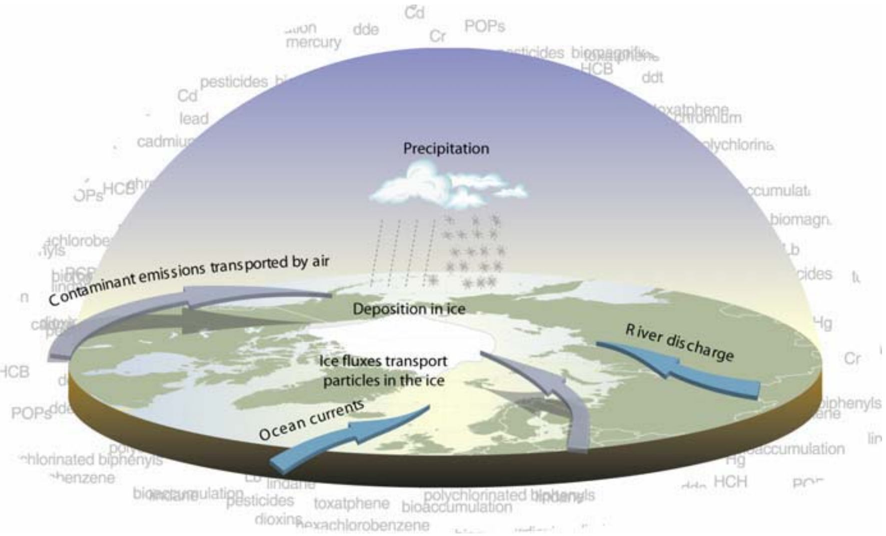

Fig. 1.2. Contamination pathways. UNEP-Grid-Arendal, Vital Arctic Graphics Source: AMAP (2002), ACIA (2004)

Sea ice and water currents in the Polar Ocean is also an important medium for pollutants transport (Korsnes 2002). These pathways undergo significant changes in the Arctic (AMAP 2003). Pavlov et al. (Chap. 18) have made several numerical experiments elucidating the spatial structure of contaminant spreading by water from potential sources in different parts of the coastal zone of the Arctic seas. The experiments have been carried out to estimate the transport of passive tracers by water and ice from potential sources of contaminants in the Arctic Ocean, especially from potential pollutant sources in the vicinity of river-mouths of major rivers flowing into the Arctic Ocean (Pavlov and Pavlov 1999). The numerical experiments, earmarking zones with maximum and minimum contamination, show that some regions, such as for example the northern and western parts of the Laptev Sea and Fram Strait, would be contaminated for all possible source locations in the coastal zone of the Arctic seas.

Kallenborn et al. (Chap. 19) argue that the global pathways of long-range contaminant transport and the principal atmospheric transport of inorganic and organic contaminants, nutrients, aerosols and particulate matter into the polar regions, can only be revealed by the concerted efforts from multinational atmospheric long-term pollution monitoring programs. Their empirically derived monitoring data, involving rapid and effective adaptation for the identification and implementation of priority contaminants, common sampling and analytical protocols etc., is at present the only way to evaluate the accuracy of the predictions calculated by modern models of future contamination scenarios.

As these monitoring programmes give important documentation on pollutant levels in the physical environment, they are a prerequisite to explain the levels of contaminants stored and bio-accumulated in the ecosystems. Gabrielsen et al. (Chap. 20) summarizes recent studies on the levels of heavy metals (HM) and persistent organic pollutants (POPs) in arctic animals, using data on biological effects related to POPs in polar bears *(Ursus maritimus)* and glaucous gulls *(Larus hyperboreus)* from the Svalbard archipelago. According to them, mercury, lead and calsium are the HM of most concern in the arctic environment. The monitoring programmes show that while the global emissions of cadmium and lead have decreased, the emission of mercury is increasing. For POPs, the levels are generally lower in the arctic environment than in more temperate regions. However, high levels of POPs exceeding the critical effect thresholds for effects on behavioural-, biochemical-, physiological- and immunological parameters, as found by laboratory and field studies, have been found in the marine food chain in glaucous gulls from Bjørnøya and in polar bears from Svalbard, Franz Josef Land and Kara Sea (Borgå et al. 2004).

The effective bio-accumulation of POPs in Arctic ecosystems are partly due to their lipid-rich food-chains, and pollutants are therefore also accumulate where Arctic people is at the top of these food chains. According to Gabrielsen et al. (Chap. 20), the levels of cadmium in arctic biota has been stable or is decreasing during the past 5-10 years, while the mercury level is increasing in most marine arctic species. In some arctic areas the levels of mercury and cadmium are high enough to cause health effects in animals and humans. Based on studies of the Greenland Inuit population, Mulvad (Chap. 21) explains that the traditional diet in Greenland to a large extend is based upon marine animals and fish, rich in fat. The partly isolated population with ethnic background provides good conditions for genetic and health impact studies under unique social circumstances, light and extreme cold weather.

1.5 Integrated aspects

Arctic and alpine areas are experiencing significant environmental change related to climate change, pollutant levels, changing pathways, stratospheric ozone depletion and surface UV radiation (AMAP 2003,2004; WMO 2003; ACIA 2004). The environmental changes and effects are in many cases amplified in these areas and closely coupled to the global climate change processes as documented in previous IPCC assessments (Houghton 2001). The Arctic biodiversity and indigenous peoples are vulnerable and constantly under pressure from these changes as well as from the effects of globalization (Nuttall Chap. 2). The decreasing sea-ice in the arctic ocean is one of the most pronounced features of climate change, with a decrease in spring and summer sea ice of the order 10-15% during the last 4 decades (Hougthton et al. 2001). According to Hansen-Bauer (Chap. 3), the variations in sea-ice concentration and air temperature during the last decades are partly accounted for by variations in atmospheric circulation indices such as the Arctic Oscillation (AO). The AO, which describes the general modes of large scale atmospheric circulation over the Northern Hemisphere, has gradually been more positive since the 1970s, with lower than normal surface air pressure anomalies over the Arctic (Thompson et al. 2000).

There is a close relationship between the atmospheric circulation patterns and the different global pathways bringing pollutants into the arctic and alpine environments. According to McDonald (Chap. 17), there is a general agreement that these changing pathways are caused by a combination of natural variability and anthropogenic forcing factors, and that the interdependence between contaminant pathways and climate change patterns, as manifested in anomalies of temperature, winds, precipitation, river flow and ocean circulation, ice and snow cover etc., involves a complex distribution of transport mechanisms, source regions, chemical transformation and magnifying processes.

The bio-accumulation of POPs in the arctic environment is high especially for the marine food chains, due to the fundamental specialisation of the lipid-based energy flux in Arctic bio-production, as discussed by Falk-Petersen et al. (Chap. 9). According to Gabrielsen (Chap. 20), the contaminant levels found in polar bears and glaucous gulls on Svalbard and Bjørnøya exceed critical effect thresholds and affect their health. Sea-ice both directly and indirectly challenge the polar bear population by reducing their habitat along with the forecasted future dramatic reduction of Arctic summer ice during this century (ACIA 2004), as well as by modifying the primary sea-ice related bio-production.

Indigenous peoples of the circumpolar North fundamentally depend on the health of arctic marine and terrestrial ecosystems. As discussed by Nuttall (Chap. 2), changes in climate, weather patterns, migration of animals and human actions all influence their traditional resource use, making e everyday life uncertain and unpredictable. Thus, the integrated effects of pollution, climate change and industrial development have consequences for the ecosystems, food security and human health that seriously may constrain their abilities to achieve sustainable livelihoods.

Atmospheric UV radiation is both physically, politically and biologically closely integrated with the problems of anthropogenic contaminant transport and climate change. The Vienna Convention (1985) with the Montreal protocol (1987) is a successful example of political countermeasures aimed at mitigating anthropogenic environmental change. This framework for reduction of both production and emission of ozone depleting substances are expected to lead to a slow recovery of the ozone layer over the next century (Madronich et al., 1999). However, more evidence of climate related interaction processes at stratospheric altitudes now suggests that ozone depletion is not purely chemically driven. Conditions with stronger and colder than normal polar stratospheric vortices, related to the persistent positive phase of the AO, have lead to an increased abundance of polar stratospheric clouds (PSCs) in the Arctic. And PSCs are effective catalysts in ozone depletion (Shindell et al., 1998). As pointed out by Slaper et al. (Chap. 16), it is therefore assumed that the ozone layer will need longer time to return to the “normal” 1980-levels, even with reduced active chlorine levels in the stratosphere.

This situation will certainly modify future UV levels especially in the Arctic. At the same time a number of atmospheric and surface physical parameters closely modified by climate change processes, significantly influence the surface UV radiation, as described by Blumthaler (Chap. 11). The surface albedo, as determined by the abundance of snow and ice, atmospheric aerosols and the amount and type of clouds represent parameters that are of almost equal importance in shaping the surface UV spectrum, as compared to the influence of ozone. In a similar way, ice cover, sediment particles and coloured dissolved organic matter (CDOM) are the primary controls of UV radiation under water, and these main controlling factors are highly responsive to climate warming or cooling trends. Vincent et al. (Chap. 14) argue that the climate induced shifts in underwater UV radiation can be of much greater magnitude than those caused by moderate ozone depletion. Arctic, antarctic and alpine aquatic ecosystems are particularly vulnerable to such effects because of the importance of snow and ice cover and the typically low CDOM concentrations in these regions. Hessen (Chap. 13) argue that the widespread small, shallow and highly transparent tundra ponds situated on permfrost in the circumpolar Arctic represent distinct ecosystems and unique biota that may be especially vulnerable to changes in UV-radiation, climate warming and changes in the hydrological cycle. Climate change interactions also affect the UV radiation conditions and primary production of seaweeds. According to Hanelt et al. (Chap. 15), organisms in the eulittoral and upper sublittoral zone are affected by UV radiation throughout the polar day. However, during the warm summer seasons with intense runoff, turbid melt water from glaciers and rivers significantly reduce the underwater UV transparency.

1.6 Conclusions

Obviously, the many challenges involving climate and stratospheric change, pollutant transport and social changes are related. A number of other significant dependencies also naturally exist between the various aspects of environmental change parameters and human activities in arctic and alpine areas. The scope here is not to give a complete review of all single processes but to outline the level of interaction between the main contemporary challenges in environmental change, on the basis of the studies presented in the book. Both with respect to the physical processes as well as dealing with their biological impacts and the anthropogenic forcing factors, the changes related to the climate change processes, long range transported pollutants and UV radiation, can not be treated alone or independently but need to be analysed as multiple pressures of the high latitude and high altitude, arctic and alpine environments.

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2 An environment at risk: Arctic indigenous peoples, local livelihoods and climate change

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2.1 Introduction

Over the last two decades the Arctic has emerged as a region of dramatic environmental change. This vast part of the planet, once seen as pristine and remote, is now represented increasingly as a vulnerable and fragile place, its biodiversity and peoples at risk from climate change, contaminants and globalization. These drivers of far-reaching change have a diffuse distribution around the globe, their origins often difficult to identify and almost impossible to allocate specific moral and legal responsibility to. They are also subject to a contested political debate over whether mitigation or adaptation are the most feasible or possible strategies for protecting Arctic ecosystems and human well-being.

Arctic marine and terrestrial ecosystems provide a variety of ecosystem services which are of fundamental importance to the livelihoods of indigenous peoples (Chapin *et al.*, in press). Yet, the indigenous peoples of the circumpolar North increasingly perceive the Arctic as both an environment *of* risk and an environment *at* risk (Nuttall 1998: 170). It is an environment of risk in that climate variability and local weather events, changes in the movement and behaviour of animals, and human actions all influence traditional resource use activities and make everyday life uncertain and unpredictable. It is also an environment at risk from pollution, global climate change and industrial development. Such threats continue to influence the climate, have an impact on ecosystems, animal habitats and movement, and also have consequences for food security and human health, thus seriously constraining the abilities of indigenous peoples to achieve sustainable livelihoods.

Scientific scenarios suggest that the scale and nature of Arctic climate change in the coming decades may not only be greater than previous changes in the region’s history, but within the context of global climate change northern regions will experience a greater degree of change than countries in the tropics (e.g. ACIA 2005, Weller 2000). Indeed, the results of scientific research and the compelling observations from indigenous peoples are documenting current climate changes that are more pronounced in the Arctic than in any other region of the world (ACIA 2005, Huntington *et al.*2005, Krupnik and Jolly 2002). The significance of these studies goes far beyond the northern reaches of the Earth and enriches our understanding of living on a planet undergoing constant change.

This chapter provides a brief assessment of climate change impacts on the local livelihoods and traditional resource use practices of the Arctic's indigenous peoples. It draws on, and summarizes, recent research on climate change impacts on indigenous livelihoods as well as some of the key work undertaken for the human dimensions chapters of the Arctic Climate Impact Assessment (ACIA 2005).

2.2 Indigenous Peoples and Traditional Livelihoods

The indigenous peoples of the Arctic include the Inupiat, Yup'iit, Alutiit, Aleuts and Athapaskans of Alaska; the Inuit, Inuvialuit, Athapaskans and Dene of northern Canada; the Kalaallit and Inughuit of Greenland; the Saami of Fennoscandia and Russia's Kola peninsula; and the Chukchi, Even, Evenk, Nenets, Nivkhi and Yukaghir of the Russian Far North and Siberia. Arctic peoples have depended for thousands of years on the living resources of land and sea, as hunters, fishers and reindeer herders. Today, many indigenous communities across the Arctic continue to depend largely on harvesting and using living terrestrial, marine and freshwater resources. The most commonly harvested species are marine mammals such as seals, walrus, narwhals, beluga, fin and minke whales, and polar bear and land mammals such as caribou, reindeer and musk-ox; and fish such as salmon, Arctic char, northern pike and other species, such as coregonids (whitefishes). Many of these species are used as food, for clothing and other products, but they also figure prominently in the cash-economy of local households and communities (Caulfield 2000, Dahl 2000, Huntington 1992, Nuttall 1992).

Indigenous peoples maintain a strong connection to the Arctic environment through these activities, which provide the basis for food production, in a way that marks them off from non-indigenous communities. Indeed, one of the defining attributes of being indigenous is that it refers to the quality of a specific people relating their identity to a particular area and to their traditional cultural and economic dependence on local resources, thus distinguishing them culturally from other peoples who came to the territory subsequently (Gray 1995).

Historically, cultural adaptations and the ability of the Arctic's indigenous peoples to utilize their local resources have often been associated with or affected by seasonal variation and changing ecological conditions. Climatic variability and weather events often greatly affect the abundance and availability of animals and therefore the abilities and opportunities to harvest and process animals for food, clothing and other uses. Many species are only available seasonally and in localized areas and indigenous cultures have developed the capacity and flexibility to harvest a diversity of animal and plant species. Indigenous cultures have, in many cases, also shown resilience in the face of severe social, cultural, and economic change, particularly in the last 100 years.

The longstanding dependence of present indigenous societies on hunting, herding, fishing, and gathering continues for several critically important reasons. One is the economic and dietary importance of being able to access customary, local foods. Many of these local foods – fish, and meat from marine mammals or caribou and birds, for instance, as well as berries and edible plants – are nutritionally superior to the foodstuffs which are presently imported (and which are often expensive to buy). Another reason is the cultural and social importance of hunting, herding, and gathering animals, fish, and plants, as well as processing, distributing, consuming, and celebrating them (Freeman, 2000).

The Arctic's living resources, therefore, not only provide indigenous peoples with the economic and nutritional bases for survival, they remain important for social identity, cultural survival and spiritual life, and so are as much important cultural resources as they are economic ones. This dependence on animals for food and social, cultural and economic well-being is reflected in community hunting regulations, in herding practices and in patterns of sharing and gift-giving based on family ties and other forms of kinship and close social relatedness (Nuttall 1992). However, Arctic communities have experienced, and are experiencing, stress from a number of different forces that threaten to restrict harvesting activities and sever these relationships. The Arctic regions are tightly tied politically, economically and socially to the national mainstream and are inextricably linked to the global economy. Rapid social, economic and demographic change, resource development, resource management and quota systems, trade barriers and animal-rights campaigns have all had their impacts on hunting, herding, fishing and gathering activities (Caulfield 2000, Nuttall 1998, Wenzel 1991). By and large, hunting, herding, fishing and gathering

Fig. 2.1. Small-scale hunting and fishing continues to be the primary occupation in many Arctic coastal communities. Ilulissat, Greenland, Spring 2005. Photograph by Niels Einarsson.

are also being challenged by environmental changes such as climate variability and change.

As the Arctic Climate Impact Assessment shows (ACIA 2005), scientific projections and scenarios suggest there will be significant changes in the climate of the Arctic, the character of the environment and its resources. Human activities, industrial development, resource use regulations and global economic processes have far-reaching consequences for the environment and therefore magnify the likely impacts on indigenous livelihoods due to variations in weather and climate. Indigenous economies are not self-reliant closed systems and although their involvement in global networks of production and consumption may provide avenues to strengthen and extend the possibilities for Arctic communities, it also introduces greater elements of risk and perhaps makes people and their livelihoods less resilient to coping with and adapting to climate impacts.

2.3 Renewable Resource Use and Climate Change: Risk and Access to Food Resources

Renewable resources and the harvesting of renewable resources by indigenous peoples in the Arctic could be affected by global climate change and increased ultraviolet radiation caused by ozone depletion. Climate change scenarios suggest that climate change will have impacts on marine and terrestrial animal populations, affecting population size, structure, reproduction rates and migration routes (ACIA 2005, IPCC 2001). Arctic residents, particularly indigenous peoples, will feel these climate change impacts first and most intensely.

However, because of the interdependence between Arctic economies and global markets, indigenous peoples are multiply exposed -- to climate change, to changes caused by the global processes affecting markets, technologies and public policies and to local and regional political and economic situations. It is important to contextualise climate change impacts with reference to other changes experienced by Arctic residents. Being able to access traditional food resources and ensuring food security will be one major challenge in an Arctic affected increasingly by climate change and global processes.

The Arctic Climate Impact Assessment (ACIA 2005) shows that the results of scientific research and evidence from indigenous peoples are increasingly documenting climatic changes that are more pronounced in the Arctic than in any other region of the world. Although this indicates that the physical environment, as well as the flora and fauna, has been undergoing noticeable change, the impacts felt throughout the Arctic will be unique and will vary from region to region. Different climatic trends have been observed in different parts of the Arctic – while average temperatures in the North American western Arctic and Siberia have been increasing in the last 30 years (e.g. annual temperatures in the Canadian western Arctic have climbed by 1.5°C and those over the central Arctic have warmed by 0.5°C), temperatures in Canada’s Hudson Bay and in Greenland, particularly in the Davis Strait area have decreased (Chapman and Walsh 1993), suggesting that climate change involves regional cooling as well as global warming.

If the scientific predictions and scenarios are realised, climate change could have a potentially devastating impact on the Arctic environment and on the peoples who live there, particularly those indigenous peoples whose livelihoods and cultures are inextricably linked to the Arctic environment and its wildlife. Some scenarios suggest that the most direct changes will be noticeable in the reduction of the extent of sea ice and permafrost, less ice in lakes and rivers, pronounced reductions in seasonal snow, and the disappearance of the existing glacier mass, leading to a corresponding shift in landscape processes (Lange, 2000, Siegert and Dowdeswell 2000, Weller 2000).

Scientific research shows that over the last 100 years there has already been a significant reduction in Arctic ice cover extent and thickness. Since 1979 alone, the extent of sea ice throughout the Arctic has decreased by 0.35%, and record reductions of sea ice coverage were observed in the Beaufort and Chukchi seas in 1998 (Johannessen *et al.*, 1999, Maslanik *et al.*, 1999). Sea ice is highly dependent on the temperature gradient between ocean and atmosphere and on near-surface oceanic heat flow and will react swiftly to changes in atmospheric conditions (Lange 2000). Atmosphere-ocean climate models project a reduction in sea ice of around 60% in the next 50-100 years under a scenario in which CO_2 is doubled. Permafrost will thaw more quickly in spring, but take longer to refreeze in autumn, and permafrost boundaries will gradually move poleward, with most of the ice-rich discontinuous permafrost disappearing by the end of the 21st century.

Climate variability appears to have caused relatively rapid shifts in the organisation of Arctic marine ecosystems. In the Bering Sea ecosystem and the Barents Sea ecosystem climate-driven variability is significant (Sakshaug and Slagstad 1992). There are difficulties, however, in determining what biological changes in marine ecosystems are due to natural environmental fluctuations or human activities. In the eastern Bering Sea upper trophic levels have undergone significant changes in the past 100-150 years, largely due in part to commercial exploitation of mammals, fish and invertebrates (ACIA 2005). Climatic changes may have contributed in part to the changes in animal populations. Higher ocean temperatures and lower salinities, changes in seasonal sea ice extent, rising sea levels and many other (as yet undefined) effects are certain to have significant impacts on marine species, with implications for Arctic coastal communities dependent on hunting and fishing (Weller and Lange 1999).

Most Arctic marine species depend upon the presence of sea ice and many indigenous coastal communities depend on harvesting marine species (marine mammals and fish). The ice-edge is unique among the world's ecosystems in that it moves thousands of kilometres each year, north in spring and south in autumn. Walrus, numerous species of seals and cetaceans such as beluga and narwhals all follow the ice-edge as it moves, taking advantage of the ready access to food and (for the walrus and seals) the availability of ice to haul-out on for sunning, mating and raising pups in late winter and spring (an important time for Inuit hunting communities).

The almost complete elimination of multi-year ice in the Arctic Ocean is also likely to be immensely disruptive to ice-dependent micro-organisms, which will lack a permanent habitat. Preliminary results from research in the Beaufort Sea suggest that ice algae and other micro-organisms may have already been significantly affected by warming over the last 20 years. Research indicates that most of the larger marine algae have died out, and have been replaced with a much less productive community of microorganisms more usually associated with freshwater ecosystems.

It is anticipated that marine mammals such as walrus, seals and whales are likely to undergo shifts in range and abundance, while the migration routes of caribou will be disrupted (Nuttall *et al.* 2005). Such changes could impact upon the hunting, trapping and fishing economies of many small, remote Arctic settlements. Although warming may increase biological production in some wildlife species, the distribution of many species crucial to the livelihoods and well-being of indigenous peoples could change. Important wetlands may disappear, or drainage patterns and tundra landscapes will be altered significantly, which could affect ducks and other waterfowl. Changes in terrestrial vegetation will have consequences for reindeer herding and subsistence lifestyles.

Terrestrial wildlife such as caribou and reindeer, two major species important for indigenous communities throughout the Arctic, would be affected by climate change directly through changes in thermal stress in animals, and indirectly by significant difficulties gaining access to food and water (Nuttall *et al.* 2005). Arctic communities located on coastlines may be affected by rising sea levels, increased coastal erosion, and severe storms. The fortunes of subsistence fisheries will depend on marine fish stocks and their climate related variations (Lange 2000). As the amount of sea ice decreases, seals, walrus, polar bears and other species that depend on it would suffer drastically.

Recent observations have demonstrated that there has been a distinct warming trend in lowland permafrost of 2-4°C over the last 100 hundred years (Fitzharris *et al.* 1996, Lange 2000), leading to disturbances of animal and human activities due to thawing, thermokarst formation and severe erosion. Further warming is likely to continue this trend and increase the likelihood of natural hazards for people (particularly affecting hunting and herding), buildings, communication links and pipelines. The documentation of widespread thawing of discontinuous permafrost in Alaska illustrates some of these hazards and the implications for habitat change and the physical infrastructure of communities. In western Alaska several communities in low-lying areas, including Shishmaref, Kivalina and Little Diomede are affected by recent climate changes and face severe problems as a result of erosion and thawing of the discontinuous permafrost (Callaway *et al*. 1999).

Unstable sea ice could make ice-edge hunting more difficult and dangerous. Temperature and precipitation changes could affect migration patterns of terrestrial mammals like caribou and alter breeding and moulting areas for birds. Salmon, herring, walrus, seals whales, caribou, moose and various species of waterfowl are expected to undergo shifts in range and abundance (ACIA 2005). Changes in snow cover could affect the growth and distribution of plants essential for survival of caribou and reindeer. Changes in snow cover could also make accessing hunting, fishing and herding areas more difficult by dogsled, snow-machine or other vehicles, making local adjustments in hunting practices and harvesting strategies necessary.

In many parts of the Arctic indigenous peoples are reporting that they are already experiencing the effects of climate change. In Canada’s Nunavut Territory, Inuit hunters have noticed the thinning of sea ice and the appearance of birds not usually found in their region; Inupiat hunters in Alaska report that ice cellars are too warm to keep food frozen; Inuvialuit in the western Canadian Arctic report thunderstorms and lightning (a rare occurrence in the region); Gwich'in in Alaska have witnessed dramatic changes in weather, vegetation, and animal distribution patterns over the last 50 years or so; Saami reindeer herders in Norway have observed that prevailing winds relied on for navigation have shifted or that snow cannot be relied on to travel over on trails that people have always used and considered safe (Nuttall *et al*. 2005).

In the Kitikmeot region of Nunavut, Inuit observations of climate change have been recently documented (Thorpe *et al*. 2002). People have spoken of a changed climate in the 1990s compared with previous decades: increasing temperatures with earlier spring melts and later freeze-ups in autumn have meant periods of longer summer-like conditions, while weather has become variable and unpredictable. This change and variability has had many significant impacts on caribou. Migration routes and the location of calving grounds have shifted and food sources have sometimes become inaccessible. Inuit have recently noticed more frequent short-term changes in temperature, especially in freeze-thaw cycles, which, because these cycles help form an icy layer on the top of snow or tundra, prevent access to vegetation (Thorpe *et al*. 2002).

2.4 Concerns Over Irreversible Impacts

Indigenous peoples live with fluctuations in weather and climatic conditions. Experiencing year-to-year changes in weather, ice and snow patterns, animal behaviour and movement, and in hunting and fishing conditions is part of life in the Arctic. Yet the trends currently being observed give concern over major, irreversible impacts on indigenous communities and livelihoods. For example, since the late 1970s Alaska Natives in communities along the coast of the northern Bering and Chukchi Seas have noticed substantial changes in the ocean and the animals that live there, particularly in the patterns of wind, temperature, ice, and currents (Nuttall *et al*. 2005).

A significant collection of indigenous environmental observations was recorded during a study of environment changes in Canada's Hudson Bay region. The results are published in *Voices from the Bay* by the Canadian Arctic Resources Committee and the Municipality of Sanikiluaq, a small Inuit community on the Belcher Islands in the midst of Hudson Bay. Completed in 1996 and published in 1997 (McDonald *et al.* 1997), the study brought together 78 Inuit and Cree hunters and elders from 28 communities on the shores of Hudson and James bays in a series of workshops over three years to describe, record and verify ecological changes in the region, including but not limited to climate change. Observations include wholesale changes in location, number and duration of polynas—open water areas in winter—in eastern Hudson Bay, and changing routes of Canada and snow geese, but the study indicates that alterations in weather and climate are by no means uniform within the bioregion. *Voices from the Bay* and other recently reported observations from indigenous peoples (e.g. Krupnik and Jolly 2002, Nunavut Tunngavik 2001) illustrates an important and inescapable fact: much of the impact of climate change on northern indigenous peoples will be channelled through ecological changes to which they will have to respond, cope with and adapt to.

As indigenous peoples perceive and experience it, the Arctic is becoming an environment of risk and an environment at risk (Nuttall 1998) in the sense that sea ice is now unstable where hunters previously knew it to be safe, more dramatic weather patterns such as floods are occurring, vegetation cover is changing, and particular animals are no longer found in traditional hunting areas during specific seasons. The weather is becoming increasingly unpredictable and local landscapes, seascapes and icescapes are becoming unfamiliar.

2.5 Responding to Climate Change: Flexibility, Adaptation, Barriers and Opportunities

The archaeological record, ethnohistorical accounts and the memories of elders provide detailed accounts of how human life in the Arctic has always been dominated and influenced by periodic, irregular and often dramatic ecosystem changes, triggered by periods of warming and cooling, extreme weather events and fluctuations in animal populations (Krupnik 2000). The successful long-term occupation of the Arctic by indigenous peoples has been possible, in part, because of their adaptive capacity (in social, economic and cultural practices) to adjust to climate variation and change. Hundreds and even thousands of years ago, Arctic populations adapted to gradual or even rapid environmental change by settling amid favourable climate conditions and along the paths of animal migration routes. Many of these adaptations bore the hallmark of what is the essence of successful indigenous resource use systems throughout the Arctic -- flexibility in technology and social organisation and an ability to cope with climate change, responding both to its associated risks and seizing its opportunities. Cultural and ecological diversity required flexibility and resilient coping strategies during periods of extreme change. Subsistence diversity was the outcome of a successful cultural and social response to climatic variation and the resource instability of the Arctic environment (Krupnik 1993).

Today, Arctic peoples are not in a position to adapt, relocate or change resource use activities in the same ways as in the past, because most now live in permanent communities and have to negotiate greatly circumscribed social and economic situations. The majority of indigenous peoples live in planned settlements with elaborate infrastructures, and their hunting and herding activities are determined to a large extent by resource management regimes, land use and land ownership regulations and local and global markets. The mobility that indigenous peoples once possessed to move in response to shifts in the pattern and state of their resource base is no longer possible.

Changes to settlement patterns and the ecological relations between humans and animals often arise from government attempts to introduce new economic activities or to sedentarize indigenous peoples. In northern Russia and Siberia, for example, the Soviet authorities ‘industrialised’ reindeer herding as a way of facilitating the development of the Soviet North. The new settlements and industries in Siberia came to depend on reindeer herders to supply them with meat. Today, in post-Soviet Russia, privatisation and the transition to a market economy bring new challenges

Fig. 2.2. Greenlandic seal hunter. Ilulissat, Greenland, Spring 2005. Photograph by Niels Einarsson.

to reindeer herding peoples in Siberia and the Russian Far East, highlighting the dependence of Arctic reindeer systems on the complex interlinkages between local, regional and global economies.

Strict regulatory regimes, management practices and quota systems imposed by states and federal and provincial agencies increasingly affect hunting, fishing and herding (Anderson and Nuttall 2004). Some, while aiming, in principle, to protect and conserve wildlife also restrict access to resources. In Alaska, for example, state and federal policies make subsistence issues extremely complex. State and federal law define subsistence as the customary and traditional non-commercial use of wild resources and regulations limit the prospects of finding markets for caribou meat. Earning money through more commercial channels is not an option for Alaskan subsistence hunters. In northern Fennoscandia, Saami reindeer herders have traditionally ranged far and wide, crossing national borders as they follow their reindeer herds between winter and summer pastures. In modern times, political developments have restricted migration routes over the last one hundred years or so. Economic development in the nineteenth and twentieth centuries, such as mining, forestry, railways, roads, hydroelectric power and tourism have all had their impact on traditional Saami livelihoods. In Greenland, threats to the cultural and economic viability of hunting livelihoods in small communities come from transformations in resource management regimes and Home Rule government regulations, which conflict with local customary practices and knowledge systems (Dahl 2000; Nuttall 1992). Caribou, whales, seals, and fish, which have traditionally been subject to common use rights vested in members of a local community, are becoming national and privately-owned divisible commodities subject to rational management regimes defined by the state and the interest groups of hunters and fishers, rather than to locally understood and worked out rights, obligations, and practices.

Hunters and herders are increasingly constrained by institutional frameworks and management structures, as well as the legal recognition to resource use rights. They are commonly experiencing a transition from herding and hunting from what we may call a ‘way of life’ to an occupation and industry (Anderson and Nuttall 2004). The contemporary reality for many hunters and herders is that they are placed in very inflexible situations. Faced with climate change they are not necessarily in a position to respond appropriately. How indigenous peoples are in a position to take advantage of the opportunities that may arise, as well as being able to modify or change their mode of production in response to climatic variability, for example by switching hunting and fishing activities, is a critical research need.

For some peoples of the Arctic, the political and management systems are already in place that could assess the impacts of climate change, allow local and regional governments to act on policy recommendations to deal with the consequences, and improve the chances for indigenous peoples to deal successfully with climate change. Although complex, solutions to environmental problems are potentially realistic

Significant political changes since the 1970s have included land claims in Alaska and Canada and the formation of regional governments in Greenland and Nunavut. Settlements include the Alaska Native Claims Settlement Act (1971), Greenland Home Rule (1979), the James Bay and Northern Quebec Agreement (1975-77), the Inuvialuit Final Agreement (1984) and the Nunavut Agreement of 1992 (the Territory of Nunavut was inaugurated in 1999). These political changes often include changes in the ways that living and non-living resources are managed. A greater degree of local involvement in resource use management decisions has been introduced, including in some cases the actual transfer of decision-making authority to the local or regional level (AHDR 2004, CAFF 2001).

In addition, significant steps have been taken with innovative co-management regimes that allow for the sharing of responsibility for resource management between indigenous and other uses and the state

(Caulfield 2004, Huntington 1992). Examples include the Alaska Eskimo Whaling Commission, the Kola Saami Reindeer Breeding Project, the Inuvialuit Game Council and the North Atlantic Marine Mammal Commission (NAMMCO). Self-government is about being able to practise autonomy. The devolution of authority and the introduction of co-management allow indigenous peoples opportunities to improve the degree to which management and the regulation of resource use considers and incorporates indigenous views and traditional resource use systems (Huntington 1992).

Co-management projects involve greater recognition of indigenous rights to resource use and emphasise the importance of decentralised, non-hierarchical institutions and consensus decision-making. This presents tremendous opportunities for collaboration between indigenous peoples, scientists and policy-makers concerned with the sustainable use of living resources (Caulfield 2000, 2004). And it is within this new political and scientific environment of power sharing and dialogue that indigenous communities, scientists and policy-makers can work together to find solutions (such as building flexibility into otherwise constraining wildlife management regimes) to the pressing problems climate change may bring to the Arctic.

2.6 Conclusions

Indigenous communities across the Arctic are culturally and economically diverse and are affected by environmental change in different ways. Such diversity also means that local experiences of climate impacts and responses to climate variability and change may not be universal. As Scheraga and Grambsch (1998: 87) put it, there ‘is a regional texture to changes in climate, and therefore to the effects of climate change,’ as well as a regional texture to the risks and opportunities that climate change presents. For the Arctic, the Arctic Climate Impact Assessment points to significant regional variation in climate changes. This raises a question, therefore, about how communities differ in the ways they perceive risk, how they differ in the ways they utilise strategies for mitigating negative change and in the effectiveness of local adaptive capacity. This points to the importance for research on localised, regional and circumpolar studies of socio-economic impacts of recent climate change. Such work is necessary for a thorough understanding of how potential impacts of climate change are distributed across different regions and populations (e.g. see Scheraga and Grambsch 1998).

The emphasis of scientific research on climate change is to assess the impacts on the environment, ecosystem processes and wildlife. One gap in knowledge is how climate change affects social relations in indigenous communities. Nuttall *et al.*(2005) highlight this as a critical aspect of climate change research, arguing that a change in the ability of indigenous peoples to access traditional food resources can have a corresponding impact on the social fabric of their communities. In a very real sense, therefore, the discussion of climate impacts on traditional resource use activities by indigenous peoples is about sustaining human/food resource relationships and activities in indigenous societies, as well as being aware that climate change impacts pose a threat of severe and irreversible social changes. Arguing that research should place emphasis on understanding climate change impacts within the broader context of rapid social and economic change, Nuttall *et al.* (2005) illustrate the complexity of problems faced by indigenous peoples today and underscore the reality that climate change is but one of several problems affecting their livelihoods.

Is an ability to respond and cope with climate change, mainly by adjusting subsistence activities, a reliable indication of an ability to adapt in the future? Research is needed on understanding how much change can be accommodated by the existing ways of life of indigenous peoples. Case studies in the human dimensions chapters of the Arctic Climate Impact Assessment have pointed to the *resilience*, or the amount of perturbation that the resource use systems of indigenous peoples can absorb, and how they can adapt by learning and self-organization. The question of resilience (both social and ecological) is important, as it is a crucial aspect of the sustainability of local livelihoods and resource utilization (Adger 2000), and further research is needed in the Arctic because little is known about building adaptive capacity in the face of climate change.

As resilience not only depends on ecosystem diversity, but on the institutional rules which govern social and economic systems (Adger 2000), further research is also needed on co-management and the effectiveness of governance institutions and whether they can create additional opportunities to increase resilience, flexibility and the ability to deal with change (Nuttall *et al.* 2005, Young and Einarsson 2004). How can, for example, new governance mechanisms help indigenous peoples negotiate and manage the impacts of climate change? The answer to this will depend on a range of factors, including the importance of understanding the nature of the relationships between people, communities and institutions if effective policy responses are to be developed (O'Riordan and Jordan 1999). With a capacity-building strategy now being a key objective for the Arctic Council, tremendous opportunities exist for co-operation and constructive dialogue on dealing with climate change between communities, organisations, institutions and governments at circumpolar and wider international levels.

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Climate change and ecosystem response

3 Climate variation in the European sector of the Arctic: Observations and scenarios

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3.1 Introduction

Global climate models typically indicate that increased concentrations of atmospheric greenhouse gases will lead to a larger temperature increase at high northern latitudes than anywhere else in the world (Cubasch et al. 2001, Räisänen 2003). On the other hand, a majority of the models indicate an area of minimum temperature response around southern Greenland. Large gradients in warming rates are thus projected in the Arctic.

The mean temperature in the Arctic did increase during the 20th century (e.g. Polyakov et al. 2003), but there are regional differences within the area. This paper is focused on the observed and modeled atmospheric climate in the European sector of the Arctic from 1900 to 2100. Are the observed changes in accordance with results from climate models? And what are the prospects for the future climate?

3.2 Observed climate variability in the European Arctic

The following climatic description is based upon observations from the European Arctic (Figure 3.1). Temperature and precipitation series from the NARP-dataset (http://projects.met.no/~narp/data) are analysed and related to sea-ice cover and atmospheric circulation indices. The climate in the European Arctic is also discussed in an Arctic and a global context.

3.2.1 Temperature

There are large spatial differences in surface air temperature (SAT) in the European sector of the Arctic. Annual mean temperature measured at the weather stations in Figure 3.1 span from -12.3 °C in Danmarkshavn

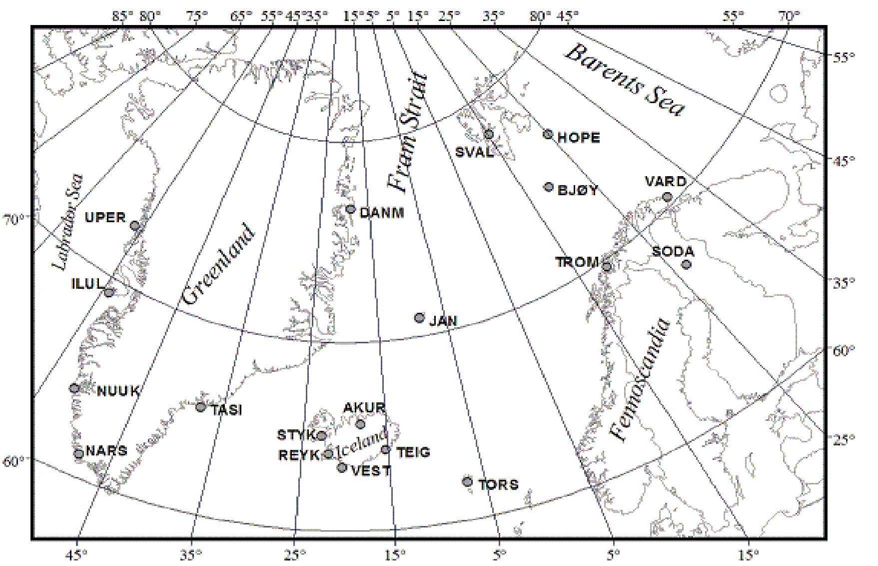

Fig. 3.1. Map showing the climate stations applied in the present analysis. The letter codes give the first letters in names applied in the text.

to +6.5 °C in Torshavn (Førland et al. 2002). Nevertheless, when the temperature series are standardised (by subtracting the 1961-1990 average and dividing by the standard deviation), they show similar long-term variability during the 20th century (Figure 3.2). Two periods with mainly positive temperature trends, the so-called “early 20th century warming” and a period towards the end of the century, are separated by a period with cooling. At most stations in the area, the thermal optimum of the century was experienced in the 1930s. In the north-eastern part of the area, the following period of cooling culminated in the1960s, followed by three decades with a warming trend. In Iceland and the Faroe Islands, there was a more gradual cooling to a minimum around 1980. At the westernmost stations in Greenland, the cooling continued even to around 1990. According to Mann-Kendalls non-parametric test, only series from northern Iceland and from Fennoscandia show a statistically significant warming (5 % level or better) from 1900 to 2002.

The multi-decadal temperature variation in the European Arctic during the 20th century is generally in accordance with the SAT series averaged over the whole Arctic north of 62°N (Polyakov et al. 2003). Also this time series shows a cold period around 1900, a period of warming up to about 1940, a cold spell in the 1960s and warming during the latest decades. The Arctic SAT series, however, shows a statistically significant long-term

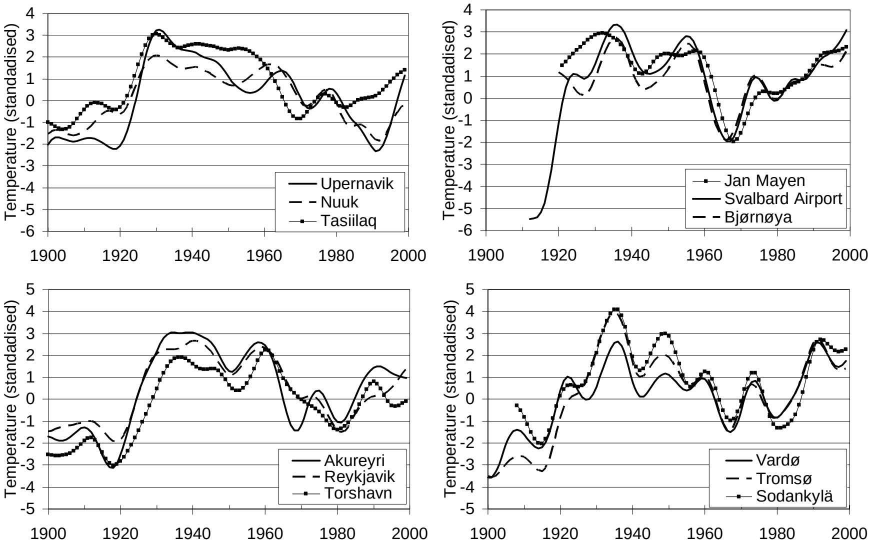

Fig. 3.2. Decadal scale variability in standardised series of annual mean temperature from climate stations in the European sector of the Arctic.

trend of +0.094 °C per decade from 1875 to 2000 (Polyakov et al. 2003).

The global SAT curve also shows one early and one recent period of warming during the 20th century, but there is no statistically significant cooling in the period between them (Folland et al. 2001). Johannessen et al. (2004) show that the early 20th century warming and the following cooling mainly are restricted to high northern latitudes. The recent warming is of more globally homogeneous character, though also this is enhanced in the Arctic (Serreze et al. 2000), and especially over the continents (Moritz et al. 2002). Whether or not the long-term positive temperature trend shows an Arctic amplification depend critically on the exact choice of period and dataset. Polyakov et al. (2003) conclude that there is no significant difference between the Arctic and global SAT trends during the 20th century. From 1875 to 2000 on the other hand, the temperature increase was larger in the Arctic.

3.2.2 Precipitation

The measured annual precipitation in the European Arctic spans from about 200 mm at some of the northernmost stations to more than 1500 mm at some stations in Iceland and the Faroe Islands (Førland et al. 2002). The decadal scale variability is less spatially consistent for precipitation than

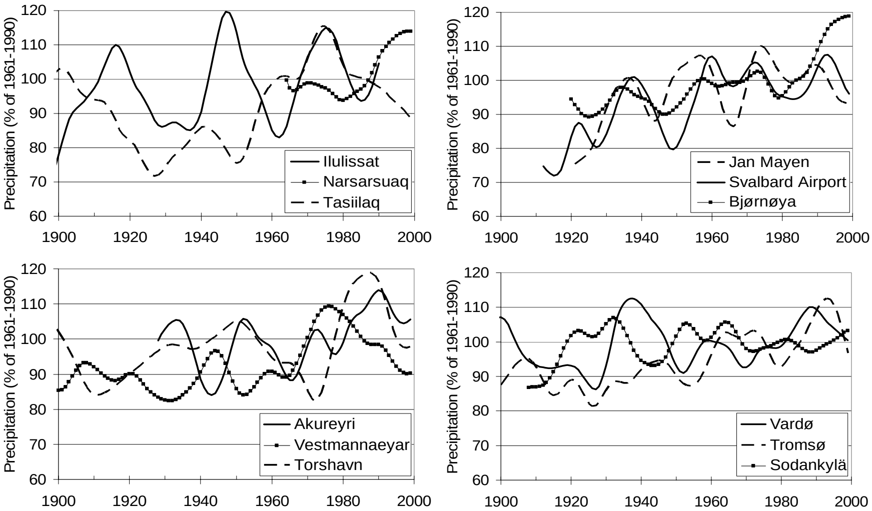

Fig. 3.3. Decadal scale variability in annual precipitation (in %) from climate stations in the European sector of the Arctic.

for temperature (Figure 3.3). However, Førland et al. (2002) conclude that none of the reliable series in the area show negative precipitation trends during the 20th century. According to Mann-Kendall non-parametric test, there are statistically significant positive trends in a belt from eastern parts north in the area to central parts in the south, while there tend to be no significant trend in eastern parts of Fennoscandia and at the westernmost stations. Positive trends of more than 2.0 % per decade were found in Svalbard, Bjørnøya and Tromsø, while trends from 1.5 to 2.0 % per decade were found at Jan Mayen, and parts of Iceland and the Faroe Islands.

The relative precipitation increase in northeastern and central parts of the area is considerably higher than the increase of 0.8 % per decade over the 20^{th} century reported by New et al. (2001) for the 60-80°N land area.

3.2.3 Sea-ice

According to an estimate of Vinje (2001), the April sea-ice extent in the Arctic sector from 30°W to 70°E was reduced by 33 % of its 1864 value from 1864 to 1998. Vinje analysed the ice extent in sub-sectors west and east of 10°E, and found that the larger reduction (40 %) took place in the western sector. The reduction was not linear in time, and according to Vinje (2001) it was larger in the last decades of the 19^{th} century than during the 20^{th} century. Trend studies in the periods 1900-30, 1930-70 and

1970-2000 show that the April sea-ice extent tend to decrease in both subsectors during the first and the last decades of the 20th century (periods of warming), while they tend to increase slightly in the period around the middle of the century (period of cooling). All trends are stronger in the western area. In the eastern area, only the long-term trend is statistically significant.

Vinnikov et al. (1999) analysed in situ sea-ice data from the 20th century for the entire Arctic. The dataset is incomplete during the earlier decades, but shows a negative trend since about 1950, mainly caused by a 15 % decrease in summer sea-ice extent. Satellite-based sea-ice observations confirm a noticeable decrease during the last two decades of the 20th century, especially during summer (Johannessen et al. 1999; Cavalieri et al. 1997). However, Parkinson (2000) found that the trends vary by region. Deser et al. (2000) showed that the dominant mode of Northern Hemisphere winter sea-ice variability in the period 1958-1997 is an anti-phase decadal-scale fluctuation between the Labrador Sea and the Greenland/Barents Seas, which may be linked to atmospheric circulation.

3.2.4 Atmospheric circulation vs. temperature and sea-ice

Regional climate varies not only directly in response to variation in local radiative forcing, but also because of variations in the dominating atmospheric (and ocean) circulation patterns, which again may or may not be triggered by external forcing. The North Atlantic Oscillation (NAO, Hurrell 1995, 1996) and the Arctic Oscillation (AO, Thomson & Wallace 1998) winter indices are two correlated indicators of the mode of the northern hemisphere atmospheric circulation. Positive (negative) values of the AO index indicate increased (reduced) advection of cold Arctic air into western Greenland, and of warm humid air towards north-western Europe and the eastern Arctic. Thompson et al. (2000) conclude that a positive AO trend can account for half the observed winter warming over Eurasia from 1968-1997, while Rigor et al. (2000) show that more than half the warming over the eastern Arctic Ocean and the cooling over the Labrador Sea from the 1970s to the 1990s is accounted for by the AO. Also trends in extreme temperatures in western Greenland and Fennoscandia during the last five decades are in accordance with the positive NAO/AO trend (Tuomenvirta et al. 2000), and so is the antiphase fluctuation between the sea-ice conditions in the Labrador and Greenland/Barents Seas during the latest 4 decades (Deser et al. 2000).

Correlation analysis of the present dataset confirms that temperatures in the eastern part of the European Arctic are positively correlated with the

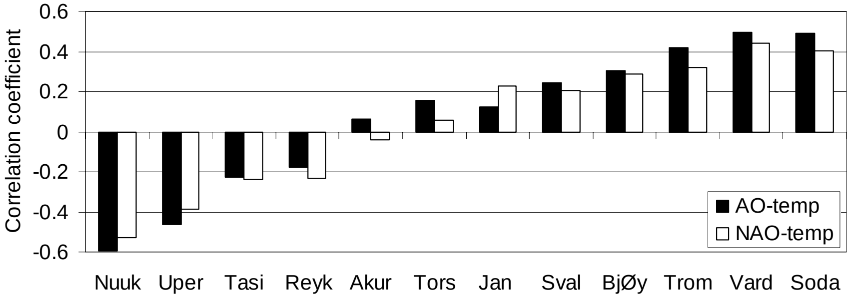

Fig. 3.4. Correlation coefficients between the annual mean temperature at different stations (Fig. 3.1) and the AO-index (black bars) and NAO-index (white bars).

NAO/AO indices, while the tendency is opposite at the westerly stations (Figure 3.4). Still, the AO's ability to account for decadal and multidecadal variability, is definitely not stationary. While a positive trend in AO is consistent with the warming in Vardø and cooling in Nuuk from the 1960s to the 1990s, there is no positive AO trend which can account for the early 20th century warming (e.g. Moritz et al. 2002).

The early 20th century warming might still be connected to atmospheric circulation variability, as AO explains only a fraction of this variability. Further, the hemispheric circulation variability is highly nonlinear, and the AO index is only a linear approximation (Fyfe 2002).

3.2.5 Possible causes for the observed climate variation

Local and regional climate may change in response to variation in external forcing (natural or antropogenic), or because of internal variations in the climate system. The Arctic warming during the later decades is part of a global warming which is seen also in lower latitudes (Jones et al. 1999, Johannessen et al. 2002). Its signature agrees well with results from climate model runs where increasing concentrations of greenhouse gases and aerosols are included, but not with control simulations (Stott et al. 2000, Johannessen et al. 2002). It is thus concluded that the warming during the later decades most likely are induced mainly by antropogenic forcing. A matter of debate is still that, though several climate models produce a certain positive AO trend in response to increased greenhouse forcing, only one model produce an increase of the magnitude we have seen lately (Moritz et al. 2002).

Climate model experiments including historic variations in natural forcings (solar radiation and volcano activity) show realistic temperature variation during the early 20th century warming (Stott et al. 2000). It may thus be argued that this warming was caused by natural external forcing. Recent modelling studies (Delworth and Knutson 2000, Johannessen et al. 2004) showed, however, that climate models can produce similar features, just as a result of internal variability in the climate system. Bengtsson et al. (2003) argue that the early 20th century warming and the following cooling is an internal low frequency fluctuation involving atmospheric and ocean circulation and their effect on sea-ice extent. There are thus at least 2 different hypotheses concerning the early 20th century warming, but none of them include antropogenic forcing as a main factor.

3.3 Climate scenarios for the European Arctic

Atmosphere-ocean general circulation models (AOGCMs) are used to produce scenarios for future climate variation caused by increased atmospheric concentrations of “greenhouse-gases” and aerosols. Scenarios for future climate in the Arctic produced by different AOGCMs show substantial differences on local and regional scales. Still, climate scenarios at doubled CO_2 concentration from 19 AOGCMs run with the same emission scenario (“CMIP2 runs”) show similarities (Räisänen 2003). Sections 3.1 and 3.2 are mainly based upon results from Räisänen (2003). The projected climate changes in these scenarios are defined as the differences between a 20-year period centred when the atmospheric CO_2 concentration is doubled and a 20-year period in the control simulation.

3.3.1 Temperature

Of the 19 CMIP2 models, 18 project a temperature increase in the Arctic area (north of 60°N) which exceeds the global mean warming. While the projected average global warming at doubled CO_2 is 1.75 °C, the Arctic area mean change is 3.4 °C (Räisänen 2003). The largest warming is projected in autumn and winter; the smallest warming in summer. A majority of the models show an area of reduced warming in the northern North Atlantic, which is also reflected in the average of the 19 scenarios (Figure 3.5, left panel). The reduced warming (which is qualitatively in accordance with observations during the latest decades) is mainly due to a projected reduction in the Atlantic meridional overturning circulation (Cubasch et al. 2001). The gradient in projected warming rates from 60 to 90°N is larger in the European sector of the Arctic than in any other sector. The inter-model variability is also considerable in the area, and has a

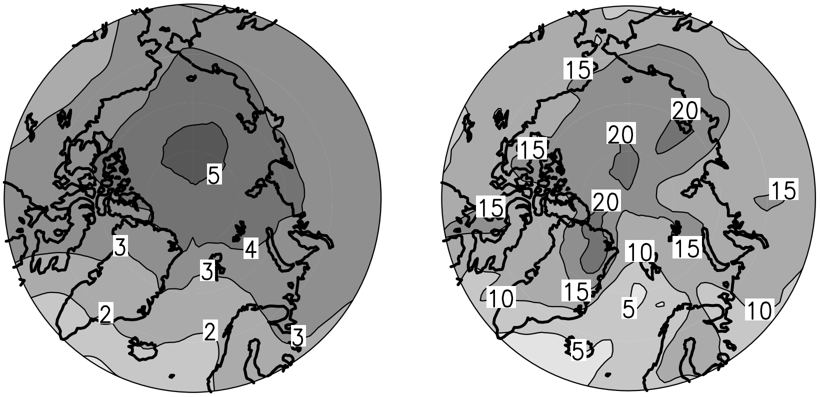

Fig. 3.5. Average from the 19 CMIP2 models of projected climate change at doubled CO_2 concentration north of 60°N (after Räisänen 2003). Left panel: Increased annual mean temperature ($^{\circ}$C). Right panel: Increased precipitation (%).

maximum east of Svalbard. Some models show maximum warming and large sea-ice retreat in this area, while others indicate that the area of reduced warming includes the whole Barents Sea.

The global climate models have too coarse spatial resolution to give good regional climate scenarios. Downscaling is required to produce more detailed regional and local climate scenarios. Few such studies have been performed in the Arctic. However, Benestad et al. (2002) showed that local temperature scenarios in the Svalbard area are closely related to the projected changes in the regional sea-ice cover in the AOGCM. If the present sea-ice extent or the future melting in the region is unrealistic, the local temperature scenarios will thus be dubious. Downscaling studies from Fennoscandia (Christensen et al. 2001, Hanssen-Bauer et al. 2003) confirm that we can expect local spatial variation which is not resolved by the global models. The projected warming is larger in the inland than along the coast, especially during winter. Further, at high latitudes larger winter warming rates are projected in valleys than in mountain areas. This differs from projections from the Alps (Beniston et al. 2003) where projected warming rates tend to increase with altitude.

3.3.2 Precipitation

The ratio between projected increase in precipitation (in %) and temperature (in $^{\circ}$C) in the Arctic is between 2 and 4 in all the 19 CMIP2 models (Räisänen 2003). On local scale, the scatter between the models concerning precipitation changes is larger than for temperature. A general feature is still that the projected precipitation increase averaged over the area north of 60°N is larger than the global average. Further, the Arctic is one of the few regions in the world where the 19 model average projected precipitation increase exceeds the inter-model standard deviation (Räisänen 2003). Figure 3.5 (right panel) illustrates that the average projected increase in annual precipitation at doubled CO_2 is smaller in the northern North Atlantic (5-10 %) than in other parts of the Arctic (10-20 %). This differs somewhat from the patterns of observed change during the 20th century. The projected increase in precipitation is largest in autumn and winter, and smallest in summer.

3.3.3 Other climate variables

With one exception, the 19 CMIP2 models project substantial reduction in the sea-ice extent. The spatial pattern varies a lot, partly because the simulations of the present-day sea-ice extent vary (e.g. Benestad et al. 2002). Sea-ice simulations from the ECHAM4 climate model reproduce the variability of the 20th century satisfactorily (Johannessen et al. 2004). For the 21st century, under the “old” emission scenario IS92a (IPCC 2001, p 14), the model projects a modest reduction during winter, but a radical (~80%) reduction in the summer ice extent. These results agree well with results from the HadCM3 model (Gregory et al. 2002), under the “new” B2 emission scenario (IPCC 2001, p 14).

Concerning changes in sea level pressure and atmospheric circulation, the models show a large spread in projections. Several (but not all) models project a modest positive trend in the NAO/AO indices. Several models also tend to show an eastward relocation of the Icelandic low. This would affect the southward transportation of cold air in western parts of the European sector as well as the advection of mild humid air into the eastern Arctic in a way that is not necessarily captured by the NAO/AO indices.

3.4 Summary and conclusions

The annual mean precipitation increased significantly in large parts of the European Arctic sector during the 20th century. Statistically significant warming is found in parts of Iceland and in Fennoscandia, while temperature series from other parts of the European Arctic show no significant long-term trend. “The early 20th century warming”, which culminated around the 1930s and was followed by a period with cooling, is a dominating feature in all temperature series from the area. This feature may have been triggered by variation in solar radiation and volcano activity, or it may result from internal variability in the climate system. Positive temperature trends during the last decades of the 20th century are found in central and especially in eastern parts of the European Arctic. This recent warming, which is associated with a positive trend in the NAO index, is probably at least partly triggered by antropogenic forcing of the climate system. The sea-ice extent in the European sector of the Arctic has decreased during the 20th century. The April sea-ice extent shows negative trends during the first and last 30-year periods of the century, but a small (insignificant) increase in the period 1930-1970.

Though the global climate models (AOGCMs) certainly have their limitations, they are the best tools we have for projecting future climate. Comparison of results from several models may indicate the level of uncertainty. Projected changes in temperature, sea-ice extent and large-scale precipitation seem to be qualitatively robust. Generally, the AOGCMs project larger warming in the Arctic than the global average. However, a majority of the AOGCMs project an area of minimum warming near southern Greenland. In the European sector of the Arctic, there is thus a considerable gradient in the projected warming rates from 60°N to the high Arctic. As for temperature, the projected increase in precipitation is generally larger in the Arctic than globally averaged. Likewise for precipitation, most models project a smaller response in southwestern parts of the European sector than elsewhere in the Arctic. Projected changes in sea-ice extent for the 21st century show moderate reduction during winter, but large reduction during summer.

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4 Impact of climate change on arctic and alpine lakes: Effects on phenology and community dynamics

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4.1 Introduction

The ecology of Arctic and Alpine lake communities is heavily influenced by ice and snow, two factors governed by climatic conditions (Rouse et al. 1997). Climate change generates variation in ice and snow cover phenology, thickness and texture that triggers a broad spectrum of physical, chemical and biotic responses (Quayle et al. 2002). Changes in community structure and dynamics caused by these environmental responses are early symptoms of an ecological impact of climate change. The simple character of Arctic and Alpine lake communities, with a small number of species arranged along few trophic levels, facilitates detection of such structural changes and permits detailed studies of dynamics. The sharp influence of climate and simple community structure, combined with the opportunity of tracking past ecological change using paleoecological records (Smol et al. 2005), make Arctic and Alpine lakes suitable ecosystems for an early, reliable assessment of ecological impacts of global climate change.

Global climate change is expected to modify the range and phenology of many terrestrial and aquatic species (Parmesan and Yohe 2003). Projections of the future impact of climate change on biodiversity, based on species-area relationships (Rosenzweig 1995) and the assumption that climate determines present distributions, stress how climate induced range alteration will greatly enhance the risk of extinction for many species (Thomas et al. 2004). Meanwhile, range expansion and changes in phenology consistent with global warming scenarios are being documented for an increasing number of taxa (Root et al. 2003). The above assessments of ecological impact of climate change are mainly based on comparative studies from tropical and temperate regions, the focus of past research efforts.

Evaluation of an impact of recent climate change on Arctic and Alpine communities must rely on evidence that is more sparse or indirect. Information needed for the extrapolation of climate impact scenarios in Arctic and Alpine systems is richer, for it includes data from lower latitudes and altitudes that may be assumed to reproduce relevant aspects of future environmental conditions.

Arctic and Alpine lakes are characterized by an extended period of ice cover, cold water and low production. Warming results in anticipated ice melt and delayed ice formation (Magnuson et al. 2000), and in increased water temperature (Schindler 1997). The resulting prolonged ice-free season, stronger thermal stratification and enhanced nutrient resuspension are expected to increase lake production (Rouse et al. 1997). Further increases in production may derive from indirect effects of warming on external inputs of nutrients and organic carbon (Quayle et al. 2002). The above changes in environmental conditions may also shift the main contribution to lake production from benthic to pelagic (Korhola et al. 2002). Increased temperature and production will facilitate successful invasion and introduction of species adapted to warmer and more productive waters. The ecological implications of the above environmental changes, however, reach beyond range alteration driven by physiological limitations. Within a lake, a longer productive season protracts the active period of community members increasing the scope for ecological interactions and ecosystem engineering. By relaxing the physical and energetic limitations on demographic and interaction parameters, and by modifying the nature and structure of interactions, warming resets the internal machinery that drives community dynamics (Harrington et al. 1999, Schmitz et al. 2003).

The above qualitative generalization is intended as a reference scenario for the following discussion of climatic impact on phenology and community dynamics of plankton, benthos and fish. The scenario invites some general considerations about impact on biodiversity. Medium term projections (year 2100) rank climate change as a main driver of future biodiversity loss in Arctic and Alpine freshwaters (Sala et al. 2000). Many of the cold stenothermal species populating these regions are relictual endemics that are forced into deep, cool waters of lakes in order to survive. Under warming, the deep refuges would gradually become unbearable due to the higher temperatures and lower oxygen concentrations. Loss of even a few endemic species will have a strong impact on regional diversity, considering that high altitudes and latitudes have relatively few species to begin with (Lomolino 2001, Willig et al. 2003). Empirical, hump shaped relations between productivity and species richness in lakes suggest that the expected increase in productivity will be followed by increased species richness (Rosenzweig 1995, Dodson et al. 2000). This does not contradict the expectation of higher exctinction rates given that recipient communities will experience substitutions by exotic species that are expanding their range. The rates of change in species composition and richness may also increase, due to higher propagule pressure. The latter effect is most likely in low latitude Alpine lakes, where the distance between different ecoclimatic regions is short and the species pool at lower altitudes is large.

The scenario of a warmer, wetter climate that will increase ice-free season duration, water temperature and productivity of Alpine and Arctic lakes must be treated with caution. The magnitude and even direction of ecological response to climate change will depend on a variety of environmental conditions that were not addressed. Basin morphometry, hydrology, catchment and geographic position are all likely to affect the character of climatic impact and will be considered in more detail below. The literature reviewed includes assessment and prognostic studies of climatic impact on Arctic and Alpine lakes. As mentioned earlier, the evidence of recent ecological changes reported in these studies is seldom direct. Reviews of assessment studies dealing with climatic impact on lakes mainly refer to data collected in temperate regions (Schindler 1997, Straile et al. 2003). In the absence of direct observations, microfossil accumulations in lake sediments provide compelling indication of climate driven ecological change (Smol et al. 2005). Paleolimnological records may even allow the detection of changes in the intensity of ecological interactions, as in the case of fish predation on the planktonic prey *Daphnia* (Jeppesen et al. 2002).

4.2 Plankton

A comparable environment leads to similarities in the structure and dynamics of plankton inhabiting Arctic and Alpine lakes. In these lakes, light and nutrients are available in measures adequate to support life for only a short period of the year. This productive, ice-free period has a limited temperature excursion, and summer thermal stratification, when present, lasts only a few weeks (Fig. 4.1, upper panels). The result is a relatively brief and environmentally homogeneous productive season with low food production sufficient to sustain only a small number of trophic levels. The limited scope for differentiation along resource and safety axes constrains the diversity of consumers. Accordingly, zooplankton species richness rapidly declines along the upper interval of latitudinal and altitudinal gradients (Patalas 1990, Rautio 1998). The species richness of algae is higher, but there is lower equitability, with a dominance of chrysophyceans and

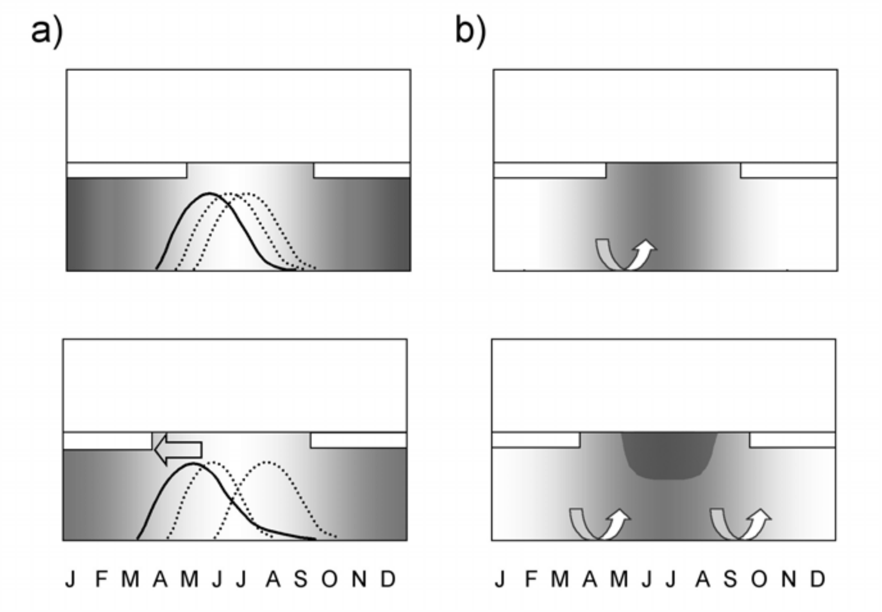

Fig. 4.1. Climate change affects both a) light, and b) temperature regimes in Arctic and Alpine lakes (darker shades depict low light and high temperature, respectively). A warmer climate (lower panels) anticipates ice melt increasing the amount of light available for photosynthesis during spring. The long photoperiod of high latitudes strengthens this effect. The growing season of algae (solid line) and herbivores (dotted lines) is anticipated and prolonged, increasing the scope for temporal segregation of competing species. Increased temperature promotes thermal stratification, boosting productivity in the epilimnion and producing an additional mixing event at the end of summer when temperature drops (bottom arrows). Mixing increases nutrients availability via sediment resuspension.

diatoms, typical of cool, unproductive waters. More surprising are the similarities in taxonomic composition. Some of the dominant planktonic species found in Alpine lakes are also present across the Arctic. The broad biogeographic distributions are obtained via passive dispersal powered by winds and animals (Kristiansen 1996, Bilton et al. 2001, Bohnak and Jenkins 2003). Migratory birds play an important role in this respect (Santamaria and Klaassen 2002), and the observed migration range expansions associated with warming will intensify plankton propagule pressure at the higher latitudes. The planktonic propagules that tolerate long-range dispersal are adaptive, dormant stages that have evolved to survive harsh conditions within lakes (Hairston 1998).

4.2.1 Phenology

Many planktonic species overwinter in a dormant state (Rengefors et al. 1998, Williams-Howze 1997, Brendonck and DeMeester 2003). The phenology of the onset and end of dormancy is bound to the timing of ice formation and melt by environmental changes that function as triggering cues for the planktonic organism. The environmental cues include physical stimuli connected with light and temperature regime shifts, and chemical stimuli related to biotic conditions (Rengefors et al. 1998, Brendonck and DeMeester 2003). Ice melt is accompanied by changes in light and temperature conditions that operate in concert to terminate winter dormancy. Earlier ice-melt, as brought about by warming (Fig. 4.1, lower panels), anticipates hatching and activation of dormant stages. The temporal relation between ice melt and the emergence of plankton is documented by variation in the timing of algal blooms and zooplankton outbursts in long-term series under variable interannual weather (Straile et al. 2003), and along altitudinal and latitudinal gradients (Reynolds 1989). The phenology of dormancy expected on the basis of the abiotic regime shifts can be modified by chemical cues associated with predation risk and crowding that inhibit emergence or induce dormancy (Hansson 2000, Lass and Spaak 2003). Control mechanisms triggered by chemicals, documented for both winter and summer dormancy (Rengefors et al. 1998, Williams-Howze 1997), imply that indirect effects of climate on timing and magnitude of predation risk and population peaks, discussed below, will contribute to further modify the phenology of dormancy.

Warming will also affect breeding phenology and the timing of ontogenetic stage shifts, with implications for population growth rates and stage-structured interactions. The dramatic impact of climate on breeding phenology and growth is best illustrated by copepods, which have complex and relatively long life cycles (Santer 1998). Copepods time reproduction with specific seasonal events to minimize the risk of predation and offspring starvation (DeMott 1989). In cyclopoids, hatching typically occurs during the algal bloom, minimizing the risk of starvation of the herbivorous larvae. But life cycles are flexible, as shown by *Cyclops scutifer*, a species that can vary life cycle duration from three years to one year depending on temperature and food conditions (Williams-Howze 1997). Increased temperature and food availability accelerate growth and reduce the need for summer dormancy, promoting short generation time (Maier 1989, Williams-Howze 1997). Calanoids often breed before the spring algal bloom, and their earliest larval stages rely on the rich egg reserves to survive and grow under the ice. The widespread genus *Eudiaptomus*

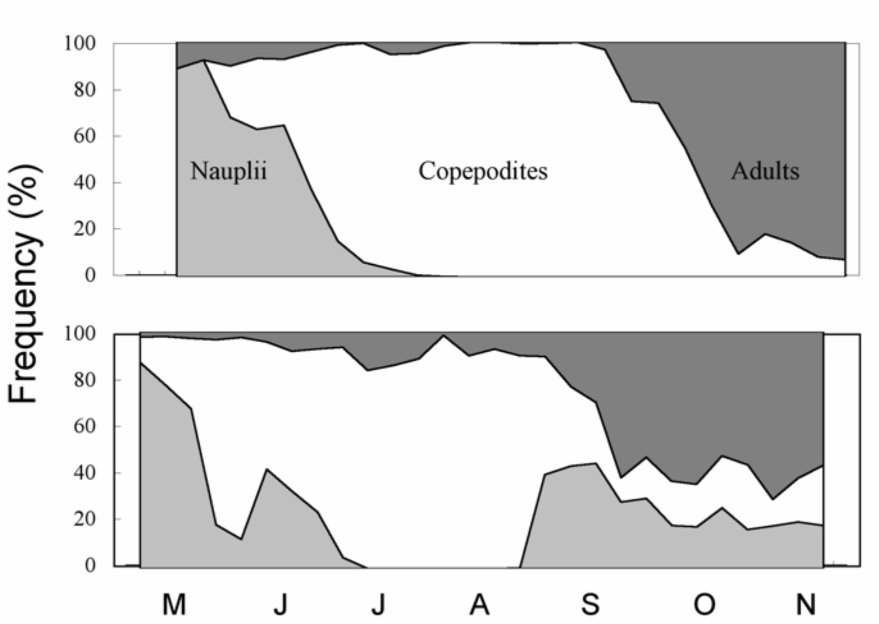

Fig. 4.2. The calanoid *Eudiaptomus intermedius* has typically a yearly life cycle in the subalpine lake Scuro (1527 m a.s.l., Italy), with nauplii being born in spring, under the ice (upper panel - 1992). But an early ice-free season, with relatively high water temperature, shortens the life cycle of the calanoid, allowing it to anticipate reproduction, and to double the number of generations per year (lower panel - 1993).

illustrates how such life history strategies may be drastically modified in response to warming (Fig. 4.2).

4.2.2 Community dynamics

Plankton communities are particularly sensitive to spring warming because the main dynamic events take place during the productive, ice-free season, when light is readily available (Sommer et al. 1986, Straile et al. 2003). After ice melt, egg banks and dormant stages seed the population and community dynamics in the pelagic (Rengefors 1998, Hairston et al. 2000, Brendonck and DeMeester 2003). Spring recruitment from dormant stages is particularly important in Arctic and Alpine lakes, as shown by demographic (Edmondson 1955, DeStasio 1990) and genetic studies of natural populations (Rossi et al. 1998). This is due to a limited scope for direct recruitment given the low density of individuals actively overwintering. After activation, population growth is constrained by long generation time

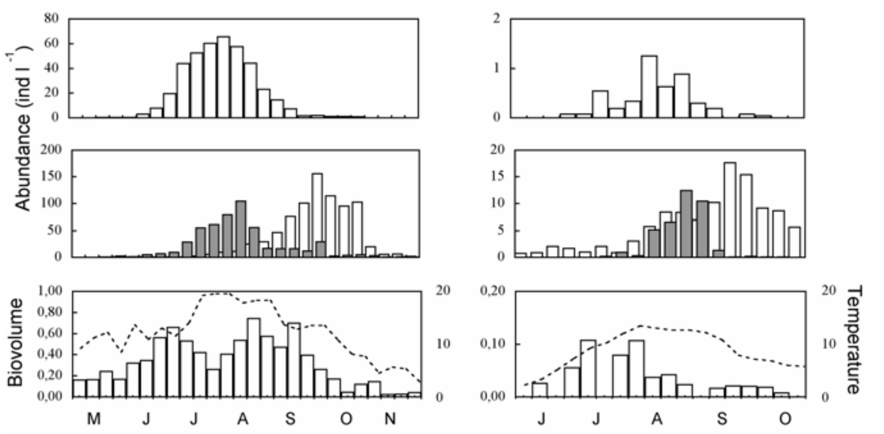

Fig. 4.3. Seasonal dynamics of the rotifer predator *Asplanchna priodonta* (top panels) and of its competing prey (middle panels), *Keratella cochlearis* and *Conochilus unicornis* (gray bars), in the subalpine lake Scuro (left panels) and subarctic lake Takvatn (right panels). Lower panels, stippled line, temperature (°C) at 1 m depth, bars, algae biovolume (mm3 l-1). The longer ice-free season of lake Scuro allows a greater temporal segregation among competing prey. In lake Takvatn, the high temporal overlap of competitors is permitted by their segregation along the water column, with the vulnerable, but competitively superior *Keratella* hiding in deep water layers.

and, in zooplankton, by relatively small clutch sizes. Even slight increases in temperature and production early in the ice-free season can burst population growth reducing the time from activation to peak density. The timing, duration and magnitude of the spring phytoplankton bloom are subject to climate forcing mediated by ice phenology, mixing, water temperature, and thermal stratification, which affect the light, nutrient and temperature environment experienced by the algae (Reynolds 1989). Climatic events also affect zooplankton grazing on algae (Scheffer et al. 2001). An early, warm productive season favours the early build up of zooplankton numbers resulting in a rapid decline of algae abundance (Straile et al. 2003). Prolonged and intensified herbivory, and sharper epipelagic gradients of nutrient availability due to increased thermal stratification, generate clearer patterns of succession in phytoplankton, with seasonal shifts to species with lower nutrient requirements or greater resistance to grazing (Sterner 1989, Reynolds 1997). Zooplankton may also experience new opportunities for temporal segregation under climate warming, as illustrated by the seasonal dynamics of rotifers (Fig. 4.3). In size structured populations (e.g. *Daphnia*), the number of synchronized generations between activation and dormancy, limited by ice phenology and water temperature, determines the seasonal change in size distribution and, consequently, in size dependent interactions (Primicerio 2003).

4.3 Benthos

Benthos is a key component of Arctic and Alpine lake food webs being responsible for a large portion of total production (Korhola et al. 2002). The composition and structure of benthic communities is affected by structural characteristics of the substrate on, or in, which they live (Moss 1998). This condition distinguishes the ecology of plankton and benthos and adds new sources of heterogeneity in the environment experienced by benthic organisms. In particular, variation in substrate steadiness and texture, two properties that affect the opportunity for attachment and hiding, promotes diversity. Stones, pebbles, sand, and lime establish a gradient of stability and interstitial grain often associated with increasing depth (Moss 1998). In the littoral zone, the character and heterogeneity of substrate depends also on the presence and composition of macrovegetation, used by other organisms to attach, hide and feed. The abundance and diversity of macrophytes decreases with increasing altitude and latitude; warming is expected to favour their expansion. Several benthic organisms have dispersal stages, such as adults of chironomids or resting propagules of algae and crustaceans (Kristiansen 1996, Bilton et al. 2001), that will ensure their rapid range expansion under favourable conditions promoted by warming.

4.3.1 Phenology

Timing of emergence of dormant benthic organisms is associated with physico-chemical regime shifts following ice melt. Data on the relation between phenology of emergence and interannual variation in ice phenology and water temperature are less rich for benthos than for plankton (Straile et al. 2003), but the available information suggests similar conclusions. Warming will anticipate emergence, prolonging the active season of benthic organisms. Breeding phenology, and seasonality and duration of life cycles will also change as a consequence of increased temperature and production. Long-term studies of aquatic insects illustrate how climatic events can modify the phenology of stage transition, as shown by Elliott (1996) for adult emergence of alder-flies living in the littoral zone of lake Windermere. Another example of climate driven change in timing of stage transition is provided by larvae of chironomids, which are often the numerically dominant component of benthic macroinvertebrates. Larvae of chironomids are likely to pupate earlier in warmer waters. Pupation is associated with a massive migration towards surface during summer, an event with important energetic implications for fish predators.

4.3.2 Community dynamics

In the recent past (~150 years), compositional shifts of algae in Arctic and Alpine lakes have occurred concomitantly with warming events (Douglas et al. 1994, Lotter and Bigler 2000). These taxonomic changes, traced in the paleolimnological record, can be explained by climate change impact (Sorvari et al. 2002). Similar changes in benthic algae are expected to occur in the near future as a consequence of temperature increases of similar magnitude (about 2 °C – Sorvari et al. 2002). In particular, diatoms, which play a central ecological role via their strong contribution to lake primary production, are sensitive to climate forcing and are likely to switch from a dominance of benthic species (e.g. members of *Fragilaria*) to mainly pelagic forms (e.g. species of *Cyclotella*). The change is expected due to the prolonged ice-free period and increased thermal stratification favouring small, lightly silicified planktonic diatoms that shade deep dwelling, benthic forms. Such changes from benthic to pelagic primary production may affect benthic consumers, although increased sedimentation may provide alternative food sources. The expected changes in phenology discussed above will influence demography and interactions among benthic species, but may also reverberate across the entire lake food web, as exemplified by the effects of chironomid larvae pupation. By diverting the attention of fish, chironomid pupation temporarily releases from predation other vulnerable prey, indirectly influencing their population dynamics. In turn, fish affect the structure of chironomid communities via predation (Mousavi et al. 2002).

4.4 Fish

Freshwater fish need water corridors to colonize new aquatic environments. They have therefore greater dispersal limitations than many planktonic and benthic species. As a result, the geographical range of a fish species maintains the historical pattern of colonization (Rosenfield 2002), unless this has been altered by human introductions. Introductions are common for recreational fish like salmonids, the dominant taxon in Arctic and Alpine lakes. Fish species dominance and composition changes with latitude and altitude, suggesting an influence of climate on the outcome of ecological interactions. Trophic interactions vary with season and fish ontogeny, although different fish species are not equally flexible in their habitat and diet use (Persson et al 1997). High flexibility characterizes Arctic charr, *Salvelinus alpinus*, the freshwater fish with the northernmost range limits, common in Arctic and Alpine lakes (Maitland 1995, Klemetsen et al. 2003). A distribution restricted to cool waters, as observed in Arctic charr, suggests vulnerability to global warming due to physiological stress (Lehtonen 1998). However, thermal stress need not be the driving factor behind cool water distributions. In Arctic charr, for example, the upper critical limits and optimum temperatures are relatively high (Lytikäinen et al. 1997, Thyrel et al. 1999), and vary little with latitude (Elliott and Klemetsen 2002). Also, cold stenothermal species may be able to adapt to warmer temperatures, as suggested for lake trout, *Salvelinus namaycush* (Sellers et al. 1998). Thus, thermal stress may pose serious threats only under rapid change and extreme water temperatures, as could be experienced in shallow lakes. Changes in timing of life history events and seasonal resource availability, and new regimes of biotic interactions are likely to play a more decisive role in mediating the impact of climate change on fish (Davis et al. 1998).

4.4.1 Phenology

Seasonal changes in prey availability modify diet and habitat choice by fish (Persson et al 1997). After ice melt, higher zooplankton abundance increases the degree of planktivory and use of the pelagic habitat. In salmonids, this seasonal dietary shift is sharp (Klemetsen et al. 2003). Earlier zooplankton availability anticipates and prolongs the period of planktivory, as seen along latitudinal and elevational gradients (Fig. 4.4). Seasonal shifts in diet are not restricted to increased planktivory after ice melt, but include changes to insectivory, benthivory, and piscivory at different times of the year (Klemetsen et al. 2003). The timing of such foraging events is subject to indirect climatic influences via regulation of prey phenology. In addition to prey availability, the seasonal succession in diet composition depends on fish size and taxonomic identity. Higher specialization of given fish stages or taxa reduces the number and extent of their seasonal changes in diet. Because of the strong seasonality and low levels of prey availability, high latitude and altitude lakes are unfavourable environments for specialists, whereas flexible species like Arctic charr are well adapted to such conditions.

Warming will favour specialists, such as planktivorous coregonids, by prolonging and increasing the availability of their preferred prey group. In

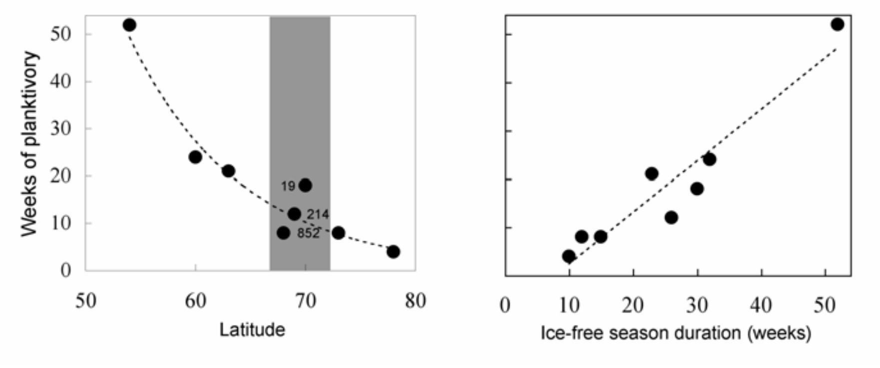

Fig. 4.4. Duration of planktivory in Arctic charr populations decreases with increasing latitude and altitude (left panel – labels within gray band mark altitude in m a.s.l. for lakes along elevation gradient) and is positively related to the duration of the ice-free season (right panel). The threshold for planktivory is set at 20 % in frequency of occurrence or stomach contents volume. Data are from lakes located in Western Europe, Bear Island and Spitzbergen. See Table 4.1 for a summary of lakes physiography. Data obtained from: Klemetsen & Grotnes (1975, 1980); Frost (1977); Hindar & Jonsson (1982); Klemetsen et al. (1985); Amundsen (1989); Christensen (1994); Forseth et al. (1994); and Elliott & Baroudy (1995).

most fish species, newly born individuals are specialist planktivores, highly vulnerable to seasonal changes in prey availability (Wootton 1999). Emergence must therefore be timed with zooplankton peak availability to avoid starvation after exhaustion of yolk reserves. Fish that are not able to synchronize emergence with earlier zooplankton outbursts driven by climate warming will risk extinction (McDonald et al. 1996). Fish that anticipate emergence will experience a prolonged, warmer and more productive growth season. Prolonged and accelerated growth allows earlier access to alternative prey not readily available to small juveniles due to size constraints.

4.4.2 Community dynamics

Indirect effects of warming, such as increased plankton production, generate new opportunities for resource specialization and growth of fish. The effects of increased plankton production on fish diet and growth are illustrated by nutrient enrichment studies at high latitudes. One such study from Norway (69°N) registered an increase in plankton contribution to Arctic charr stomach contents from less than 40% to more than 80% of the bio-volume, with *Daphnia* becoming the most important prey. Increased

Table 4.1. Physiography of lakes used to compare seasonal duration of planktivory in Arctic charr along gradients of latitude and altitude (Fig. 4.4). Area is lake area in km^2, Zmax is maximum depth in m, Lat is latitude in °N, Alt is altitude in m a.s.l., Open is the duration of the ice-free period in weeks, Tmax is maximum temperature in °C. Data obtained from: Klemetsen & Grotnes (1975, 1980); Frost (1977); Bøyum & Kjensmo (1978); Hindar & Jonsson (1982); Klemetsen et al. (1985); Amundsen (1989); Christensen (1994); and Elliott & Baroudy (1995).

Lake	Area	Z_{max}	Lat	Alt	Open	T_{max}
Windermere (UK)	15	64	54	39	52	24
Vangsvatn (Norway)	8	60	60	46	32	20
Høysjøen (Norway)	1	27	63	222	23	na
Takvatn (Norway)	15	80	69	214	26	14
Ellasjøen (Bear Island)	1	43	73	21	12	7
Linnévatn (Spitsbergen)	5	37	78	4	10	3
Gautelisvatn (Norway)	6	40	68	852	15	12
Skogsfjordvatn (Norway)	14	80	70	19	30	15

availability of large, easy to catch zooplankton produced a dramatic acceleration in fish somatic growth within three years since the beginning of the nutrient enrichment program (Dahl-Hansen et al. 2001). Enhanced growth rates influence the size distribution of the whole fish population, affecting size dependent interactions. Similar effects driven by climate change are expected to modify the outcome of interactions among fish species. Competition between Arctic charr and whitefish (*Coregonus lavaretus*) illustrates the mechanisms involved. The whitefish is often regarded as the competitively superior species (Svärdson 1976, Lehtonen 1998), but ranking seems to depend on environmental conditions influenced by climate. A recurrent pattern is Arctic charr substituting whitefish, and other species, as latitude and elevation increase (Svärdson 1976, Heino 2001). These changes in composition and dominance are likely to be mediated by climatic effects on duration and productivity of the ice-free season. Greater availability of zooplanktonic prey, experienced at lower altitude and latitude, and promoted by warming, favours the coregonids, which are more efficient planktivores. Intensive, long-term studies of succesfull invasions of subarctic freshwaters by planktivorous fish species (e.g. Bøhn and Amundsen 2001) document the ecological mechanisms that may promote colonization of Arctic and Alpine lakes by exotics under warming (Shuter and Post 1990). The accelerated spread of non-native aquatic organisms (Lodge 1993), boosted by global warming, will result in a drastic change in the diversity and structure of Arctic and Alpine fish communities.

4.5 Higher-order effects of climate change and lake communities

Increased plankton production exemplifies a higher order effect of climate change that may reach the top of the lake food web altering fish assemblages. In turn, changes in fish composition, relative abundance, and size distribution will have top-down effects on plankton and benthos. These top-down, higher order effects of climate change are likely to generate some of the main structural alterations in lake communities (Schmitz et al. 2003). General predictions concerning the direction of such higher order effects are not easy due to the variation generated by the interplay between taxonomic composition, adaptation, and degree of environmental heterogeneity. This is illustrated by how size-structured interactions, anti-predator adaptation, and lake morphometry may modulate climate impact. The effect of predation by fish has a strong size-dependent component (Persson et al. 1997). In the absence of fish, invertebrates become the main top predators in Arctic and Alpine lakes. The top-down influence of invertebrates also depends on prey size, but the character of size dependence differs from that of fish (Hall et al 1976). Different configurations of size-structured interactions in absence vs. presence of fish will produce different ecological responses to climate change.

The indirect influence of top-predators on abundance and composition of planktonic and benthic species is mediated by changes in prey density and phenotypic traits. Inducible anti-predator adaptations responsible for trait-mediated interactions in plankton and benthos are predator specific (Tollrian and Harvell 1999). The importance of indirect interactions mediated by adaptive traits, such as risk sensitive foraging behaviour, is likely to increase with increasing productivity brought about by warming (Luttbeg et al. 2003). In lakes, a common anti-predator response that structures prey communities is the adaptive use of deep habitat refuges (Fig. 4.3 - Primicerio 2005). Shallow lakes lack deep habitat refuges, a simple consideration that stresses the influence of lake morphometry, and associated degree of environmental heterogeneity, on the effects of climatic variation.

Clearly the mechanisms by which climate change may affect lake communities, either directly or via an interplay with other sources of environmental stress (Schindler 2001), are sufficiently complicated to beg for a carefully designed, experimental research program with regional implementation (Harrington 1999). For Arctic and Alpine lakes, this research program is presently under way and will soon provide the information needed for more quantitative prediction.

4.6 Conclusions

Available data from extensive surveys, paleolimnological records, and long-term studies of natural and whole lake experiments confirm the sensitivity to climate change of these vulnerable ecosystems. Under the warming scenario, production is expected to increase and the seasonal dynamics of plankton and benthos should change, in accordance with observed alterations associated with temporal variation in temperature regimes. Plankton and benthos may also face compositional and structural changes resulting from range expansion of exotic species and local changes in nature and intensity of ecological interactions. When present, fish can play a central role in driving such structural changes by modifying the phenology and ontogeny of habitat and dietary shifts, and the character of resource specialization. In turn, the above phenotypic responses will affect fish population and community structure. Phenology of emergence and other frequency-dependent adaptations affected by climate generate nonlinear relations among interacting populations that amplify the effects of small change and influence the impact of environmental variation on population and community dynamics (Chesson 2003). The complex causal structure leading to higher order effects of climate change challenges assessments and predictions of ecological impact and has prompted carefully planned experimental investigations that will soon allow more quantitative projections.

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5 Changes in growing season in Fennoscandia 1982-1999

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5.1 Introduction

Phenology is the science dealing with the influence of climate on the recurrence of annual phenomena of animal and plant life such as budburst and leaf fall etc. Changes in the phenological events are early indications of effects of changes in the climate. The distribution of plant species and vegetation types tends to be controlled by the climate (Moen 1999, Woodward 1987). Changes in the timing of phenological events are often the first indications of transitions of ecosystems, as e.g. the rise of the tree line and transitions from tundra to boreal forest. Accordingly, it is of interest to monitor the timing of important phenological events like the start of spring and autumn.

There is now ample evidence of the ecological impacts of recent climate change, from polar terrestrial to tropical marine environments (Walther et al. 2002). The responses of both flora and fauna span an array of ecosystems and organizational hierarchies, from the species to the community levels. Although we are only at an early stage in the projected trends of global warming, ecological responses to recent climate change are already clearly visible.

Traditional phenological studies in Europe indicate that the average annual growing season has lengthened during the past decades in western and central Europe (Menzel & Fabian 1999, Chmielewski and Rötzer 2002, Sparks and Menzel 2002, Ahas et al. 2002). Most of this lengthening of the growing season is due to an earlier start of spring, while the effect of a later end of the growing season is less. The earlier onset of spring is most likely due to increased winter/spring temperature. However, there are indications of regional differences in Europe (Ahas et al. 2002). A delay trend in onset of birch-pollen seasons in northern Finland for the last two decades has been reported (Emberlin et al. 2002). From Kola Peninsula in north-western Russia, Kozlov and Berlina (2002) showed a decline in length of growing season for the last 70-years. However, we should be aware that a delay in spring is not necessarily a result of colder climate in northern areas, it could be the result of more snow in the winter, and thereby later snowmelt. We should also be aware of that the phenological response to changes in climate would change with the altitude, latitude and longitude gradients.

Use of satellite data is a way to examine these geographical differences in climatic change and corresponding phenological responses. Several studies show the possibilities to combine Normalized Difference Vegetation Index images (NDVI) derived form satellite images with phenological ground registrations (i.e. Reed et al. 1994, Schwartz and Reed 1999, Chen et al. 2001). Reed et al. (1994) estimated twelve metrics linked to phenological events based on NDVI data from National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) data. These were compared to certain agricultural crops, grasslands, shrub-lands and forests for the United States. Chen et al. (2001) used phenological data from the Chinese Yearbooks of Animal and Plant Phenological Observations from the period 1982-1993 and compared these with NDVI data estimated form NOAA AVHRR images. Using threshold NDVI values, they found a high correlation between the end of the growing season, but a low correlation for the beginning of the growing season. Schwartz and Reed (1999) found a good agreement between NOAA AVHRR NDVI data and modelled phenology based on phenological registrations across eastern United States. However, in Europe, and in particular in Fennoscandia, these types of comparative studies have not been published.

On a global scale, the use of satellite data support the general trend against earlier onset of spring and prolonged growing season in most of Eurasia towards the end of the 20th century (Myneni et al. 1997, Zhou et al. 2001, Tucker et al. 2001, Bogaert et al. 2002, Shabanov et al. 2002). Tucker et al. (2001) analyzed a time series from 1982 to 1999 of NDVI data from the NOAA AVHRR series of satellites. They found that there where significant variations in photosynthetic activity and growing season length at northern latitudes above 35°N. They especially noticed that two distinct periods of increasing plant growth where apparent, 1982 to 1991 and 1992 to 1999. The decline from 1991 to 1992 where explained by global cooling caused by the eruption of Mt. Pinatubo in 1991. Tucker et al. (2001) found that average May to September NDVI values from 45°N to 75°N increased by 9% from 1982 to 1991, decreased 5% from 1991 to 1992 and again increased 8% from 1992 to 1999. In the same time periods, the start of the growing season varied with –5.6, +3.9 and –1.7 days, respectively.

Zhou et al. (2001) estimated that about 61% of the total vegetated area between 40°N and 70°N in Eurasia shows a persistent increase in the growing season from central Europe through Siberia to the Aldan plateau. The increase in the length of the growing season in the period 1981-1999 was estimated to be in the range 18-24 days, depending on a NDVI threshold value set to define the growing season. In Zhou et al. (2002), the coastal and northern Fennoscandia was determined too sparsely vegetated to be included. In North America they found a fragmented pattern of change in smaller areas, mostly in the forests of southeast and grasslands of the upper Midwest. They also found a larger increase in growing season NDVI magnitude (12% versus 8%) and a longer active growing season (18 versus 12 days) caused by an earlier spring and delayed autumn in Eurasia relative to North America. They observed NDVI decrease in parts of Alaska, boreal Canada and northeastern Asia. They explained this decrease by temperature-induced drought caused by pronounced warming without a concurrent increase in rainfall.

We used the NOAA AVHRR NDVI satellite dataset, produced by the Global Inventory Modeling and Mapping Studies (GIMMS) group, to investigate regional climate change impact on the length of the growing season in Fennoscandia during the last two decades. The study area is characterized by large regional climatic differences from south to north, from west to east, and from lowland to mountains. The aim of this study is to reveal the regional pattern of changes in start of spring and autumn. In order to achieve our aim, we developed a method using individual threshold NDVI values for each pixel for defining the start and end of the growing season. The individual pixel specific threshold value is tuned to give the highest correlation with selected phenological, climate and pollen in-situ data for the period 1982-1999.

The estimated onset of spring is shown to be well correlated with ground data on onset of leafing of birch. The results show high regional differences in trends in the onset of spring. In the southern part of Fennoscandia, and on the oceanic west coast of Norway, the spring starts considerably earlier in the late nineties compared to the early eighties. This earlier trend fits with the pattern from western and central Europe, and is likely to be related to increased spring temperature. On the other hand, the results indicate no or even a slightly delayed trend in onset of spring in the mountain areas in southern Norway and in the continental parts of northern Fennoscandia. At the same time the autumn is delayed in the whole area except an area in the continental part of northern Fennoscandia. This also means that the growing season is prolonged for the whole area, except the northern continental parts of Fennoscandia.

5.2 Data and Methods

5.2.1 Satellite Data

We have used the NOAA AVHRR NDVI satellite dataset produced by the Global Inventory Monitoring and Modelling Studies (GIMMS) group for the period January 1982 to December 1999, with 8x8 km^2 spatial resolution (Tucker et al. 2001, Zhou et al. 2001, Bogart et al. 2002). The GIMMS dataset is composed of the maximum value NDVI for 15-day periods. The highest NDVI value for each composite is chosen as the NDVI for the compositing period as it corresponds to lower aerosol and cloud contamination. This procedure ensures the highest possible degree of data coverage. It is also sufficiently accurate for detecting phenology change, as absolute NDVI values throughout the growing season can be compared, and not only the date for specific events.

The processing for the particular dataset used in this work include improved navigation (Rosborough, 1994), calibration of the four different sensors by the method of Vermote and Kaufman (1995), and corrections for sensor degradation and partial atmospheric correction of the data (Los 1998). The GIMMS data from April 1982 to December 1984 and from June 1991 to December 1993 are corrected to remove the effects of stratospheric aerosols from El Chichon and Mt. Pinatubo eruptions applying the method of Vermote and El Saleous (1994). No explicit atmospheric correction except for stratospheric aerosols is applied to this GIMMS NDVI dataset (Zhou et al. 2001). However, the 15-days maximum value NDVI composition minimizes residual atmospheric and bidirectional effects.

5.2.2 Ground Data

In this study phenological data on birch (*Betula* spp.) collected at four stations are used (see Table 5.1). Due to the lack of phenological stations in southern parts of Scandinavia, the dataset is supplemented by pollen data from birch in this area. Birch has a strong correlation between budburst and appearance of first pollen. However, the Scandinavian countries have different methods for defining the onset of the pollen season. In Sweden

(Stockholm) the first of five continuous days with pollen are used as the onset criteria. In Denmark (Copenhagen) the start of the pollen season is defined when the accumulated level reaches 2.5% of the seasonal level. In Norway (Tromsø, Trondheim, and Oslo) the criteria is equal to Denmark, but the accumulation level is defined at 5%. In this study we use the first day of recorded pollen as a start of the onset period in Norway. However, this date could be influenced by long-distance pollen transport, and in Tromsø in 1984 and 1995 the second day of recorded pollen is used due to obvious long-distance pollen transport at the first recorded pollen. In addition to the biological data, air temperature and snow cover data from Karesuando in northern Sweden and Karlstad in southern Sweden are used as reference data in this study. The time of a 21 days moving average mean temperature 0^oC and 5^oC crossing at spring and autumn, and snow melt at spring is compared with the NDVI value.

5.2.3 Growing Season Analysis

A common method is to define e.g. the start of the growing-season as the point in time when the NDVI value exceeds a certain threshold (Zhou et al. 2001). This method works well in areas with a rich and homogenous vegetation cover. However, in areas, like the cost of Norway where each pixel most likely will represent a mixture of water, farmland, forest, and alpine vegetation, this method does not work. We have therefore used a method to set the threshold individually for each pixel. Approaches where the thresholds are estimated individually for each pixel, a geographic cell, or land cover types can be found in Reed et al. (1994), Chen et al. (2001), and Tucker et al. (2001). This is an objective method that works well over Fennoscandia.

For each pixel an 18 years mean NDVI value (NDVI > 0) for the period from 1982 to 1999 was computed. The timing for the 15 days composite NDVI value upward and downward passing of this mean value was used as a threshold for determining the start and end of the growing season at each pixel for each year. This threshold value was found to best correlate with ground data. The procedure ensures sensitivity for changes in timing during the 18 years period, independent of the actual ground cover present at each pixel. A standard linear regression model was applied to the timing data. The difference of the start and the end of the model was used as an estimate of changes in timing of the growing season. Correlation analysis was carried out between NDVI based events and in-situ observed dates for metrics such as “leaf onset” and start of pollen season.

5.3 Results

5.3.1 Onset of Growing Season

Table 5.1 shows the relationship between the timing of spring measured from the NDVI images and the ground based data. Difference is the mean difference in number of days from the ground based and the NDVI based onset/end of growing season, meaning that negative values indicate that the ground measurements were before the NDVI based date. The 0 °C and 5 °C are crossing upward (spring) and downward (autumn), and is based on 21 days moving average. Positions of the stations are shown in Fig. 5.2.

For the onset of spring, data from the four phenological stations and the five pollen stations show a correlation with the NDVI based measurements in the range of r=0.58 to r=0.86, with a mean correlation of r=0.68. The correlations were significant (< 0.05) or highly significant (< 0.01) (Table 5.1) for the two of the phenological stations and all the pollen stations. While the timing of onset of leafing of birch is tuned to have almost exactly the same date as onset of spring measured from NDVI, the onset of birch pollen season is about 10 days earlier (Fig 5.1a).

Table 5.1. Correlation between onset of growing season measured from NDVI and as defined from birch-pollen, phenology on birch, or climatic data. *Correlation significant (< 0.05), **correlation highly significant (< 0.01). Trend measured in (day year-1) and difference measured in (days).

Station	Type of data	Period	r	Trend	Diff. ground– sat.
Svanhovd	Onset of leafing	1994-99	0.63	1.9	-1
Abisko	Onset of leafing	1982-99	0.58*	0.7	1
Kevo	Onset of leafing	1982-99	0.86**	0.1	0
Kilpisjärvi	Onset of leafing	1989-99	0.60	1.0	1
Tromsø	Pollen	1984-99	0.72**	0.9	-14
Trondheim	Pollen	1982-99	0.59*	-0.4	-15
Oslo	Pollen	1984-99	0.85**	-0.6	-10
Stockholm	Pollen	1982-99	0.61**	-0.5	-10
Copenhagen	Pollen	1982-99	0.64**	-0.7	-12
Karesuando	Last day snow	1982-98	0.39	0.2	-4
Karesuando	0°C	1982-98	0.48	0.2	-29
Karesuando	5°C	1982-98	0.36	0.3	-2
Karlstad	Last day snow	1982-97	-0.19	-0.8	-54
Karlstad	5°C	1982-98	0.24	-0.1	-40

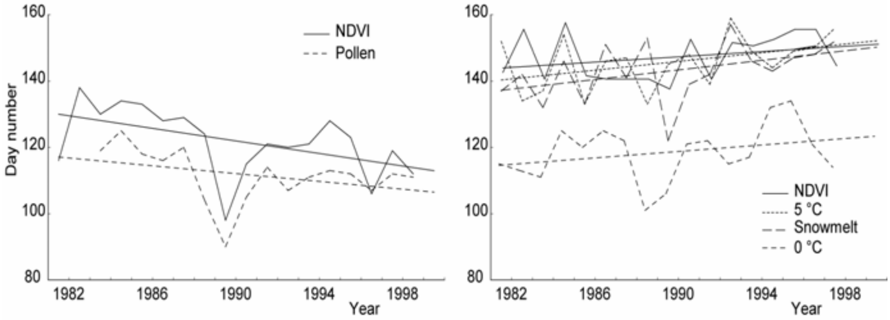

Fig. 5.1ab. a) Data from Oslo. Date of first recorded birch pollen and onset of spring measured from NDVI. b) Data from Karesuando in northern Sweden. Onset of spring measured from temperature data and from NDVI. Temperature data are 21 days smoothed average.

According to climatic data at spring, in Karesuando (Fig. 5.1b) the NDVI values show good fit with the temperature passing 5 °C and staying above (2 days mean difference). However, in southern Sweden (Karlstad), the mean difference is 40 days.

In Fig. 5.2 the changes in time of onset of spring are illustrated. In general, the results show a pattern according to the north-south, the oceanic-continental, and the altitude gradient. In the southern part of Fennoscandia the spring starts considerably earlier. The most significant change is within southern Sweden, with changes up to one month. In the most oceanic parts of Fennoscandia, the coastline of western Norway, the spring starts 2-3 weeks earlier. A slightly delay trend is observed in the alpine and in the northern continental parts.

In general the ground data support the trends in onset of spring as measured from NDVI. All the data from the southern ground stations in this study have a trend of earlier onset of spring, and all the corresponding NDVI values have a similar trend. On the other hand, ground data from the northern parts show a delayed trend. Using linear regression, the onset of birch pollen season in Tromsø in northern Norway, show a delay trend on 0.9 day year^{-1}, and the corresponding NDVI values show a delay trend of 0.8 day year^{-1}. In the year 1990 in Tromsø the onset of birch-pollen season was fourteen days later than the normal for the period 1984 to 1999.

When we relate the different trends in north and south to changes in climate, the climatic station in southern Sweden has a trend of considerably earlier disappearing of the snow cover. In 1998 there was no snow cover at all. During the period 1982 to 1998 annual mean temperature has increased 1.8 °C, March mean temperature has increased 1.8 °C

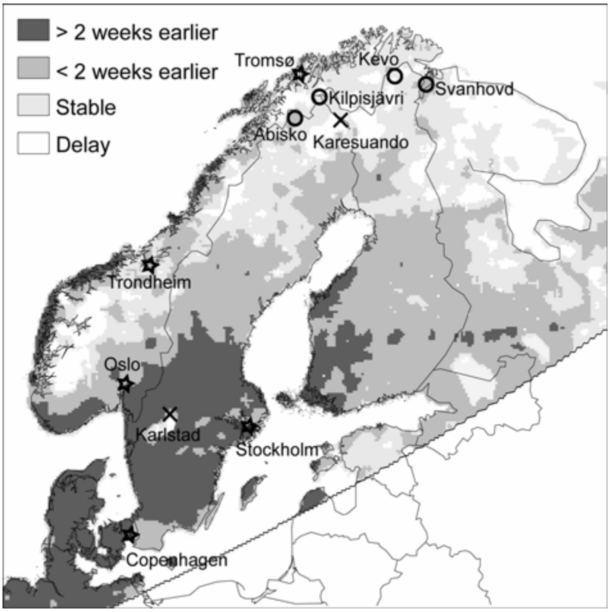

Fig. 5.2. Change in onset of spring during the period 1982 to 1999. Position of the pollen stations (star), phenological observation points (circle), and climatic stations (cross) used in this study.

(from -0.6 to 1.2 °C), and April mean temperature has increased 0.9 °C (from 3.7 to 4.6 °C).

Concerning the climatic station in Karesuando in northern Sweden, this station has a trend towards warmer yearly average, but colder springs. We estimate that during the period 1982 to 1998 annual mean temperature has increased with 1.5 °C. April mean temperature has decreased with 1.4 °C (from –2.5 to –3.9 °C) and May mean temperature has decreased with 2.4 °C (from 4.9 to 2.5 °C).

5.3.2 End of Growing Season

As in-situ data from autumn, data from two phenological stations and one climatic station were used, all located in the northern part of Fennoscandia (Fig. 5.2 and Table 5.2). The six-year series of data on more than 50 % yellowing of birch leaves from Svanhovd in north-easternmost Norway show a correlation on 0.50 with the NDVI based measurements. However, a 12 years series from Kilpisjärvi, in northernmost Finland, of similar ground data show low correlation with NDVI values. Concerning climatic

Table 5.2. Correlation between end of growing season measured from NDVI and as defined from phenology on birch. *Correlation significant (< 0.05), **correlation higly significant (< 0.01). Trend measured in (day year^{-1}) and difference measured in (days).

Station	Type of data	Period	r	Trend	Diff. ground– sat.
Svanhovd	Yellowing >50 %	1994-99	0.50	-2.9	-11
Kilpisjärvi	Yellowing >50 %	1988-99	0.15	-0.2	3
Karesuando	5°C	1982-98	0.60	0.1	-32
Karesuando	0°C	1982-98	-0.03	0.1	-8

data, there is a correlation of 0.60 between passing 5 °C at autumn and NDVI values. However, the climatic event happens more than a month before in mean.

The map of changes in onset of autumn (Fig. 5.3) indicates that the autumn is delayed 1-3 weeks in the whole area. There is no clear pattern, but in the continental parts in the north, in the border area between Norway, Sweden, and Finland, the situation is stable. This area partly overlaps with the area that has a delay trend in onset of spring (Fig. 5.2).

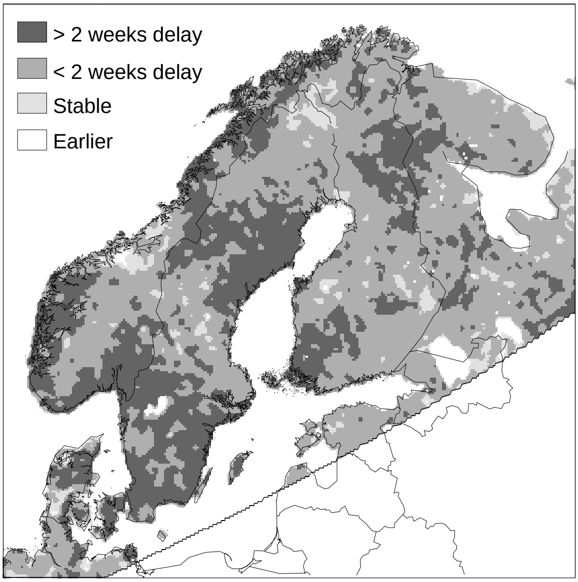

Fig. 5.3. Change in onset of autumn during the period 1982 to 1999.

5.4 Discussion

Due to the high relationship between NDVI and photosynthesis activity, and the method with a threshold value for each individual pixel, it is likely we measure real variations in nature. At spring, the correlation between phenological data on birch (bud burst and pollen) and NDVI values (interpreted as start of growing) are high and significant. Birch *(Betula pubescens)* is common in most of Fennoscandia and dominating in large parts of the oceanic north (Hulten 1971, Påhlsson 1998). In areas where birch is frequent but do not dominate, it is reasonable that the NDVI based measurements shows the timing of the phenophases of the photosynthetic dominating species that correspond with the timing of the nearby onset of leafing of birch. However, in mountain areas and farming land, where birch not even occurs, a calibration of the NDVI images with surface observations remains to be investigated.

In this study, less attention was given the autumn phenophases, and the correlations with the few observation points are weak and not significant. A botanical description of the changes on the ground in relation to the measured NDVI values at autumn remain to be investigated. For autumn, and for spring in areas where birch not occur, the nearest biological description of the phenological events is a threshold passing of the mean photosynthesis activity from all the plants in a 8x8 km^2 large area, upward passing in spring and downward in autumn.

There are several possible error sources in the measurements. Extended changes in forestry management, in the grazing pressure by reindeer and sheep, in long-transported air pollution (e.g. nitrogen in precipitation), in agricultural practice, or other activities that causes large changes in land cover, would affect the results. Due to an ending of subsidies in 1994 extended reduction in cleaning of birch and willows on the clear cut areas has occurred in Sweden (Anonymous 2003). This may affect the proportion of deciduous forest and the thereby the NDVI value and the timing of the growing season. Denmark and large parts of southwestern Sweden are totally dominated by agriculture. Extended changes in crop type, for instance from spring wheat to autumn wheat, with earlier green up in spring would be misinterpret as measurements of earlier spring. Possible influence of changing land cover remains to be investigated. However, due to the large pixel size of 8x8 km^2, and since in most cases the agricultural areas shows the same trend as the nearby natural vegetation not heavily influenced by human impact, we believe the main pattern is due to real changes in onset of spring and autumn. This is even believed to be the case in southernmost Fennoscandia much more influenced of human impact than in the north.

The NDVI based spring trend observed in southern Sweden is statistically significant on the 5% level. More than two weeks earlier onset of spring occurs in Denmark, southern Sweden, southernmost Norway, and south-westernmost Finland. These areas belong to the Nemoral and Boreonemoral zone, and are characterized by broad-leaved deciduous woodland that requires warm summers (Moen 1999). The oceanic coast of west and central Norway also have considerably earlier onset of spring. Climatically the oceanic area is characterized by having few frosty days, high frequency of precipitation, and long growing season (Moen 1999). In both these areas, warmer winters and warmer spring often leads to precipitation as rain, and the snow cover is disappearing either totally or earlier in the spring. The climatic station in Karlstad is situated in the middle of southern Fennoscandia with indications of one-month earlier onset of spring. The climate station has an increase of mean May and April temperature and significant earlier disappearing of the snow cover consistent with an earlier spring/end of winter. The pattern of earlier onset of spring in southern parts during the last decades fits with phenological studies in western and central Europe, and has been linked to increased early spring temperature (Chmielewski and Rötzer 2002, Menzel and Fabian 1999, Ahas et al. 2002, Menzel 2002).

In the continental part of northern Fennoscandia and mountains areas in southern Norway, the spring is stable or there are indications of a slightly delayed trend (Fig. 5.2). However, the delay trend in Fig. 5.2 is not statistically significant. On the other hand the phenological observation data (bud burst and pollen) showed a significant correlation with the NDVI-based phenological metrics. Climatically the continental north is characterized by short growing season and very cold winters with mean January temperature of less than -15 °C (Moen 1999, Tuhkanen 1980, Tveito et al. 2000). In such areas increased precipitation at winter will lead to thicker snow cover, and could result in delay in snow melt, even if the temperature increase. The delayed onset of spring in Karesuando in northernmost Sweden is correlated with colder April and May and delayed temperature passing of 0 ºC and 5 ºC and more snow in May. The few studies in the north within the stable/slightly delayed areas somewhat support our results. During the period 1930 to 1998, at one phenological station on Kola Peninsula, Kozlov and Berlina (2002) show a slightly delayed trend in snow melt, and a stable situation for onset of leafing on birch. The leaf unrolling showed highest correlation with temperature sum from March to May ($r=0.52$, $p< 0.001$). In Kevo in northern Finland (Fig. 5.2), Emberline et al. (2002) have shown distinct trends towards later onset of birch pollen seasons during 1982-1999, and in the same period the March temperature has increased and May temperature decreased. However, the delayed trend in the continental north could be a result of a more complicated pattern of changes in both temperature and precipitation, and the full explanation remains unknown.

For autumn, there is much less information available. The phenological gardens throughout Europe indicate that the beginning of autumn is gradually delayed (Menzel and Fabian 1999, Menzel 2000). Our results indicate a delay in most areas. Kozlov and Berlina (2002) found indications of earlier onset of autumn phases, however, they investigated the last 70 years, and in this study we only investigate 18 years. On the other hand they used the metric “beginning of leaf fall in mountain birch”, which is not a good phenological metric to detect using earth observation. The “beginning of leaf fall” metric is very dependent of the wind regime and a little local gale can wipe out the leaves on the observation site leaving the surrounding areas untouched. By using GIMMS data with a spatial resolution of 8x8 km^2, it is very difficult to detect such local events. We applied the metric, “yellowing of leaves more than 50 %”, which fit better with NDVI measurements done at Svanhovd, although we will consider other metrics or a combination of several metrics to detect and monitor the autumn in the future. Experimentation with several different threshold values applied on each individual pixel for the autumn season is also necessary to perform in order to obtain a better fit between earth observations and ground data.

5.5 Conclusion

This study has shown large regional differences in the changes of the length of the growing season, during the period 1982-1999 in Fennoscandia. It clearly indicates that the impact on length of growing season of global warming will be different depending on the regional climate. Whether the measured changes in spring and autumn events are caused by climate change or are of a temporal and stochastic nature remains to be seen. This study also demonstrates that NOAA AVHRR data, with a method using a different threshold value applied on each individual pixel, are well suited for studying the regional impact of a changing climate even in heterogeneous and sparsely vegetated areas.

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6 Northern climates and woody plant distribution

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6.1 Introduction

Northern regions have always engendered enquiry in relation to how far temperate plants can migrate north or arctic plants migrate south before they reach some climatic limitation either from a failure to grow or from an inability to reproduce. Consequently, any attempt to predict the consequences of current climatic change for northern plant species has to give particular attention to marginal regions and consider the biological causes for the failure of plants to survive outside any given area. Limits to plant distribution in the Arctic invite investigation as they represent the ultimate peripheral locations for high-latitude survival. Biologically, plants are ideally suited for the study of peripheral situations as their sedentary nature facilitates mapping. Many atlases record limits to plant distribution both past and present at high latitudes (Hultén and Fries 1986b; Huntley and Birks 1983; Löve and Löve 1975; Meusel and Jäger 1992). These circumpolar plant distribution maps are unique, for in no other area of the World is it possible to examine across adjacent continents both the north-south and east-west extensions of species ranges. The ease with which temperature records can now be collated and compared with past and present plant distribution maps can create an impression that cartographic representation combined with mathematical modeling is all that is needed to relate climatic limits with plant distribution. Unfortunately, as pointed by the pioneering Norwegian eco-physiologist Eilif Dahl "the many indices that have been used for correlation between the northern and alpine limits of plants and meteorological factors are rarely based on any eco-physiological foundation" (Dahl 1998). As he expressed the problem "the question is in which way does temperature affect plant performance?"

Despite the attractive convenience of the concept of a generalised temperature limit for plant growth it is important to take note of the fact that mean temperatures do not exist in nature and therefore should be considered only as indicators and not causal factors (Holtmeier 2003). Maps which make some accommodation for seasonality and the differences between oceanic and continental climates can begin to answer some of the problems raised by Dahl in relation to matching climatic data with plant performance.

6.2 Interpreting distribution maps

Presenting data in the form of maps is intellectually satisfying. Maps create a global perception of distribution that permits comparisons to be made readily with physical factors such as climate and soils. Unfortunately, this simplicity of representation may be misleading in relating cause to effect as the factors which control distribution along any particular temperature boundary may differ from one region to another. The southern limit of the Tundra is generally determined by the northern limits of the boreal forest. However, the northern limit of the boreal forest may be controlled by differing ecological circumstances in diverse regions (Callaghan et al. 2002). Temperature, as it affects the length of the growing season, can be related to the position of the boreal treeline over large land-masses in regions with marked continental climates. However, over extensive regions of western Siberia the northern limit of the boreal forest is displaced southwards by the development of vast bogs. It follows therefore that although the boreal treeline (the tundra-taiga interface) is a global phenomenon that can be mapped and even observed by remote sensing (Fig. 6.1a-b), the reasons for its position from one area to another may differ (Crawford et al. 2003). Consequently, if the factors controlling distribution are not understood then information that may be derived from maps is open to misinterpretation.

Given these uncertainties about the physiological impact of temperature change it is relevant to examine in closer detail the natural distribution of plants in relation to seasonal variations in temperature. Predicting plant migration in terms of temperature change demands correlative observations from a range of variables. Iversen’s classical studies pioneered the matching of plant distribution to summer and winter isotherms (Iversen 1944). In such studies the choice of isotherm is often arbitrary and the coincidence of a species boundary and an isotherm is not necessarily causal

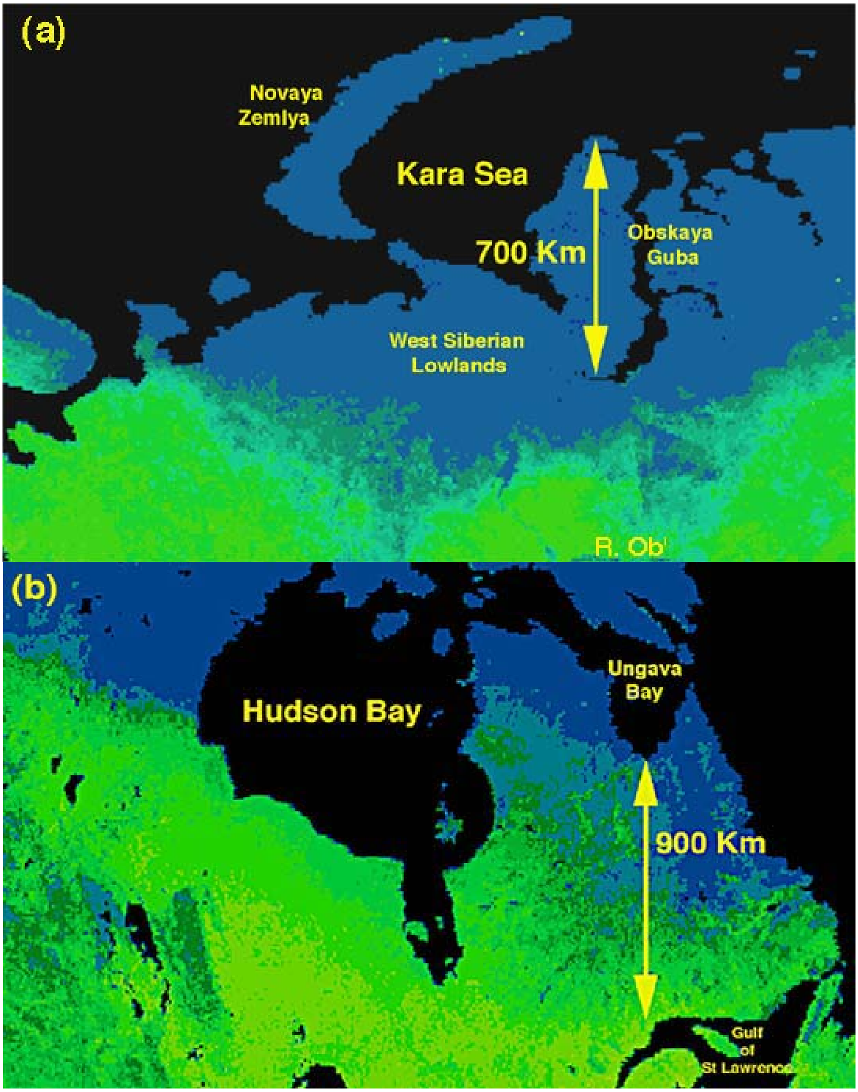


Fig. 6.1. Transition zone between Forest and Tundra as seen at the northern limits of (a) Western Siberian Lowlands and (b) the eastern section of the North American Boreal Forest boundary in normalised vegetation index (NDVI) images recorded in May 1999. Colour scale; blue = 0 as the Tundra is still covered by snow and ice. Other colours from green towards yellow represent increasing positive values in the NDVI index denoting the presence of photosynthetically active woody evergreen species emerging above the snow cover (images by courtesy of Goddard Space Flight Center).

Fig. 6.2. Photograph taken at the southernmost occurrence of lichen–spruce (*Picea mariana*) forest in Québec at 47˚N (photo R.M.M. Crawford).

(Crawford 1989; Hengeveld 1990) and may over-estimate the geographical area occupied by species (Jeffree and Jeffree, 1994, 1996). There are many situations where a demographic or probability approach provides a better assessment of plant distribution, as can be seen below in the positions of the northern boreal treeline which cannot always be delineated by a simple line on a map.

Satellite NDVI images can be used with care to detect various vegetation zones including the boreal treeline (Rees et al., 2002). The problems of distinguishing between vegetation zones in relation to the evergreen treeline is greatly simplified when images are collected before the tundra ice and snow have melted as the woody evergreen species emerging above the snow cover stand out against the photosynthetically inert tundra surface. Images taken in the month of May in western Siberia reveal in many areas a marked transition zones between continuous tree cover and total absence of emergent evergreen vegetation.

Examination of Figs. 6.1a-b shows that in some regions the treeline is not a distinct boundary but a mosaic. This condition is found particularly in areas where bog formation occurs as in the West Siberian Lowlands where the transition extends North-South for approximately 600 km from the South-eastern shore of Obskaya Guba to the east-west flowing section of the River Ob'. This mosaic is considered by Russian ecologists to be a self-renewing cyclic process taking place over hundreds of years. Cryoperturbation causes the soil surface in localised areas to rise above the general level of the bog (Chernov and Matveyeva 1997). In some areas this permits the active layer to dry out sufficiently to allow the re-establishment of trees for a period until they shade the ground and cause the permafrost to rise and favour once again the growth of mosses as opposed to trees (Crawford et al. 2003). In Northern Quebec, a similar situation occurs under different circumstances. Here, the impact of combined insect and fire disturbances translates into a dramatic decrease in post-fire tree regeneration of the forest inducing the shift to lichen woodland (Payette et al. 2000). The result is a transition zone which begins at 47°N (Fig. 6.2) and extends over several hundred kilometers in a north–south direction (Fig. 6.1b).

6.3 Mapping species occurrence probability in relation to temperature

In terms of relating temperature conditions to the presence or absence of particular species it would appear more realistic to use a method that related probability of occurrence to geographical distribution rather than any supposed absolute temperate limit. Attention therefore has to be given to the nature of isotherms and what they represent. In essence, winter (x) and summer (y) isotherms are equivalent to straight lines in x, y cartesian space. Therefore, sets of 4 isotherms (upper and lower, x and y temperature limits) map out rectangles of temperature space. Species however, occupy scatters which have the form of inclined ellipses. Consequently, the fit of an isotherm to an ellipse is good only locally, and any isotherm-box overestimates species distributions in environmental space by adding unoccupied corners (Jeffree and Jeffree 1994).

A more objective manner of comparing species distribution to the interaction of winter and summer temperatures has been described and examined for a number of European species (Jeffree and Jeffree 1994, 1996), in which climatic temperature preferences of species are described in terms of the temperatures of the coldest (t_X) and warmest (t_Y) months of the year recorded at locations within a species' geographical distribution. Plotted on Cartesian co-ordinates for t_X and t_Y, the temperature data for locations occupied by a species form a bell-shaped probability density distribution described about the bivariate mean t_X bar, t_Y bar. Elliptical contours on this surface, representing defined limits on the continuously diminishing scale of probability at which a species may occur with increasing distance from the bivariate mean, may be calculated using the equations given by Jeffree & Jeffree (1994) for any desired level of probability. Consequently, ellipses calculated from temperatures within species distributions may be used to define and map those parts of the world's surface in which temperatures are potentially suitable for the species at a specified level of probability. Thus, a temperature ellipsoid calculated for a species distribution under current climatic conditions may be used as a template for identifying those geographical areas which may fall within the temperature range suitable for the species in any scenario of past or future climate change (Jeffree and Jeffree 1996). The use of ellipsoids derived from t_x and t_y for a number of woody species (Figs 6.3-6) allows a probability approach to relating temperature to the presence or absence of species. This approach enables the preparation of maps which not only show the probability of occurrence of the species in relation to temperature, but also where the species are absent even although the temperature regime is suitable for their occurrence. Such areas of non-occurrence may indicate that the absence of the species may be due to some factor other than temperature and deserve careful study, especially if they are contiguous with the main area of distribution.

Two types of map can be produced. The first, which are referred to as the *normal* (**N maps**), record the areas actually occupied by the species and compare this with the potential distribution as represented by the calculated ellipse. Logically, any location on Earth could be either inside or outside the species distribution and the temperatures associated with that location could be either inside or outside the calculated species temperature ellipse. Consequently, any one site can have one of four possible states;

1. Inside the ellipse with the species present (IESP - shown in maps as green) - here the species distribution agrees with the prediction based on the calculated ellipse.
2. Inside ellipse with the species absent (IESA – shown in maps as blue) - indicating an unoccupied potential environmental space for the species in question.
3. Outside the ellipse with the species present, (OESP – shown in maps as red) indicating that the temperature conditions may be marginal for the species.
4. Outside the ellipse with the species absent - indicating an unoccupied space probably with unsuitable temperatures for survival (OESA - shown in maps as grey).

In the second type of map, probability or (**P maps),** the colours represent bands of increasing probability that specified winter and summer temperature combinations are suitable for the species with the most favourable zones being shown in red, and the least favorable as purple and grey.

6.4 Woody shrub case histories

The following case studies are based on distribution maps specifically prepared for Northern Europe (Hultén and Fries 1986). The data representing the baseline temperature regime are taken from the University of East Anglia 0.5°gridded monthly temperature data for the years 1961 to 1990 (New et al. 1999; New et al. 2000). Hypothetical changes of +/- 1C° or +/- 4C° are imposed on each species as separate and opposing changes to both summer and winter temperatures in order to model the potential impact of mean annual temperature changes of + or – 2,5C° with contrasting seasonality on the species distributions. An important aspect of these maps is that they also represent areas where the thermal regime is suitable for the species in question but where the species is nevertheless absent.

6.4.1 Possible migration anomalies and case histories

From the results of these models it can be deduced that the following phenomena occur in relation to the effects of temperature on species distribution.

1. Species migration is sensitive to existing temperature *seasonality* and the superimposed *seasonality* of temperature change.
2. Migration cannot be predicted from annual mean temperature alone.
3. For the same patterns of change, in different parts of their ranges, species could migrate in *opposite* directions.
4. Seasonality gradients may present barriers to migration notwithstanding overall warming, particularly near coastal or continental margins.

(a) *Cassiope hypnoides* The Dwarf Arctic Heath (*Cassiope hypnoides*) is a species of transatlantic distribution which under the present climatic regime extends from Eastern Canada northwards to 75°N in Labrador. It is widespread latitudinaly in Greenland to 75°N on the west coast and 80°N on the east coast. The species also occurs in central and northern Iceland and the more northern montane regions of Scandinavia, the Kola Peninsula, and N. Siberia extending to the Southern part of Novaya Zemlya. The most northerly currently known location is on the West Coast of Svalbard

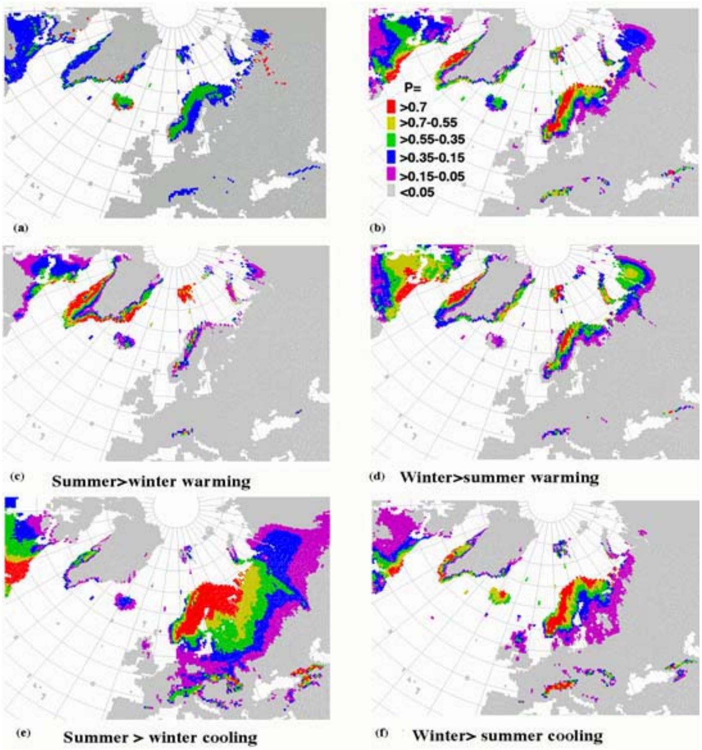


Fig. 6.3. Probability density plots of the possible ranges of *Cassiope hypnoides* in relation to temperature. **(a)** Distribution based on the temperature data from the CRU 1961-1990 Global Climate Dataset (New et al., 1999, 2000) relative to an ellipse enclosing 75 per cent of the observations. Green sites are within this “optimum” ellipse with the species present (IESP). Red sites (OESP) are outside the ellipse, but with the species present. These red sites can be regarded as current locations in which the species is at the low-probability margins of its temperature range. The blue sites (IESA) are inside the ellipse but where the species is currently absent and may be seen as representing potentially-suitable locations, where temperatures in summer and winter are suitable for the species. In plots **(b-f)** the colours represent bands of increasing probability of the (x), winter and (y) summer temperatures being suitable for the species. Red is most suitable (see inserted scale); **(b) P map** zones of increasing probability for winter and summer temperatures being suitable for the species at 1961-1990 temperatures; (**c)** 1961-1990 temperatures + 4C° in summer and + 1C° I winter; (**d**) 1961-1990 temperatures + 1C° in summer and + 4C° in winter; **(e)** 1961-1990 temperature - 4C° in summer and - 1C° in winter; **(f)** 1961-1990 temperature - 1C° in summer and –4 C° in winter.

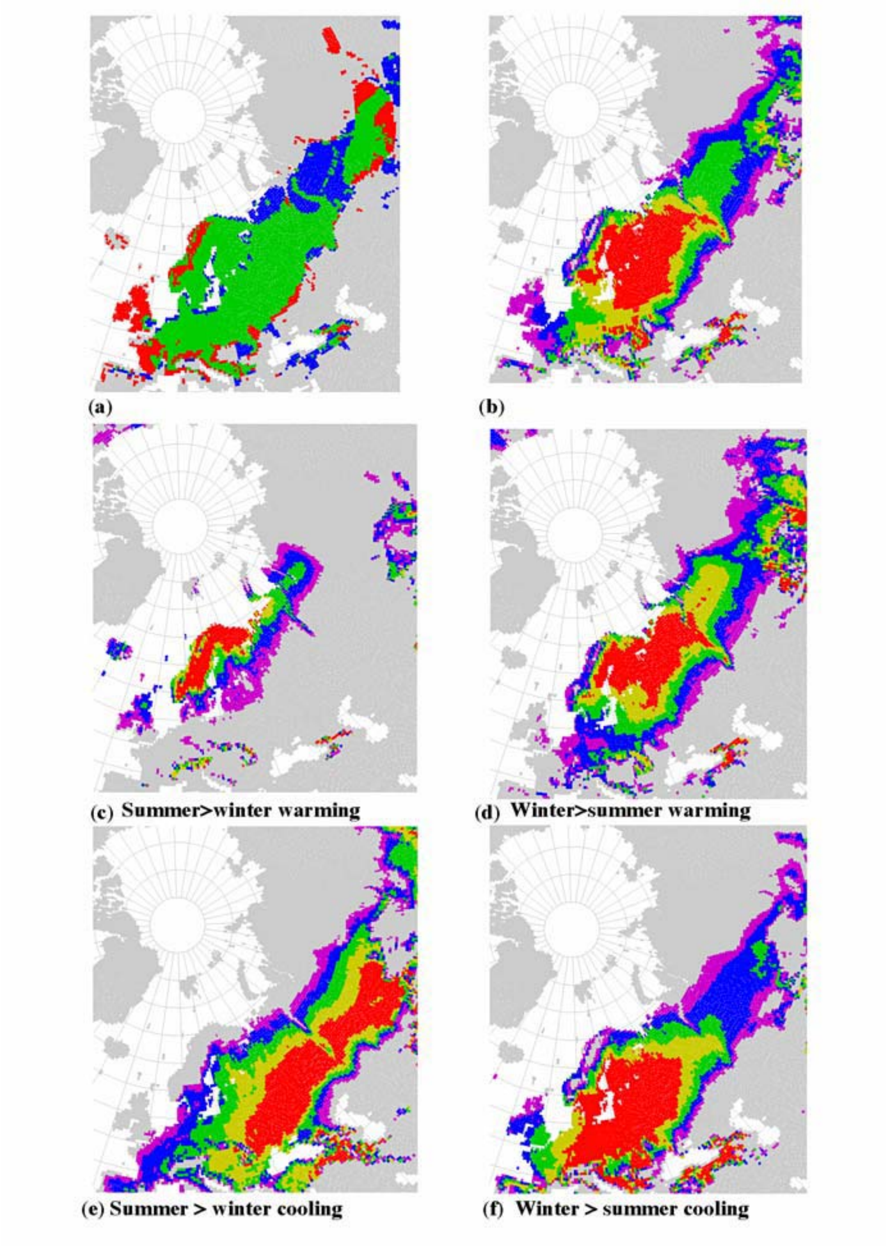


Fig. 6.4. Probability density plots of the possible ranges of *Vaccinium myrtillus* in relation to temperature. See legend Fig. 6.3 for details of images (a-f).

at 79˚N in Kongsfjord (Rønning 1996). The present temperature conditions appear suitable for a wider extension in the region to the East of the Hudson Bay and in Western Greenland. When examined as a probability of occurrence (**P maps**) it is possible to compare the effects of winter versus summer warming or cooling on its distribution. Increased summer warming would result in an increased presence in Greenland, Svalbard and Novaya Zemlya, but would reduce the occurrence of the species in Scandinavia and Northern Siberia. The converse conditions with warmer winters would appear to favour an expansion westwards in N. America and eastwards in Siberia. Winter cooling would be likely to favour a southern extension of the species in Europe and a retreat in Eastern Siberia.

(b*) Vaccinium myrtillus* The bilberry (*Vaccinium myrtillus*) is a plant of northern Europe but with a much wider distribution southwards and eastwards than *Cassiope hypnoides*. The probability map for its present distribution based on temperature classifies its western extension in the British Isles Western France and Northern Spain as marginal. Summer warming would appear to lead to a major decline in this species while winter warming would result in a western retreat and an eastward expansion. However, climatic cooling, if it took place largely through a reduction in summer temperatures, would have a different effect and would be likely to increase the presence of the species in western Europe. Colder summer temperatures, would cause a retreat from the northernmost habitats and an expansion southwards and eastwards. Winter cooling would be likely to favour a southern extension of the species in Europe and a retreat in Eastern Siberia.

(**c**) *Calluna vulgaris* Heather (*Calluna vulgaris*) under present conditions is more oceanic in its distribution than *V. myrtillus* even although the temperature–based probability distribution suggests that its presence in Scotland is marginal. It has been proposed that optimal conditions for heather establishment exist in those regions bordering the North Sea from the eastern side of the British Isles through North Germany to Denmark (Gimmingham, 1972). It has also been found that heather suffers a decline in seed-setting ability with increasing oceanicity and altitude (Miller, 2001). Further west, increasing oceanicity and winter-saturated soil saturation favours *Erica tetralix* rather than *Calluna vulgaris*. Here it should be recognized that the current prevalence of heather in Scotland and Ireland has been accentuated by the late Holocene deforestation that has taken place in these regions (Fossitt 1996). Summer warmth appears from these predictions to be a limiting factor as summer warming would expand the range while winter warming would cause a further retreat from the west an and advance eastwards. As might therefore be expected, summer cooling by 4 C° below the present temperature levels would cause a south-western migration which would not take place if it were the winter temperatures that had been reduced.

(d) *Salix polaris* The polar willow (*Salix polaris*) is at present mainly restricted to the Arctic. These maps suggest that summer warming would probably lead to a retreat from its present Scandinavian occurrences, which agrees with a physiological study of this species carried out in Spitsbergen (Muraoka, et al., 2002), where a large increase in respiration with rising temperatures during the growing season is predicted as likely to cause a marked decrease in net primary productivity. However, in contrast to the other species examined in the maps presented here i.e., *Vaccinium myrtillus, Calluna vulgaris* and *Pinus sylvestris* (see below), it is probable that winter-warming, would result in a less marked retreat from oceanic areas in the distribution of *S. polaris* than that which is predicted for these other species.

6.5 Ecological limitations for the survival of woody plants

The most thoroughly examined aspects of the ecology of woody plants in relation to temperature are the altitudinal and latitudinal limits for the survival of trees. Many studies have sought to determine whether or not the low temperature regimes of high latitudes and altitudes cause trees to come into a carbon balance deficit. Intuitively, this would appear a simple and logical explanation. It might be expected that woody plants which devote a considerable part of their resources into the formation of non-productive trunks and stems may be unable to support such a growth strategy when growing seasons are cool and short. However, an extensive world-wide study of the carbon balance in trees at their upper altitudinal boundaries has shown the converse, namely, that tree growth near the timberline is not limited by carbon supply and that is more probable that it is sink activity and its direct control by the environment that restricts biomass production of trees under current ambient carbon dioxide concentrations (Körner 2003). Although carbon limitation is not a feature of woody plants at their upper limits of distribution it is nevertheless possible that certain organs can be seriously carbon-deficient under specific conditions. Over-wintering tree roots in oceanic climates, if not fully dormant when flooded can through anaerobic respiration rapidly deplete their carbohydrate supplies and thus become vulnerable to post-anoxic injury when aeration is

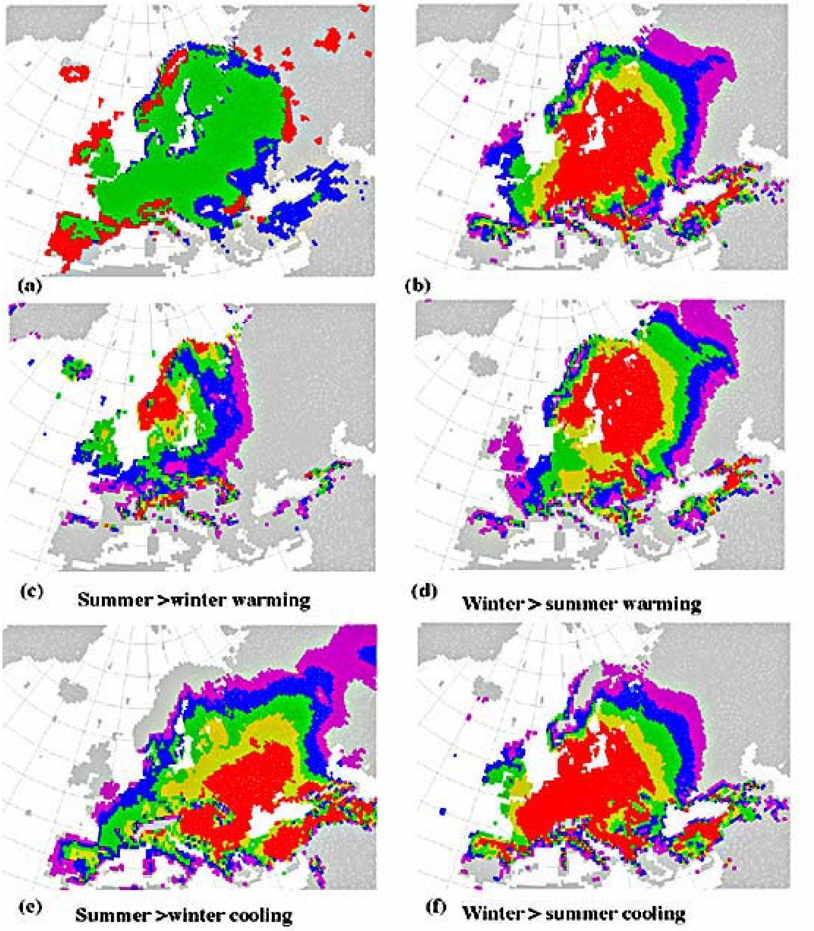
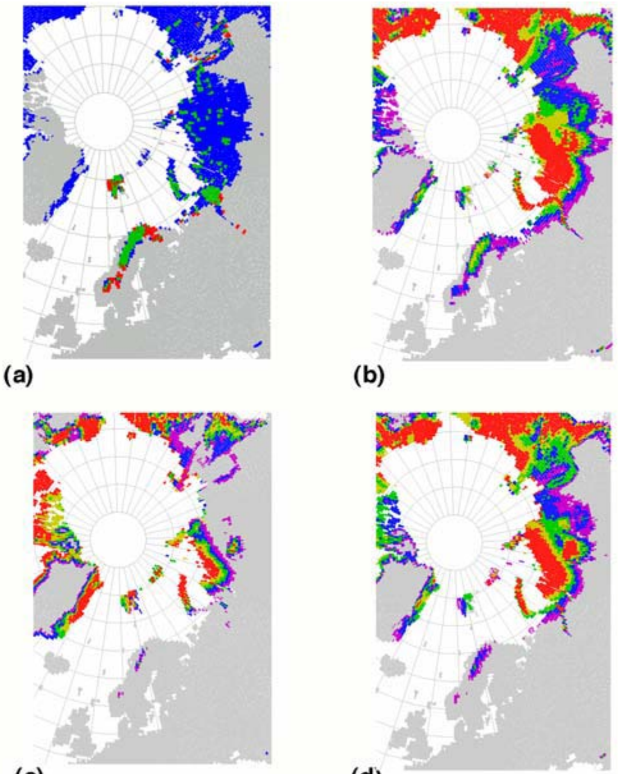


Fig. 6.5. Probability density plots of the possible ranges of *Calluna vulgaris* in relation to temperature. See legend Fig. 6.3 for details of images (a-f).

restored in spring (Crawford et al. 2003). Similarly, intermittent mild winter periods can deplete carbohydrate levels and render over-wintering shoots sensitive to frost injury (see below).

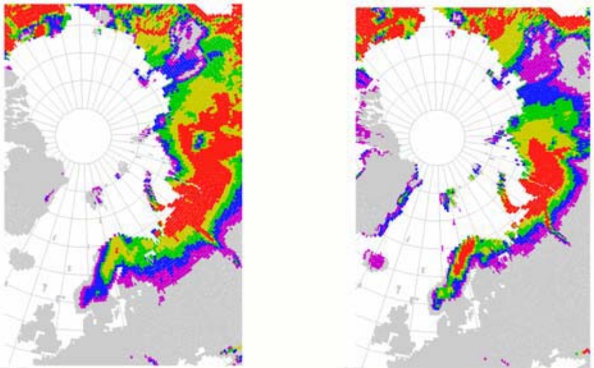
Oceanic conditions have long been known to reduce both the altitudinal and latitudinal position of the treeline (Fig. 6.1a-b). It would appear (see above) that this is also the case for a number of shrubby woody species. The blanket bogs of Scotland and Ireland stand out among the habitats that are significantly correlated with regions of high oceanicity. The basis on which this community is distinguished from less oceanic associations is



(a) (b)

(c) Summer > winter warming

(d) Winter > summer warming



(e) Summer > winter cooling

(f) Winter > summer cooling

Fig. 6.6. Probability density plots of the possible ranges of *Salix polaris* in relation to temperature. See legend Fig. 6.3 for details of images (a-f).

determined in the British National Vegetation Classification not so much by the plants that are in this community, but more in negative terms by the species that are absent. In particular it is marked by the absence of woody shrub species such as *Vaccinium vitis-idaea, V. uliginosum* and *Empetrum nigrum* ssp. *hermaphroditum,* although there is a high frequency of *Myrica gale*. In these blanket bogs, although bryophytes flourish, oceanicity exerts a predominantly negative influence on many higher plants in that it gives rise to communities that are species poor, particularly in woody species, with the ericoid species being represented mainly by the flood-tolerant *Erica tetralix* with a relative paucity of *Calluna vulgaris*. This latter case agrees with the increasingly marginal position that is predicted for *Vaccinium myrtillus* and *C. vulgaris* should winters become warmer (Fig. 6.4-5).

6.6 Physiological disadvantages of warm winters

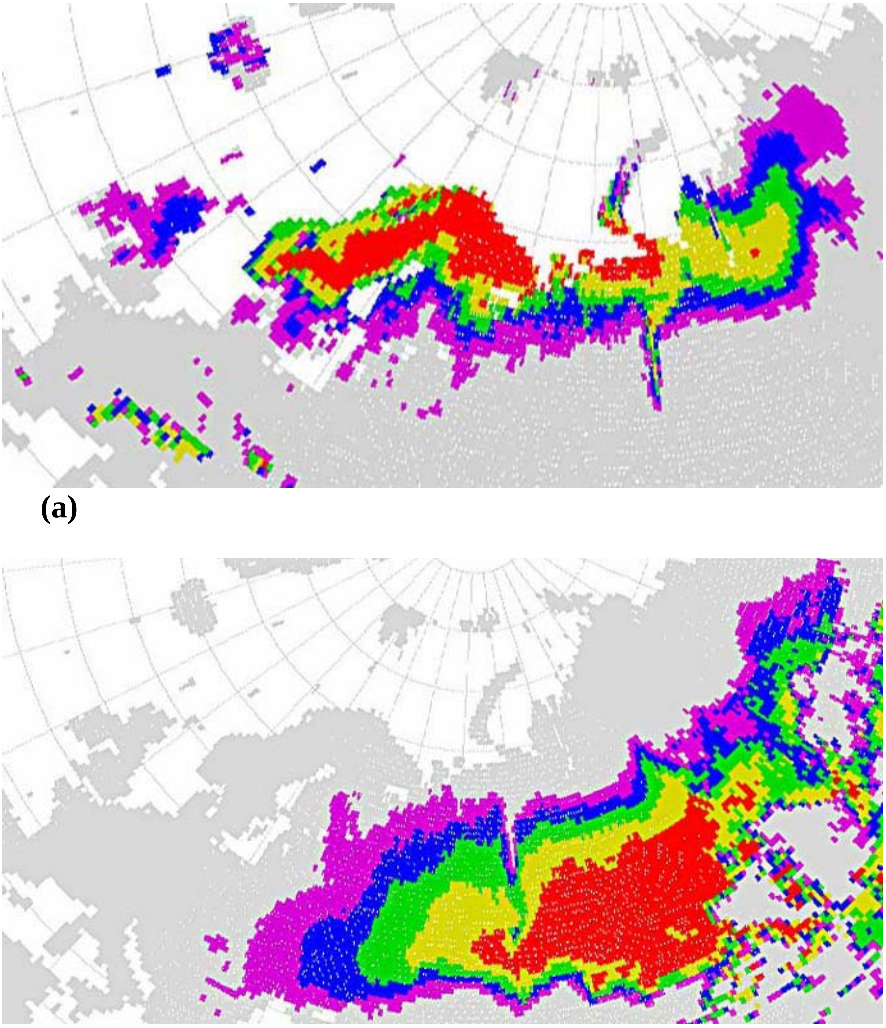
Some physiological explanation is required to explain why milder oceanic conditions should be disadvantageous for woody species. The Norwegian plant ecologist Eilif Dahl was one of the first to distinguish between the positive and negative effects of oceanic conditions on mountains. The relatively species-poor mountain floras of the Scottish Highlands and south-west Norway, were considered by Dahl to be due to mild periods of winter weather that encouraged premature spring growth causing severe die-back of non-hardy shoots. He described Norwegian montane species such as the woody *Rhododendron lapponicum* and the herbaceous *Aconitum septentrionale* that are absent from more oceanic mountains as “south-west coast avoiders” (Dahl 1951; Dahl 1990).

Vaccinium myrtillus has been observed in north-eastern Sweden to show a significant loss in frost hardiness leading to lethal injuries after a warmer than usual winter (Ögren 1996). This loss of frost tolerance was accompanied by a decrease in the solute content of the shoots, suggesting a progressive respiratory loss of cryoprotective sugars. Gas exchange measurements estimated that the initial carbohydrate reserves would have lasted for only four months if tissue water content remained high. When thin snow cover was coupled with clear skies then shoot dehydration could improve cold tolerance by 5-10 C°. However, in mild winters, with recurrent periods of mist and rain, increased metabolic activity resulted in shoot damage that was twice as frequent as a result of long-term de-hardening. It has also been demonstrated in Finland that a small elevation in air temperature can accelerate de-hardening in *V. myrtillus* (Taulavuori, et al., 1997).

Depending on habitat type the impact of oceanicity on woody species is likely to vary. On the sides of Norwegian fjords and Scottish sea-lochs, the steep inclination of the terrain encourages the survival of trees. However, in level areas there is frequently a tendency for bog formation to replace forest. In many northern maritime regions, with large areas of level ground, bog may be the climax vegetation and not forest (Klinger 1996). Once bog vegetation becomes established forest regeneration becomes problematic. Palynological studies show that the paludification of north-west Europe has a long history. A marked climatic deterioration (Klitgaard-Kristensen et al. 1998), commonly termed 'the 8200 BP event' (probably due to freshwater fluxes in the final de-glaciation of the Laurentide ice sheet), appears to have been accompanied by a temporary reduction in tree cover throughout western Europe, which in the oceanic conditions of Scotland set in train the development of blanket peat. In the Outer Hebrides blanket peat began its appearance between 9000 and 8000 BP, most probably as a consequence of this climatic episode, before there was any significant human settlement (Fossitt 1996).

It may seem counter intuitive, but there is even an argument for suggesting that in oceanic areas climatic warming may lead to a retreat rather than an advance of the treeline. Examination of temperature variations over the past century for Europe and the Arctic from Northern Norway to Siberia suggests that variations in the North Atlantic Oscillation are associated with an increase in oceanicity in certain maritime regions. A southward depression of the treeline in favour of wet heaths, bogs and wetland tundra communities is also observed in several northern oceanic environments. The heightened values currently detected in the North Atlantic Oscillation Index, together with rising winter temperatures, and increased rainfall in many areas in Northern Europe, present an increasing risk of paludification with adverse consequences for forest regeneration, particularly in areas with oceanic climates. Climatic warming in oceanic areas may increase the area covered by bogs and thus, contrary to general expectations, may lead to a retreat rather than an advance in the northern limit of the boreal forest (Crawford et al. 2003).

It is also to be expected at high latitudes, as woody plants approach their most northerly limits, that the distinction between oceanic and continental climates will become more critical for plant survival. A detailed dendroclimatological study of Scots Pine (*Pinus sylvestris*) in northern Norway (69°N) has shown that high winter temperatures represent a stress factor at the limit of pine in oceanic habitats. Consequently, a period around 1920, with low winter temperatures, co-coincided with a marked rise in growth (Kirchhefer, 2001). As with the studies on *Vaccinium myrtillus* discussed above (Ögren, 1996) mild periods in winter, causing bud dormancy to



(a)

(b)

Fig. 6.7. Comparison of possible contrasting changes in distribution of *Pinus sylvestris* with varying climate conditions as compared with 1961-1990. **(a)** Winter 4C° colder, summer 4C°warmer; **(b)** winter 4C° warmer, summer 4C° colder. Note the retreat from western Europe with the imposition of warmer winters.

break and increasing subsequent frost damage may be implicated, as may also heavy needle loss after mild winters (Kirchhefer, 1999). Fig. 6.7(a-b) shows the contrasting effects that might be produced on the distribution of *Pinus sylvestris* should there be significant climatic warming. In the event of warm winters prevailing there could be a marked retreat of Scots pine from western Europe.

There may be many reasons as to why oceanic conditions are detrimental for the survival of Scots Pine and other woody species. Among these is the effect of mild winters combined with wet soil conditions. Warm weather in autumn and early winter delays the onset of dormancy in tree roots which if followed by soil saturation or flooding can induce anaerobic conditions which result in a rapid winter consumption of winter carbohydrate reserves Crawford, 2003).

Studies which seek to match species range against changing environmental conditions may be geographically illuminating, but are nevertheless only a first step in understanding ecological limitations. Just as there are many causes of damage to plants, so there are many variations in local populations which have evolved to withstand particular local situations. Further mapping studies are needed at the sub-species level to determine if intra-specific differences exist between populations in their responses to oceanic and continental climates.

6.7 Conclusions

Climatic warming in northern latitudes will undoubtedly create new ecological opportunities for vegetation advance as ice sheets retreat and permanent snow cover is reduced. Depending on proximity to the oceans, and this includes the Arctic Ocean, the degree of winter versus summer warming is likely to differ. In northern regions the influence of oceanicity on plant distribution is very marked. The models described in this paper show that among some of the commonest woody species winter warming may in some cases cause a significant retreat in areas that where the climate is influenced by the ocean, while in other areas the species may make significant advances. Due to seasonal differentiation in responses to temperature the nature of the migration of species into these vacated areas or changing communities is unlikely to be a mere latitudinal shift northwards of existing species assemblages. It appears therefore highly probable that species migration will be strongly influenced by *seasonality* of temperature change, and for any one species similar patterns of climatic change in different parts of its range, could result in migration in *opposite* directions. Consequently, changing thermal conditions will be likely to alter species composition of existing northern plant communities. Attention will therefore have to be given to the roles of seasonality gradients as potential barriers to migration notwithstanding overall warming.

Acknowledgements

Figures 6.1a and b were generated from the 8-km resolution Pathfinder data set. The authors thank Dr. W.G. Rees for assistance in the use of satellite images and the Distributed Active Archive Centre (Code 902.2) at the Goddard Space Flight Center, Greenbelt, MD. 20771, for producing and distributing the data in their present form. We are also greatly indebted to Professor Christian Körner for careful and helpful reading of earlier versions of this chapter.

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7 Topographic complexity and terrestrial biotic response to high-latitude climate change: Variance is as important as the mean

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7.1 Introduction

Climate changes that occur as a result of the increased greenhouse effect are expected to be greatest at high latitudes (Cattle and Crossley 1995; Watson et al. 2001), and resultant earth-system responses are likely to be dramatic (Weller 1998). For example, even the small increase in temperature witnessed over the past few decades has melted permafrost in many places, causing major changes in soil drainage, chemistry, and biology, as well as damage to roads, buildings, airports, and pipelines (Williams 1995; Weller 1998; Osterkamp and Romanovsky 1999). The expectation of dramatic environmental change has stimulated numerous empirical and model-based studies addressing both ecosystem responses to predicted changes in temperature and CO_2 concentration and how these responses feed back to the climate system (e.g. Sellers et al 1997; Kane and Reeburgh 1998; Arft et al. 1999; Chapin et al. 2000; Eugster et al. 2000; Rupp et al. 2001; Levis et al. 1999, 2000; Friedlingstein et al 2003; Ichii et al. 2003; Jones et al. 2003; Kaplan et al. 2003; McGuire et al. 2002, 2003).

Nearly all studies of environmental change are based on modelling and scaling-up activities that use mean values or properties as input. Yet it is well known that the values of climatic parameters vary locally due to topographic influences (e.g. Hungerford et al. 1989; Young et al. 1997). Elevation has well documented effects on temperature and precipitation. Microclimate is also influenced by the radiation load, which varies in response to variation in aspect of slopes (“aspect”) and steepness of slopes (“slope”). Hence, rough (mountainous or hilly) landscapes generate a mosaic of diverse microclimates, with direct effects on organism physiology and ecology and biotic community structure and function (Knapp 1985; Young et al. 1997, Porter et al. 2002). Implicit in this variation is variation in ecosystem processes. For example, an increase in temperature will probably lead to a release of CO_2 from many high-latitude soils, at least transiently, generating a positive feedback and further warming (Chapin et al. 2000; Jones et al. 2003; Knorr et al. 2005). However, carbon sources and sinks are finely balanced, and the sign of the projected change may be sensitive to scaling-up procedures (Chapin et al. 2000).

While analysis of means is practical and necessary in current modelling, ignoring variation about the mean may leave out complexity of potentially great ecological importance. Most studies of biotic response to climate depend on the mean environmental parameters because these are the only data that are widely available. However, all terrestrial biotic response to climate change is mediated by the local microclimate actually experienced by the organism. Some of the ecological complexity that exists on the landscape due to small-scale variation in topographic setting has been studied using dense arrays of micro-loggers; results indicate the potential importance of local microclimate variation for both modelling and empirical studies of terrestrial biotic responses to environmental change (Edwards and Armbruster 1989; Wesser and Armbruster 1991; Lloyd et al 1995; Rae 2003). Large-scale patterns in elevation-generated microclimate variation are determined by the location of mountain ranges. In contrast, patterns in the amount of variation induced by aspect and slope appear to have a latitudinal trend. For reasons explained below, aspect/slope-induced variation in microclimate appears to peak near the Arctic and Antarctic Circles. Thus, the sensitivities of vegetation and ecological processes to small-scale climate variation may be especially great in the Arctic and Antarctic.

7.2 Variation and climate models

Models that simulate global- and continental-scale patterns of interactions between climate, vegetation, and biogeochemical processes, e.g. VEMAP (Vegetation/Ecosystem Modeling and Analysis Project; Pan et al. 1998) and LPJC (Lund-Potsdam-Jena dynamic global vegetation model; Sitch et al. 2003), have focused on large-scale patterns and processes. The significance of small-scale heterogeneity to such large-scale modelling efforts lies in the need to scale down to, and up from, landscape-level processes when estimating the potential feedbacks inherent in the climate system

(Bonan et al. 1995). Error may result from non-additive and non-linear responses to variation, which may generate values that depart significantly from response to mean values ("aggregation error").

It is well known that microclimates vary significantly at high latitudes, because the angle of the sun is low during the growing season, and north- and south-facing slopes experience very different radiation loads. Theoretical micro- and regional-scale climate models can help assess potential microclimate variation (e.g. MTCLIM; Hungerford et al. 1989) and its effects on the distribution of species, communities, and ecosystem processes, but the sensitivity of microclimate to cloudiness and wind (e.g., Porter et al. 2002) argues for direct estimation and testing with empirical observations. There is surprisingly little detailed empirical information on the nature of microclimatic variation and its effects, perhaps because, until recently, it has been prohibitively expensive to install dense grids of weather stations (or other climatic instruments) on rough landscapes.

7.3 Biotic response to microclimatic variation

Organisms generally respond to the local climate and not regional means. This has many direct implications for the ecology and population biology of most organisms, especially those that are sedentary or disperse locally (see Porter et al. 2002). For example, the extinction of a plant species may be predicted from models of mean temperature change, whereas in reality the species may persist locally in favourable microsites, such as on cool, moist, north-facing slopes in scenarios of climate warming (e.g. Coker and Coker 1973; Sydes 1997), or on warm south-facing slopes in scenarios of climate cooling (another kind of aggregation error).

The biological importance of micro- and regional-scale climatic heterogeneity is implicit in the current shift in paleoecological thinking about the post-glacial re-colonization of landscapes adjacent to retreating ice-sheets. There is increasing recognition that many local refugia probably existed and played important roles in the recolonisation of post-glacial landscapes, rather than recolonisation occurring through waves of long-distance migration from lower latitudes (Stewart and Lister 2001, Schauffler & Jacobson 2002, Clark et al. 2003, Brubaker et al. 2005). With respect to biotic response to ongoing climate change, it is therefore important to focus on the local reorganisation of communities in addition to major latitudinal shifts in distribution (Rupp et al. 2001).

The possible scale of biotic response to past and ongoing climate change (by genes, populations, or species) has received insufficient attention (but see Davis and Shaw 2001). Increases and decreases in local abundances of species with different climatic tolerances are likely, with the extreme case being local extinction and replacement of species. This may come about through processes of long-distance migration or may result from the reshuffling of co-occurring (parapatric) species with diverse climatic tolerances, as a result of, in part, the local heterogeneity in microclimate (e.g. Brockway 1998; Goldblatt and Manning 2002; but also see Chapin et al. 1995; Chapin and Shaver 1996). In addition, a change in climate may induce a plastic response by genetic individuals (within genotypes; Crawford and Abbott 1994, Bret-Harte et al. 2001, Edwards et al. 2005), or there may be changes in the relative frequencies of genotypes and alleles as a result of natural selection and/or gene flow (i.e. evolution; Davis and Shaw 2001).

In this context it becomes important to know the degree to which microclimate varies on the local landscape and the degree to which organisms respond to this variation. Research challenges include assessing i) whether local spatial variation in microclimate is large or small relative to the kinds of regional temperature changes expected from the anthropogenically enhanced greenhouse effect over the next century, ii) how local variation compares with larger-scale temperature variation with altitude and latitude, iii) the extent of associated shifts in species composition of communities, if any. With respect to this last question, little species-composition change associated with significant microclimate variation suggests that plasticity and/or local evolution (ecotypic differentiation) are the biotic responses to climate changes of this scale. Alternatively, strong changes in species composition in response to microclimate variation suggest that replacement of some species by others will occur with climate change of this scale. Thus, additional work on biotic response to spatial variation in microclimate would have value for understanding biotic response to temporal climate change.

7.4 Latitudinal Trends in Variation in Radiation Load

Well established theory and empirical data show that radiation loads striking the earth’s surface vary with latitude and season (Strahler and Strahler 1989). Furthermore, incident radiation varies with the slope angle of the surface, with a surface perpendicular to the incident radiation receiving the greatest load. Combining these two analytical results into a simple spreadsheet model (see Weiss et al. 1993) allows us to explore latitudinal patterns of variation in radiation environments experienced by rough landscapes.

For heuristic purposes, consider the difference in radiation loads between north- and south-facing surfaces at 35° inclination. On the summer solstice at 30° and ~90° latitude (N. Hemisphere), south-facing surfaces receive about the same radiation as north-facing surfaces, but between 30° and ~90° they receive up to 50% more radiation. On 1 September, south-facing surfaces at ~90° latitude receive the same radiation load as north-facing surfaces. Between 30° and 80° they receive 60-400% more radiation.

Integrating this over the high-latitude growing season results in minimal differences between south- and north-facing surfaces at 30° and 90° but about a doubling of radiation sums on south-facing surfaces relative to north-facing in the subarctic and low Arctic (60° -70°). Thus the contrast between radiation budgets on south- versus north-facing slopes reaches its theoretical maximum near the Arctic Circle, remains high throughout the subarctic and low-Arctic regions and declines sharply in the low temperate and extreme high-Arctic latitudes (Fig. 7.1).

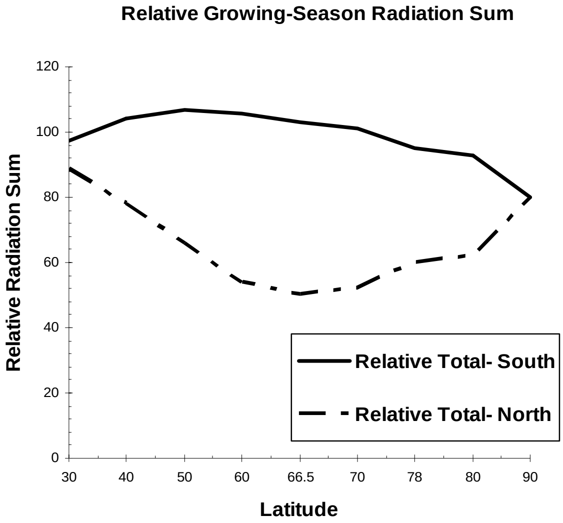

Fig. 7.1. Growing-season radiation sums on north-facing and south-facing surfaces (at 35° inclination) across a range of latitudes. Atmospheric transmissivity was assumed to be 83%.

7.5 Measuring Microclimate and Biotic Response to Variation in Slope and Aspect

The above arguments demonstrate the importance of obtaining better information on small- to medium-scale variation in climate, and the potential effects of this variation on the distribution of species, communities, and ecosystem processes in Arctic and Antarctic regions.

7.5.1 Effect of Topography on Seasonal Radiation Sums and Microclimate

Very few empirical studies of local variation in microclimate have been conducted, so we review here one conducted recently in Svalbard. The approach is to place in the field three thermal microloggers at each of a series of plots of different slope and/or aspect. The three microloggers are in: 1) silver film canisters, shielded from sun (measuring air temperature,

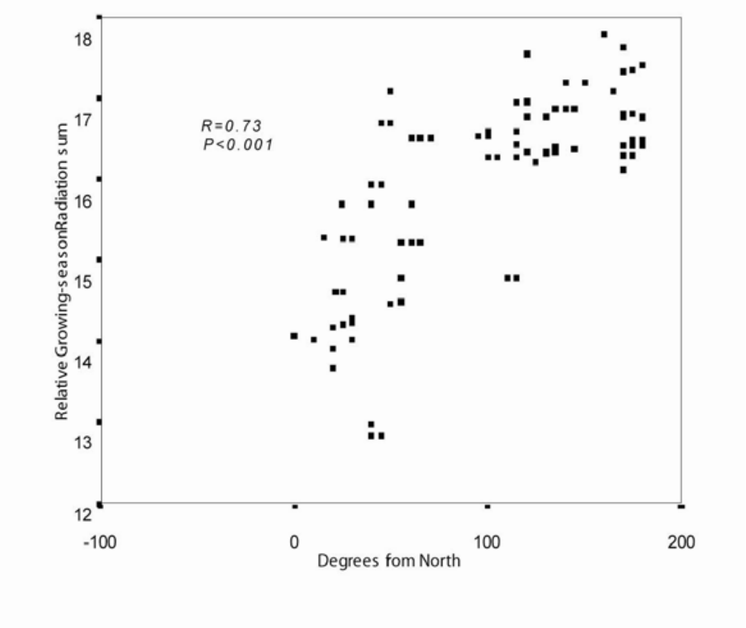

Fig. 7.2. Relative growing-season radiation sums measured on plots located on slopes across a range of aspects, from south facing (180°) to north facing (0°). Plots were located in Adventdalen, Spitsbergen and measurements made July-August 2000. Aspect explained 53% of the variance in radiation sum (P < 0.001).

T_a); 2) black film canisters, shielded from wind, but not the sun (= radiation load); and 3) black film canisters, exposed to sun and wind (operative environmental temperature, T_e; Bakken 1992; Bishop and Armbruster 1999).

Using these three measures of thermal parameters it is possible to estimate directly, or by calculation: air temperature (T_a), operative environmental temperature (T_e), radiation load, and wind speed (Moe 2000; Rae 2002; Armbruster et al. submitted). To check the accuracy of these estimates, we compared estimated values of radiation load and wind speed with directly measured values of radiation and wind at a subset of plots. We found reasonably close correspondence in both cases ($R = 0.97$, $P < 0.001$; $R = 0.64$, $P < 0.001$; respectively). Three thermal microloggers, as described above, were placed in each of 45 plots an area of complex micro-relief in Todalen, a side valley of Adventdalen, near Longyearbyen, Spitsbergen, Svalbard (78° N) in July-August 1999 and 2000.

The seasonal radiation sums at 45 micro-sites on Spitsbergen were estimated from the data recorded by the three loggers at each sites using the formula derived in Rae (2003). These radiation values were strongly influenced by the aspect of the slopes on which the loggers were placed (Fig. 7.2). South-facing slopes experienced about 50% higher radiation loads than

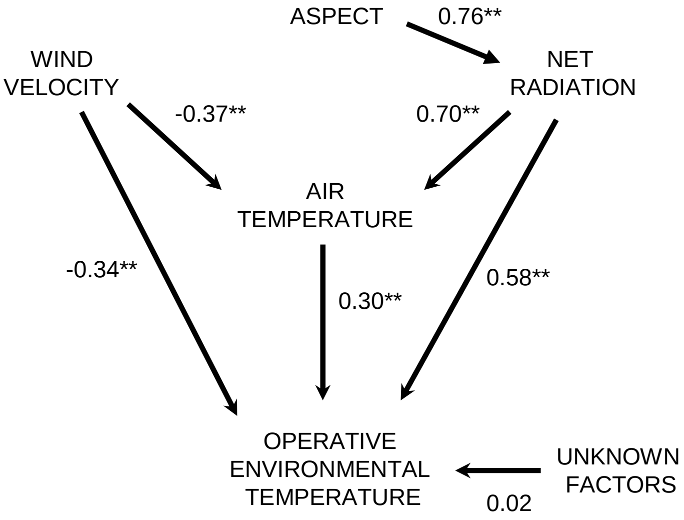

Fig. 7.3. Estimated influences of various measured or calculated microclimate variables on operative environmental temperature, Adventdalen, Spitsbergen, July 2001.

north-facing slopes during the study period. South-facing slopes also experienced up to 5.0° C higher maximum air temperatures and 1.0° C higher mean air temperatures than north-facing slopes during the study period. The overall thermal environment experienced by small surface-dwelling organisms ("operative environmental temperature") on south-facing slopes was up to 6.6° C higher (maximum T_e), and the mean was up to 2.6° C higher, than on north-facing slopes. This approach also allows one to estimate the relative contributions of variation in radiation load, wind, and air temperature to the variation in operative environmental temperature across plots. While aspect had a major influence on radiation load, radiation load positively affected thermal environment, both directly and indirectly via air temperature. Wind had a significant negative effect on operative environmental temperature (Fig. 7.3). A surprising 96% of the variance in operative environmental temperature was explained by the estimated wind speed, radiation load, and air temperature (Moe, 2000; Rae 2003).

7.5.2 Effects of Topography and Microclimate on Composition of the Biotic Communities and Soil Environment

We estimated the percent cover of each vascular plant species in each plot and sampled ground-dwelling insects with a small pitfall trap (150 ml plastic cup) in each plot. We then ordinated the plant (see Table 7.1) and invertebrate community-composition data using detrended correspondence

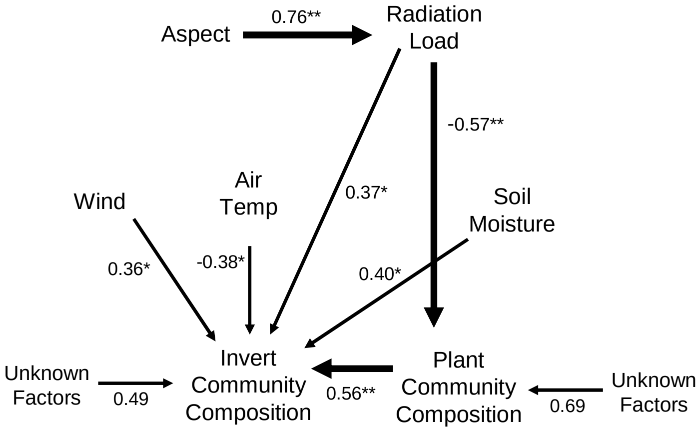

Fig. 7.4. Estimated influences of topography on microclimate, and microclimate on the composition of biotic communities, Adventdalen, Spitsbergen.

Table 7.1. Species and species scores on first axis of the detrended correspondence analysis (DCA) run on the plants recorded in each plot at the study site in Todalen, Adventdalen, Spitsbergen.

Species	DCA Score	Species	DCA Score
Ranunculus nivalis	432	Cerastium arcticum	169
Sphagnum spp.	413	Equisetum scirpoides	138
Trisetum spicatum	402	Salix polaris	126
Minuartia biflora	386	Poa arctica	118
Ranunculus pygmaeus	381	Alopecurus borealis	102
Arnica angustifolia	380	Luzula confusa	94
Equisetum arvense	379	Rhacomitrium spp.	77
Dicranum spp.	369	Papaver dahlianum	62
Oxyria digyna	331	Stellaria crassipes	61
Betula nana	311	Crustose lichens	60
Selene uralensis	305	Draba subcapitata	52
Saxifraga cernua	297	Draba micropetala	44
Festuca cryophila	293	Pedicularis hirsuta	27
Selene acaulis	283	Saxifraga cespitosa	25
Cardamine bellidifolia	245	Cassiope tetragona	-2
Saxifraga hieracifolia	224	Carex rupestris	-2
Polytrichum spp.	218	Saxifraga nivalis	-12
Taraxacum arcticum	204	Hierochloe alpina	-12
Polygonum viviparum	170	Dryas octopetala	-14
Potentilla rubricaulis	177	Saxifraga oppositifolia	-27

analysis (DCA), implemented on the PC-Ord 4.0 package (McCune and Mefford 1999) to reduce dimensionality and create a linear variable (Table 7.1). We related variation in community composition among plots to variation in measured or calculated microclimate variables using path analysis (Li 1975; Shipley 2000).

Microclimate and, indirectly, topography had profound effects on the composition of the plant community and to a lesser extent, the invertebrate community. Radiation load appeared to have the biggest "direct" influence on the composition of the plant community, while all measured environmental variables appeared to influence the invertebrate community directly and almost equally (Fig. 7.4). (Note that "direct" in this context must be qualified by the caveat that radiation and other effects could influence the communities indirectly via environmental variables not included in the model, e.g., soil temperature, snow accumulation and persistence, etc.) Aspect, slope, and microclimate also induced variation in soil temperature, (not shown in the figure). Although other soil-environment factors were not measured in this study, similar studies in Alaska showed that radiation loads and environmental temperatures also influence soil moisture, soil pH, soil-nutrient availability, and soil carbon storage (Wesser and Armbruster 1991; Lloyd et al. 1994).

7.5.3 Complex Indirect Effects of Microclimate

In addition to the direct (or apparently direct) effects of microclimate on the structure of the invertebrate community, indirect effects of microclimate were mediated via changes in the plant community (Fig. 7.4). At low-arctic and subarctic latitudes, grazing animals such as sheep (both wild and domestic) utilize south-facing slopes more intensively, because 1) they are snow-free for more of the year, 2) they offer more and/or better forage, and/or 3) the microclimate is more favourable and vertebrates experience reduced thermoregulatory costs (Pearson et al. 1995; Mysterud et al. 2001; Porter et al. 2002). Herbivore behaviour, in turn, can have major effects on the amount of disturbed and open ground, the species composition of the plant community, and hence —by extension— factors such as soil temperature, nutrient availability, and carbon storage in the soil. For example, at an alpine site near the Arctic Circle in Norway (Loftan), microclimate appeared to influence the grazing intensity of sheep, and hence the former indirectly affected plant community composition (Svengård Barre 2000).

7.6 Scaling Micro-scale Patterns up to “Real Space” Landscape Models of Ecosystem Response to Climate Change

Incorporating microclimatic variation, and the community and ecosystem variation it generates, into large-scale models requires scaling up from the micro-landscape to the regional landscape. One approach involves the use of high-resolution digital elevation models (DEM’s). Modelling on the scale of real landscapes allows investigation of the consequences of making aggregation assumptions. Landscape-based outcomes can be compared to grid-cell means over a modest area to see just how much the two deviate for a variety of functions and conditions. In this way it is possible to assess the risk involved in running standard large-scale models, whether they are species-distribution models or ecosystem-function models.

Such an exercise was attempted by Wesser et al. (1994) for a small region (Kathul Mountain; 65^o 21’ N, 142^o 17’ W) in Yukon-Charley National Preserve, in subarctic Alaska. They explored the potential effects of increases and decreases in regional temperature on the response of vegetation on the actual mountainous landscape. The goal was to simulate the effects of past colder conditions (-2^o C) and future climate warming (+2^o C) on the distribution of plants on the slopes of Kathul Mountain. There were clear and dramatic rearrangements of communities on the landscape, with major increases and decreases in the abundance of extreme community types (Fig. 7.5). Notably, a decrease by 2^o C caused warm steppe (red) to almost disappear from the landscape, and an increase by 2^o C caused it to dominate the south-facing slopes of Kathul Mountain.

It thus seems probable that the climatic and biotic variation as documented by this and similar studies is indicative of similar magnitudes of variation in ecosystem properties and processes. Ecosystem responses to climate variation are likely non-linear, in which case ecological complexity generated by topography could pose difficulties in scaling from topographically complex local landscapes up to coarse grid-scale means. The latitudinal variation in patterns of radiation across diverse topographic settings suggests that such aggregation problems may be especially large at high latitudes. It is here that the modelling of ecosystem response to climate change may be the most vulnerable to aggregation errors, and further assessment of the potential magnitude and consequences of such errors is desirable.

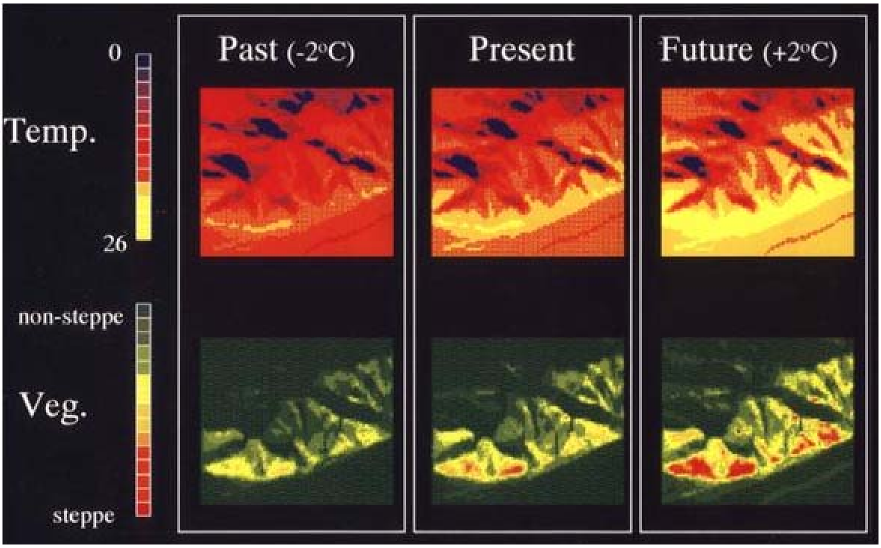

Fig. 7.5. Model outputs under scenarios of climate cooling (e.g. past climates) and warming (e.g. future climate). Codes for vegetation reconstruction: red = steppe, green = forest (low elevation) or tundra (high elevation). Figure modified from Wesser et al. 1994, with permission of S. D. Wesser.

7.7 Topographically induced variation in UV stress

Ongoing thinning of the ozone layer is causing significant increases in ultraviolet (UV) radiation in Polar regions, and this and projected changes may pose serious threats to terrestrial as well as aquatic/marine life (see chapters by Blumthaler; Vincent; Hanelt et al.; Hessen; and Nybakken; this volume). The variation in UV radiation loads on the terrestrial landscape and its consequences have received less attention than in the marine environment. UV radiation loads are distributed on rough landscapes in fundamentally the same way as are other radiation wavelengths. This suggests similar excesses in UV radiation load on south-facing slopes, potentially leading to significantly higher UV stress at these sites. Correspondingly, north-facing slopes could act as refugia from UV-stress, even with ozone thinning.

There is likely to be a genotype-environment correlation, however, in that organisms already living on south-facing slopes may have adaptations allowing them to cope with higher radiation loads (see Feder and Hofmann 1999). Thus, they may be pre-adapted to dealing with higher UV loads associated with ozone thinning (e.g. more phenolics, anthocyanins, or heatshock proteins in leaves), perhaps in combination with migrating off the most stressful sites. This line of investigation deserves considerably more attention from researchers using UV-specific instrumentation, as well as those studying the genetics of UV tolerance.

7.8 Conclusions

Rough landscapes experience a mosaic of radiation budgets and microclimates, even when that roughness occurs at a small spatial scale. In our study area, growing-season means of environmental temperatures on slopes of different aspect separated by only a few tens of meters differed by up to 2.6 °C; this is near the middle of the range of projected temperature increases for CO_2-enhanced warming over the next 100 years (Watson et al. 2001). Microclimatic variation of this magnitude affects local community composition of both plants and animals. For plants in the study area, nearly 100% species replacement occurs between north-facing and south-facing slopes (Moe 2000). This suggests that the main biological response to future climate change may occur by species replacement through shifts in local distribution, rather than by phenotypic plasticity or ecotypic differentiation within taxa. Observations of dramatic variation in species composition in response to microclimatic variation suggest that landscapes have significant capacity to respond to large changes in temperature by local rearrangement of species already present. This is likely to occur more rapidly than long-distance migration of extra-limital species.

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8 The flow of Atlantic water to the Nordic Seas and Arctic Ocean

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8.1 Introduction

The Nordic Seas, encompassing the Greenland, Iceland, Norwegian and Barents Seas, act as a buffer zone between the warm and saline waters of the North Atlantic Ocean, and the cold and fresh waters of the Arctic Ocean. The region, with its area of $4.1\text{x}10^6$ km^2 and a water volume of $4.5\text{x}10^6$ km^3, covers 1% and 0.3% of the World Ocean area and volume respectively (Jakobsson, 2002). Despite these modest numbers, the Nordic Seas with their complex topography, water mass distribution and flow regimes, is recognized as a key area for the conversion from light surface water to dense deep waters, having climatic impacts over large parts of the globe.

The most important factor for the Nordic Seas marine climate is the amount of warm and saline Atlantic Water (AW) entering over the Greenland-Scotland Ridge, and flowing north in the eastern part of the Norwegian Sea eventually reaching the Arctic Ocean via the Barents Sea or through the Fram Strait between Greenland and Svalbard (Fig. 8.1). Its vital importance for the marine climate, water mass transformation and biomass production was recognized almost a century ago (Helland-Hansen and Nansen, 1909). Despite this, there is still no consensus on what is actually driving the inflow of AW to the Nordic Seas, or what are the main mechanisms for transforming the AW into the dense overflow water that is returning south over the Greenland-Scotland Ridge. This overflow water ventilates the world oceans as the deepest part of the Atlantic meridional overturning circulation (AMOC), the Atlantic part of what is commonly referred to as the "great conveyor belt" (Broecker, 1991).

Besides the heat transported by the ocean currents, the Nordic Seas and northwest Europe owe a very mild and favourable climate to the heat

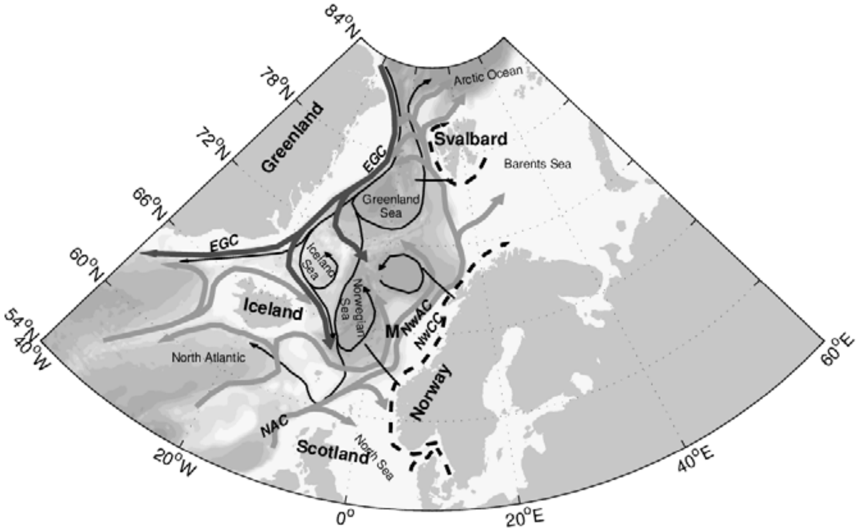

Fig. 8.1. Schematic flow map of the Nordic Seas showing the northward flow of Atlantic Water (light arrows), the southward flow of Polar Water (dark arrows), the coastal currents (dashed arrows), and finally the intermediate and deep circulation (black arrows). The thin straight lines show from south to north the position of the Svinøy, Gimsøy and Sørkapp sections (Fig. 8.2), and M marks the position of the OWSM. Depths are shaded at 500m intervals. Abbreviations are explained in the main text.

associated with the North Atlantic storm track. As a consequence of the dependency on heat transported into the region, the North Atlantic region has been particularly sensitive to climate changes in the past. Abrupt climate changes with ~10ºC temperature jumps over just a few decades occurred in the wake of the last glacial maximum. The last major climate perturbation in the region was the Younger Dryas termination some 11 600 years ago (Dansgaard et al., 1989). Observational evidence suggests that the abrupt changes in climate have been driven by sudden switches in the strength or positioning of the Gulf Stream and its extension into the Nordic Seas. These switches may have been caused by large ice discharges from inland glaciers or fresh water flushing from dammed lakes that have made the surface waters fresh enough to inhibit the deepwater formation (Clark et al., 2001).

The findings in paleo records and early results based on relatively simple numerical climate models, have generated much debate on what may happen to the inflow of AW in a global warming scenario, and in particular if unpleasant surprises are laying ahead of us (Broecker, 1997;

Rahmstorf, 1995). Despite the fact that our climate has been very stable for more than 10 000 years, and abrupt climate changes therefore may seem unlikely in present day climate, the release of greenhouse gases and the associated global warming may perturb the balance. Since the late ‘60s there has been no deep-reaching convection in the Greenland Sea (Dickson et al., 1996), the deep waters of the Nordic Seas have become warmer (Østerhus and Gammelsrød, 1999), the intermediate waters have become fresher (Blindheim et al., 2000), and there are indications of a reduced southward flow of cold, dense water over the Greenland-Scotland Ridge (Hansen et al., 2001). Most state-of-the-art climate models participating in the third assessment report of the Intergovernmental Panel of Climate Change (IPCC-TAR) suggested a 30-40% reduction in the strength of the AMOC during this century (Houghton et al., 2001). It is therefore tempting to ask if the recent observations in the Nordic Seas are indicating that such a reduction has already started.

In this review we will focus on the inflow of AW to the Nordic Seas, the pathways and transformation of the AW within the Nordic Seas and Arctic Ocean, and the expected consequences of global warming. In section 2, we outline the main bathymetric features, the circulation patterns and the hydrographical distribution. In section 3, some of the large-scale changes that have taken place in the Nordic Seas climate during the last couple of decades will be reviewed. In section 4, different forcing mechanisms for inflow and conversion of water masses are discussed in the context of the changes that have taken place. Finally the review is concluded and summarized in section 5.

8.2 Nordic Seas bathymetry, circulation, and water mass transformation

8.2.1 Bathymetry

The Nordic Seas are characterized by a complex topography, with deep basins, generally shallow shelves and steep continental slopes (Fig. 8.1). The deepest areas are found in the Greenland, Norwegian and Lofoten basins. They have depths exceeding 3000 m, and are separated by the Jan Mayen fracture zone and the Mohn Ridge. In the east, the continental shelf extends from west of Ireland to the Fram Strait, with the North Sea and the Barents Sea regions being part of the shelf. Off the western coast of Norway, and in particular off Lofoten, the continental shelf becomes narrow, having a sharp shelf break and a very steep slope towards the deep basins.

In the west, the continental shelf becomes more narrow towards south, from approximately ~300 km in the north to only ~100 km in the Denmark Strait. The Greenland-Scotland Ridge, which separates the Nordic Seas from the Atlantic Ocean, is shallow. The sill depths of the three main passages are, from west to east, 620 m, 480 m, and 840 m, where the deepest sill is found in the narrow Faroe-Bank Channel. Thus waters at depths between 620 m and 840 m can only escape through the Faroese Channels, while waters below 840 m cannot directly cross the ridge. The exchange with the Arctic Ocean is much less restricted; the sill depth of the Fram Strait is ~ 2600 meters.

8.2.2 Circulation

The AW that eventually enters the Nordic Seas originates in the tropical Atlantic from where it is transported north by the Gulf Stream and its northward extension known as the North Atlantic Current (NAC). By the time the AW reaches the Nordic Seas it has been significantly cooled and freshened compared to its tropical origin.

The AW enters the Nordic Seas along three relatively distinct paths; west of Shetland, west of the Faroes and west of Iceland (Fig. 8.1). Given the heat losses over the Nordic Seas and Arctic Ocean, simple heat and volume budget calculations demand that the exchange between those seas and the Atlantic Ocean ought to be around 8-9 Sv (Worthington 1970). Systematic measurements during the last decade confirm this estimate:

The eastern branch of the NAC enters the Nordic Seas at the eastern slope of the Faroe-Shetland Channel. The mean volume and heat transports (relative to 0ºC) based on direct measurements from summer 1998 through 2002 are 3.2 Sv (1 Sv=10^6 m^3s^{-1}) and 123 TW (1 TW=10^{12} W) respectively (Turrell et al., 2003). The annual cycle is found to be only 0.2 Sv.

The middle branch of the NAC enters the Nordic Seas between Iceland and the Faroe Islands. This branch veers to the right upon crossing the ridge, and can be seen as a sharply defined warm current north of the Faroe Islands. East of the Faroes some of this water flows south and partly mixes with the eastern branch of the NAC. From summer 1997 to summer 2001 the mean volume and heat transports north of the Faroes were 3.5 Sv and 124 TW respectively (Hansen et al., 2003), with insignificant annual or interannual variability. The average volume flux is thus slightly higher than the volume flux of the eastern branch, while the heat flux remains the same due to lower temperatures of the inflowing water.

The third and westernmost branch of the NAC enters the Nordic Seas along the eastern rim of the Denmark Strait, where it is known as the North

Icelandic Irminger Current. The flow continues to the east and southeast around the periphery of the Iceland shelf, where it looses most of its heat through atmospheric forcing and mixing with local water masses. Based on measurements from summer 1997 to summer 2000 the amount of water and heat carried by this current are roughly 1 Sv and 25 TW respectively (Jónsson and Briem, 2003).

The former two branches constitute the Norwegian Atlantic Current (NwAC), which flows towards the Barents Sea and the Fram Strait (Fig. 8.1). Both branches follow topography; the inner branch follows roughly the 500-meter isobath whereas the outer branch follows roughly the 2000-meter isobath. The warm waters of the current are found not only in the high-velocity cores but also in the broad region between the cores. This gives the current a broad, sluggish river-like appearance in hydrography data.

During the 2000 km long transit northwards from the southern Norwegian Sea the warm current continues to loose heat and gain freshwater. It has also lost some volume to the surrounding water masses; of the roughly 6.5 Sv entering the southern Norwegian Sea an estimated 1.5 Sv exits to the Barents Sea (Ingvaldsen et al., 2004) and 3-5 Sv exits through the Fram Strait (Schauer et al., 2004). Assuming that the changes in heat and salinity only require entrainment of small volumes of the surrounding water masses, there can only be of the order of 1 Sv (between 0 and 2) of AW that can be lost to the surroundings within the Nordic Seas.

There are however large uncertainties in both entrainment and transport rates that make this a rather crude estimate.

8.2.3 Water mass transformation

Fresher and mostly colder waters surround the NwAC during the transit through the Norwegian Sea; inshore is the fresh water in the Norwegian Coastal Current (NwCC), and offshore is the Polar Water (often called Arctic Water). The NwCC originates as a roughly 1 Sv branch (Furnes et al., 1986) of the Faroe-Shetland inflow of warm AW takes a detour into the North Sea and gains freshwater through runoff from the continents, export of brackish water from the Baltic Sea, and mixing with ambient water masses. The low-salinity current continues from the North Sea towards the Barents Sea along the coast of Norway. Offshore, the Polar Water is brought south with the East Greenland Current (EGC in fig. 8.1) and into the interior basin with the Jan Mayen and East Icelandic Currents.

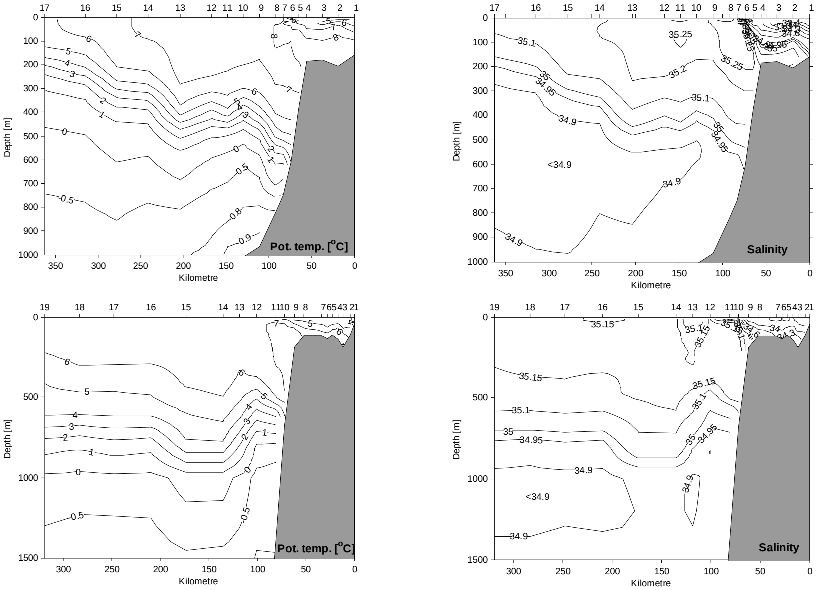

Fig. 8.2. Distribution of potential temperature (left fig.) and salinity (right fig.) in the Svinøy and Gimsøy sections (locations shown in fig. 8.1). The data are based on respectively 17 and 19 regular CTD-stations taken by the R/V Johan Hjort in the period 2-18 March 2001. The numbers over each plot indicate the standard stations (Courtesy of Kjell Arne Mork, Institute of Marine Research, Bergen, Norway).

The NwAC interacts with the surrounding waters; satellite images show vigorous eddy activity on both sides of the warm current (not shown). This results in mixing of water masses and a lowering of temperature and salinity of the AW as it flows northwards. The other main agent of transformation is air-sea heat loss (the freshwater fluxes here do not make a large direct impact on density). Near the inflow region the AW typically has temperature and salinity (TS) values in the range 7-9ºC and 35.10-35.40 (Blindheim and Østerhus, 2004), with TS values close to 8ºC and 35.3 when averaged over the 50-200 m depth interval (Furevik et al., 2002). At the Svinøy section located at approximately 63ºN, typical TS values are 7-8ºC and 35.2, decreasing to 6-7ºC and 35.15 at the Gimsøy section crossing the Lofoten Basin some 400 km further to the north (Fig. 8.2). From Svinøy to Gimsøy a significant deepening of the Atlantic layer is seen both in the temperature and salinity structures, recently described to be a result of the AW meeting a southward flowing deep current in this region (Orvik, 2004). This feature is also seen in fig. 8.3, where climatological mean

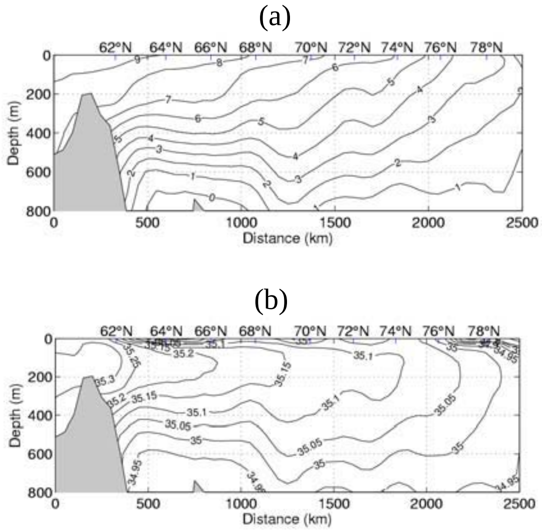

Fig. 8.3: Mean temperature and salinity profiles along the pathway of the AW inflow (defined by the positions of the salinity maximum) from the Faroe-Shetland inflow to the Fram Strait. The plots are based on a climatology compiled from ~100 000 hydrographical station (Furevik et al., 2002).

temperature and salinities are plotted for a section following the core of the maximum salinity through the Nordic Seas.

Further to the north, where the Barents Sea and the West Spitsbergen branches separate, the Atlantic layer shallows, and typical TS values are 3-5ºC and 34.90-35.15 (Fig. 8.3). By the time the AW reaches the 79ºN latitude off northwest Spitsbergen, the TS values have dropped below 2ºC and 35 respectively. North of Spitsbergen the AW continues east as a subsurface current insulated from the atmospheric forcing by fresh Polar Water above. In the Arctic Ocean maximum temperature of the Atlantic layer decreases from 2ºC near the inflowing region in the Nansen Basin, to 0ºC in the Canadian Basin (Carmack, 2000), while the mean depth descends from about 200 m to about 400 m along this path.

In the Barents Sea the AW completely looses its TS characteristics during its passage to the Arctic Ocean due to a very strong cooling by the atmosphere. When the water eventually leaves the Barents Sea between Novaja Zemlja and Frantz Josef Land, the TS characteristics are close to 0ºC and 34.85 respectively (Schauer et al., 2002). Thus the AW flowing into the Arctic Ocean through the Barents Sea is much colder than the water entering through the Fram Strait, and is not contributing to the warmest parts of the AW layer in the Arctic Ocean.

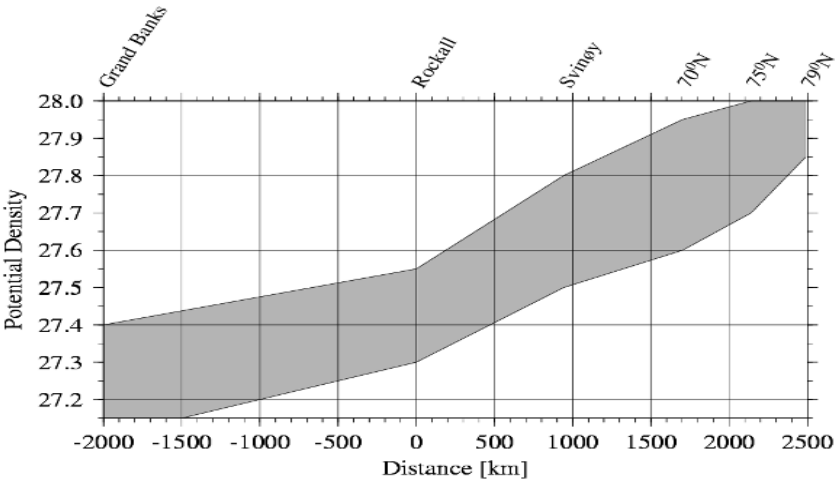

Fig. 8.4: Schematic changes in AW density from Grand Banks (east of New Foundland, Canada) via Rockall (west of Ireland) to the Svinøy section and eventually into the Fram Strait. The shading represents the spread of the measurements within the core of the AW at each location. The numbers on the y-axis are in σ_θ units, thus 28.0 equals 1028 kgm^{-3}. The plot is based on the World Ocean Atlas 1998 data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.

The buoyancy evolution along the path of the NAC and the NwAC is visualized in fig. 8.4. The largest buoyancy losses of the AW are experienced in the Nordic Seas, and the region from the Lofoten Basin to Spitsbergen and the Barents Sea is an area of particularly large change in density. This is also the region that experiences the highest mean annual heat losses of the Nordic Seas (Fig. 8.5a), so a large change in density is not a surprising result. According to the NCEP-NCAR reanalysis data, winter mean heat loss reaches close to 300 Wm-2 in the northern Fram Strait and Barents Sea (Fig. 8.5b). The sensible heat flux is found to be the dominant flux component (Furevik and Nilsen, 2004).

The return flow to the North Atlantic, which also adds up to between 6 and 8 Sv (the Bering Strait inflow to the Arctic is roughly balanced by the outflow through the Canadian Archipelago), is still colder and fresher than the transformed AW at 75-80°N. Some of it exits the Denmark Strait with the East Greenland Current as relatively light water; this is the very fresh Polar Water, which does not sink upon entering the North Atlantic. But the bulk of the return flow (roughly 5 Sv, see Dickson and Brown, 1994) is dense and thus constitutes “overflow water”. Many processes have been mentioned as contributing to that final transformation; the most classical

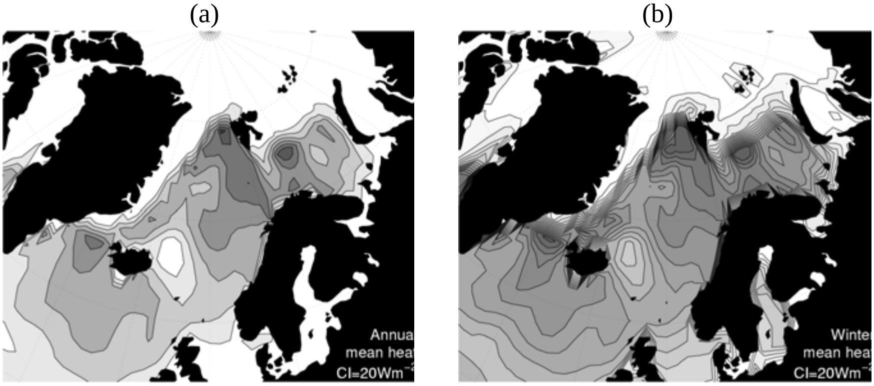

Fig. 8.5: Annual and winter (Dec-Mar) mean total heat flux calculated from the NCEP/NCAR re-analysis data 1948-2003, provided by the NOAA-CIRES Climate Diagnostic Center, Boulder, Colorado, USA from their Web site at http://www.cdc.noaa.gov/. Contour intervals are 20Wm-2. The fluxes are everywhere directed out of the ocean.

explanation, going back to Helland-Hansen and Nansen (1909), is that of open-ocean convection in the Greenland Sea, where cooling of warm, saline AW makes the upper waters dense enough to sink. Another process discussed is dense water formation, by cooling and/or brine rejection, on the Arctic shelves (see e.g. Aagaard et al., 1985; Schauer, 1995).

Mauritzen (1996a,b) aims to quantify the various processes of transformation, and finds that 1) it is unrealistic that the production rate through open-ocean convection is larger than 1 Sv (consistent with the recent transport estimates discussed in the previous section, where the implicit volume loss to the Nordic Seas interior is 0 – 2 Sv); 2) the main product, by volume, of the Greenland and Iceland Seas open-ocean gyres is Arctic Intermediate Water (the water discussed e.g. in Blindheim, 1990); 3) transformation to dense water within the NwAC itself actually is the most important process for the overturning (roughly 7 Sv of water is made denser by roughly 0.5 kgm^{-3} from Rockall, and 0.7 kgm^{-3} from the Grand Banks; see fig. 8.4). Finally, Mauritzen (1996a,b) finds that since the branch that enters the Barents Sea (which has a strength of roughly 1.5 Sv, see above) is transformed to truly dense water by the time it reaches the Arctic Ocean (as discussed above), shelf production in that sea is of first-order importance for the transformation process.

To summarize, many steps are involved in completing the overturn. The largest steps are taken within the NAC and NwAC where the warm water is being made cooler and fresher. Our best quantitative estimates suggest that the most important final steps are open-ocean convection in the Greenland and Iceland Seas, shelf production in the Barents Sea and interior mixing within the Atlantic layer under the ice and the halocline in the Arctic Ocean, each of which contribute roughly equally.

Note that the overturn does not take the shape of a vertical overturn until the return flow sinks to depth in the North Atlantic Ocean; within the Nordic Seas light northward-flowing and dense southward-flowing waters are both found at shallow depths (and above sill levels), above the densest waters. Note also that the main product of the Greenland and Iceland Sea convection, the Arctic Intermediate Water, exits primarily through the Faroese Channels (the Denmark Strait being too shallow). As we shall see in the next section, it is this water that has undergone the largest changes in recent decades.

8.3 Observed changes in the Nordic Seas marine climate

8.3.1 North Atlantic Oscillation

The leading mode of atmospheric variability in the Atlantic sector is the well-known North Atlantic Oscillation (NAO), representing a shift of atmospheric mass between the Icelandic low and the Azores high, directly influencing the strength of the westerlies (Hurrell, 1995). Several indices in use are based on the pressure difference across the westerlies. Measurements from Gibraltar and Iceland going back to 1824 show strong year-to-year variability in the strength of the westerlies, and also indications of more decadal-scale variability (Fig. 8.6a). A pronounces shift occurred from the relatively weak westerlies in the ‘60s to the strong westerlies in the ‘90s. During positive NAO winters (high index years), a strong Azores high and a deep Icelandic low make the meridional pressure gradient and thus the westerlies stronger than normal (Fig. 8.6b). This results in higher temperatures and more precipitation over northern Europe, and correspondingly colder and dryer conditions over southern Europe (see Marshall et al., 2001, Hurrell et al., 2003 for reviews on the NAO and its many impacts on several physical, ecological, and biological parameters).

While the NAO is the dominant mode for the North Atlantic region as a whole, it should be noted that for more regional studies the NAO index has often proved insufficient in describing the main climatic variations. A reason for this is that the spatial pattern of the NAO has shifted throughout the years, as more low pressure systems have gone further northeast into the Nordic Seas. As a consequence sea-level pressure (SLP) variability in

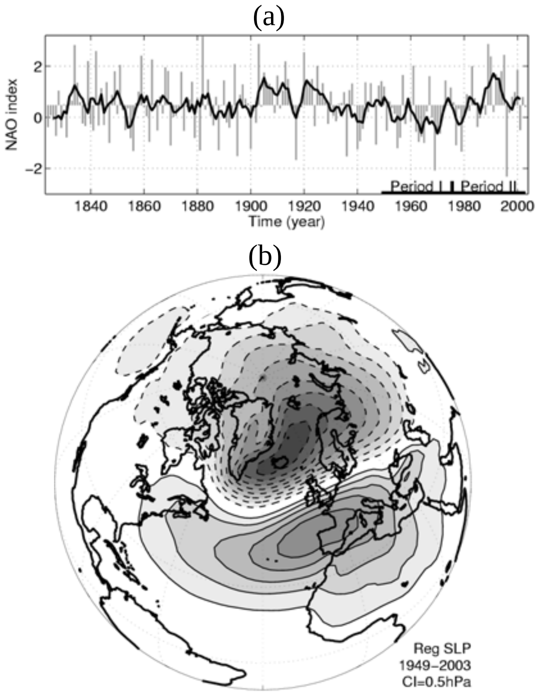

Fig. 8.6: a) The NAO index based on sea-level pressure at Gibraltar and Stykkisholmur, Iceland (updated from Jones et al., 1997). Thin line shows the winter (Dec-Mar) means, thick line shows the data filtered with a 5 years moving average. Periods used for making the regression maps in fig. 8.7, are marked on the time axis. b) The winter-mean sea-level pressure regressed on the NAO index in (a). Contour intervals are 0.5 hPa, with negative values dashed. The plotted values correspond to changes in the sea-level pressure associated with a unit increase in the index. Data are from the NCEP/NCAR reanalysis product.

the Barents Sea and Fram Strait not captured by the NAO index in the ‘50s and ‘60s, show a strong correlation with the NAO index during the ‘80s and ‘90s. The regression plots between SLP and NAO index in fig. 8.7 demonstrate this.

The NAO can influence the ocean circulation by a variety of mechanisms and on a wide range of time scales. The fastest responses are due to anomalous momentum forcing (wind), where divergences in the Ekman transports change the surface elevation and accelerate the flows due to horizontal pressure gradients. Time scales are here on the order of days. Slower responses involve changes of the internal density structures that can be due to anomalous momentum forcing, heat fluxes, or fresh water fluxes. These mechanisms can work locally in the Nordic Seas, or they can

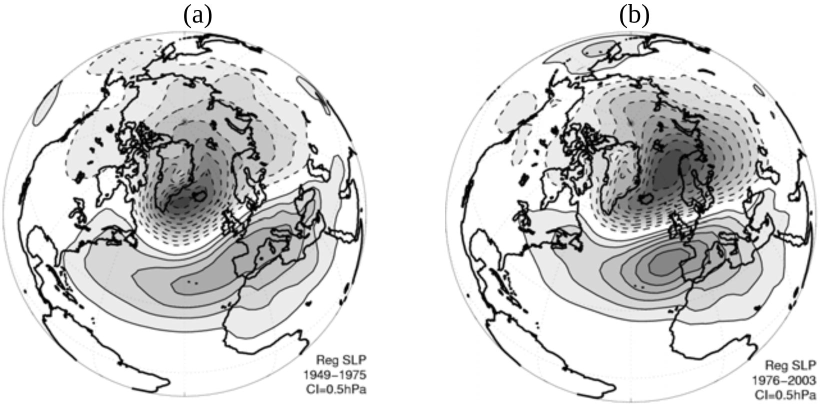

Fig. 8.7: Winter-mean sea-level pressure regressed on the NAO index shown in fig. 8.6a for the periods 1949-1975 (a) and 1976-2003 (b). Contour intervals are 0.5 hPa, with negative values dashed. The plotted values correspond to changes in the sea-level pressure associated with a unit increase in the index. Data are from the NCEP/NCAR reanalysis product.

invoke signals in the ocean that are either advected with the mean flow into the region, or propagating as slow baroclinic waves. Time scales can here be from weeks to years (see papers by Marshall et al., 2001; Visbeck et al., 2003; Furevik and Nilsen, 2004 for reviews).

8.3.2 Atlantic inflow

Due to the baroclinic structure of the Gulf Stream and its NAC extension, it is not surprising that the flow seems to be susceptible to atmospheric forcing on a variety of time scales. Drifter data from the ‘90s combined with sea surface temperature and sea level height data suggest that during positive NAO years, the branch going towards the Irish-Scottish Shelf is strengthened, and there is also a stronger cyclonic circulation in the Iceland and Irminger Basins (Flatau et al., 2003). The latter is in concordance with estimates based on changes in hydrography (Bersch, 2002), and from advection rates for various salinity anomalies observed during the last three decades (Belkin, 2004). Also observations at the Svinøy section indicate that the eastward branch of the NwAC is stronger during winter than during summer, and that there is a positive correlation between the NAO and the flow (Orvik et al., 2001). Similar results are indicated by altimeter data (Furevik and Nilsen, 2004; Skagseth et al., 2004), and also model simulations by Karcher et al. (2003) showed an increased inflow of AW through the Faroe-Shetland Channel during the strongly positive NAO years of the early ‘90s.

In contrast, direct measurements from the three branches of AW inflow to the Nordic Seas, fail to show any significant seasonal signal in the total inflow, nor do they show any correlation with the strength of the NAO (Hansen et al., 2003). A way to explain the seasonality and NAO correlation downstream at the Svinøy section, is that with enhanced cyclonic wind forcing (more lows), a larger fraction of the waters that originally enter the Nordic Seas over the Iceland-Faroe Ridge, recirculates and mixes with the Faroe-Shetland branch east of the Faroes before eventually flowing north in the eastern branch of the NwAC (Hansen et al., 2003). Thus the eastern branch of the NwAC is strengthened and the western branch weakened during strong cyclonic wind forcing (positive NAO years). It should nonetheless be noted that there are still discrepancies between this explanation and the altimeter and drifter data.

Considering the variability in the Fram Strait and the Barents Sea branches, direct measurements show that both branches have strong variability on a variety of time scales, including interannual. The AW transport in the West Spitsbergen Current in the Fram Strait increased between 1997 and 2000 from about 3 to 4 Sv (Schauer et al., 2004). The stronger flow, in combination with higher temperatures, resulted in a more than a doubling of the annual mean net heat transport into the Arctic Ocean (Schauer et al., 2004). A similar increase could explain the warming of the intermediate layers of the Eurasian Basin in the early ‘90s. During the same period as the Fram Strait branch increased (1997 to 2000), the Barents Sea branch decreased from about 2 to 1.5 Sv (Ingvaldsen et al., 2002; 2004). Considering that the AW flowing into the Arctic Ocean from the Barents Sea is much colder than the water entering through the Fram Strait, a reduction in the Barents Sea branch may enhance an eventual warming signal in the Arctic Ocean.

While direct evidence for long-term changes in the flow regimes are sparse due to lack of long-term homogeneous measurements, indirect evidence in the form of changes in hydrography may be found. Blindheim et al. (2000) reported a 2-3 year time lag between the phase of the NAO and the western extension of the AW in the Nordic Seas (defined as the 35 salinity contour), where positive NAO years were associated with a more eastern position of the front. Furevik et al. (2002) showed that the Iceland-Faroe Front migrated further south during positive NAO years, and finally geostrophic calculations from the Svinøy Section since 1955 have indicated an out-of-phase relation between the inner and outer branch of the NwAC (Mork and Blindheim, 2000). Without being conclusive, it is likely that the effect of strengthened westerlies over the North Atlantic is to increase the AW inflow through the Faroe-Shetland Channel, and correspondingly reduce the inflow over the Iceland-Faroe Ridge. Less is known about the total inflow, although Dickson et al., (2000) suggested that the total inflow of AW increases during high-NAO years, and Nilsen et al., (2003) find a slight increase in their model simulations of the total inflow.

During the generally positive NAO period of the last 40 years, the volume and temperature flux of the NwAC that eventually flows into the Arctic Ocean is thus likely to have increased.

8.3.3 Atlantic Water temperatures

Thanks to traditions going back to the latter part of the 19th century (see Blindheim and Østerhus, 2004, for a review), the NwAC is among the best-sampled ocean currents in the world. The many repeated hydrographical sections with multi-decadal long temperature and salinity records provide us with a well of information to be used to study natural climate variability. Among the well-known sections are the Scotland-Faroe section conducted by the Marine Laboratory in Aberdeen, Scotland, the Svinøy, Gimsøy, Bjørnøya-Fugløya, and Sørkapp sections conducted by the Institute of Marine Research in Bergen, Norway, and the 78ºN and 79ºN Fram Strait sections conducted by the Norwegian Polar Institute in Tromsø, Norway and the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany.

The temperature measurements show high year-to-year correlations, as anomalous high or low temperatures have a tendency to persist for some years. Furevik (2000, 2001) combined satellite measurements of sea-surface temperature with in situ observations to look at the temperature anomalies that propagated through the system in the ‘80s and ‘90s. In contrast to a warm anomaly that propagated from the Faroe-Shetland Channel to the Barents Sea and Fram Strait in the first half of the ‘80s, the warm period of the early ‘90s was much larger in magnitude, lasted for a longer period, and was generated inside the Nordic Seas rather than being advected with the flow of AW from the south. The main reason for the warming was higher air temperatures over the Nordic Seas, possibly a more narrow flow of AW, and possibly an increased inflow of AW through the Faroe-Shetland Channel as discussed above. Together these forcing factors, all probably related to the extreme positive phase of the NAO from the 1989 to 1995, contributed to very high AW temperatures in the Barents Sea and Fram Strait, and subsequently in the Arctic Ocean. And numerous observations from icebreaker and submarine cruises in the Arctic Ocean during the early ‘90s, revealed that the Atlantic layer in the

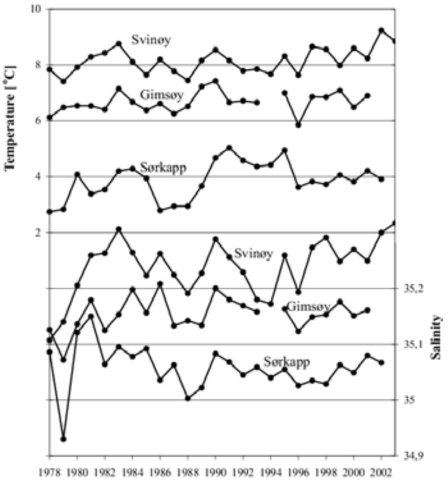

Fig. 8.8: Temperature and salinity in the core of the Atlantic Water in the Svinøy, Gimsøy and Sørkapp sections, averaged between 50 and 200 m depth. Updated from Mork and Blindheim (2003).

Arctic was warmer than ever before (Carmack et al., 1995; Grotefendt et al., 1998). In addition, the front between the waters of Atlantic and Pacific origins, shifted from the Lomonosov Ridge to the Mendeleyev Ridge (McLaughlin et al., 1996; Morison et al., 1998), implying that also the total volume of the Atlantic layer had increased. A new warm anomaly was observed in the Barents Sea (Ingvaldsen et al., 2003) and the Fram Strait (Schauer et al., 2004) in the late ‘90s, and it is likely that this water has later spread into the central Arctic (Karcher et al., 2003; Schauer et al., 2004).

The warm and cold episodes are clearly shown in fig. 8.8, where temperatures and salinities in the core of the AW are shown. The plots reveal that the signals generally propagate from south (Svinøy) to north (Sørkapp), and also the strong amplification of the warm signal of the ‘90s. The cold and fresh episodes occurring at the Svinøy section in 1978, 1987, and 1994 are known as the great salinity anomalies of the ‘70s, ‘80s, and ‘90s. They have been shown to originate in the northwestern North Atlantic, probably as a result of strong outflow of Polar Water. From here they have propagated south with the sub-polar gyre, and east and north with the North Atlantic Current before entering the Nordic Seas after 5-7 years (see Belkin, 2004, and the references therein). A new strong warm and saline anomaly is seen in the southernmost section in the last year. This can be traced back to the Faroe-Shetland inflowing region, which in 2003 had the warmest and most saline AW inflow since the measurements started in

1902 (Mork, 2004). It is probable that the warm and saline water will be advected downstream into the other sections and into the Fram Strait and Barents Sea in the years to come.

8.3.4 Intermediate Waters and Overflows

As discussed above, the overflows do not originate from the deepest parts of the Nordic Seas, but rather from intermediate levels. At least one of these intermediate water masses (Arctic Intermediate Water) has seen extreme changes in salinity since the late ‘60s or early ‘70s (Turrell et al., 1999, Blindheim et al., 2000, Dickson et al., 2002). As readily seen in fig. 8.9a, there has been a pronounced freshening during the last 30 years. Further on, the signal can be followed south through the gaps in the Greenland-Scotland Ridge, from where the Labrador Sea and the rest of the North Atlantic Ocean are being diluted (see Dickson et al. 2002, Visbeck et al., 2003). The freshening signal has continued equatorward in the Deep Western Boundary Current, the deepest part of the AMOC, and can now be found even south of the Equator (Dickson et al., 2002).

Different sources for this extra fresh water, which correspond to mixing several meters of fresh water into the ocean, have been proposed; increased fresh water and ice export from the Arctic, more precipitation over the region, or internal redistribution of the water masses. In a recent study, Curry et al. (2003) suggest that global warming is the cause. In an analysis of salinity data from the entire Atlantic Ocean, they found clear indications of a freshening at depth also in the southernmost part of the Atlantic, showing that the freshening was not only a North Atlantic feature. In addition, the upper water of the tropical Atlantic was found to become more saline, which as they state clearly suggest a spin-up of the global hydrological cycle. Warmer air can contain more moisture, and a global warming should therefore be accompanied by increased atmospheric fresh water transport from the tropical oceans towards the high latitudes. If they are right the Nordic Seas freshening is a strong indication of global warming.

At the same time there is indirect evidence that the dense overflows may be decreasing in strength: Hansen et al. (2001) combined density measurements at ocean weather station M (OWSM) in the Norwegian Sea (Fig. 8.1) with direct measurements of volume transports through the Faroe-Shetland Channel, and suggest a 20% reduction in that transport since the

‘50s. Their simple argument is that less deep-water formation in the Nordic Seas has made the intermediate and deep waters less dense, resulting in a less north-south pressure gradient to drive the flow. In Hansen et

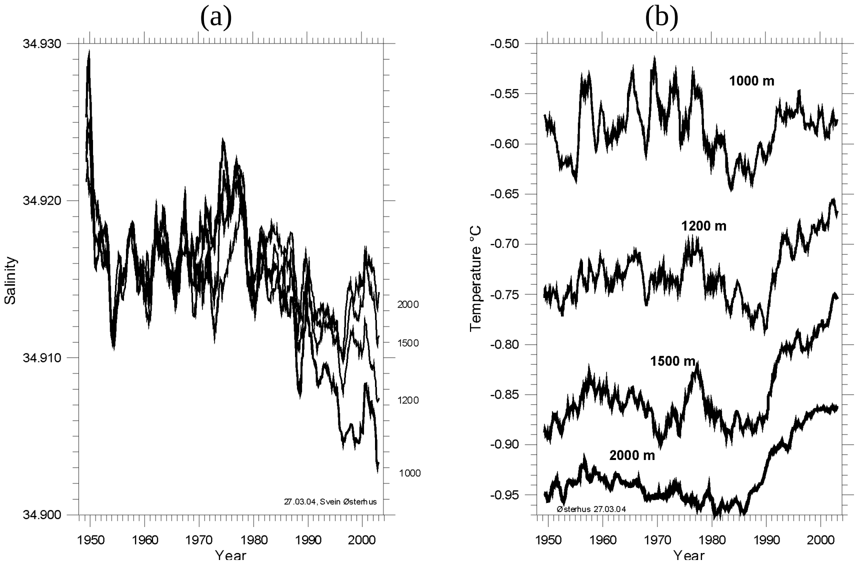

Fig. 8.9: Observed salinity (a) and temperature (b) at 1000, 1200, 1500, and 2000 m depths at OWSM. The position is shown on map in fig. 8.1 (courtesy of Svein Østerhus, Bjerknes Centre for Climate Research, Norway).

al. (2003), they draw the same conclusion for the cold component of the overflow across the southern part of the Iceland-Faroe Ridge and for the cold component of the overflow across the Wyville-Thomson Ridge.

8.3.5 Deep Waters

The densest waters of the Nordic Seas consist of Greenland Sea Deep Water (the product of convection reaching below ~ 2000 m in the Greenland Sea) and Arctic Ocean Deep Water (which enters the Nordic Seas in the western Fram Strait). The open ocean convection in the Greenland Sea was at its maximum depth in the ‘60s, resulting in very cold and dense deep waters in the region (Dickson et al., 1996). Since then, convection has in general not reached as deep, due to mild winters and fresher surface waters, and the warmer Arctic Ocean Deep Water influence has increased (Meincke et al., 1997). With a few years time lag, the warming signal continued into the Nordic Seas, where the long deep-water record from the OWSM provides an excellent historical record of the change (Østerhus and Gammelsrød, 1999), as seen in fig. 8.9b. In the Norwegian Sea, below the AW and the Intermediate Waters, a mixture of these two deep-water masses is found.

8.4 Expected impacts of anthropogenic climate change

Substantial changes in the Nordic Seas climate have been observed during the last decades. The increased hydrological cycle and increased melting of Arctic land ice under global warming is of particular concern because both fresher surface waters and milder winters will act to reduce the upper water density and thus stabilise the water column. Based on simple model experiments (e.g. Rahmstorf, 1995) and paleo data (Alley et al., 1993), a worst-case scenario has been proposed. That is that a consequence of global warming may be a total shutdown of the AMOC with a substantial cooling of the North Atlantic region.

There are several reasons for why we believe that is a highly unlikely scenario: The northward flow of AW does not depend on a single factor that easily can be switched on or off. The large-scale oceanic circulation in the North Atlantic is mainly wind driven. Prolonged wind forcing results in enhanced horizontal gradients of surface elevation and internal pressure fields that maintain a relatively steady circulation. The driving forces for the inflow to the Nordic Seas are subtler. They probably consist of wind forcing that pushes the waters against the northwest European coasts, buoyancy forcing that produces dense southward flowing water which has to be compensated by an equal inflow, and the estuarine forcing which is simply that water entrained by the southward flowing light waters from the Arctic, also requires a compensating inflow.

Global warming will likely affect these forcing mechanisms in different ways. While the response in wind differs between the climate models, there is a general tendency for most models to respond to increased greenhouse gas concentrations by producing stronger westerlies and more cyclonic circulations over the Nordic Seas (see Furevik and Nilsen, 2004, for a review). Stronger or more persistent westerlies are likely to enhance the general oceanic circulation in the Atlantic, and also to increase the inflow to the Nordic Seas, in particular through the Faro-Shetland Channel.

Another response to global warming is a warming and freshening of the surface waters in the high-latitude convection regions in the ocean, both acting to reduce the surface density and stabilise the water column. While the latter is usually blamed to be responsible for the rapid (abrupt) climate changes in previous climate, reduction in the rate of deep-water formation in present day climate models seem to be a combined result of warming and freshening, and there is no consensus on what is the most important of the two. While there has been a substantial reduction in the production of deep waters by open-ocean convection in the Nordic Seas, less is known about the shelf convection that is mainly driven by brine release during ice-freezing. As ice freezing and thus the rate of salt release are negatively correlated with the ice thickness (thick ice insulates the waters below and prohibits the freezing), a thinner ice cover is likely to enhance the ice production. Shelf processes and down slope sinking of waters is generally poorly described in climate models, and there is therefore little knowledge on how this will change in a future climate. It may nevertheless happen to be of increasing importance in a future climate. Thus, despite the fact that most of the climate models participating in the third assessment report of the IPCC show a modest decline in the strength of the AMOC, unresolved processes may modify these results.

Finally, we have strong reasons to believe that global warming will also affect the third driving force for the Atlantic Water inflow to the Nordic Seas, the estuarine forcing. An enhanced atmospheric fresh water flux to the Arctic, with more precipitation and river runoff, will likely increase the sea-level difference between the Arctic and the Atlantic Ocean, and thus the southward transport of freshwater through the Nordic Seas. In addition, a thinner sea-ice cover will reduce the fraction of the freshwater that is exported in solid form. The net result of this will probably be more entrainment and a stronger estuarine forcing, again a factor that will work to maintain the inflow of AW to the Nordic Seas. In a recent paper, de Boer and Nof (2004) argued that the present day stable AMOC conditions started when sea-level rise opened the Bering Strait 10 400 years ago, and fresh-water anomalies in the convection regions could be flushed south and replaced by denser AW. With their interpretation, a substantial or complete shutdown of the AMOC is unlikely to appear in present day climate, and global warming will not change this.

8.5 Summary and conclusion

In this paper we have discussed the flow of AW through the Nordic Seas, an important factor for ocean climate and biomass production in the area. The average volume and heat transports from the North Atlantic to the Nordic Seas are slightly below $8x10^6m^3s^{-1}$ and $300x10^{12}W$ respectively, with the main passages being the Faroe-Shetland Channel and the Iceland-Faroe Ridge. Observations suggest that more than ¾ of this water is carried into the Arctic through the Fram Strait and Barents Sea. Due to atmospheric forcing and mixing with ambient fresh water masses, a substantial cooling and freshening of the water masses occurs within the Nordic Seas and Arctic Ocean. Most of the heat is released in the Nordic Seas, mainly in the Lofoten Basin, Fram Strait and Barents Sea, where the annual mean heat loss exceeds 100 Wm^{-2}. Within the Nordic Seas and Arctic Ocean the AW is transformed into a denser water mass that is known as the over-flow water. This water spills over the ridges to the south, and forms the deepest parts of the AMOC.

During the last decades, substantial changes in the Nordic Seas ocean climate have been observed. The primary forcing mechanism seems to have been the low-frequency change from weak westerlies in the ‘60s to record strong westerlies in the ‘90s. The result of the changed atmospheric forcing seems to have been a stronger flow of AW through the Faroe-Shetland Channel, and possibly a weaker inflow over the Iceland-Faroe Ridge. Less is known about the total inflow. Other, better-documented changes have been that the AW has become much warmer and also more saline during the last decades, the intermediate waters that end up as overflow water has freshened, and the deep waters of the Nordic Seas have become warmer.

Paleo-records have shown that the North Atlantic region has undergone periods characterised by rapid changes in climate, probably linked to abrupt changes in the AMOC. Furthermore, most climate models indicate a significant reduction in the strength of the AMOC in a global warming scenario. We here review the mechanisms responsible for producing dense water and maintaining the AW inflow to the Nordic Seas. Observations and model runs indicate a reduction in the open-ocean convections of the north. The result may be a weaker AMOC and a reduced inflow of AW to the Nordic Seas. We believe, however, that other forcing mechanisms at least partly will compensate this: stronger wind forcing, increased shelf convections, or strengthened estuarine forcing. The effect of global warming will likely affect all forcing mechanisms in various ways. We therefore believe that a total shutdown of the AMOC under global warming is unlikely, and that the inflow of AW to a large degree will be maintained. We may nevertheless expect that the trends we have seen in AW temperatures and salinity can be sustained in the decades to come, and that this can have significant physical and ecological impacts in various parts of the region.

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9 Climate variability and possible effects on arctic food chains: The role of *Calanus*

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9.1 Introduction

The large oscillations of abiotic factors in the Arctic is critical in structuring its marine biota and the biodiversity of its indigenous populations and communities. The seasonal light cycle is modified by the sea ice cover, creating a situation dominated by phytoplankton blooms, that follow the receding ice edge, and in leads as the sea ice opens during the Arctic summer (Sakshaug 1997, 2003; Hegseth 1998; Falk-Petersen et al. 2000a; Engelsen et al. 2002). Blooms of phytoplankton propagate through Arctic waters (Zenkevich 1963) and carbon fixed through photosynthesis is rapidly converted into large, specialised lipid (marine fat) stores by the herbivorous *Calanus* species (Lee 1975; Sargent and Henderson 1986). These high-energy lipids are then rapidly transferred upwards through the food chain in large amounts (Falk-Petersen et al. 1990). The increase in lipid level from 10-20% of dry mass in phytoplankton to 50 - 70% in herbivorous zooplankton is probably one of the most fundamental specialisations in polar bioproduction. The lipid – based energy flux is one of the primary reasons for the large stocks of fish and mammals in Arctic waters.

The importance of the diatom => *Calanus* food chain in the Arctic pelagic food has been demonstrated by Falk-Petersen et al. (1986; 2002) and Scott et al. (2002). A wide spectrum of predators from zooplankton to fish and sea birds has also been analysed by using fatty acid trophic markers in Arctic waters. In all of these studies the *Calanus* C20 and C22 lipid trophic markers were strikingly dominant, demonstrating the importance of the

Calanus species in the Arctic pelagic ecosystem (Falk-Petersen et al. 2001, 2002, 2004; Dahl et al. 2003.

The population size spectrum and energy content of the key *Calanus* species, being potential prey for zooplankton-eating fish and sea birds, is therefore instrumental in structuring the biodiversity of Arctic ecosystems. We believe that understanding the climate variability is a key to understand the biology of Arctic animals and the biodiversity of Arctic systems. In this paper we discuss how different climate regimes in the Nordic Seas can influence *Calanus*- based Arctic food chains**.**

9.2 Climate variability and species distribution

9.2.1 The distribution of the *Calanus* species and the current system.

The circulation of water in the Nordic Seas, the modification of water masses and changes of ice conditions are important for a) the local climate and b) the larger-scale systems of oceanic and atmospheric circulation affecting the climate of northern Europe and c) the marine food resources.

The distribution of the three main *Calanus* species in the Nordic Seas and the Eurasian Basin of the Arctic Ocean is strongly influenced by two large, interconnected current systems (Fig. 9.1). The current system is mainly governed by the topography (Rudels et al. 1999; Hansen and Østerhus 2000). In the south the North Atlantic Current enters the Norwegian Sea on both sides of the Faroe Islands and flows northwards parallel to the Norwegian Coast (Hansen and Østerhus 2000). North of the Lofoten Islands at approx. 72 ^{o}N one branch turns northwest and flows along the Barents Sea margin as the West Spitsbergen Current. Northwest of Spitsbergen, a part of the current branch westward and southwards and meets the East Greenland Currents flowing southwards before part of the current turns eastwards first into the Iceland Sea and then into the Norwegian Sea north of Iceland.

In the north the Atlantic water enters the Arctic north of Spitsbergen, Svalbard where it submerges under the Arctic water masses (Nansen 1902). It then circulates the Eurasian basin and returns into the Fram Strait on the Greenland side as Arctic Intermediate Waters at depths of 500-900 m. This deep and cold-water mass turns east north of Jan Mayen, and follows the same circulation system as surface water along the Spitsbergen

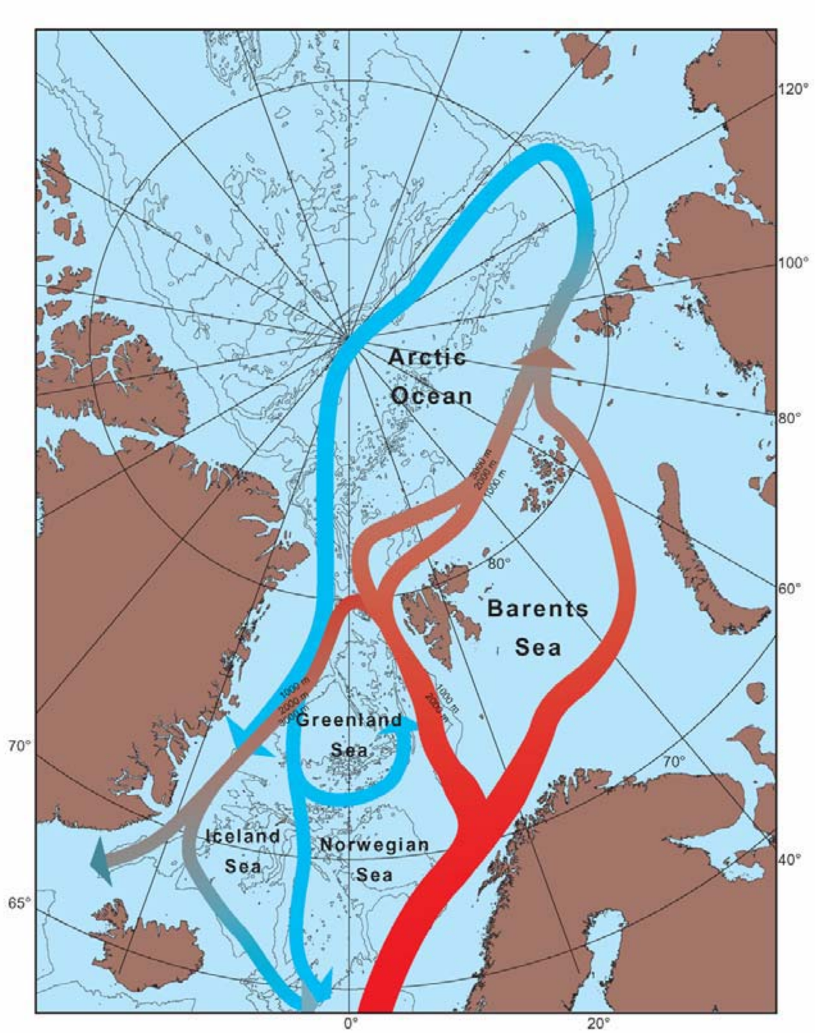

Fig. 9.1. The current system in the European Arctic. The red arrow showing the North Atlantic current entering the Arctic and the blue indicating gradually cooling and sinking (modified after Hansen and Østerhus 2000, Jones et al. 1995).

Shelf slope. In the Fram Strait, therefore, there is an exchange of the waters between the Polar Ocean and the Nordic Seas, with a southward flow on the western side and a northward flow on the eastern side (Jones et al. 1995). The North Cape Branch of the North Atlantic Current enters Barents Sea through the Bear Island Trough (The Barents sea opening) before it flows into the eastern Barents Sea. It then flows northwards along Novaya Zemla before it enters the Arctic Ocean between Franz Josef Land and Novaya Zemlya, flowing parallel to the northern branch around the Eurasian basin (Rudels et al. 1999).

The two interconnected current systems in the Atlantic and Arctic (Fig. 9.1) transports *Calanus finmarchicus, C. glacialis* and *C. hyperboreus* long distances and they are found distributed all over the Arctic, including the Norwegian Sea, the Barents Sea, the White Sea, the Arctic Ocean, the Greenland Sea and coastal waters bordering Siberia, East Canada and Alaska. The different species do, however, originate from different centres of distribution and are used as indicator species for the different water masses (Van Aken et al. 1991). The three *Calanus* species also have different core areas for over-wintering, the Norwegian Sea being central for *Calanus finmarchicus*, the Arctic shelf area for *C. glacialis* and the Greenland Sea and the Arctic Ocean for *C. hyperboreus* (Jaschnov 1970; Runge et al. 1986; Conover 1988; Tande 1991; Hirche and Mumm 1992; Hirche and Kwasniewski 1997; Hirche 1997).

9.2.2 Climate variability.

Arctic systems are characterised by pronounced seasonal oscillations in incident solar radiation such that the light regime changes dramatically during the year, from a period of darkness lasting approximately 4.5 month at 80°N to a period of midnight sun during summer. The ice cover and sea water temperature also changes dramatically, both on very short time scales from hours to days and on long time scales from years to decades (Polyakov 1999, Falk-Petersen et al. 2000a; Vinje 2001; Engelsen et al. 2002). The extent to which ice cover can vary is emphasised by the fact that the North Pole can be largely ice - free during summer in some years while it is totally ice covered in others (Polyakov et al. 1999) and phytoplankton blooms are regularly registered in North Pole waters (Zenkevich 1963). Starting and continuation of the bloom in the different parts of the Arctic Ocean corresponds to features of the annual cycle of the ice concentration (Fig. 9.2).

Analysis of the inter-annual water temperature variations along a section across the Atlantic water inflow in the Norwegian, Barents and Greenland seas (Tereshchenko 1997; Furevik 2001) have shown several cold and warm periods during last five decades, varying in periods of 2 to 7 years. Inter-annual and decadal variability of the summer water temperature (Fig. 9.3) was studied between 1950 and 2000 in the core Atlantic inflow in the West Spitsbergen Current (data extracted from a box delineated by 78-79N, 8-10E) and the Barents Sea Opening (box delineated by 72.5-73.5N,

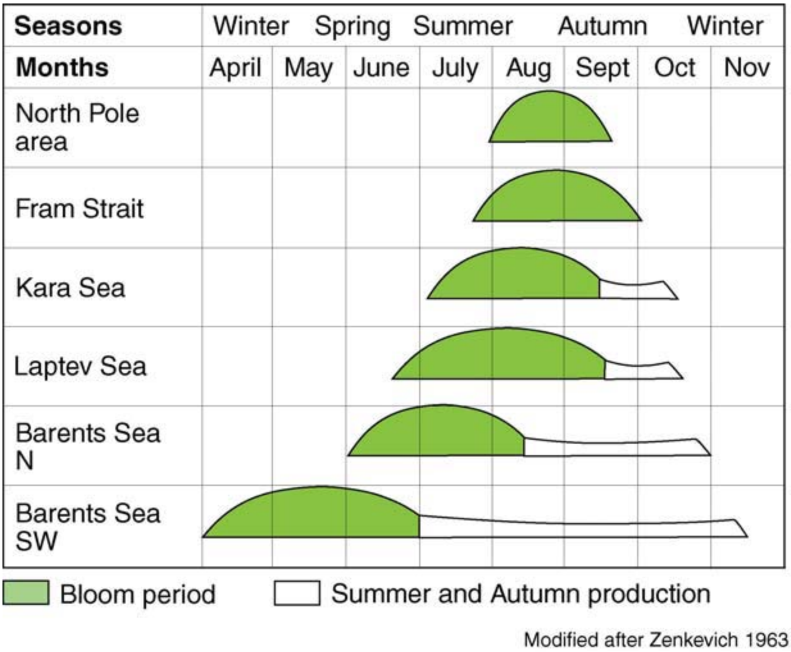

Fig. 9.2. Time related plankton blooms in the Arctic Oceans (modified after Zenkevitch 1963).

19.5-21.5E). For this study all available data from the National Oceanographic Data Center archive (NODC-02, period 1900-1990), Greenland Sea Project dataset (period 1987-1993), ESOP project I and II dataset (period 1993-1998), VEINS project dataset (period 1997-2000), NPI dataset (period 1959-2003), Russian data collected at the NPI (period 1959-1992) and Climatic atlas of the Barents Sea (Matishov et al. 1998) were used. The temperature decrease in the 50’s, 60’s and 70’s and increased in the 80’s and 90’s in both areas. The regime shift, between the two periods took place between 1978 and 1979. The surface water of the West Spitsbergen Current had a maximum values at the start of the 50s and the end of the 90s of 4 to 6.5°C and a minimum at the end of the 70s of 1.5 to 3 °C. The Barents Sea Opening had higher temperatures with a maximum at the start of the 50ties and the end of the 90s of 6 to 7 °C and a minimum at the end of the 80s of 4.5 to 5.5°C at 50 m. Periods with warming is related to high North Atlantic Oscillation (NAO) modus and increased Atlantic water inflow (Furevik et al. 2005).

Analysis of historical data of sea ice (Vinje 2001) shows that the ice extent has been reduced monotonically over a period 135 years (Fig. 9.4).

April ice extent has decreased by ~33% over the past 135 years and reached minima in the 1990s. A strong negative correlation is found between NAO winter index and the Nordic Seas April ice extent (Fig. 9.4, Vinje 2001). For example most of the Barents Sea, parts of the Greenland Sea and the Norwegian Sea were ice covered in the spring of 1966 when NAO index was low while in 1995 (high NAO) most of the same areas were ice free.

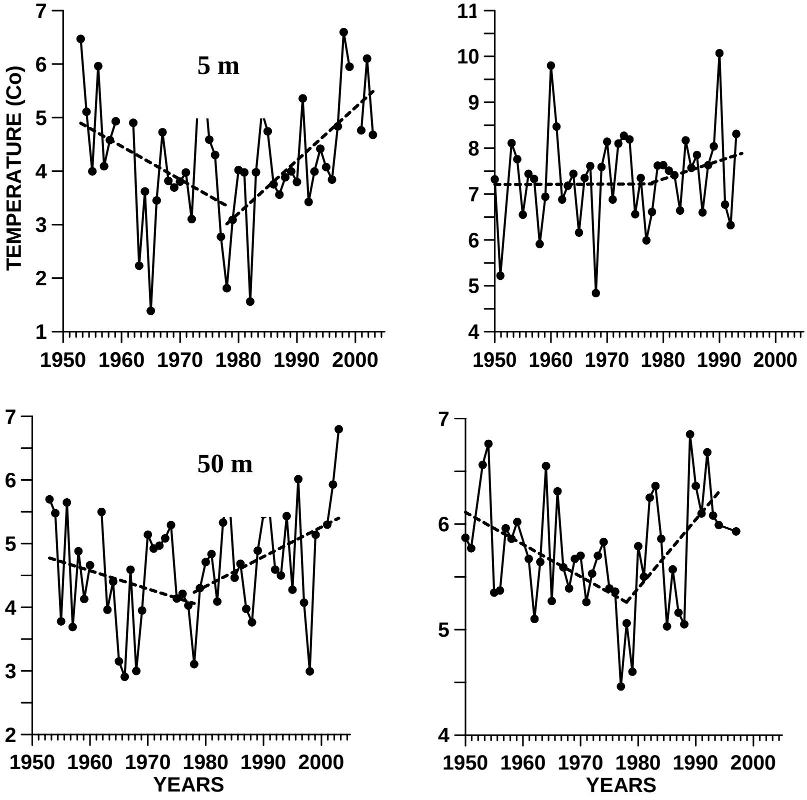

Fig. 9.3. The time series of the summer (July-September) water temperature (solid line and points) along the path of Atlantic water in the West Spitsbergen current for box: 78-79N, 8-10E (left panels) and in the Barents Sea Opening for box: 72.5-73.5N, 19.5-21.5E (right panels) at the depths 5 and 50 m. Linear trends (dashed lines) are shown for two periods 1953-1978 and 1978 – 2003 in West Spitsbergen current and 1950-1978 and 1978-1995 in the Barents Sea Opening.

9.2.3 Phytoplankton bloom.

The large and spatial changes in ice concentration directly influence the light available for primary production. Blooms of phytoplankton develop as the ice opens (Engelsen et al. 2002) and Zenkevich (1963) described the propagation of the algal bloom along a latitudinal gradient from the southern Barents Sea to the North Pole (Fig. 9.2). The algal bloom is often found in the southern Barents Sea as early as March – April, during the summer in the northern Barents Sea and in August – September in the Fram Strait and in the Arctic Ocean. Thus, herbivorous zooplankton in high latitude, ice-covered seas is exposed to large variations in food availability, not only between seasons (Lee and Hirota 1973; Falk-Petersen et al. 2000b) but also between years, decades and longer periods. The pelagic *Calanus* species being one of the major components of the Arctic marine ecosystem must, therefore, be adapted to an environment changing markedly on different time scales. This readily accounts for the biodiversity of the *Calanus* complex in terms of the species' different life strategies, different ecological niches and different centres of distribution.

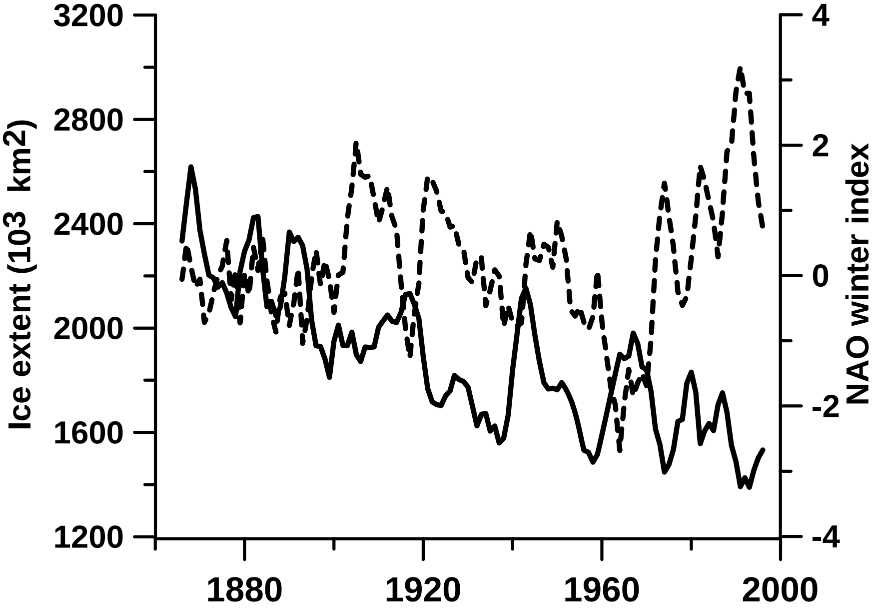

Fig. 9.4. 5-yr running means April ice extent in the Nordic Seas (solid line) and NAO winter index (dashed line). Modified after Vinje (2001).

9.3 The *Calanus* species

Table 9.1 shows the impressive plasticity of the Arctic *Calanus* species. In the North Sea, *C. finmarchicus* can have a life span of less than a year (Wiborg 1954; Marshall and Orr 1955) while in the Norwegian Sea, along the coasts of north Norway, Greenland and east Canada and the Nordic Seas, the life span is mainly one year (MacLellan 1967, Lie 1968, Sekerak et al. 1976, Tande 1991, Falk-Petersen et al. 1999). *C. glacialis* has a life span of 1 to 3 years but for most areas a life span of 2 years is reported (Conover and Huntly 1991, Kosobokova 1999). *C. hyperboreus* shows the most impressive plasticity, with a life span from two to five years (Dawsen 1978, Conover and Huntly 1991, Hirche 1997, Falk-Petersen et al. 1999). Such plasticity in the different species reflects differences in their environments. The central Arctic Ocean has the highest variability in sea climate and, therefore, the lowest predictability of food available for herbivorous zooplankton. The ability of the different developmental stages of calanoids to over-winter depends on their abilities to store energy. It is interesting to note that all three species have similar energy content (dry weight 0.14, lipid 0.05 mg pr individual), at their first main over-wintering stage (Fig. 9.5). The similarity of the energy content of the first over - wintering copepodite stages, V, IV and III for *C. finmarchicus*, *C. glacialis* and *C. hyperboreus,* respectively, is consistent with the energy demand of the first over - wintering being the same for the three species.

Table 9.1. The Arctic *Calanus* complex. Life span (years), maximum size (mm), lipid weight (LW) as mg • ind-1, and % total lipid (TL) of DW, % wax ester (WE) of TL. IV and V = copepodite stages, F = females.

Species	Life span	Stage	Max. size	LW	% TL	% WE
C.finmarchicus.	1	IV	2.2	0.02	53	63
.		V	3.0	0.04	34	68
		F	3.2	0.08	31	62
C. glacialis	2-3	IV	2.8	0.05	56	68
		V	4.0	0.38	61	72
		F	4.6	0.45	70	68
C.hyperboreus.	2-5	IV	4.0	0.28	54	72
		V	6.0	1.03	65	75
		F	7.0	1.81	62	75

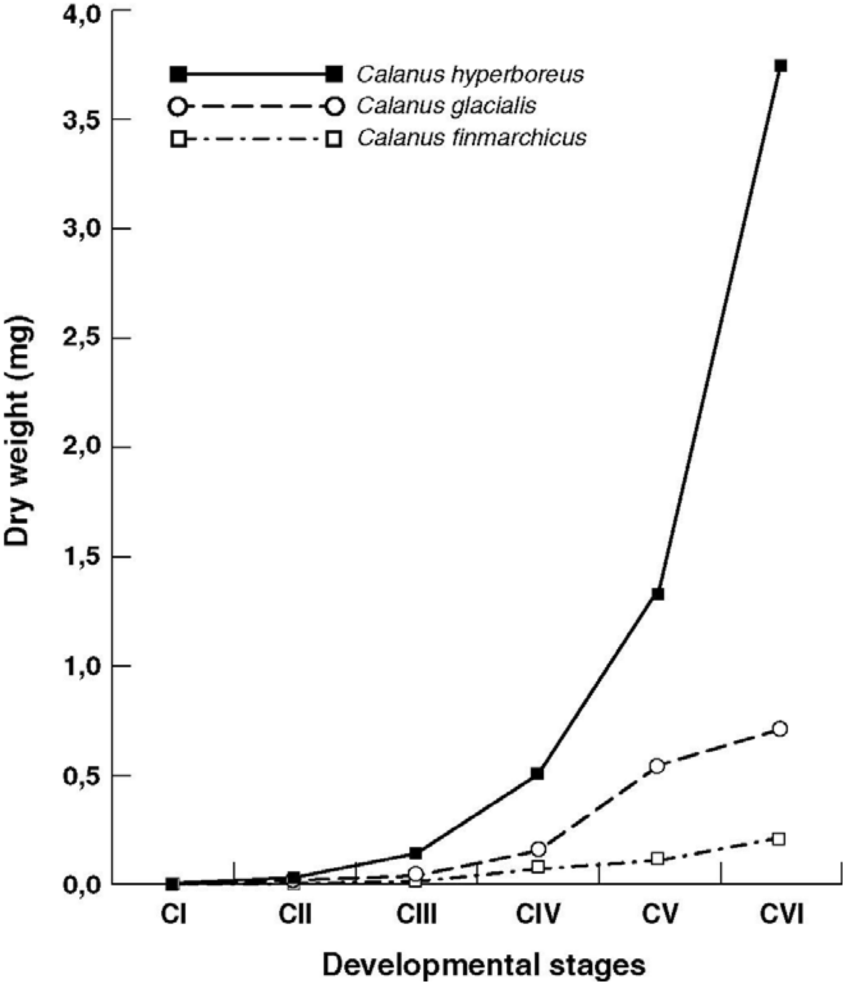

Fig. 9.5. Growth in terms of dry weights of the different copepodite stages (I to VI) of Calanus finmarchicus, Calanus glacialis and Calanus hyperboreus. Data from Mauchline 1998.

9.3.1 *Calanus hyperboreus*

C. hyperboreus, the most polar species, has its centre of distribution in the current system connecting the deep-sea areas such as the Greenland Sea, the Fram Strait and the Arctic Ocean (Fig. 9.1). These are areas with marked annual and inter-annual variations in ice conditions. In favourable seasons, when the ice cover opens up for longer periods, food is plenty, while in years with permanent ice cover food is scarce. *C. hyperboreus* has adapted to this condition by developing a large plasticity in its life strategy (Table 9.1). It is a large copepod and can over - winter, as early as stage III, after accumulating large energy reserves in the form of high - energy wax esters (Hirche 1997; Scott et al. 2000). Under favourable conditions when primary production is high, the animal has a life span of 2 years, while under extensive ice cover it has a life span from 3 to 5 years. *C. hyperboreus* females store large quantities of wax esters which are consumed in the spawning process during winter. Spawning takes place independent of the algal bloom and the fertilised eggs will normally develop rapidly via the naupliar stages to stage III or IV copepodites during the short bloom in the following summer/ autumn. When *C. hyperboreus* has accumulated sufficient lipid reserves it migrates down to deep waters (500-2000 m) and enters diapause (Vinogradov 1997). Under these conditions it has sufficient high-energy reserves to meet its minimal metabolic requirements for long periods, exceeding a single season if need be. It is logical that the greater the variation in ice cover and especially the greater the likelihood of prolonged ice cover, the greater the advantage for an herbivorous copepod to arrest development at any stage. This is more likely to occur in large copepods with large reserves of high-energy lipids in early as well as late developmental stages.

9.3.2 *Calanus glacialis*

C. glacialis is a typical shelf species which spawns in waters all around the Arctic shelf and in the White Sea. Although the shelf areas experience large variations in ice cover, the ice nearly always opens up for shorter or longer periods during the summer or autumn allowing an annual algal bloom to occur. *C. glacialis* has a life span of 1-3 years. It spawns before or during the yearly spring bloom (Niehoff et al. 2002) and it grows rapidly in the same year to reach its over-wintering stage IV, with large energy-rich wax ester reserves (Table 9.1). It then descends to deep areas on the shelf (200 to 300 m) to enter diapause and over-winter. Scott et al. (2000) suggested that this species is well capable of developing from eggs via the naupliar stages to wax ester-rich stage III and stage IV copepodites within a single year. However, the large increment in body mass and lipid reserves as it develops further from stage IV to stage V copepodites is unlikely to be achieved in a single year, except under very favourable conditions. Thus, development from stage IV to stage V probably occurs in two year-old *C. glacialis*. The resulting large, wax ester-rich stage V copepodites then over-winter and spawn immediately prior to or during the spring bloom in their subsequent third year of life.

9.3.3 *Calanus finmarchicus*

C. *finmarchicus*, the smallest of the three *Calanus* species, is an Atlantic boreal deep-water species. It has two main centres of distribution, one connected to the large gyre in the Norwegian Sea (Fig. 9.1) and the other in the Subarctic Gyre south of the Labrador Sea and east of Newfoundland. In addition there is a small sub-population south of Newfoundland (Matthews 1969; Aksnes and Blindheim 1996; Planque et al. 1997; Bucklin et al 2000). Breeding populations are also found along the Norwegian coast and in the southern Barents Sea. These are areas where a predictable annual spring bloom occurs between March and May. North of the Arctic Circle, *C. finmarchicus* develops from eggs, via 6 naupliar and several copepodite stages to their major over-wintering stage V within 6 to 10 weeks in favourable years (Sargent and Falk-Petersen 1988). They also accumulated high-energy wax esters as reserves and over-winter in diapause at depths of 500 to more than 2000m (Gislason and Astthorson 2000). The onset of reproductive maturity and egg production occur before the onset of the phytoplankton bloom and are mainly fuelled by internal reserves of wax esters (Ohman and Hirche 2001). The per capita egg production rate increases at the time of the bloom (Niehoff et al. 1999) and final gonad maturation followed by successful spawning depends on timing of the spring bloom (Niehoff et al. 2002).

9.4 Ecosystem effects of Arctic warming

According to our present understanding there are two possible scenarios of climate change in the region. The first is based on the hypotheses that the Arctic climate varies in cycles (Proshutinsky et al. 1999) and that we now are at the beginning of a cold period, leading to heavy ice conditions in the Barents, Greenland and parts of the Norwegian Seas (Vinje 2001). The second scenario is based on a hypothesis of a continuation of the present trend, resulting in a permanent warming of the Arctic climate (IPPC 2001) and a decrease of the ice extent of the Barents Sea and the Southern Arctic Ocean. The extent of the ice cover in the Nordic Seas in spring has decreased since 1860 due to the net thermal effect of the north-bound currents in the area (Vinje 2001). A warming of the water masses in the central Arctic Ocean has been observed in the 1990s, explained by increased

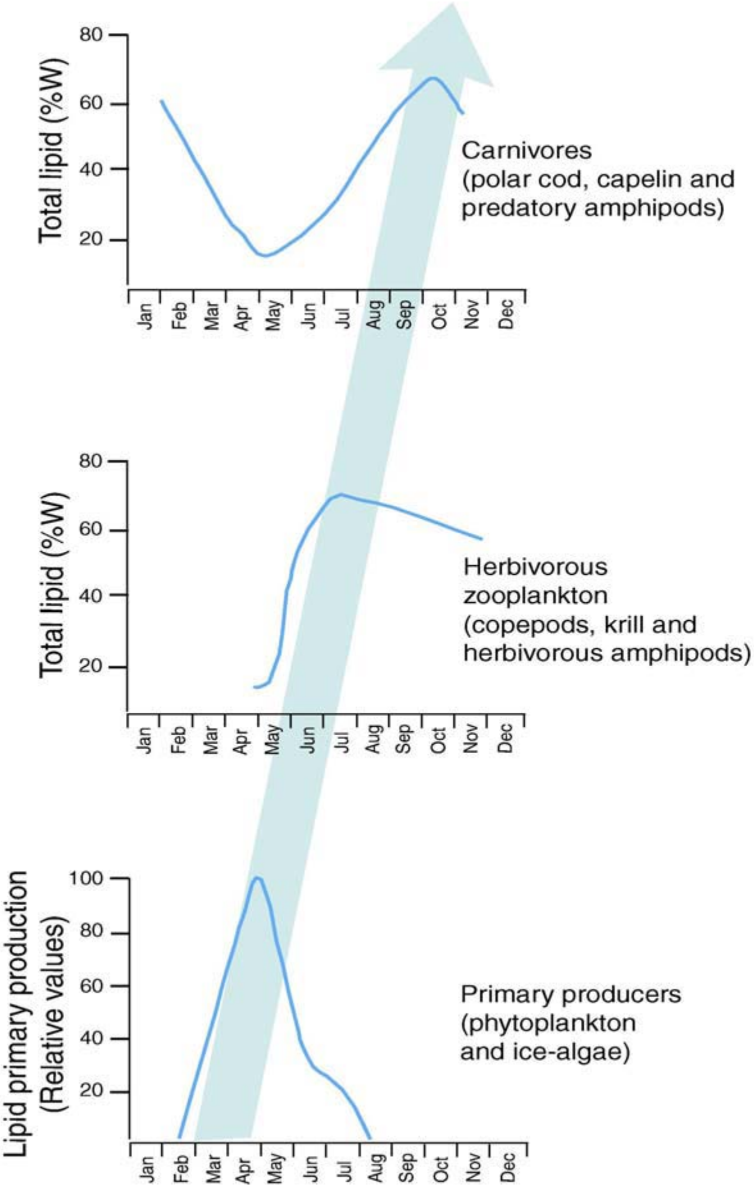

Fig. 9.6. The transfer of lipid from the spring bloom via Calanus and krill to capelin within six months (modified after Falk-Petersen et al. 1990).

Atlantic water influx in periods with high NAO modus (Furevik et al. 2005). Should Arctic warming be a long-term trend, as suggested by IPPC, and much of the southern part of the Arctic Ocean become ice - free during spring and summer, a yearly spring algal bloom will occur in this area, resulting in a large increase in “new” primary production. This will probably create an environment favourable to *C. finmarchicus* and detrimental to *C. glacialis* and especially to *C. hyperboreus.*

Polar pelagic systems are notoriously instable (Sakshaug 1997) and herbivorous zooplankton exposed to marked variations in food available has adapted by storing lipids as energy reserves. The lipid accumulated in large amounts by calanoid copepods is exploited as an energy source by large-stocks of fishes like herring (*Clupea harengus*) and the capelin (*Mallotus villosus*), which themselves can store large quantities of oil derived from zooplankton (Fig. 9.6). These energy rich fishes, together with *Calanus*, krill and amphipods species, occurring in dense schools and swarms, constitute large energy-packed food items for sea birds and marine mammals enabling them to sustain over-wintering populations (Welch et al. 1992). This lipid-based energy flux, from algae to marine mammals (Fig. 9.6), is likely to be a key determinant of the biodiversity and productivity of this environment.

The size spectrum and energy content of the major zooplankton species in Arctic ecosystems determine their value as food sources for the upper trophic levels. Both vary substantially among the three *Calanus* species. For example, *C. glacialis* and *C. hyperboreus* are considerably larger and adults contain approx. 10 and 25 times more energy (lipids), respectively, than *C. finmarchicus*. Fig. 9.5 and Table 9.1 summarise the important characteristics of the individual *Calanus* CV. Taken together this tells us that in the Arctic basin *C. hyperboreus* is the most highly adapted of the three species in accumulating large, energy-rich lipid reserves, followed by the Arctic shelf *C. glacialis* and the north Atlantic *C. finmarchicus* (Sargent & Falk-Petersen 1988; Scott et al. 2000). Perhaps more important for a zooplankton predator, is the difference in the food size spectrum between the three *Calanus* species, decreasing from the large energy-rich quanta provided by *C. hyperboreus* to the smaller less energy-rich quanta provided by *C. finmarchicus*.

9.5 Conclusions

From the above we conclude that *Calanus finmarchicus* is a deep-water species adapted to an environment with a regular yearly spring bloom, as occurs in the Norwegian Sea. *Calanus glacialis* is a shelf species adapted to an environment subjected to large variations in the timing and length of the annual bloom, as found in the northern Barents Sea and the Arctic

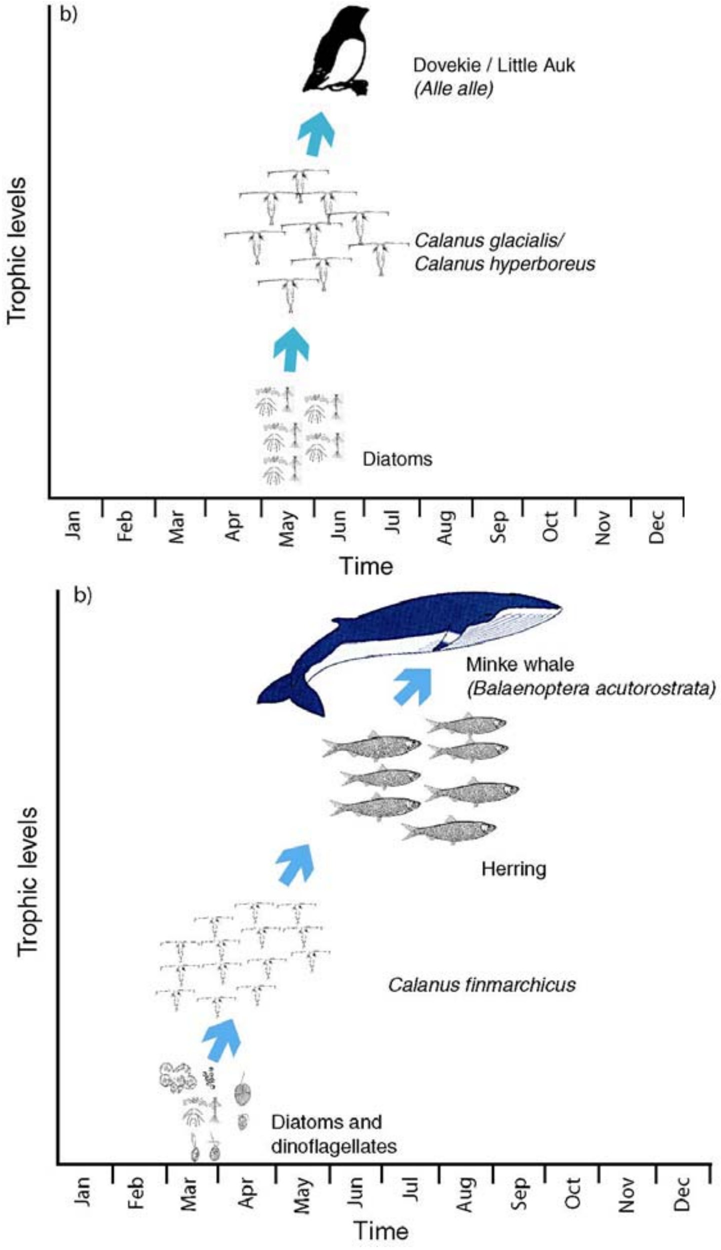

Fig. 9.7. *Calanus* based food web in the Nordic Seas. a) *C. glacialis / C. hyperboreus* based food web b) *C. finmarchicus* based food web.

shelves. *Calanus hyperboreus* is a deep-water species adapted to an environment with large inter-annual variations in ice cover and algal blooms, as found in the central Arctic Ocean and the Fram Strait.

We postulate that a warmer climate with reduced ice cover and new phytoplankton bloom regimes will shift zooplankton community structure towards a smaller zooplankton size spectrum (*C. finmarchicus*), with lower energy content per individual. The changes in zooplankton communities will be reflected in the diet composition and affect the general ecology of specialised seabirds. The little auk (*Alle alle*) requires access large energy-rich zooplankton (*C. glacialis and C. hyperboreus*) to successfully raise their chicks (Fig. 9.7a, Weslawski et al. 1994; Pedersen and Falk 2001). In Iceland, colonies of this high - arctic seabird were heavily reduced during the first half of the last century associated with the rapid warming in the Icelandic climate during the same period (Gudmundsson 1952). The rise in temperature probably triggered a shift in the zooplankton distribution favouring *C. finmarchicus* instead of *C. hyperboreus*, a situation having fatal impact on the little auk. It is more difficult to deduce consequences for generalised sea birds and sea mammals. However, Kitaysky and Golubova (2000) concluded, after 8 years of observation in the Okhotsk Sea, that internal oceanographic change impacted alcid reproduction performances by affecting food accessibility to planktivorous auklets and piscivorous puffins in opposite ways. A northward expansion of *C. finmarchicus* to the northern Barents Sea and into the Arctic Ocean north of Svalbard, due to a continuous warming of the water masses and new phytoplankton bloom regime, will create a prey base in the area that will favour the development of herring stocks. From this we postulate that Arctic warming will cause a ecosystem shift, from today's *C. glacialis* / *C. hyperboreus* based energy transfer favouring little auk (Fig. 9.7a) to a *C. finmarchicus* based food chain leading to minke whale (*Balaenoptera acutorostata*) via herring (Fig. 9.5b).

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10 Adjustment to reality: Social responses to climate changes in Greenland

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10.1 Introduction

Greenland has experienced three major socio-economic shifts during the 19th and 20th century, all of them induced by the interactions between the natural system of climate change, and the socio-economic and socio-technical system of resource exploitation (Hamilton et al., 2003; Rasmussen and Tommasini 2003).

The first was the shift from a sea mammal based economy to fisheries during the latter part of the 19th century and up till around World War II (WWII). This had to do with a marked increase in sea temperature, resulting in a decrease in the sea mammal stock, combined with a dwindling world market for blubber and sealskin. The cod became the dominating species, and in general the changes resulted in the process of sedentarization as well as the starting point of the modernization of Greenland.

The second transformation was the shift from cod fisheries to a mono economy based on shrimp fisheries during the 1970’s and the 1980's. The main reason for this shift was a reduction in sea temperature. This process of diminishing cod resources had already started in the 1960’s and leading to a low in the 1970’s. The decline – in combination with over-exploitation of the stock - basically eliminated the spawning possibilities of the cod stock. At the same time it gave way for a massive expansion of the shrimp fisheries, an expansion which was facilitated by a shift from inshore to off-shore fisheries. Parallel to the transition in resource base Greenland experienced a modernization process. This process created the present infrastructure as well as the production structures dominating Greenland today. Politically it lead to the creating of Home Rule in Greenland in 1979, and in relation to production it resulted in massive investment in the off-shore shrimp fleet during the 1980s.

The third transformation is the ongoing shift towards a more diversified focus of fisheries. This shift has definitely been influenced by the present temperature changes, and is based on shrimp fisheries as the backbone of the economy, in combination with Greenland Halibut, Snowcrab and other species offering substantial contributions to the economy. At the same time the economy seem to be directing towards a situation where major contributions from other business activities outside renewable resource extraction have become crucial. Besides the importance of the local environment on the resource situation in general, however, the characteristics of the world market are instrumental in this new transition process.

10.2 General patterns of resource usage

The marine ecosystem of Greenland waters are in terms of renewable resources among the most productive in the world. They are intermediate between the cold polar water masses of the Arctic region and the temperate water masses of the Atlantic Ocean (Pedersen and Zeller, 2001). The resource situation is characterized by three major water masses. First, the cold (–1.8 °C) polar water coming through the Nares Strait, Baffin Bay and Davis Strait. Secondly, the comparatively warm (3–4 ºC) Irminger Current, a branch of the North Atlantic Current, which transports warm water from the Gulf of Mexico to Europe (Smidt 1989:13). On Greenland's east coast the Irminger Current meets the Polar Current moving south, and both flow south of Cape Farewell and then northward along the west coast of Greenland. The third water mass is the fresh water melting from Greenland's ice sheet (Nielsen et al 1970:57–58).

As the resource situation is determined by water from both the polar and temperate regions, the marine productivity in the Greenland shelf areas is highly influenced by changes in the North Atlantic circulation system. These changes are impacting the distribution of species and fisheries yield around Greenland (Pedersen and Rice, 2002; Buch et al., 2003). And as the distribution of several species are marginal to their core distribution, even a small variations in summer temperatures will highly affect the composition of the marine species.

10.3 Historic changes in resource usage patterns

Hunting, especially for sea mammals, had been the main focus of the traditional lifestyle of the Inuit in Greenland, and also the focus of the colonial

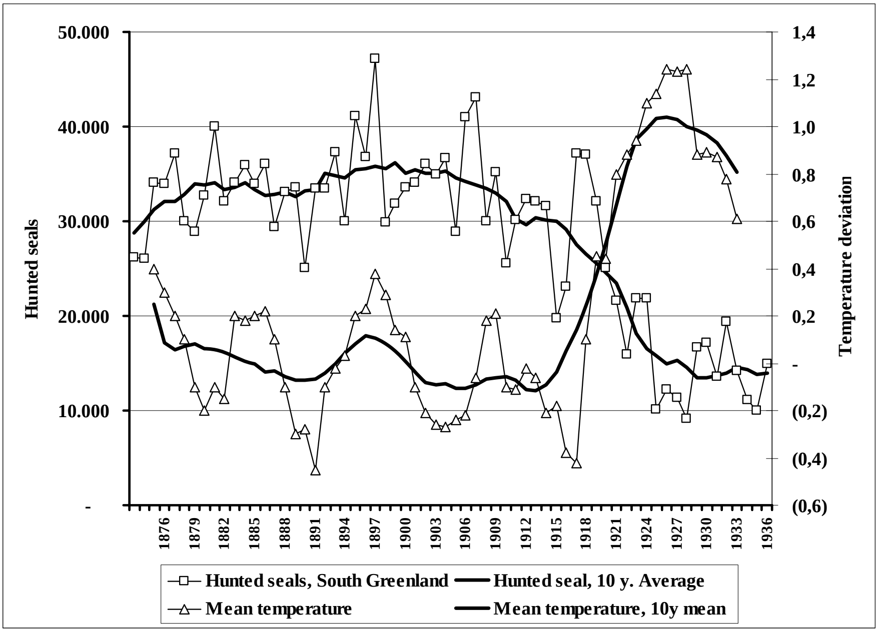

Fig. 10.1: Relationship between decline in seal hunting and temperature change in Greenland 1876-1936. The increase in seal hunting up till 1900 was due to an increase in population. The higher pressure on the resource caused a process of depreciation of the stock, and consequently a decline in number of hunted seals. The process of depreciation of the stock was accelerated by the rather sudden change in temperature from 1918. Partly based on Rasmussen, 2003b.

economic policy for Greenland well into the 20th century. An increase in the population, however, demanded more resources for survival, and as an increase in sea temperatures resulted in a natural decline of the stock, a general problem emerged. Simultaneously the European and North American markets for seal blubber based lamp oil was replaced by mineral oil, so a new basis for as well subsistence as commercial activities was highly needed. The result of the dramatic increase in sea temperature within a 10-year period shows clearly on fig. 10.1, and was followed by a change in resource base from sea mammals - mainly seals - toward fisheries.

10.3.1 The process of sedentarization

The first commercial fishery began in Ilulissat in the 1890s (Nørrevang et al. 1971), followed by an initiative in 1904 towards commercialization by enabling sale of Greenland halibut (Reinhardtius hippoglossoides) in

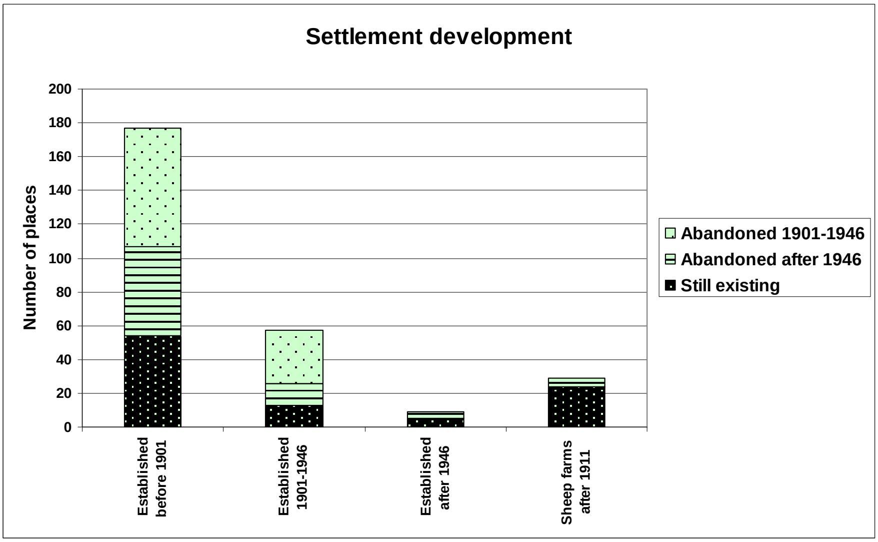

Fig. 10.2: The sedentarization process in Greenland. The major part of the settlements in Greenland have been established in the latter part of the 19th and the early years of the 20th century. Based on data from Rasmussen, 2003b.

Ilulissat, and Arctic char (Salvelinus alpinus) in other parts of Greenland. (Smidt 1989). The Tjalfe research expedition in 1908–1909 had shown that fish were available in several other places along the coast, so in 1910 foreign fisheries for halibut (Hippoglossus hippoglossus) started around Sisimiut, just as a fishery for Greenland halibut was established in the fjords around Qaqortoq. At the same time, the first processing plant for salted cod was established at Qeqertarsuatsiaat south of Nuuk.

The experiences from this plant were of great importance for the further development and expansion of fish processing activities, as several Greenlanders became experienced in the processing technique (Nørrevang et al. 1971). In the following years additional salting plants were established along the coast, and as waters warmed markedly the seals declined, and cod fishing replaced seal hunting (Mattox, 1973). But whereas seals had traditionally provided Greenlanders with almost everything they needed to survive, not only food but also basic elements of clothing, cooking and heating, the fisheries provided only food. This created an obvious demand for commercial activities (Smidt 1989), eventually leading to the sedentarization of the population.

As shown on fig. 10.2, the major part of settlements have been established in the late 19th century, and even a large number of settlements have been abandoned – most of them due to limited or just temporary resource access – the present settlement pattern is more or less reflecting this transition process from a semi-nomadic hunting society to a pattern of fisheries dependent settlements.

10.3.2 Industrialization

After World War II a new approach to development was initiated (Rasmussen and Hamilton, 2001). Its purpose was to reduce the backwardness of the economy, and to bring a modern standard of living to the population. The starting point was the recognition of Greenland as a county in Denmark, and the G50 plan which paved the way for new development of the economy based on fisheries, primarily based on private initiatives. After 10 years, however, it became obvious that the privatization had not succeeded, as there were not any private initiatives on which to build the economy. By 1964 the next plan – the G60-plan - was ready, stressing that public activities were necessary to create a take-off situation for the home economy.

The promotion of large scale industrial activities led to a situation where the major population increase took place in the larger settlements, and especially in settlements with a high potential for development in fisheries. The population growth was matched by massive investments in new infrastructure such as concrete housing on a large scale industrial base. And fisheries, which were considered to be the backbone of the economy, received special attention.

The cod resource was considered inexhaustible, and the world market open and available for new products (Poppel, 1997), so the development perspectives seemed to be unlimited. Consequently the capacity of the fleet was doubled from 1965 to 1975. The total volume of output from fisheries was 50.000 tons and increasing, as shown on fig. 10.3 below. The expansion of the fisheries was almost solely in cod fisheries, but slowly commercial fishing for other species was introduced as well.

The fishermen were aware of the fluctuations in the resources, but the fishing industry - and especially the Royal Greenland Trading Company - was very slow to respond to the ongoing changes. The industry was based on large-scale processing of cod, but it seemed difficult to react to the fact that the situation was changing. So it was not recognized by the authorities until during the 1970s that the changes in sea temperature on one hand contributed to the diminishing of the cod stock, and on the other hand gave way to a new shift in resource base, as indicated on fig. 10.4 below. The decline in sea temperature contributed to the decline in cod stock, which eventually opened up for a boom in shrimp fisheries. And when the

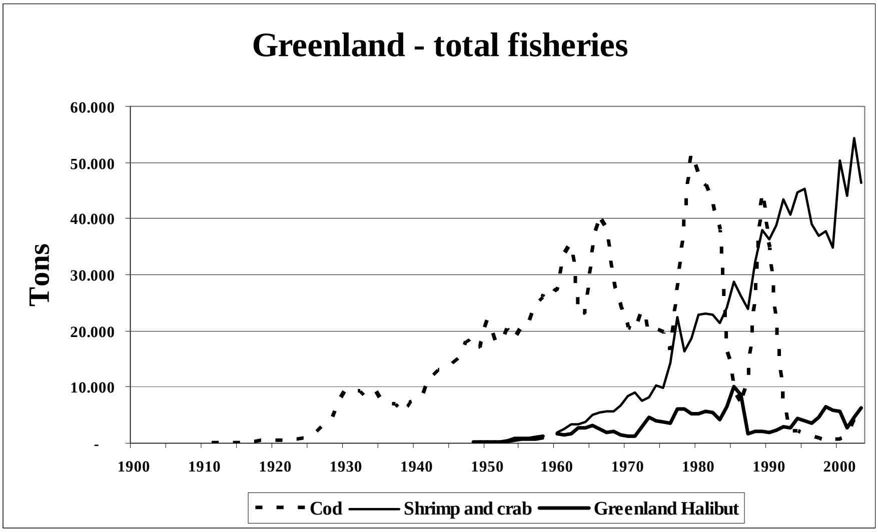

Fig. 10.3: Development of fisheries in Greenland during the 20th century. Cod was the dominating resource until it collapsed in the 1980s, when the dominating position was taken over by shrimp fisheries. During the last 10 years Greenland Halibut has become a major resource for fisheries. Based on data from Rasmussen and Hamilton (2001).

temperature again increased in the late 1980s and 1990s, the cod was not able to regenerate so other species consequently became dominant (Hamilton et al, 2003).

10.3.3 From a cod to a shrimp based economy

It was realized by the Home Rule Government in Greenland, when they took over in 1979, that the changes in the cod stock were permanent and could therefore not be a proper basis for an economic development. A 5-year development plan was introduced in 1984, aiming at investments that should create a massive change of focus from cod towards the much more promising shrimp fisheries.

Until the 1950s, shrimps were mainly pursued by inshore vessels on in-shore banks. But the combination of the cooling of water and a reduced cod stock led to a massive expansion of the shrimp stock. And consequently it caused a massive investment in new fishing gear and off-shore vessels. When the Home Rule took over the government of Greenland, the economic basis was partly transfer money from Denmark. The money were supposed to cover the continuation of both the social and the institutional structures inherited from the colonial days. Instead the Home Rule

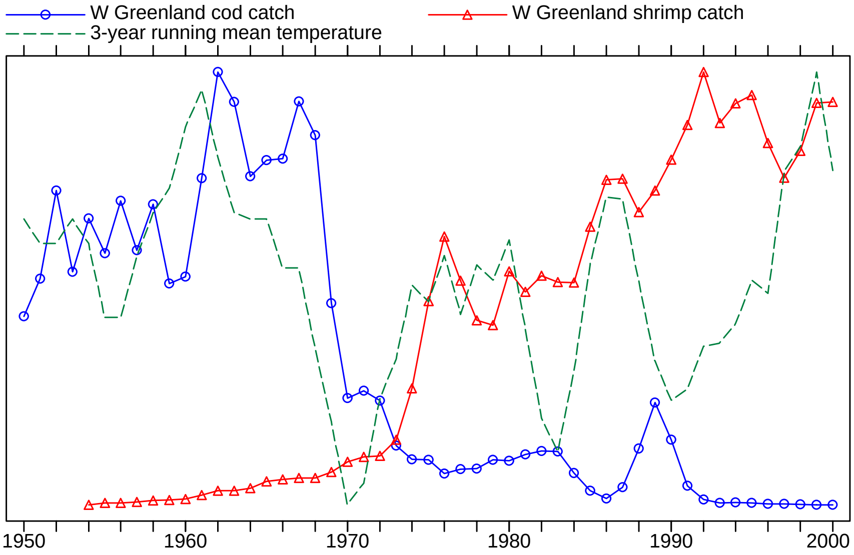

Fig. 10.4: The shift in resource base partly induced by changes in sea temperatures. The marked decline in temperature from 1960 to 1980 was paralleled by the collapse of the cod stock. The following temperature increase then was paralleled by the expansion of the shrimp fisheries. From Hamilton, Brown and Rasmussen, 2003.

Government used part of the money for new initiatives – primarily investments in connection with fisheries, and first of all in the larger west-coast towns. Consequently, a new era was established. The shrimp resource and shrimp related activities became the backbone of the economy, with the Home Rule owned processing plants and a very efficient off-shore fleet as the major players in the game. This shift is very evident when looking at fig. 10.3 and 10.4, eventually transforming Greenland into the worlds largest producer of coldwater shrimp.

10.3.4 The need for diversification

During the last decade the Home Rule government has been confronted with two major obstacles for the economic expansion based on the shrimp resource. First of all, the shrimp fisheries has now been developed to its maximum. Both national and international fisheries advisors are recommending maintenance of the fisheries at the present level, only with minimal adjustments, and this reality seem to be accepted generally by the trade (Det Rådgivende Udvalg, 2004). Secondly, the fishing industry is

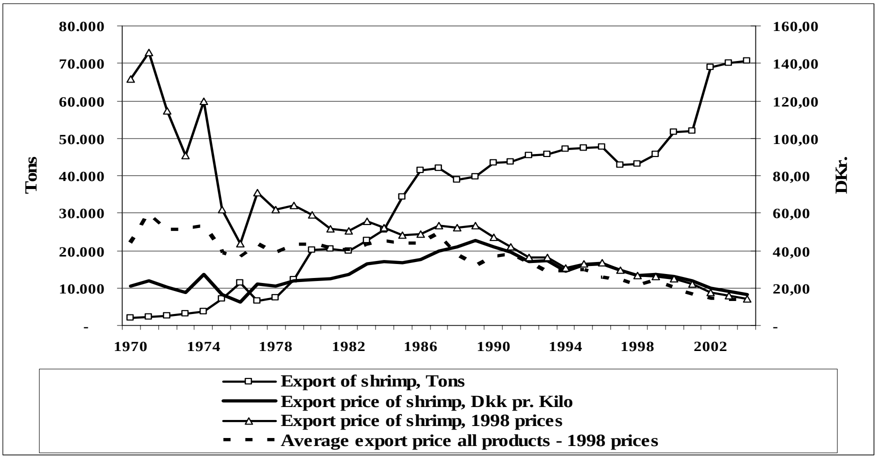

Fig. 10.5: Export volume and export price development of shrimp production in Greenland. Up till the late 1980s both volume and average prices were increasing, but during the last 15 years the average price has declined, while production volume has increased in order to compensate for this decline.

confronted with the harsh reality of the world market. This situation becomes clear when looking at fig. 10.5. The average fixed price of fish products has been more or less in a situation of constant decline. The average price per kilo of export products from Greenland, mainly cooked shrimp, has declined from a level around 30 DKK in the 1980s to the present level around 15 DKK per kilo (both in fixed 1998 prices), and when looking at the price development for shrimp the situation has been even worse.

With a continuation of this trend in world market prices, maintaining a future income at the present level would require a production increase of at least 4-5% per year. And this is not possible - as discussed above - with the present exploitation of the shrimp resource at its maximum.

The changes in the environment and the lack of influx of a new cod stock, however, have contributed to increased access to other renewable resources (fig. 10.6). First of all Greenland halibut has turned out to be an important asset for most of the northern communities in Northwest Greenland during the last 10 years. Settlements in the municipalities of Upernavik and Uummannaq which previously were depending on hunting of seals has become thriving fisheries communities (Det Rådgivende Udvalg, 2003, 2004, 2005). And during the recent years also an increased fishing for snow crab has turned out to be an important contributor to the total economy. Parallel to the development of fisheries, the hunting for both land- and sea-mammals are still contributing to both subsistence and

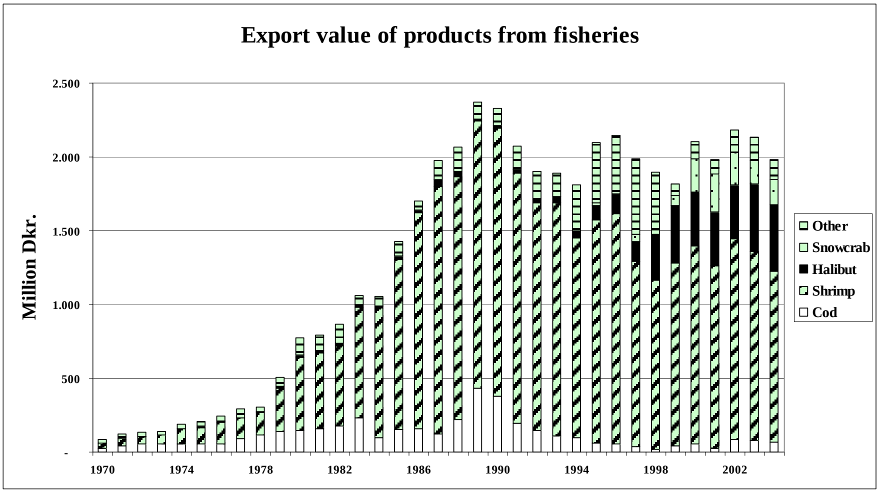

Fig. 10.6: Value of export of fish and fish products from Greenland. The export which was previously dominated by a mono-economy of shrimp products has emerged into a more diverse structure, with more than 1/3 of the total export covered by other species. Partly based on Rasmussen, 2003a.

commercial activities. As shown by Rasmussen (1993b), between 10 to 30 percent of the local economy is still due to contributions from the informal and subsistence sector!

Since the mid 1990s, however, the political aims for the Home Rule in Greenland have been towards consolidation and new business strategies (Poppel, 1997). It has become obvious that there are limitations to economic expansion based on renewable resources, and as a consequence the concept of " the three pillars" - Fishing, Minerals and Tourism – was developed as a strategy for further development. More recently the whole concept of “land based activities” has been added as a crucial cornerstone for future economic development, and if these steps succeed, substantial changes in the resource dependency may eventually appear.

10.4 Conclusions

As presented above, Greenland has experienced three major socio-economic changes during the last 150 years. The first was the shift from a sea mammal to fisheries based economy during the latter part of the 19th century and up till around WWII. It resulted in sedentarization as well as the first steps of modernization of Greenland. While an increase in sea temperature pushed towards a change in resource base, the dwindling world market for blubber and sealskin combined with a growing market for salted and dried fish pulled the economy towards fisheries. This, however, required more centralized processing facilities, and therefore also a more permanent settlement structure.

The second transformation was the shift from cod fisheries to a mono economy based on shrimp fisheries during the 1970’s and the 1980's. Again a shift in sea temperature – this time a temperature reduction which prevented spawning of the cod – in combination with over-exploitation eliminated the previous resource base. Instead the changes gave way for a massive expansion of the shrimp fisheries, an expansion which was facilitated by a shift from inshore to offshore fisheries. This shift, however, was also rather easily adapted to the general modernization process, because the focus already was on concentration and centralization of production as well as of population.

The third transformation is the ongoing shift towards a more diversified focus of fisheries as well as of the economy. This shift is also influenced by the present temperature change, a temperature increase which eventually may lead to a re-introduction of the cod stock, but so far has pushed the Greenland Halibut-fisheries towards Northwest Greenland, and has opened up for a substantial Snowcrab fisheries in the southern and central parts of Greenland’s Westcoast. An important pull in this process towards a more diversified fisheries has been the continuous decline in world market prices of shrimp products. Even a substantial increase in production has not been able to compensate the diminishing revenue, so the diversification has simply been required in order just to maintain a stable income from fisheries. And it has been still clearer that not even a diversified fisheries is enough for the future, but that a diversified economy would be needed.

A common characteristic of all three cases is that both the process and the outcome has been the result of an interaction between environmental changes and changes in the socio-economic structures. In none of the cases the result has been determined by only one of the factors, just as there has been no simple one-way causality. The implications of climate change have been the strengthening of ongoing socio-economic changes, just as it has contributed to the outlining of possible development paths. The socio-economic changes, on the other hand, have been reflecting a more or less pragmatic approach to both the material and the political reality – what could be characterized as an “adjustment to reality”.

The differences between the cases have been the level of implications of the environmental changes. The shift from a sea mammal based economy to a fisheries economy had profound consequences on society, first of all through the sedentratization process. The shift from a cod to a shrimp based economy strengthened an already ongoing process of concentration and centralization, which made the villages more or less redundant, but did not totally re-structure the organization of the communities. And the present diversification of both renewable resource exploitation and the economy in general seems to have reversed parts of the former concentration policy, by making some of the villages close to the new resources as a more active part of the economy.

There is little doubt that the living conditions in Greenland also in the future will experience social changes in interaction with the environmental dynamics similar to what has been the case during the last 150 years.

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UV radiation and biological effects

11 Factors, trends and scenarios of UV radiation in arctic-alpine environments

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11.1 Introduction

The levels of UV radiation at the Earth's surface vary widely, depending on the atmospheric and environmental conditions of the observation site. The knowledge of the effects of the individual parameters affecting UV radiation as well as their interaction is a prerequisite for any analysis of possible long-term trends.

A special situation is found for UV radiation in the Alps and similarly in the Arctic. There the effects of parameters like aerosol amount, altitude above sea level and reflectivity of the ground (albedo) work together to yield the highest possible levels of UV radiation, in addition to the effects of solar zenith angle and atmospheric ozone. Detailed measurements of solar UV radiation levels in Arctic and Alpine regions have been carried out, allowing the estimation of the different effects of these parameters on future UV radiation scenarios.

The measurements of solar UV radiation discussed here are carried out with detectors with a horizontal detector surface, thus determining the irradiance, which assumes a weighting of the incoming radiation with the cosine of the zenith angle. One part of the irradiance comes in a straight line from the sun (direct component), the other part is scattered and arrives as the radiance of the upper hemisphere of the sky (diffuse component). Both parts together form the global irradiance, which is the usual quantity for any meteorological or biological discussion of UV effects.

The measurement results presented here stem from two types of instruments. Measurements with a spectroradiometer (spectral resolution of 0.5 to 1 nm) provide the most valuable data, allowing a range of analyses of the results. However, especially in the UV-B range this is still challenging and it requires highly experienced manpower to reach an absolute level of uncertainty of ±5% (Bais et al. 2001). Therefore, routine observations are often carried out with broadband detectors, which are less costly to acquire and operate, but are usually also less accurate. Still they need careful maintenance. The most widely used are broadband detectors which have a spectral sensitivity simulating the sensitivity of the human skin for erythema (McKinlay and Diffey 1987). With proper calibration, these detectors can directly measure biologically relevant irradiance.

11.2 Variability of solar UV radiation

Assuming cloudless conditions, the most important parameters for solar UV irradiance are solar zenith angle, ozone content of the atmosphere, amount of aerosols, albedo of the ground and altitude above sea level. Some other parameters are of less significance, i.e. further absorbing gases in the atmosphere besides ozone, type and optical characteristics of aerosols or vertical distribution of the constituents of the atmosphere. For Alpine and Arctic environments, albedo of the ground and altitude above sea level are of special significance. If clouds cover the sky, then the radiation levels are dominated by the type and distribution of the clouds.

11.2.1 Effect of solar zenith angle

The solar zenith angle (SZA) at the time of observation is the most significant parameter, determining the level of UV radiation. It is fixed by the latitude of the observation site and by the local time. The higher the SZA the smaller is the irradiance as a consequence of increasing absorption and backscattering in the atmosphere with increasing path length of the radiation from the sun. This effect is especially pronounced for UV-B irradiance (280 - 315 nm), as additionally these wavelengths are absorbed more efficiently in the ozone layer of the atmosphere when the SZA is higher. Therefore, the diurnal and annual course of UV-B irradiance is much steeper than the course of UV-A irradiance (315 - 400 nm) or visible irradiance. As an example, in Innsbruck (47.3°N, 577 m above sea level) the ratio between maximum values of daily sums in summer relative to winter is about 5 for UV-A irradiance and about 15 for erythemally weighted UV-B irradiance.

Another consequence of the effect of the SZA on irradiance is the decrease of daily maximum irradiance levels, when going from mid latitudes towards the North Pole (assuming that all other parameters remain constant). Again, this effect is more pronounced for UV-B radiation compared to UV-A radiation. However, also the length of the day in summer is increasing, so that daily totals are less reduced than daily maxima.

11.2.2 Effect of ozone

The total ozone content of the atmosphere is the second most important parameter, to influence UV-B radiation. The absorption cross section of ozone is strongly decreasing in the UV range. Almost no radiation with wavelengths below 285 nm can be measured at the earth's surface, whereas the effect of ozone can almost be neglected at wavelengths above 330 nm. About 9% of the total amount of ozone is in the troposphere, the maximum concentration is located at altitudes between about 20 to 30 km in the so-called ozone layer.

The total amount of ozone varies strongly both locally and temporally, generally being between about 250 and 400 Dobson Units. Maximum values in mid-latitudes are observed in spring-time, when the day to day variability is also the highest, minimum values occur in autumn.

The reduction of global UV irradiance (*I*) by ozone (*O*) can be quantified by complex radiative transfer models, but it can be simplified with a power-law: $I \approx O^{-RAF}$. The exponent *RAF* is the radiation amplification factor. For relatively small variations of O (ΔO) the power law can be transformed to a linear form:

$$\frac{\Delta I}{I} = -RAF * \frac{\Delta O}{O}$$

This law is valid for specific wavelengths as well as for broadband wavelength ranges. For erythemally weighted irradiance the RAF amounts to about 1.1, thus a reduction of ozone by 1% will result in an increase of erythemal irradiance by 1.1%. This relation has been verified by many measurements under the assumption that all other relevant parameters are constant (McKenzie et al. 1991, Blumthaler et al. 1995). The RAF is only slightly dependent on SZA, therefore it is a useful fast tool to estimate the effect of ozone changes.

11.2.3 Effect of aerosols

In many environments the amount of aerosols in the atmosphere is a further important parameter affecting UV radiation. The influence of aerosols depends only slightly on wavelength, with an increasing effect towards shorter wavelengths. In many cases, aerosol scattering is dominant, thus

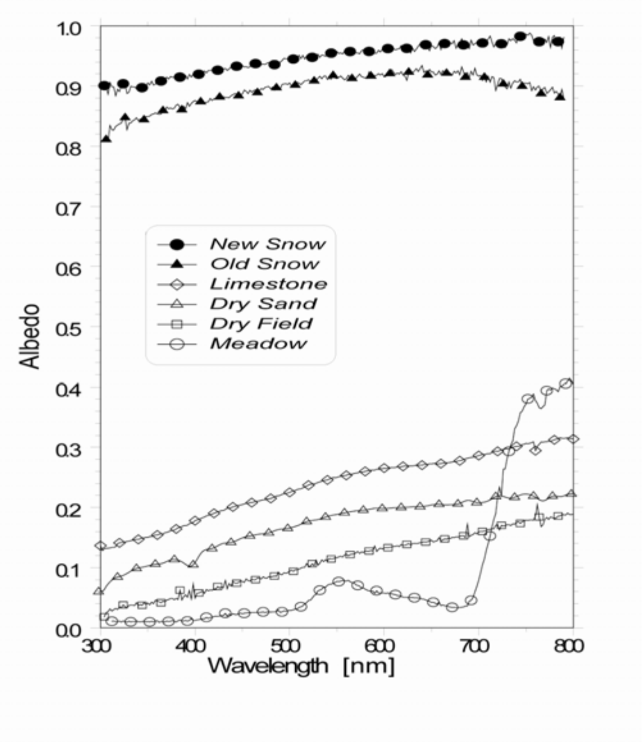

Fig. 11.1. Spectral albedo of various types of surfaces.

the amount of direct irradiance is reduced and the amount of diffuse irradiance is increased. However, if the absorbing component of the aerosols is high, then global irradiance can be reduced significantly. In urban areas, reductions of up to 30% for erythemal irradiance have been measured, compared to an aerosol-free atmosphere (Kylling et al. 1998).

In Alpine environments and especially at higher altitudes as well as in Arctic regions, the aerosol load is usually low. Only in basin areas layers of aerosols can appear when no exchange of the air mass by local winds occurs for certain time periods.

11.2.4 Effect of albedo

The albedo of a horizontal terrain is defined as the ratio between reflected radiation and incoming radiation. The reflected radiation enhances the diffuse irradiance due to multiple reflections between the ground and the atmosphere. Therefore the albedo effect is generally higher with a cloud layer, compared with a cloud-free situation.

The amount of reflected radiation depends on the type of surface, and furthermore it is dependent on the wavelength. Spectral measurements of albedo of various types of surfaces (Fig. 11.1) show a clear division into two regions: all snow-free surfaces have relatively small values of albedo, which are especially small in the UV range. The smallest values for albedo were found for green grassland, where in the UV-B the albedo was less than 1%. On the other hand, snow-covered surfaces show very high values of the albedo, which can be higher than 90%. However, these very high values are only valid for snow-covered surfaces with fresh, clean snow. Due to aging and deposition of pollution the snow can become less reflective, which may reduce the albedo down to approximately 60%, depending on the local conditions (Ambach and Eisner 1986).

Since the share of diffuse irradiance is higher in the UV than in the visible range, the effect of high albedo is especially pronounced in this wavelength range. The amplification of global irradiance due to increasing albedo has a maximum at around 320 nm (Fig. 11.2). The albedo effect decreases in the UV-B range due to absorption of the multiply scattered UV-B radiation by tropospheric ozone. The increase in global irradiance when changing from a snow-free surface (average albedo 7%) to a snow-covered surface (average albedo 75%) amounts to about 25% at 320 nm

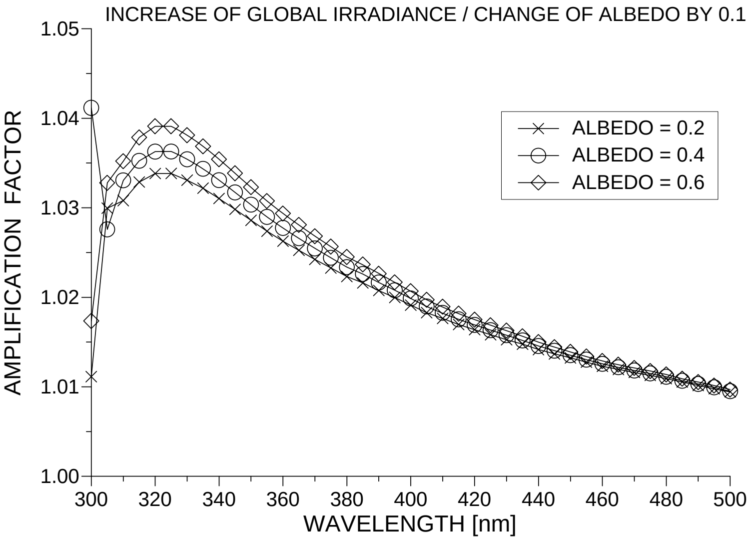

Fig. 11.2. Increase of global irradiance due to an increase of albedo by 0.1 for albedo values of 0.2, 0.4 and 0.6.

and 7% at 500 nm, which is a significant contribution to the high UV levels in Alpine and Arctic environments.

For estimating the effect of a surface with a certain albedo on UV irradiance an area up to 30 km around the measurement site is significant (Degünther et al. 1998). If the terrain is covered by snow it is usually not a homogenous surface. For example, trees usually lose their snow cover rapidly so that the regional albedo can be significantly lower than the albedo of a homogenous snow surface. This effect can be estimated when the ‘effective’ albedo is determined. This is the value of albedo for a homogenous, infinite surface, introduced into a one-dimensional radiative transfer model. The value of the albedo is then used to fit the model output to measurement results of spectral global irradiance (Weihs et al. 2001). By applying this method, temporal variations of the effective albedo can be followed (Fig. 11.3). During a measurement campaign at the High Mountain Station Jungfraujoch (Swiss Alps, 3576 m above sea level) in spring 1998, the effective albedo decreased from about 0.7 to 0.45. At the beginning, most of the surrounding was covered by snow, although several rocks and the trees at the lower altitudes were snow free. Later, when the snow at altitudes below about 2500 m (covering about 50% of the surrounding of the station) melted away, the overall effective albedo was reduced due to the average effect of snow-covered and snow-free terrain. During periods with cold weather and precipitation, snow returned for a short period at lower altitudes again (around days 30-35 in Fig. 11.3), and the effective albedo increased to values around 0.6. During a following period of good-weather, the snow melted again and the effective albedo became smaller again (days 35-40 in Fig. 11.3).

11.2.5 Effect of altitude

The increase of UV radiation with increasing altitude is a consequence of several factors working together. The basic effect is that at higher altitudes the air mass above the site is less and therefore the attenuation of radiation due to scattering and absorption is less too. This effect is especially pronounced for direct irradiance, whereas diffuse irradiance is only slightly reduced at higher altitudes. As a consequence, at higher altitudes a greater part of the global irradiance stems from the direct component. The scattering processes in the atmosphere are much more pronounced for shorter wavelengths and therefore the increase of irradiance with increasing altitude is greater for the shorter wavelengths. Additionally, in the UV-B range the altitude effect (increase of global irradiance for an increase of altitude of 1000 m) increases strongly due to the effect of absorption by

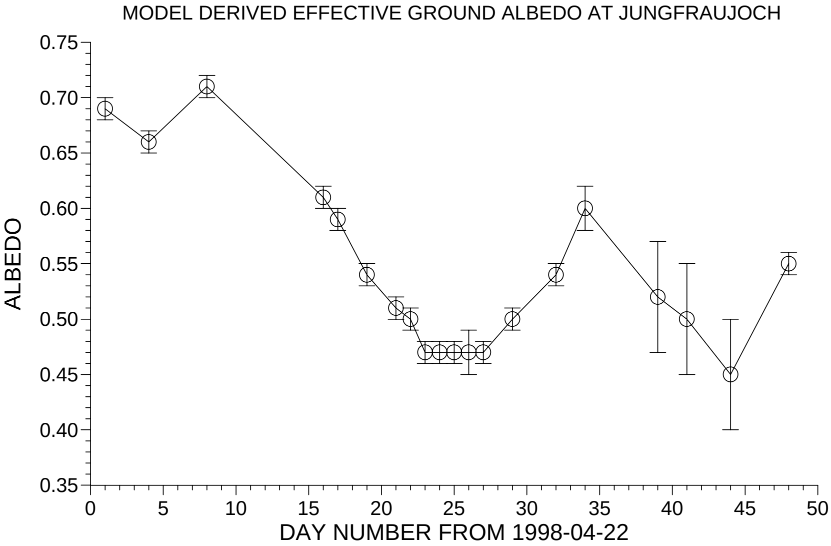

Fig. 11.3. Temporal variation of effective albedo at Jungfraujoch (3576 m above sea level).

tropospheric ozone. Furthermore, with increasing altitude usually the amount of aerosols above the observer is reduced, so that the irradiance is enhanced, only very slightly increasing with decreasing wavelength. Consequently, the altitude effect depends strongly on the local situation of the amount and vertical distribution of aerosols and ozone. Finally, albedo can increase the irradiance at higher altitudes, because there the surroundings are often covered by snow, whereas the lower altitudes are snow-free. This will increase the altitude effect (Gröbner et al. 2000).

All the afore-mentioned processes contribute together in a variable way to the final altitude effect. Therefore, it is not meaningful to mention only one number for the altitude effect but it is more realistic to consider a broad range of values. In any case, at shorter wavelengths the altitude effect becomes more pronounced.

From synchronous spectral measurements in the Alps at different altitudes the increase per 1000 m was found to be around 10% at 360 nm and 25% at 300 nm (Fig. 11.4) (Blumthaler et al. 1994a). Measurements of the altitude effect with broadband detectors in the Alps showed values of 15-25% for erythemal UV irradiance and about 10-15% for total irradiance (300 nm to 3000 nm) (Blumthaler et al. 1997). In contrast, measurements in the Andean mountains with small amounts of aerosol and no snow cover showed values for the altitude effect of about 9% in the UV-B (Piazena 1996).

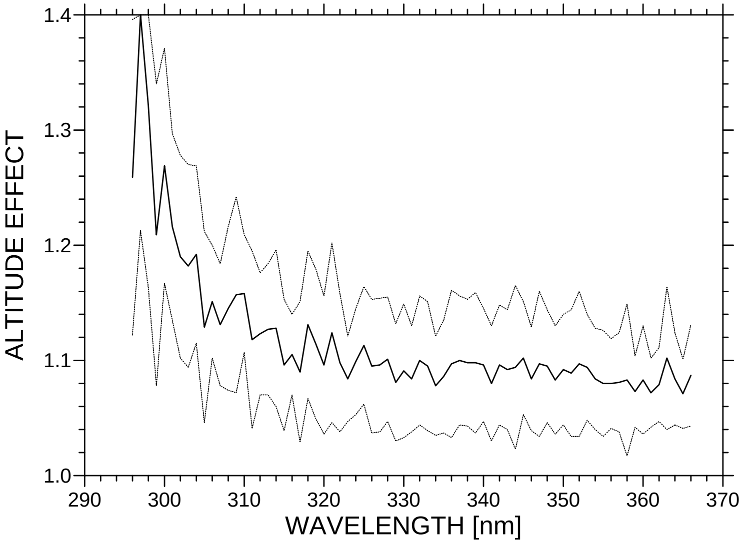

Fig. 11.4. Increase of spectral irradiance with altitude, average (solid line) and range of variation (dashed lines). From Blumthaler et al. 1994a.

11.2.6 Effect of clouds

Clouds in front of the sun attenuate the direct irradiance in proportion to their optical thickness. Clouds covering the sky usually cause an attenuation of global irradiance too. The overall reduction of global irradiance by clouds can vary over a broad range, on the average under completely overcast sky the UV irradiance is reduced by 50-80% (Josefsson and Landelius 2000). Measurements at higher altitudes show less attenuation because the optical depth of the clouds is on average smaller than at sea level. For very thick clouds, the reduction can be up to 90%. These numbers show that clouds represent the most dominant factor governing the level of global UV irradiance, and all other parameters, discussed previously, are less significant.

Short term intensification of UV irradiance of up to 20% can occur when clouds are close to the sun and the sun itself is not covered by clouds (i.e. Cede et al. 2002). Usually this happens only for short time periods of minutes, because clouds are moving with the wind and therefore this special situation with reflections is only transient.

The attenuation of global irradiance by clouds is also wavelength dependent. Simultaneous measurements of irradiance in the total wavelength range, in the UV-A and in the UV-B range show that the irradiance in the UV range is less attenuated than in the total wavelength range by up to 40% under completely overcast conditions (Blumthaler et al. 1994b). This is a consequence of the high diffuse component of UV irradiance compared to total irradiance. Also measurements of global irradiance above and below a homogeneous cloud layer in the Alps show that the transmission is higher at shorter wavelengths (Seckmeyer et al. 1996).

11.3 Long-term variations

Long-term variations of solar UV radiation at the Earth's surface can occur due to long-term variations of one or more of the parameters discussed above. Concerning specifically the Alpine and Arctic environment, the possible parameters responsible for any long-term variation of UV radiation are total ozone, snow-coverage and cloudiness.

Long-term variations of total ozone have been monitored world-wide for several decades, and significant changes have been observed, which are partly global and partly regional. For middle Northern latitudes, a slight ozone decrease was observed from beginning of the 80's to the middle of the 90's, since then the levels have been about constant at about 3% below the pre-1980 values. For high Northern latitudes, especially in spring-time a higher ozone reduction has been observed, with strong variations from year to year (WMO 2003).

The very small amount of aerosols at high altitudes allows investigation of the long-term effects of changing total ozone on UV irradiance on clear sky days without disturbance by changing aerosol amounts. Measurements of erythemally weighted UV irradiance over more than 20 years at the High Mountain Station Jungfraujoch (Swiss Alps, 3576 m above sea level) demonstrate these long-term variations (Fig. 11.5). The data are collected during measurement campaigns of about 8 weeks every year, at varying seasons from year to year. Cloudless conditions at 30° solar elevation are analysed. The relative variation of total radiation shows the effect of varying albedo, which gives about ±10% variability with highest values during measurements in winter time. The relative variation of erythemally weighted irradiance shows a variability of about -30% to +40%, which is generally in phase with the variation of total irradiance and therefore correlated with albedo variations. In addition, the variability of total ozone modulates the UV variations in the sense that during periods of low ozone

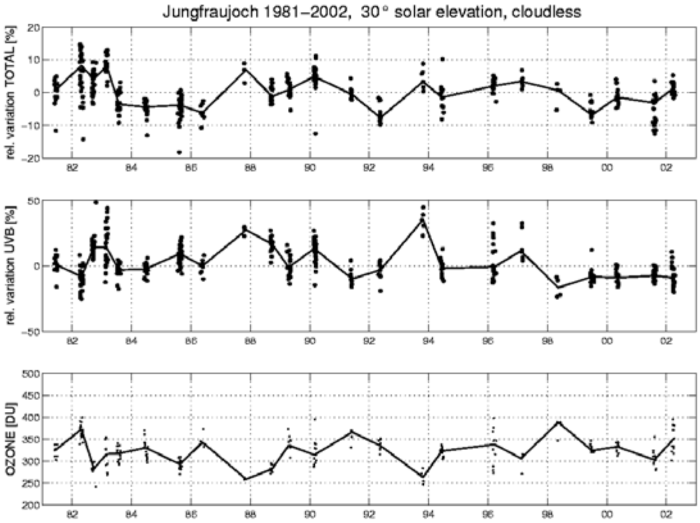

Fig. 11.5. Long-term variation of total irradiance, erythemal UV irradiance ('UV-B') and total ozone on cloudless days of the measurement campaigns at Jungfraujoch (Swiss Alps, 3576 m above sea level) between 1981 and 2002. For total and UV-B irradiance the relative variation from the mean over the whole period is shown. Total ozone data are from Arosa, Switzerland, taken from the World Ozone and UV Data Center, Canada (http://www.woudc.org).

and high albedo an especially high erythemal irradiance is observed, whereas with high ozone and low albedo especially low values of erythemal irradiance are observed. Besides the short-term variability of erythemal irradiance, no systematic long-term trend can be observed over the whole period from 1981 to 2002. For shorter time intervals in the 80's, a small but significant trend of increasing erythemal irradiance was observed (Blumthaler and Ambach 1990), in agreement with the ozone trend at that time.

Trends of erythemal UV irradiance between 5-10% per decade during the last 2 decades have been found by Kaurola et al. (2000) in Northern Europe, and are most significant during spring time.

Long-term spectral measurements in the Arctic (Sodankylä, Finland, 67° N) report spring season increases of irradiance at 310 nm of about 20% from 1990 to 1998 and of more than 40% at 305 nm, showing clearly an effect associated with ozone decrease (Masson and Kyrö 2001). In the same time period, irradiance at 325 nm increased by about 10%, which could be caused by albedo changes during that period and at that site. However, although this time series of spectroradiometric measurements at Sodankylä is among the longest in Europe, it is still relatively short, and the choice of the time interval may affect the results.

These examples of experimental results show how important long-term observations of solar UV radiation are for interpretation of any trend. Both analyses were carried out for almost clear sky conditions, because if all sky conditions would have been analysed, then the strong variability of cloudiness would require much longer time series (Weatherhead et al. 1997). For separation of any long-term variation of UV radiation into the contributing factors, spectral measurements would be preferable, because the different spectral behaviour of changes in ozone, in albedo and in cloudiness could be identified in the results. Such spectral time series are shorter and less frequent than broadband data, so that results cannot be expected soon.

11.4 Conclusions

The main parameters determining solar UV radiation in arctic-alpine environments, which might be changing over longer time periods, are ozone, aerosols, albedo and cloudiness. Based on measurements, quantifications of the effects of these parameters on solar UV radiation are derived. This allows estimating consequences for solar UV radiation in the future, if certain scenarios for the variations of these parameters are assumed. Some possible examples for future scenarios are:

UV radiation at middle and northern latitudes will decrease slightly, if stratospheric ozone is recovering due to the actions of the Montreal protocol and its successors.

UV radiation will increase due to a decrease of aerosols, if air pollution is reduced in industrial areas due to actions for protecting the environment.

UV radiation will decrease, if the area of snow-covered terrain is reduced due to increasing temperatures.

UV radiation will increase, if the average amount of cloudiness is decreasing.

In practice, all these possible changes are linked together and coupled by feedback mechanisms. Therefore, predictions about future levels of UV radiation are at the moment very uncertain. However, the knowledge of the quantitative relations between the significant parameters and the level of solar UV radiation at the Earth's surface is available and therefore any scenario for the future can be described. Nevertheless, also in the future, high quality measurements of UV radiation will be necessary to monitor any significant variation.

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12 Effects of enhanced UV-B radiation and epidermal UV screening in arctic and alpine plants

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12.1 Introduction

Plants, as sessile organisms dependent on sunlight for their very existence, are often expected to be vulnerable to increasing UV-B radiation. During the last three decades, more than 800 articles have been published concerning UV-effects on plants (ISI database). Studies have been performed at all levels, from cellular investigations to large projects concerning the effects on entire ecosystems. Of the large number, however, less than 5 % of UV-B response studies on plants have been conducted in the field, and even fewer with plants growing in their natural ecosystems (Caldwell et al. 1998). Only about ten studies have been published on the effects on plants from arctic and alpine areas.

This chapter focuses on possible negative effects of increased UV-B radiation and protection against UV-B offered by absorbing pigments. The UV-absorbing compounds in higher plants are mainly located in the epidermis of leaves, where they screen damaging radiation before reaching the mesophyll cells. Experiments with mutants of higher plants have shown that the UV-B sensitivity of leaves and whole plants is strongly correlated with the concentrations of constitutive and UV-B induced screening pigments in the epidermis (e.g. Lois and Buchanan 1994; Landry et al. 1995). UV-B screening compounds in higher plants are often phenolics, of which hydroxycinnamic acid esters (HCAs) and flavonoids are of particular importance. HCAs absorb mainly in the UV-B, while the flavonoids have a second major absorption band in the UV-A. An increased concentration of phenolic compounds in higher plants is a common response to

UV-B, documented in numerous field and growth chamber studies, (for a review, see Searles et al. 2001).

12.2 Research on UV-B effects

UV-B radiation not attenuated by the epidermis may have various effects on plants, direct and indirect, from cellular to ecosystem level. UV-B effects on higher plants have recently been reviewed with emphasis on natural conditions by e.g. Rozema et al. (1997b), Caldwell et al. (1998) and Day (2001); on arctic terrestrial organisms by Björn (2002). Few studies have been published from the arctic environment. Apart from some extensive studies including plants from the American Arctic published in the 1980s (Robberecht et al. 1980; Caldwell et al. 1982; Barnes et al. 1987), the only "arctic results" to our knowledge come from UV-B enhancement experiments established in a subarctic heathland in Abisko, Northern Sweden (68 °N). Some of these experiments started as early as 1991, and have resulted in many publications (reviewed by Björn (2002)). Generally, these studies simulated an 11 % depletion of the ozone layer (according to the function by Caldwell (1971)) in squarewave lamp systems. Now, a "second generation" of results after 7-8 years of UV-enhancement are being published (Phoenix et al. 2001; Semerdjieva et al. 2003 a,b), allowing comparisons with the first results from the middle 1990s (Johanson et al. 1995; Gwynn-Jones and Johanson 1996, Gwynn-Jones et al. 1997, Phoenix et al. 2000).

The research group, which started the experiments in Abisko, also established UV-B enhancement installations in the arctic Adventdalen, Svalbard (78 °N) in 1996. The first results from these studies are published, (Solheim et al. 2002; Bjerke et al. 2003; Nybakken et al. 2004 a, b).

Most studies of UV-effects on alpine plants are investigations of epidermal screening in plants growing along natural UV-B gradients (see section 1.4 below). The few enhancement studies that exist will be reported on in section 1.3.

12.3 Effects of UV radiation on higher plants

DNA is damaged by absorption of UV-B quanta in aromatic residues, resulting in structural alterations such as formation of cyclobutane dimers (CPDs), and, to a lesser extent, pyrimidine (6-4) pyrimidone photoproducts (Britt 1996). Such photoproducts can inhibit replication or even cause

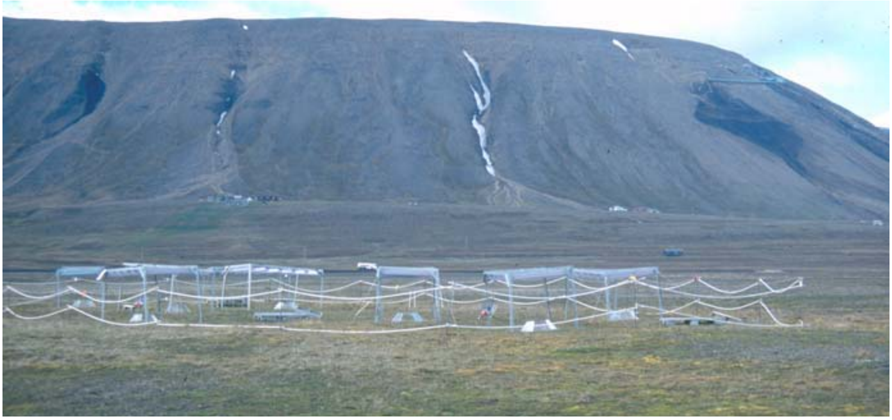

Fig. 12.1 UV-B enhancement experiment in the Adventdalen valley, Svalbard. The UV-B fluorescent tubes installed on frames above the natural vegetation simulate an 11% depletion of the ozone layer.

mutations, thereby affecting gene expression. DNA modifications may also disrupt cellular metabolism (Britt 1996; Mitchell & Karentz 1993). Normally, damage due to UV-B radiation is efficiently repaired (Britt 2002), but the enzymatic repair may be retarded in cold regions due to low temperature (Li et al. 2002). Therefore, plants in arctic-alpine environments may possibly be more sensitive to an increase in UV-B radiation than plants in warmer areas.

Early UV-B research mainly dealt with adverse effects on the photosynthetic apparatus, and growth chamber studies confirmed negative effects of UV-B (Tevini & Teramura 1989). Caldwell et al. (1982) found that photosynthetic inhibition by UV radiation was consistently more pronounced in arctic populations of the genus *Oxyria*, *Taraxacum* and *Lupinus* than in their closely related counterparts from alpine environments at middle and low latitudes. Their plants were grown from seeds in a growth chamber, and UV-B treated indoors. Allen et al. (1998) concluded in a review that effects on photosynthetic competence and light-interception measured at high UV-B irradiance relative to PAR and UV-A, disappear under field conditions with realistic spectral ratios between the different wavebands. This conclusion was confirmed by a recent field study of the alpine plants *Saussurea superba* and *Gentiana straminea* (at 3200 m a.s.l.) under UV-B enhancement simulating nearly 14% ozone reduction. Shi et al. (2004) found that neither CO_2 uptake nor photosynthetic O_2 evolution rate were decreased after 5 month’s treatment.

Increased production of free radicals is another possible threat for plants under high UV-irradiation (Hideg et al. 2002, Barta et al. 2004). As a result, peroxidation of unsaturated lipids occurs as a response to UV-B

(Panagopoulos et al. 1990). Since organisms living in cold environments need a high proportion of unsaturated fatty acids to maintain membrane fluidity (Nishida and Murata 1996), they are presumably vulnerable to radiation-induced peroxidation (Björn 2002). However, Taulavuori et al. (1998), did not find any evidence of oxidative stress in subarctic *Vaccinium vitis-idaea* exposed to enhanced UV-B radiation in the field.

Many plants exhibit morphological changes due to increased UV-B radiation. Examples of such changes are decreased plant height and leaf area (Tevini & Teramura 1989; Johanson et al. 1995; Mepsted et al. 1996), thicker leaves (Rozema et al. 1997) and reduction in dry weight (Searles et al. 2001). Changes in plant morphology may, however, be beneficial, by e.g. decreasing the amount of tissue exposed to UV-B radiation (Cen and Bornman 1993). After 7 years of UV-B treatment of dwarf shrub vegetation in a subarctic heathland (Abisko, Sweden), Semerdjieva et al. (2003a) found no effects of 15 % enhanced UV-B on leaf or cuticle thickness in the four species studied. Gwynn-Jones and Johanson (1996) studied two subarctic grass species, and found that growth (measured as total plant dry weight) was significantly reduced by 15 % enhancement of UV-B in a greenhouse (reduced tillering). Surprisingly, no reduction of growth occurred at 25 % UV-B enhancement (tillering increased compared with ambient UV-B). A negative correlation between growth and amount of UV-B absorbing compounds in one of the investigated grasses (*Calamagrostis lapponica*) indicate a possible cost for compound synthesis, and, hence, reduced growth.

Reproductive yield may also be affected by UV-B (Searles et al. 2001), by altering both the timing of flowering (Mark et al. 1996; Caldwell 1968; Ziska et al. 1992; Staxén & Bornman 1994) as well as the number of flowers (Saile-Mark & Tevini 1997; Musil 1995; Klaper et al. 1996). However, arctic-alpine plants often rely on clonal growth, and seldom reproduce sexually. Phoenix et al. (2000) investigated regeneration by clonal growth of subarctic dwarf shrubs under enhanced UV-B during four years. All aboveground plant parts were removed from the plots. Species responded differently, but the final biomass for each species was significantly affected by UV-B only for *Calamagrostis lapponica* (reduced to 50 %). U. Johanson and his collegues (pers. comm.) measured growth and reproduction responses in a number of species in the UV-B enhancement experiment on Svalbard. In *Bistorta vivipara* most growth parameters measured were significantly reduced by enhanced UV-B, as were numbers of flowers and reproductive units. Other studied species were not significantly or only slightly affected.

As species differ in susceptibility to UV-B, increased UV-B radiation may have an effect on competition between species, and, hence species composition (Barnes et al 1988, 1995). In a two years study of a subarctic heathland in Northern Sweden, Johanson et al (1995) found that growth of evergreen dwarf shrubs (*Vaccinium vitis-idaea* and *Empetrum hermaphroditum*) was repressed more than that of co-occurring deciduous dwarf shrubs *(Vaccinium myrtillus* and *V. uligonosum*). After five more years under the UV-B enhancement these effects had disappeared again. Phoenix et al (2001) reported that now *V. myrtillus* was the only species significantly affected by UV-B, and that the evergreen species showed few responses. They speculate that even if the leaves of the evergreens are exposed to UV-B for longer time during the growing season, and there is a possibility for damage to accumulate over years (Sullivan and Teramura 1990; Johanson et al. 1995), their bud burst is later and they thus avoid much of the highest radiation period in spring. After 8 years, there were still no observable changes in species frequency in these experimental plots (Björn 2002, citing U. Johanson).

In addition to direct effects on single plants, there is increasing evidence that UV radiation affects many trophic interactions and influences a variety of ecosystem functions (Paul & Gwynn-Jones 2003). Field studies have shown that UV-B may reduce insect herbivory, abundance and performance (Ballaré et al. 1996; Rousseaux et al. 1998; Salt et al. 1998; Mazza et al. 1999). The reasons for these changes are not always clear, but they may be mediated through changes in plant secondary chemistry or alterations in plant nitrogen or sugar content (Hatcher & Paul 1994; Yazawa et al. 1992; McCloud & Berenbaum 1994). Plant fungal and viral diseases respond in a number of different ways to UV-B radiation as shown in several experiments, conducted primarily in laboratory and greenhouse conditions. UV-B radiation has significant effects on leaf litter decomposition by stimulating photochemical breakdown of compounds such as lignin and/or by altering the community of decomposer organisms and so inhibiting microbial decomposition (Duguay & Klironomos 2000; Moody 1999; Paul et al. 1999). In general, enhanced UV-B in field studies in the (sub)-arctic caused so far only modest effects in the plants.

12.4 Studies along natural UV-B gradients

Arctic and alpine environments offer the plants some similar climatic conditions, like low temperatures and short growing seasons, and many plant species in the arctic extend their distribution to alpine areas further south. UV radiation, however, increases with altitude and decreases with latitude and represents a probably important difference between arctic and alpine habitats. Furthermore, this allows us to study adaptation to UV-B radiation in ecotypes of the same species (or at least closely related species) along natural UV-B gradients. Most studies of UV-B effects on plants from alpine areas have been performed along such natural UV-gradients, either from lowland to alpine (elevational) and/or from arctic to alpine (latitudinal).

Larson et al. (1990) compared responses of an alpine (*Aquilegia caerulea*) and a non-alpine plant (*A. canadensis*) to enhanced UV-B in a greenhouse. Both species became significantly shorter (greatest effect on the non-alpine species) and developed a higher number of leaves (most in alpine species); there was, however, no altitudinal difference in the effect of UV-B on parameters like biomass, net photosynthesis and flavonoid content. Sullivan et al. (1992) collected seeds of different species along a 3000 m elevation gradient in Hawaii and grew them in a greenhouse with either no or two different irradiances of UV-B. There was a great variation among species, but in general, sensitivity to UV-B, measured as reduced height and biomass, was reduced as the elevation of plant origin increased. In a subsequent study of plants from the same seed collection, Ziska et al. (1992) noted increases in pigments only in plants from low elevation exposed to UV-B, but the plants from high elevations produced a consistently higher amount of these compounds also in the absence of UV-B radiation. Plants from low elevations were also negatively affected by UV-B, showing reduced plant and floral dry biomass, apparent quantum efficiency, relative water content and light-saturated photosynthetic capacity. Species from high elevation did not display any such negative effects. Rau and Hoffmann (1996) investigated species pairs of five genera from different altitudes in the Alps grown in a greenhouse. They observed a slightly higher UV-B resistance of the alpine species, but only when the plants were preadapted to UV-B radiation. Differences in UV-B sensitivity between different genera were much more pronounced than the differences between lowland and alpine species within the same genus. Hübner and Ziegler (1998) measured photosynthetic CO_2 fixation rate under enhanced UV-B (indoors) in three species of Rumex with natural distribution at different altitudes. The lowland (*R. maritimus*) and the montane (*R. crispus*) species revealed a high UV-B tolerance, even without a preceding adaptation to UV-B irradiance, while the alpine species (*R. alpinus*) required an adaptation to a threshold UV-B irradiance to prevent UV-B caused inhibition of photosynthetic CO_2 fixation. The authors suggest that the unexpected reduced performance of non-adapted *R. alpinus* is due to the UV-B caused reduction in stomatal conductance.

There are very few investigations of UV-B effects on plants along latitudinal gradients. Since they are mainly concerned with epidermal screening and/or accumulation of UV-absorbing compounds, they will be dealt with in the next sections.

In summary, the studies along elevational gradients show evidence for a trend to higher, genetically fixed, UV-B resistance in plants from higher altitudes, although this trend is less conspicuous than one might have expected. Since in all reports, UV-B sensitivity was assessed using greenhouse grown plants, the possible contribution of a genetically fixed potential for phenotypic acclimation of resistance could not fully be evaluated.

12.5 Epidermal UV-screening in arctic and alpine plants

Resistance against UV-B radiation can be achieved in plants by three different means: epidermal screening, high antioxidative status and efficient repair of damage. Since there exist very scarce data from arctic plants in the litterature on the two latter topics, we will mainly concentrate on epidermal screening.

Screening is accomplished by UV-absorbing compounds. Hence, the content of these compounds in leaves has frequently been taken as a measure for UV-B screening. This may be misleading, as discussed extensively by Day (2001) for mainly two reasons. The compounds in whole leaf extracts may not exclusively be located in the epidermis, although only there they can serve as screens. Furthermore, it may not be possible to extract all screening compounds since part of them may be bound to the (epidermal) cell walls. Nevertheless, absorbing compound concentrations may indicate trends.

Semerdjieva et al. (2003b) found contrasting strategies for UV-B screening in three sub-arctic dwarf shrubs. In *Vaccinium myrtillus* (deciduous) the methanol-soluble UV-absorbing compounds were distributed throughout the leaf, but particularly concentrated in chlorophyll containing cells, while in *V. vitis-ideae* (perennial leaves) most phenolic compounds were cell wall bound in epidermal cells. For both species the content of phenolic compounds increased when plants were exposed to enhanced UV-B. The response of *V. uliginosum* (deciduous, but with leaf structure similar to *V.vitis-ideae*) was intermediate between the other two, with high concentrations of cell wall-bound phenolics in the epidermis but with this pool decreasing and the methanol-soluble pool tending to increase after exposure to enhanced UV-B.

In their comparison of species pairs of five genera from different altitudes in the Alps, Rau and Hoffmann (1996) found higher content of absorbing compounds in species from high altitudes for three genera, for one genus there was no difference, while the last (*Saxifraga*) had higher absorbance in the lowland species. Acclimation to low UV-B radiation exaggerated the existing trends in these greenhouse grown plants. In a field study, Caldwell (1968) investigated epidermal UV transmittance (300 – 400 nm) in 33 species along a transect in the Rocky Mountains, USA, from 1680 m to 3750 m altitude. He did not observe any elevational trend in UV transmittances nor in UV absorbing compounds in methanolic extracts. In contrast, Rozema et al. (1997a) found increasing content of UV-B absorbing compounds and increasing leaf thickness with elevation (800 m to 1600 m a.s.l.) in four species collected in the Blue Mountains, Jamaica. Comparing four different pairs of related species in a latitudinal gradient from arctic and alpine environments, all grown under field conditions in Utah, Barnes et al. (1987) observed about equal contents of UV-B absorbing compounds in the arctic and alpine species. However, upon exposure to additional UV-B radiation, only the ecotypes of arctic origin increased their content of UV-B absorbing compounds.

By measuring transmittance of epidermal peels directly, Robberecht et al. (1980) compared 11 species growing at Barrow, Alaska, with 32 different species growing at three different high altitude locations at equatorial or tropical latitudes. Mean epidermal UV-B transmittance of alpine plants from low latitudes was < 2 %, while plants from Alaska had a mean value of > 5 %. An arctic provenance of *Oxyria digyna* had a 20 % lower content of UV-B absorbing compounds and 50 % higher epidermal transmittance than an alpine ecotype under identical artificial irradiance (Caldwell et al. 1982).

The paucity of in-situ studies of epidermal transmittance at alpine and arctic locations is probably related to the their remote location in conjunction with the need for relatively elaborate equipment for proper measurement of epidermal transmittance. A recently introduced fluorescence technique employing a portable apparatus (Bilger et al. 1997, 2001) solved some of the inherent problems and allowed us to determine epidermal transmittance in a large number of arctic and alpine species at their growing sites with a sufficient number of samples (Nybakken et al. 2004 a, b)

In an experiment started 1996 in Adventdalen, Svalbard (Norwegian Arctic, 78°N, 0-50 m a.s.l.) the natural tundra vegetation was irradiated with UV-B corresponding to an 11% depletion of the ozone layer. UV transmittance of seven higher plant species growing under the UV-B lamps were measured during 1999, 2000 and 2001, but the transmittance in irradiated plants were just as high as in controls growing under natural UV-B (Nybakken et al. 2004 a). The epidermis of both control and irradiated plants transmitted from 3.8 to 11.6% of the UV-B radiation (290-320 nm), which is not more than what found for *Vicia faba* growing in the lowland in southern Germany (9.2%, Markstädter et al. 2001). Measurements of five other species not included in the enhancement experiment also showed values in the same order of magnitude. Presumably, the epidermal protection may already be sufficient in these arctic plants, implying that there is no need to invest in extra absorbing compounds under the UV-B regime applied.

Six of the studied arctic species were also measured at two high-altitude locations; Finse, Norway (60°N, 1200-1600 m a.s.l) and the area around Col du Lautaret, French Alps (45°N, 2000-2700 m a.s.l) (Nybakken et al. 2004b). Only one species, *Dryas octopetala*, consistently showed decreasing UV-B transmittance with decreasing latitude/increasing altitude all three years (Fig. 12.2). Three other species, *Bistorta vivipara*, *Saxifraga oppositifolia* and *Silene acaulis*, showed a similar trend some years. The epidermal transmittance of *Oxyria digyna* did not vary between years for any of the ecotypes (Fig. 12.2). This species also displayed low transmittance when grown from seeds at a PFD of 150 µmol m^{-2} s^{-1} in a growthroom in the absence of UV-B (Fig. 12.2). It seems that *O. digyna* exhibits a high constitutive protection, even in the ecotype from Svalbard with low ambient UV-B radiation.

The high epidermal UV-B protection in the studied arctic species and the lack of clear differences in epidermal transmittance between arctic and alpine ecotypes of several species challenges established ideas about what is the driving force behind the build-up of epidermal UV-B defense in arctic and alpine plants. Possibly, today's UV+PAR levels approach levels

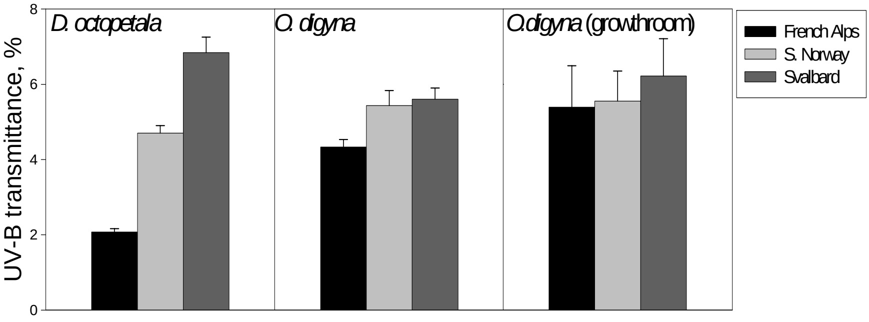

Fig. 12.2 Epidermal UV-B transmittance (%) + S.E of *D. octopetala* and *O. digyna* from three sites along a natural UV-B gradient (mean over three field seasons, 1999-2001) and *O.digyna* of all three ecotypes grown in a growthroom (Nybakken et al. 2004b).

which saturate synthesis of UV-B absorbing compounds in arctic plants. In addition, other environmental factors than light may also influence the epidermal UV-B transmittance. UV-B absorbing metabolites may be induced also by low temperature, herbivory, wounding, drought and by deficiency of certain mineral nutrients (Balakumar et al. 1993; Chaves et al. 1997; de la Rosa et al. 2001; Dixon and Paiva 1995; Hunt and McNeil 1998; Keinänen et al. 1999; Lavola and Julkunen-Tiitto 1994; Levizou et al. 2001; Solecka and Kacperska 1995; Stewart et al. 2001). One or more of these factors may possibly have saturated flavonoid synthesis, so that induction by UV-B radiation became insignificant (also discussed by Liakoura et al. 2003). Differences in temperature and precipitation along the latitudinal gradient may have counterbalanced the gradient in UV-B.

12.6 Conclusions

There are few studies on UV-B effects in arctic-alpine plants. These studies include few species, and often display contradictory results, suggesting species and habitat specific responses. Reduced growth and increased thickness of leaves are common results of UV-B enhancement, but there are no reports of any severe effects at the plant or ecosystem level. Molecular studies, including DNA-damage or other parameters do not exist. However, if there were an increased incidence of damage induced by enhanced UV-B at the cellular level, it doesn’t become apparent, possibly due to repair activities. Many results are based on relatively short-term UV-B enhancement, so that it is very difficult to predict long-term effects. But also in those studies where vegetation was monitored for several years, few effects of UV-B were found.

One reason for the missing severe UV-B effects could lie in an efficient epidermal screening. Our measurements indicated that the epidermis of the studied species absorbs a considerable part of the incident UV-B radiation. Other mechanisms such as repair capacity and antioxidative systems may further contribute to plant resistance. However, very little is known about photoreactivation *in situ* or antioxidative capacity in arctic and alpine plants.

The studies presented raises a lot of new questions concerning the mechanisms and driving forces behind the synthesis of UV-B absorbing compounds in arctic and alpine plants. Future research should investigate the importance of other enviromental factors for synthesis of UV-B absorbing compounds, and provide knowledge about the metabolic cost of UV-B protection.

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13 Effects of UV radiation in arctic and alpine freshwater ecosystems

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13.1 Introduction

Alpine and arctic waterbodies range from large, deep and ultraoligotophic lakes to small ponds that typically dominate over large areas in the Arctic. One may question whether there are some truly unique properties that are shared amongst Arctic and alpine freshwaters. Are there some distinct features with regard to physicochemical properties or biology? The numerous small and shallow tundra ponds that are widespread in the circumpolar Arctic represent a quite distinct type of ecosystems that also possess a unique biota. These ponds are situated on permafrost, making them highly susceptible also to global warming, changed precipitation and permafrost thawing. Due to their general shallowness (often < 0.5 m) and fairly high water transparency, the major proportion of solar energy reach the sediment surface. Thus, these high Arctic localities may support a substantial benthic production despite a scarcity or absence of benthic macrophytes. Dense layers of cyanobacterial mats, epibenthic diatoms, heterotrophic bacteria and fungus may cover the sediment surface, and may be major players for nutrient dynamics and carbon fluxes in these wind-exposed and well mixed localities (Vincent 2000). In general, these shallow tundra ponds are devoid of fish, and this allows for establishment of dense populations of large-sized species of crustaceans. The high Arctic does also include a few deeper and larger lakes which resembles the typically deep and oligotrophic alpine lakes. These somewhat deeper lakes (> 3 m) that do not freeze to the bottom may also house populations of fish, where Arctic charr (*Salvelinus alpinus)* are the sole species in the truly high Arctic. While there apparently are very few *species* that are endemic to the Arctic and alpine freshwaters, there is nevertheless a wide span in clonal and genetic variability among some of these groups.

There are some fairly obvious climatic properties of the high arctic that need not to be reiterated at length here. This chapter will focus on observed and potential effects of ultraviolet radiation (UVR) for the inhabitants of these ecosystems, yet touching upon various abiotic challenges that may be superimposed on the UV-stress. During summer, photon flux of short wave radiation may also negatively affect both primary and secondary production. Short wave PAR (blue light, near 400 nm) may cause a suite of cellular damages, notably DNA-breaks and membrane lipid peroxidation. In general UVR is considered the most harmful part of the spectrum, even though the total photon flux is rapidly decreasing towards shorter wavelengths due to ozone absorption of UV in the stratosphere. There are a number of reviews that cover various aspects of UVR effects on aquatic organisms, including alpine (Sommaruga 2001) and arctic (Hessen 2002) freshwaters. Here, focus is here aspects of water properties with specific relevance to the biota, as well as life history traits and evolutionary perspectives that are particularly relevant in the context of UVR.

13.2 Physico-chemical properties of arctic lakes and ponds

The key determinants of alpine and arctic freshwater ecosystems (as in fact for most systems) are light, temperature and nutrients, although immigration history and immigration barriers can be superimposed on these abiotic factors for several areas. Deglaciation and land rise also cause a chronosequence of water bodies that has major bearings for their biota and biodiversity. While probably a few lakes survived the last deglaciation in ice-free refuges, most northern alpine and arctic localities are < 10 000 years, and some are quite recently formed by ice retreat or land rise.

Few arctic lakes are perennially frozen, but a number of high arctic localities may experience open water for very brief periods only. Consequently, epilimnetic temperatures in larger water bodies rarely exceed 5 ^{o}C (commonly less), and for major parts of the year the water temperature may be < 1 ^{o}C . This is partly caused by the fact that a substantial part of the annual heat budget is involved in the melting of ice. Even surface layer of larger water bodies may never reach maximum density (4 ^{o}C), meaning that thermal stratification will never occur. Similarly alpine likes are characterized by low temperatures and short growing season. Needless to say, these low temperatures throughout the water column pose constraints on metabolic processes and hence productivity and challenge life cycle adaptations for the biota of these systems, and it is of relevance for temperature dependent damage from UVR. On the other hand, the shallowness of smaller water bodies like tundra ponds allow for a strong benthic heat absorption, and temperature may rise substantially in summer during periods with 24 h solar irradiation. For tundra ponds at Barrow, Miller (1980) typically recorded temperatures from 8 – 12 °C during July and early August, yet with a temperature range from 2 to 16 °C within 2-3 days at the extreme.

While the temperature and nutrient regimes are not basically different in arctic and alpine localities of similar size and morphometry, the light regimes may differ. Truly alpine and arctic lakes and ponds have a brief time window allowing for primary production during summer, even though sufficient light also may penetrate through the ice (provided absence of snow) to allow for a high primary productivity also before ice-off. In spite of a 24 h sun exposure during summer in the Arctic, light *intensities* are substantially lower compared with southern, alpine habitats. By using a radiation transfer model (Dahlback and Stamnes 1991), it was estimated that even during the Arctic summer, maximum biologically harmful radiation would be some 20-30 % lower at near 80 °N relative to those at 60 °N (Hessen 1996).

Furthermore, Arctic lakes are frequently ice-covered until late July, where maximum doses are reduced by another 35 % relative to mid-summer.

Nevertheless, the dose received by the biota may commonly be higher in Arctic ponds compared with lakes at lower latitudes, due to their shallowness and low attenuation of UV. In contrast, alpine lakes receives higher surface doses of UV than lowland lakes at the same altitude, and typically integrated UV-dose increase by roughly 10% per 1000 m elevation, while this altitudinal effect for longer wavelengths (PAR) are lower (Hessen 1993, Blumthaler et al. 1997). Hence there will commonly be a higher UV/PAR ratio in alpine lakes compared with lowland localities. There is an almost paradoxical relationship between light and life in the Arctic, however; levels of PAR, 380-700 nm) probably is the major limiting factor for Arctic life in general, UVR(< 380 nm) is a potential constraint on ecosystem productivity. This ratio may be highly relevant for repair capacity of UV-damage. Siebeck and Böhm (1994) found that peak recovery radiation was in the blue region (420-440 nm), and found that recovery (light repair) strongly increased when radiation was provided after UV-exposure. This positive effect was further increased when recovery radiation was provided also under UV-exposure. The recovery was rapidly decreasing with increased post-exposure darkness. The importance of photorecovery in alpine copepods was also convincingly demonstrated by Zagarese et al. (1997). These authors also noted a pronounced species-specific variability in photorecovery.

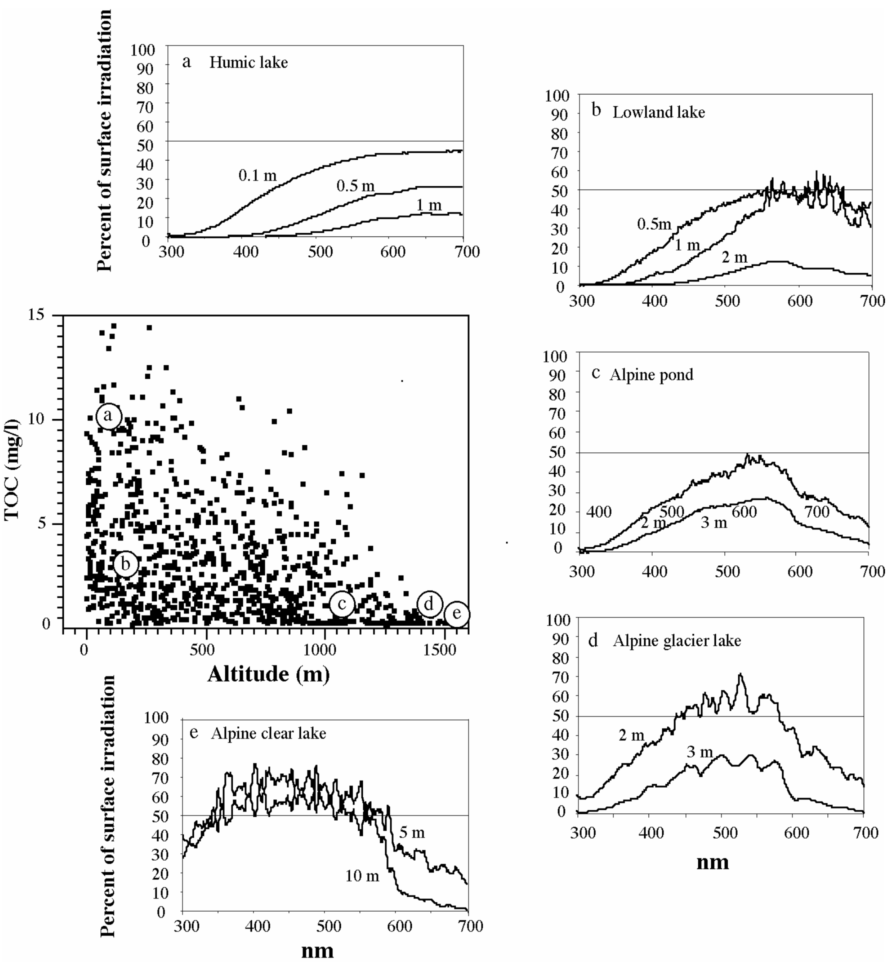

Fig. 13.1. Scatterplot of concentration of total organic carbon (TOC) versus height above sea in 997 Norwegian lakes. Spectral profiles as percent of surface (air) from selected depth in 5 types of lakes; a: Humic lake Skjervatjern, b: Lowland Lake Trollvann, c: Alpine pond at Finse, d: Alpine glacier fed Lake Gjende, e: Alpine clear Lake Bessvatn.

The key determinant of UV regimes in most lakes is the concentrations of coloured dissolved organic matter (CDOM), notably terrestrially derived humus. Most alpine and arctic localities have low concentrations of dissolved organic carbon (DOC), and typically the DOC-content decrease strongly with altitude, yielding tremendous differences on spectral properties and light attenuation (Fig. 13.1). For comparison, in the deep, clear alpine

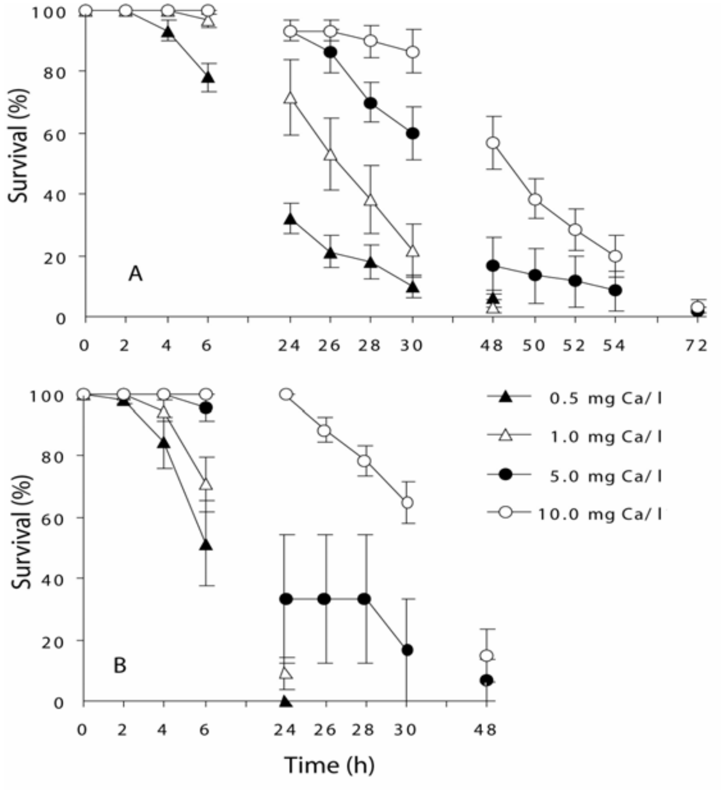

Fig. 13.2. Mean survival (±SE) of (A) *D. magna* and (B) *D. tenebrosa* reared under different Ca concentrations after different times of UV-exposure. Each point represents the mean of 6 replicates with 10 animals. Repeated 6 h exposure periods, with 35.95 W m^{-2} intensity over 300 - 400 nm (after Hessen and Rukke 2000).

Lake Bessvatn (1373 m above sea, < 1 mg DOC l^{-1}), a higher proportion of surface UVR remained at 10 m depth than at 0.1 m depth in humic lake Skjervatjern (12 mg DOC l^{-1}). The alpine lake Gjende had fairly high attenuation of UVR in spite of very low levels of DOC. This is caused by high inputs of particles from glacial runoff.

Most alpine lakes are characterized by high transparency of UVR owing to low levels of DOC and low productivity. The same holds true for most high arctic freshwaters, although for tundra-ponds in more productive areas with developed soils or in wetland areas, DOC concentrations may exceed 5 mg DOC l^{-1} (Hobbie et al. 1996). For Svalbard lakes, concentrations of < 1 – 4 mg C l^{-1} is recorded (Ørbæk et al. 2002), but even localities with 4 mg C l^{-1} have low UVR attenuation due to low influx of allochthonous humic matter, and a dominance of less colored matter of autocthonous origin, caused by a frequent mixing in these shallow water bodies.

Species richness of planktonic species may also be governed by the UV regimes related to concentrations of DOC (Williamsson et al. (2001) provided evidence that macrozooplankton community structure in a set of lakes along a deglaciation chronosequence in Glacier Bay (Alaska) could be attributed to the UV attenuation in these lakes.

Most alpine and arctic lakes and ponds have low levels of nutrients. There is, however, a tremendous scatter both in nutrients and concentrations of various ions. Coastal ponds may be strongly influenced by bird droppings, and may also possess high levels of calcium (Ca). Also local geology may faciliate high ionic content that could be an important indirect mediator of UVR susceptibility. Ca concentrations may in fact be of vial importance for a number of Ca demanding crustaceans, and it has been demonstrated that *Daphnia* is more susceptible to UVR under low ambient Ca-concentrations (Fig. 13.2).

13.3 UVR-effects and adaptations

13.3.1 Evidence for UVR-effects?

There is scattered knowledge on the UVR effects on various aquatic taxa and even less on species or various developmental stages within species, yet there is several studies that demonstrate strong effects of UVR (both UV-A and UV-B) of alpine and arctic phytoplankton and bacteria (Villafane et al. 1999; Sommaruga and Garcia-Pichel 1999; Calleri et al. 2001, Van Donk et al. 2001; Carrillo et al. 2002), zooplankton (Hebert and Emery 1990; Hessen 1993; Zagarese et al. 1997; Zellmer 1998; Tartarotti et al. 1999) and benthic communities (Vinebrooke and Leavitt 1999; Tank et al. 2003). Palelimnological studies like those of Leavitt et al. 1997; 2003) indeed suggest the balance between DOC and UVR as a major determinant of phytoplankton communities and biomass in alpine and subalpine lakes. Heterotrophic bacteria in general are assumed to be highly susceptible to UV-B (Sommaruga et al. 1997), while cyanobacteria and some phytoplankton species that rely on PAR for their biosynthesis have evolved various strategies to cope also with the short-wave part of the spectrum (Vincent 2000; Vincent and Belzile 2002). Notably the benthic bluegreens that are key producers in shallow tundra ponds display very efficient UV-defence strategies (Quesada et al. 1999; Vincent 2000). Amongst phytoplankton, the major effect may be community shifts rather that reduced primary production. There are contrasting reports as to which taxa and species that are most vulnerable to UVR. While Laurion and Vincent (1998) found arctic picocyanobacteria to be well protected against UV, Van Donk et al. (2001) found that these, and other small species, was comparatively more susceptible than larger species. In a series of experiments with the natural phytoplankton communities from three high Arctic lakes on Spitsbergen (79 ^{o}N), in situ effects at the community level was assessed under natural UV radiation. These community shifts resulted in a decreased fraction of grazable algal species in UV-transparent bottles, while no effects were seen for PAR-light only. In the more productive lake, there appeared to be negligible effects of UV on the community composition. This suggests that UV could pose strong indirect “bottom up” effects on grazers in systems with high UVR transparency. Carrillo et al. (2002) also found that UVR in an alpine lake indirectly stimulated bacterial production by inducing increased release of DOC from phytoplankton.

13.3.2 UVR and oxidation of fatty acid

For obvious reasons, indirect effects of UVR may be harder to test and detect compared with direct effects. At the food web level, one might list a number of potential impacts of UVR, i.e. like the shift to less edible phytoplankton species mentioned above. One effect that may be of specific relevance for alpine and arctic ecosystems, is the effect of UVR on fatty acid composition. Here, UVR could play a major role in the food web in shallow and clear waters, in particular by reducing the long-chained polyunsaturated fatty acids (PUFA) that play a key role in arctic ecosystems and low-temperature systems. Fatty acid profiles, and notably a few specific PUFA´s like eicosapentaenoic acid (EPA, 20:5 3) and docosahexaenoic acid (DHA, 22:6 3) have been considered as a major determinant to herbivore success and animal nutrition in general. There is some evidence that PUFAs are susceptible to oxidations by UVR (Wang and Chai 1994; Hessen et al. 1997), yet contrasting results are reported (Tank et al. 2003). Consumers cannot synthesize PUFAs de novo, and thus depend on dietary inputs of these, and thus UVR effects on algae will most likely affect also the higher trophic levels.

13.3.3 Susceptible periods and growth rate

UVR effects may probably be most severe when circumstances are especially unfavourable, like when periods with low ozone levels, clear sky and specific mixing regimes coincide with susceptible life cycle stages of key species. Based on studies from Svalbard, the general pattern for *Daphnia* is two generations per year (Hessen et al. 2004). Typically, *Daphnia* hatch from resting eggs (ephippia) during ice off around mid July, and then grow to maturity (around 2 mm) and release the first clutch of eggs after 2-3 weeks. Hence a rather synchronous cohort may develop. The second generation thus produce resting eggs normally by late August. Maximum UV-B exposure under synchronous hatching of unpigmented juvenile *Daphnia* during ice off could typically be such a “window of susceptibility”.

The main target for damage is DNA, but the site of eventually breaks will critically depend on the function of the particular part of the genome. Especially, it will make a big difference if coding or non-coding regions are subject to damage. Organisms with miniaturized genomes, such as *Daphnia*, the key players in many arctic and alpine localities, could thus be more susceptible than species with more introns. In general, small organism could be more susceptible than larger ones since all body components including reproductive organs can be reached by UVR. Also rapid cell division or growth, implying a very active gene expression, could be a major determinant of susceptibility (Naganuma et al. 1997). The selective pressure for fast growth in arctic species could thus paradoxically render these organisms highly vulnerable to UVR in spite of low ambient temperature.

13.4 Protection and adaptations

13.4.1 UVR-screening

Organisms may cope with the direct UV radiation effects in different ways, and several lines of defence may be identified that play a different role in different organisms. There may either be seasonal or spatial means of UVR avoidance by timing of reproductive season, depth distribution or diurnal migration. A second line of defence is UV screening compounds (e.g. pigments, mycosporine-lime amino acids). Third, there are several enzymes and other macromolecules serving as radical scavengers that in various ways cope with ambient or intracellular harmful photo-products. A last major defence would be the various means of enzymatic photo-repair that is a common property of all organisms. Vertical migration in zooplankton as a direct response of UVR have been demonstrated both in arctic (Hebert and Emery 1990) and alpine (Hessen 1993) localities.

Fig. 13.3. Example of dorsal melanin pigmentation in an arctic *Daphnia tenebrosa*, Svalbard

Many alpine and arctic autotrophs produce UV-screening compounds including scytonemin and mycosporine-like amino acids (MAA) (Vincent 2000). Several phytoplankton species of alpine lakes were found to produce MAAs, with the highest concentrations of MAAs and photoprotective carotenoids recorded in the clearest lakes (Tartarotti et al. 2001; Laurion et al. 2002). The surface of the benthic mats exposed to bright light is typically rich in carotenoids and the cellular concentration of carotenoids increases with increasing PAR and UV and also with decreasing temperature, and is probably crucial for the survival of these organisms under high UV exposure (Roos and Vincent 1998, Vincent and Belzile 2002). The extent of these various UV protection mechanisms varies greatly among taxa and species of autotrophs. Both carotenoids and MAAs are synthesized in autotrophs, but are also extensively used by heterotrophs for photoprotection. Grazer thus typically depends on their food for obtaining these substances, but the ability to use these for photoprotection among heterotrophs differ among taxa and species (Sommaruga and Garcia-Pichel 1999). Tartarotti et al. (2001) reported frequently high concentrations of MAAs in alpine calanoid copepods, moderate levels in sympatric rotifers, while virtually no MAAs were detected in cladocera. This point to some important taxonomic differences in pigmentation strategies at least between copepods and cladocera.

The extensive need for photoprotection in alpine zooplankton species was recognized in early works like those of Brehm (1938) and Merker (1940) who accredited the conspicuous red coloration of alpine and highly light exposed zooplankton high levels of tissue carotenoids. While the role of carotenoid photoprotection seems well justified in copepods (cf. Ringelberg et al. 1984), it is more obscure in the cladocera (Hebert and Emery 1990; Hessen and Sørensen 1990). Sub-Arctic alpine copepods (*Heterocope*) were found to have ten times more carotenoids than sympatric populations of cladocerans, and even low-land transparent copepods have higher carotenoid levels than highly light exposed *Daphnia* (Hessen and Sørensen 1990). A major difference between these groups is that while carotenoids in copepods may be distributed not only in lipid droplets, but also body fluids and tissue, they are most often (though not always) restricted to ovaries or pre-ovarian lipids in *Daphnia*. Pigmentation may also undego ontogonetic shifts. Typically, larval, pelagic stages of the Notostracan *Lepidurus arcticus* are bright red from carotenoids, while the benthic adults have lower levels (Hessen unpubl).

Most of the work on UV in alpine and arctic freshwaters have been devoted to zooplankton however, and particularly on the cladoceran *Daphnia* that possess a truly remarkable adaptation to UV-stress by a conspicuous

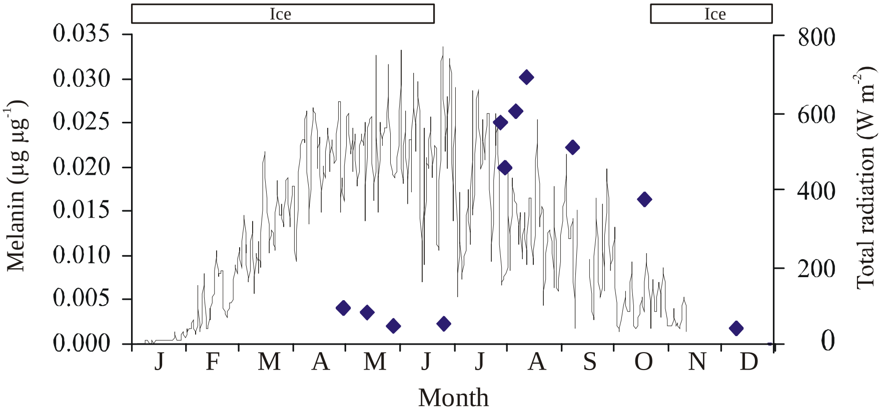

Fig. 13.4. Changes over time in the ground level total radiation and the *Daphnia umbra* melanin concentration in Lake Saanajärvi (69º05'N, 20º87'E; maximum depth = 24 m, altitude = 679 m a.s.l., DOC = 1.6 mg L^{-1}), showing the effects of increased underwater light intensity on pigment synthesis. The thickness of the ice exceeds 1 m in late spring. (From Rautio and Korhola 2002).

carapace melanization (Fig. 13.3). This melanization in zooplankton is apparently a unique property of Arctic and alpine cladocera, and in some clones it is also inducible by presence of UVR (Fig. 13.4, and Rautio and Korhola 2002). Studies on absorbance of the carapace demonstrate a very low transmission of short-wave radiation in the very dark dorsal part of melanic individuals, and a fairly low transmission also in the dorsal, less pigmented parts of the carapace relative to that of non-pigmented animals (Hessen 2003). For arctic ponds, Hebert and Emery (1990) and Hessen et al. (1999) found that melanic clones ranged freely through the water column, while unpigmented clones were restricted to the pond bottom under high light intensities. By comparing UVR tolerance of melanic and non-melanic morphs/clones both *in situ* (Hebert and Emery 1990; Zellmer 1998) and in the laboratory (Hessen 1996; Hessen et al. 1999), it is evident that melanism offer a quite efficient photo-protection. Since the melanin has to be resynthesized after each moult and this synthesis apparently is an energy demanding process. For other invertebrates, and aquatic vertebrates, there is a general lack of knowledge, yet several studies have demonstrated that fish and amphibia may suffer skin lesions, catharact-like symptoms and immunosuppression under high ambient UVR (cf. Hessen 2003).

Finally, a variety of anti-oxidants may together with repair enzymes serve as a final line of defense. However screening of anti-oxidants an a number of arctic, alpine and lowland population of *Daphnia*, including both melanized and hyaline populations did however not reveal any clear-cut differences between the populations (Borgeraas and Hessen 2002).

13.4.2 Evolutionary adaptations and “the ghost of UVR in the past”.

In nature there are rarely dramatic effects of UVR-exposure, but organisms in exposed habitats display several sign of adaptation. Adaptations such as vertical migration or the presence of UVR protective pigments suggest a major need for UV-protection in arctic and alpine localities. Evolutionary adaptations may also include a higher expression of anti-oxidants (under low temperature), more efficient repair system for DNA-breaks or membrane damage etc. Siebeck and Böhm (1994) found higher UVR susceptibility in lowland *Daphnia* compared with an alpine populations, and this probably illustrate a common phenomenon: highly light exposed organisms may tolerate very high doses of UVR. Typically, copepods from lakes at very high latitudes may tolerate truly extreme levels of UVR (Vinebrooke and Leavitt 1999; Sommaruga 2001). In general, such adaptations involve some costs, and the metabolic costs associated with photoprotection and active means of UVR avoidance could be more important effects of UV than lethal or sublethal cellular damage. Such overall fitness costs are clearly seen for melanized *Daphnia* as reduced growth rates compared with their hyaline counterparts (Weider 1987; Hessen 1996). The costs are also indicated by the down-regulation of melanin synthesis in the absence of UVR (Hessen 1996), or the increased risk of fish predation due to increased visibility (Sægrov et al. 1996, Hansson 2000). Thus present tolerance to UVR reflects a series of evolutionary adaptations and alpine and arctic freshwaters possess species and communities that must be regarded as ”the ghost of UVR in the past”.

13.5 Conclusions

We have seen that there are some aspects of alpine and arctic freshwater localities, in spite of low intensities of UVR, that could make organisms in these ecosystems particularly vulnerable to UVR;

1.Their frequent shallowness, offering no depth refugium for the biota

2. Their low levels of DOC and other UV-absorbing compounds.

3. The low levels of nutrients of thus low primary production

4. The frequent low temperatures that could slow down the anti-oxidant expression and cellular repair mechanisms that are coping with UV-induced damage.

There are nevertheless rather scattered and somewhat contrasting information on effects of UVR in Arctic and alpine habitats. Part of this can be accredited experimental condition and stage or condition of the tested organisms, but it does probably also reflect a real difference in UVR susceptibility among taxa and species. Adaptations such as vertical migration or the presence of UVR protective pigments suggest a major need for UV-protection in arctic and alpine localities. Thus alpine and arctic freshwaters communities are evolutionary shaped towards tolerance to a variety of challenges including high exposure to UVR. These evolutionary adaptations of behaviour, pigmentation and enzymes reflects the organisms´ past experience with UV. Such adaptations clearly have their costs, yet such costs may be quite subtle and hard to detect.

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14 Climate control of biological UV exposure in polar and alpine aquatic ecosystems

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14.1 Introduction

The severe depletion of stratospheric ozone in Antarctica over the last two decades has generated much concern about the effects of rising UV-B radiation on marine and freshwater ecosystems (de Mora et al. 2000; Cockell and Blaustein 2001; Sommaruga 2001; Hessen 2002; Perin and Lean 2004) and has led to a broad range of research on UV optics, photobiology and photochemistry in the aquatic environment. The studies to date imply that certain ecosystem types may be especially prone to major changes in their spectral UV regime: clear lakes and oceans in the polar regions where ozone depletion is occurring and where UV wavelengths penetrate deeply into the water column (Vincent and Belzile 2003), and oligotrophic alpine waters which have little UV-screening protection because of their low concentrations of colored dissolved organic matter (CDOM; Morris et al 1995; Williamson et al. 1996; Laurion et al. 2000; Markager and Vincent 2000). The biological communities in these ecosystems may also be more vulnerable to UV toxicity because of the inhibiting effects of cold temperatures on cellular repair of UV damage (Rae et al. 2000; Hoffman et al. 2003; MacFadyen et al. 2004).

The UV waveband is a highly reactive component of all environments exposed to the sun, and is subject to large fluctuations at multiple timescales. It is increasingly apparent that climate may exert a strong control on these fluctuations, and that the amplitude of such effects can be much greater than those caused by moderate stratospheric ozone depletion. Major shifts in underwater UV are likely to accompany future climate change, with implications for many important photobiological and photochemical processes in the aquatic environment.

The aim of this chapter is to review the mechanisms, models and observations that link underwater UV exposure and climate change. We first describe a general model that has been applied with success and variously modified to address questions about how changes in the environment translate into UV exposure and responses. We then examine each of the terms in this model and their sensitivity to climate, and how they combine to result in climate control of biological UV exposure in the underwater environment. Finally, we illustrate by way of several case studies how paleo-ecological analysis can provide a valuable approach towards assessing the long-term role of climate in controlling biological UV exposure in alpine and polar aquatic ecosystems.

14.2 Model description

One approach towards assessing the effects of environmental change on spectral UV exposure is by way of the index 'weighted transparency', T^*, where the * indicates that the radiation at each wavelength is multiplied by its biological effectiveness. This index has been applied to cold lakes and oceans (Vincent et al. 1998; Pienitz and Vincent 2000; Gibson et al. 2000; Vincent and Belzile 2002) and has been modified and extended for more general use (Neale 2001; Lehmann et al. 2004). The parameter T^* allows the effects of stratospheric ozone depletion and changes in water column attenuation of UV to be assessed on a common, biologically relevant scale, and it is calculated by integrating the transparency of the water column to biologically weighted irradiance at each wavelength λ over the UV waveband 280-400 nm:

$$T^* = \int T^*(\lambda)\, \mathrm{d}\lambda \qquad (1)$$

For an ice-covered lake or ocean, $T^*(\lambda)$ may be partitioned as follows:

$$T^*(\lambda) = E_d(0^+)\, F\, (1-r)\, (1-f)\, (1/K_{dUV})\, \varepsilon \qquad (2)$$

where the parameters at each wavelength λ are:
$E_d(0^+)$ = the incident solar irradiance in relative energy units;
F = factor modifying that flux as a function of ozone depletion in the stratosphere;
r = the fraction of UV that is removed by surface reflection (albedo) from the snow, ice or water;
f = the fraction of UV that is removed by attenuation by overlying snow and ice;

K_{dUV} = the diffuse attenuation coefficient for downwelling UV irradiance in the water column;

ε = the biological weighting factor (BWF) which expresses the relative damage incurred by UV ($\varepsilon = 1.0$ at 300 nm). In the following sections we examine the implications of climate change for each of the terms in Eq. (2).

14.2.1 Incident UV irradiance ($E_d(0^+)$ F)

Climate has the potential to substantially modify incident spectral irradiance through at least two mechanisms: changes in heat balance and transport processes in the stratosphere, and through changes in tropospheric cloud cover. The greenhouse energy-trapping effect in the troposphere is accompanied by less outgoing long-wave radiation into the lower stratosphere. In the longer term this results in stratospheric cooling, a strengthening of the polar vortex, and a prolongation of conditions that favor ozone loss (Staehelin et al. 2001). The Arctic stratosphere is thought to be on the brink of major ozone loss and would appear to be especially sensitive to a small amount of additional cooling (Dahlback 2002). There may also be larger scale transport effects. Greenhouse warming could lead to increased zonal flow in mid-latitudes causing the polar vortex to be more stable, again favoring ozone loss and a delay in the eventual recovery from CFC emissions (Shindell et al. 1998).

Cloud cover and precipitation regimes are likely to change as a result of shifts in global climate, and these effects may be especially pronounced in the polar regions (Houghton et al. 2001). Increased open sea conditions will be accompanied by increased evaporation into the overlying air masses that at warmer temperatures can hold more moisture for subsequent cloud formation and precipitation. Global warming is also likely to accelerate the hydrological cycle at lower latitudes, resulting in increased atmospheric transport of water to the polar regions. At Spitsbergen, there has been a significant rise in precipitation from the 1960s to 1990s (Hanssen-Bauer and Forland 1998), however other sectors of the Arctic have shown little change or decreases (Vincent et al. 2001).

Cloud cover can have a strong effect not only on total incident UV radiation, but also on UV spectral composition. Gautier et al. (1994) found that incident UV-B irradiance in Antarctica was more closely correlated with cloud cover than stratospheric ozone. There was a positive correlation between the ratio of DNA-damage weighted UV-B irradiance to UV-A irradiance when the surface was covered by reflective snow and ice, and a negative correlation during open ocean conditions. These authors concluded that cloud cover affects UV spectral ratios but that the effect is modulated by multiple back scattering between the surface and clouds. UV measurements over snow-covered ground have shown that incident erythemal (sunburn)-weighted UV on overcast days can be 80% higher than predicted from cloud attenuation because of these multiple reflections (Renaud et al. 2000).

14.2.2 Albedo effects (*1-r*)

Albedo, the ratio of upwelling (E_u) to downwelling (E_d) irradiance, is high in snow-covered alpine and polar environments and exerts a major control on the underwater UV radiation field. UV albedo for snow and white ice is generally > 80%, but decreases to 50-60% for bare melting ice and to as little as 30% for ponding meltwater over ice. The latter is a common feature over Arctic sea ice during late spring and summer (Perovich et al. 1998; Belzile et al. 2000), while in the drier Antarctic environment a scattering surface layer with high albedo can form during summer (Trodahl and Buckley 1990). Any climate change altering snow cover, duration of ice cover or the surface reflective properties of the ice, for example through meltwater ponds or rainwater over the ice surface, will drastically affect this albedo term and thus T^*. A snow-clearing experiment in Hudson Bay at the edge of the Arctic Ocean underscored the large albedo effect on UV transmittance through sea ice (details in Vincent and Belzile 2002). The removal of surface snow caused a 3 to 16 fold increase in the under-ice UV, thus a similar increase in T^*. Even a layer of snow only 2-cm thick reduced UV by a factor of 3, with slightly greater effects at the shorter wavelengths. Similarly, the removal of snow over a high Arctic ice-covered lake decreased albedo by 20% in the UV range and 13% in the PAR range (Belzile et al. 2001). Lake white ice, that is ice with a high air content, has a high albedo for PAR and UV, and lake ice whitening can occur with gradual warming over spring and summer (Howard-Williams et al. 1998).

14.2.3 Attenuation by snow and ice (*1-f*)

There are few published UV attenuation coefficients for snow and ice because of the difficulties of making measurements in these solid media. In early spring, about 1% of incident UV-B is transmitted through ~1.6 m of sea ice (Arctic: Perovich et al. 1998; Antarctic: Trodahl and Buckley 1990), however the development of ice algae can decrease UV transmittance by an order of magnitude (Perovich et al. 1998). Autochthonous

CDOM derived from ice algae has a significant impact on UV attenuation in sea ice, and the melting of the snow cover, ponding of the ice surface and flushing of the ice algae all tend to increase UV-B transmittance (Belzile et al. 2000). In Antarctica, a highly scattering sea-ice surface forms as the melt progresses, resulting in decreased UV-B transmission relative to early spring values (Trodahl and Buckley 1990). Freshwater ice is typically more transparent to UV irradiance than sea ice because of the absence of brine pockets and minimal ice-biota. Lake ice may even be more UV-transparent than the underlying lake water because of the exclusion of high molecular weight UV-absorbing CDOM during the freeze-up process (Belzile et al. 2002). Even Antarctic lake ice several meters thick can allow measurable transmission of UV to the waters beneath (Vincent et al. 1998), although if such ice contains high concentrations of light-scattering inclusions such as glacial sediments ('dirty ice') or bubbles ('white ice') the UV-transmittance is minimal. For example, the 5-m thick summer ice over Lake Hoare in the McMurdo Dry Valleys was highly scattering, and no UV radiation less than 310 nm was detected in the water column beneath the ice (Kepner et al. 2000).

The dynamics and timing of ice cover melting in spring have substantial effects on the UV exposure of biota in the underlying water column. In alpine lakes for example, UV irradiances at the top of the water column can be an order of magnitude higher after melt-out than under 1.8 m of snow and ice cover at similar solar zenith angles (Sommaruga 2001). Rautio and Korhola (2002) showed that the *Daphnia* population of a subarctic lake responded to ice cover break-up by immediate synthesis of UV-absorbing melanin pigment (Fig. 14.1). Towards fall, the melanin concentration decreased suggesting the pigmentation was a direct response to the increased UV exposure during the peak radiation period. Shorter ice cover duration and exposure to higher UV during the spring ozone depletion could potentially alter the aquatic communities in lakes and require them to invest more in such UV protection mechanisms. This melanin content of cladocera also offers potential to estimate ice cover regimes in the past by analysis of lake sediments, analogous to the cyanobacterial UV-pigment reconstructions that have been applied to date (see below).

Substantial melting of seasonal snow and ice cover caused by rising temperatures has already been recorded in many parts of the world for example over cold lakes and rivers (Magnuson et al. 2000), arctic sea ice (Serreze et al. 2003) and lakes in the Antarctic Peninsula region (Quayle et al. 2002). Such changes are likely to have been accompanied by drastic shifts in underwater UV exposure. T^* calculations for an Arctic marine site

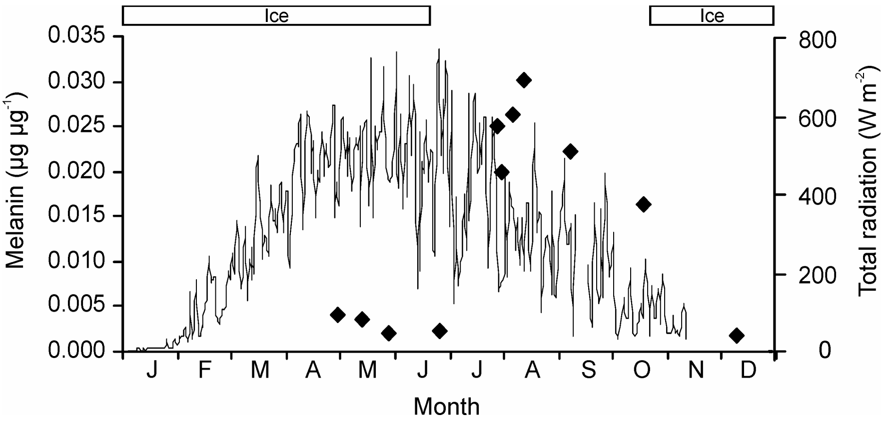

Fig. 14.1. Changes over time in the ground level total radiation and the *Daphnia umbra* melanin concentration in Lake Saanajärvi (69º05'N, 20º87'E; maximum depth = 24 m, altitude = 679 m a.s.l., DOC = 1.6 mg L^{-1}), showing the effects of increased underwater light intensity on pigment synthesis. The thickness of the ice exceeds 1 m in late spring. From Rautio and Korhola (2002)

showed that the removal of ice increased T^*_{PI} (T^* weighted for photosynthetic inhibition) by a factor of 12 and T^*_{DNA} by a factor of 22. The Arctic is likely to be more prone to this effect than the Antarctic in the immediate future. General circulation models (GCMs) predict that global warming will occur first and most intensely at high northern latitudes (Houghton et al. 2001) and there is evidence of accelerated impacts at some sites (Mueller et al. 2003). The north polar ice cap has experienced thinning and contraction over the last three decades and GCMs predict a complete loss of sea ice across the Arctic Ocean basin during summer by the end of this century (Vincent et al. 2001 and refs therein).

14.2.4 Water column transparency ($1/K_{dUV}$)

Colored dissolved organic matter (CDOM) is the primary attenuator of UV radiation in most aquatic environments. This still poorly defined mixture contains many substances, but the UV absorption is mostly due to aromatic polymers, notably humic and fulvic acids derived from terrestrial soils and vegetation. Alpine and polar lakes generally have very low concentrations of CDOM because of their sparse catchment vegetation, and the absorption coefficients for UV radiation per unit DOC may also be low because of the low relative importance of allochthonous versus aromatic, less UV-absorbing autochthonous carbon in these waters (Laurion et al. 2000). There is a non-linear relationship between UV-transparency and CDOM concentration, and between UV spectral ratios such as UVB/UVA (Laurion et al. 1997), and many high latitude and alpine waters are in a range that is responsive to small changes in CDOM. However the large arctic rivers and the coastal waters that they discharge into contain much higher CDOM concentrations because they are fed by catchments that extend far to the south, below the treeline. Antarctica has no major rivers and no well-developed terrestrial vegetation, and as a consequence there are striking differences in the attenuation of UV radiation in coastal Antarctic versus Arctic waters (Fig. 14.2). The relative lack of CDOM in Antarctic waters means that these ecosystems may be more sensitive to other factors controlling biological UV exposure such as changes in depth, ice and snow cover and atmospheric properties.

Climate change has the potential to exert a major influence on CDOM loading, with consequent impacts on underwater UV exposure. The mechanisms of effect include changes in catchment vegetation type and productivity, changes in precipitation and hydrology, and melting of permafrost soils and subsequent release of dissolved organic matter into the downstream receiving waters. For each of these processes, increasing atmospheric CO_2 and temperature are likely to result in increasing CDOM (e.g., Pastor et al. 2003; Freeman et al. 2004). This in turn will substantially release the biota from UV stress, although this positive effect may be

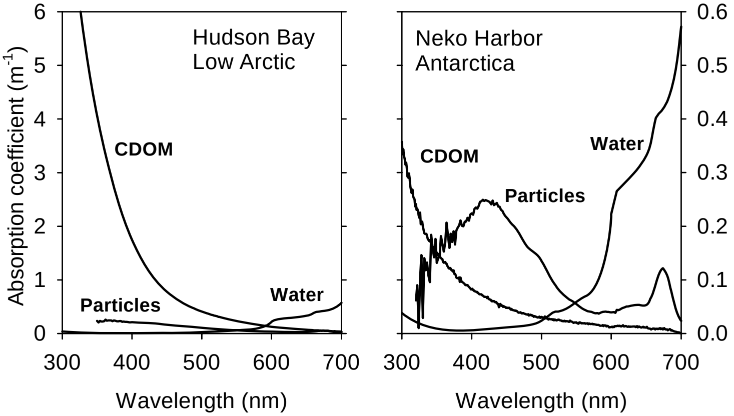

Fig. 14.2. CDOM influence in north versus south high latitude seas on underwater spectral radiation: Hudson Bay and Antarctica. Spectral absorption of water, particles and CDOM for Hudson Bay, 14 August 1999, and for Neko Harbor, Antarctic Peninsula, 3 January 2001.. Note the x10 difference in absorption scales (from Vincent and Belzile 2003).

offset by a reduced availability of PAR for photosynthesis (Arrigo and Brown 1996; Pienitz and Vincent 2000; Neale 2001; Lehmann et al. 2004).

There are steep spatial gradients in CDOM concentration across the Arctic Ocean. Coastal waters in some regions are strongly influenced by the CDOM inputs from large rivers. For example, the black waters of the Lena River have been observed up to 400 km offshore (>5 mg L^{-1} dissolved organic carbon at 4 m; Cauwet and Sidorov 1996) while in other regions, such as the North Water Polynya (NOW) between Greenland and Baffin Island, CDOM concentrations are extremely low and UV transparency is within the range reported for the Southern Ocean (Vincent and Belzile 2002). Major shifts in current patterns across the Arctic Ocean are likely to accompany any substantial change in climate. This in turn will lead to a redistribution of CDOM and large regional increases or decreases in underwater UV exposure. Large-scale shifts in the distribution of water masses have already been observed in the Arctic Ocean (Dickson 1999).

To evaluate the magnitude of spatial variability in north polar waters, T^* was calculated for an inshore water column at Hudson Bay (Canada) and for an offshore water column in the Arctic NOW polynya, both under ice-free conditions (Vincent and Belzile 2002). Moderate ozone depletion caused only a 5% increase in biological exposure weighted for UV-inhibition of photosynthesis (T^*_{PI}), whereas the difference in CDOM accounted for a 29-fold difference in underwater UV exposure between sites. For T^* weighted for DNA damage (T^*_{DNA}), moderate ozone depletion increased UV exposure by a factor of 2.3, but this was small relative to the 27-fold increase caused by differences in CDOM between sites.

In the lowest CDOM environments such as some alpine lakes (Laurion et al. 2000; Sommaruga 2001) and the Southern Ocean (Vincent and Belzile 2003), particles may also play a significant role in UV attenuation. Any climate-related effects that increase particle loading or the *in situ* growth of particles (bacteria and protists) therefore have the potential to affect underwater UV exposure. Some phytoplankton in alpine lakes contain UV-screening mycosporine-like amino acids (Sommaruga and Garcia-Pichel 1999), and stimulation of their growth by the nutrient enrichment accompanying even small rises in temperature (Sommaruga-Wögrath et al. 1997) would substantially reduce the UV transparency of the water column. Turbid glacial inputs are also known to decrease UV transparency, for example at Arctic Kongsfjord at Spitsbergen (Hanelt et al. 2001) and in the coastal Southern Ocean (Stambler et al. 1997). Climatic warming may therefore extend the magnitude and duration of these UV-attenuating effects through increased glacial melt.

14.2.5 Mixing and stratification (integral $1/K_{dUV}$)

Climate influences the depth, frequency and intensity of mixing of the surface layer of lakes and oceans, and this will directly affect UV exposure of planktonic organisms. Biota trapped at the surface during diurnal stratification will experience severe UV exposures, while deeper mixing communities will experience only intermittent, short-term UV stress. Studies on sub-arctic (Milot-Roy and Vincent 1994) and alpine lakes (Vincent et al. 1984) have shown the importance of diurnal thermoclines for UV-and PAR-dependent photoinhibition of algal photosynthesis. Diurnal stratification is likely to become more pronounced in a warmer climate, and may even select for more UV-tolerant genotypes. Deep mixing can eventually expose all of the water column plankton to surface UV, and if their rate of repair of the resultant damage is slower than the timescale of mixing then this deep circulation could potentially enhance the net water column UV damage (Neale et al. 1998b). Such effects may be especially pronounced in cold polar and alpine waters where repair is slowed by the ambient low temperatures (Rae et al. 2000). Most studies, however, show decreased UV-inhibition of total water column photosynthesis associated with deep mixing (Neale et al. 1998b; Barbieri et al. 2002). A modeling study by Huot et al. (2000) on bacterial DNA damage by UV, with repair by photoreactivation and excision, showed that variations in mixed layer depth affected the net damage in the mixed layer (and to a much greater extent than changes in CDOM concentration), and that the speed of mixing affected the vertical distribution of damage. They noted that the latter effect could be significant if biological processes such as survival, productivity and viral lysis respond non-linearly to net DNA damage.

Any future shift in high latitude and alpine lakes from cold monomixis (continuous mixing during summer) to dimixis (stratification during summer) will also result in communities exposed to much greater UV as well as PAR. There is evidence from a Finnish subarctic lake (Korhola et al. 2002) of this type of thermal shift during the 20th century. This was accompanied by an apparent increase in productivity and the appearance of cladocerans in the zooplankton community. These Finnish lake results imply that the positive effects of increased PAR on ecosystem productivity were much greater than the negative effects of increased UV exposure.

The thermal effects of global climate change are also likely to be felt more strongly in clear lakes in general. In an analysis of interannual variations in climate and lake thermal regimes, Snucins and Gunn (2000) found that the volume of cold water was significantly reduced in clear lakes during warm summers, while colored lakes (DOC > 4 mg L^{-1}) were less sensitive to the warming effects of climate change. They also suggested that clear lakes will experience large thermal regime shifts in response to small variations in DOC loading.

The Arctic Ocean has a much shallower mixed layer than the open waters of the Southern Ocean because of the strong freshwater influence, and any change in precipitation and runoff into the Arctic Basin could modify mixed layer depth and thus UV exposure. Similarly, coastal Antarctic seas are often stratified by meltwater input (e.g., Antarctic Peninsula: Mitchell and Holm-Hansen 1991; Terra Nova Bay: Arrigo et al. 2000) and changes in glacial runoff and sea ice melt would affect mixing and UV. The loss of sea ice in a warmer polar climate would drastically increase surface UV exposure, but this would be at least partially offset by the wind-induced mixing of biota throughout a deepened surface layer.

14.2.6 Biological weighting factors (ε)

Biological weighting factors (BWF) express the quantitative relationship between biological damage and UV wavelength, and generally increase sharply with decreasing wavelength. The exact form of this relationship differs greatly among different types of biological effects as well as with duration of exposure, the pre-acclimation characteristics of the biological community, species composition and a variety of other factors that are currently subject to discussion and ongoing research. For example, the modeling study by Gibson et al. (2000) for the Arctic Ocean indicated the combined effect of ozone depletion and changes in CDOM in controlling the extent of DNA damage, and the much greater influence of CDOM in controlling the variations in UV-inhibition of photosynthesis. This was because the BWF for UV-photoinhibition is strongly influenced by UV-A as well as UV-B (both controlled by CDOM) whereas DNA-damage rises much more steeply with decreasing UV wavelength and UV-A.

Climate change is likely to result in species shifts, that in turn affect the capacity of the phytoplankton to acclimate. For example, Neale et al. (1998a) found that the UV-tolerance of phytoplankton in the Weddell-Scotia Confluence was highest in assemblages from shallow mixed layers, suggesting acclimation and-or selection for tolerant genotypes. Warmer temperatures in the present changing climate may allow increased efficiency of repair, and thereby shift the BWF curves of all species.

14.3 Paleo-ecological evidence of climate-UV effects

Paleolimnological or paleoceanographic reconstructions of past irradiance regimes ('paleo-optics', Pienitz and Vincent 2000) can substantially contribute to a better understanding of the magnitude, causes and consequences of temporal variability in UV radiation. Using microfossil remains (siliceous diatoms), photo-protective pigments (e.g., scytonemin) or bulk sedimentary characteristics (% organic matter) preserved in long sedimentary sequences (cores), such retrospective analyses permit reconstructions of past concentrations of UV-absorbing dissolved organic carbon compounds (DOC) that can be used to infer water column transparency, term ($1/K_{dUV}$) in Eq. (2), and other ecological important optical properties such as UV/PAR ratios. The application of paleolimnological approaches to lakes at treeline show both that climatically-induced changes in the export of terrestrial (allochthonous) DOC to lakes are up to 100-fold more effective than modern stratospheric ozone depletion at altering biological exposure to UV (Pienitz and Vincent 2000), and that naturally occurring droughts can increase UV exposure in lakes by up to 10-fold (Yan et al. 1996). Analyses of fossil remains in arctic/boreal and alpine lakes suggest that historical variability in UV exposure has been high (e.g., Leavitt et al. 1997, 2003a,b; Pienitz and Vincent 2000; Saulnier-Talbot et al. 2003), and that lakes may have received twice as much UV prior to ca. 3000-4000 years ago than they do at present. Finally, when used in combination with long-term environmental monitoring (Schindler et al. 1996, 1997), historical reconstructions have proven valuable at identifying the importance of UV relative to other stressors in regulating lake structure and function. Thus, although further research is required to validate fossil interpretations, paleoecological analyses of lake sedimentary records can provide valuable insights into the history of UV exposure and its potential impacts on aquatic ecosystems.

Multivariate analysis of modern diatom assemblages preserved in surface lake sediments has been used to develop statistical models (transfer functions) based on the relationships between the present-day species composition and environmental conditions (e.g., Pienitz and Smol 1993; Fallu and Pienitz 1999; Fallu et al. 2005). Application of these models to fossil diatom assemblages in long sedimentary sequences (cores) allows quantitative reconstructions of past lake conditions over 100s to 1000s of years, including DOC content, water colour and optical regime (e.g., Pienitz and Vincent 2000; Dixit et al. 2001; Ponader et al. 2002; Saulnier-Talbot et al. 2003; Fallu et al. 2004). Further details on the calibration data set approach and standard procedures involved in the development of diatom-based inference models for DOC and other variables are given in Pienitz and Smol (1993) and Fallu and Pienitz (1999).

14.3.1 Lakes at the subarctic treeline

To address the potential impact of long-term climate change relative to that of ozone depletion, Pienitz and Vincent (2000) combined paleolimnological analyses with bio-optical models based on present-day conditions in lakes of northern Canada. This new paleo-optical approach allowed them to estimate past underwater light conditions from DOC concentrations that

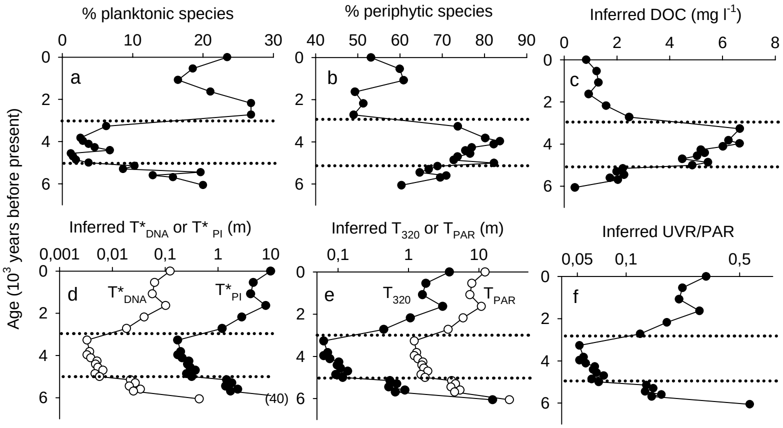

Fig. 14.3. Changes in fossil diatom community structure and inferred optical conditions in Queen's Lake, Northwest Territories (Canada). Diatom data are expressed as a percentage of the total number of valves in each sample associated with planktonic or benthic taxa. Diatom species data were used to infer DOC concentration (mg DOC L^{-1}), biologically weighted UV exposure (T*$_{PI}$ or T*$_{DNA}$) and underwater spectral balance (water column transparency for 320 nm UVR [T_{320}], PAR [T_{PAR}], and the ratio between the two [UVR/PAR]) over the last 6000 years. The dotted lines delimit the period of mid-Holocene maximum forest cover. This analysis demonstrates that biotic exposure to UVR varies substantially due to changes in catchment vegetation and DOC supply, and that during the mid-Holocene climatic warm period, UVR exposure declined by two orders of magnitude. Climatic cooling beginning at ca. 3000 yr BP reduced DOC inputs by reducing soil development and DOC supply, and led to increases in UVR penetration that were up to 4000-fold more significant than those expected to arise from a moderate (30%) ozone depletion. From Pienitz and Vincent (2000)

were inferred from fossil diatom assemblages preserved in Holocene sedimentary deposits from a lake near the northern treeline (Queen’s Lake; lat. 64°07'N, long. 110°34'W) in the central Northwest Territories, Canada (Fig. 14.3). Analysis of fossil pollen records indicates that regional vegetation cover was sparse and tundra-like following deglaciation ca. 8000 yr BP and persisted until trees colonized the catchment ca. 5000 years ago (MacDonald et al. 1993).

Diatom community structure and inferred DOC levels showed three distinct and abrupt changes during the history of Queen's Lake. Both diatom biomass and inferred DOC concentrations were low (< 2 mg DOC L^{-1}) during the initial lake phase, with particularly few fossils recovered from sediments dating prior to 5000 yr BP. This initial period of lake existence was followed by major and rapid shifts in fossil species composition and inferred chemical conditions ca. 5000 yr BP, with increased ratios of periphytic:planktonic taxa to >70% of the total diatom assemblage.

The period of forest advance corresponded to a major increase in algal production, recorded as the sediment mass-specific concentration of diatom valves, as well as a three-fold increase in inferred DOC levels. Based on fossil pollen analyses, Pienitz and Vincent (2000) argued that changes in lake chemistry and production resulted from climatic warming that stimulated treeline advance and increased forest density for about 2000 years. Finally, diatom-based reconstructions indicated that DOC concentrations declined >85% after 3000 yr BP, concomitant with the onset of Neoglacial climatic cooling and a southward retreat of treeline (MacDonald et al. 1993).

The large and rapid changes in DOC imply that Queen's Lake experienced major shifts in the underwater optical environment over the last 6000 years as a consequence of climate-induced variation in forest development (Pienitz et al. 1999). Consistent with this hypothesis, application of T^* calculations for UV-inhibition of photosynthesis and UV-damage of DNA showed that the inferred DOC shifts were equivalent to a two order-of-magnitude decrease in exposure to biologically-effective UV during the mid-Holocene vegetation maximum between ca. 5000 and 3000 yr BP. In contrast, the most recent 3000 years were characterised by a >50-fold increase in levels of damaging UV. Overall, changes in DOC concentrations arising from climatic variability increased exposure to photosynthetically damaging UV to an order-of-magnitude greater extent than a moderate (30%) decline in stratospheric ozone levels. Pienitz and Vincent (2000) noted, however, that the large photoinhibiting effect of UV irradiance after treeline retreat would be at least partially offset by the major increase in PAR for photosynthesis under these conditions of much reduced CDOM.

More recently, Lehmann et al. (2004) have modified and refined the biologically weighted transparency model by extending it out into the PAR waveband and by including separate terms for light-dependent photosynthesis and light-dependent inhibition of photosynthesis. This approach allows a quantitative estimate of water column photosynthesis ($\int P$) under different UV regimes via the relationship:

$$\int P = a\,(T_{PUR})^{b}./\,(T_{PIR})^{c} \tag{3}$$

where T_{PUR} is transparency weighted for photosynthetically utilisable radiation calculated over the waveband 400-700 nm; T_{PIR} is transparency weighted for photosynthesis-inhibiting radiation over the full waveband 280 to 700 nm; and *a*, *b* and *c* are statistically fitted constants. Lehmann et al. (2004) applied this model to the Queen's Lake paleolimnological data set and their results confirmed that decreasing CDOM concentrations during the retreat of the treeline would result in a significant increase in UV-inhibition of photosynthesis. However, this effect (as % reduction in $\int P$) was a factor of ten less than the T^* calculations predicted, in particular because the increasing water clarity also allowed greater exposure to PAR. This in turn resulted in more total water column photosynthesis that substantially offset the negative effects of increased biological UV exposure. These results have important implications for climate impact studies because they draw attention to the full spectral consequences of changing light regimes, and the need to examine the net effects of both positive and negative responses to environmental change.

14.3.2 Climate change effects on UV exposure in Rocky Mountain lakes

Climatic control of past UV exposure has also been identified as a key factor regulating lake production and algal community composition in lakes at the alpine treeline. Using fossil pigments and organic matter preserved in lake sediments, Leavitt et al. (2003b) quantified past UV exposure in the 12,000 year history of subalpine Crowfoot Lake, located near the alpine treeline in the Rocky Mountains (Alberta, Canada). Their study revealed highest concentrations of UV-absorbing algal pigments and declining algal biomass during periods of early lake existence following deglaciation as well as during the last ca. 4,000 years, when external DOM inputs are believed to have been lowest and UV exposure highest. Based on fossil pigment and bulk organic matter-derived estimates of irradiance penetration, they calculated that algal abundance was reduced 10 to 25-fold during these periods of high UV exposure. However, at all other times in the lake's history (ca. 10,050-4,000 yr BP), photoprotective pigments associated with high UV were absent from sediments and the total algal abundance was high.

14.3.3 Past UV exposure in Antarctica

The lakes at high latitudes are especially suitable for UV studies as they have limited or no terrestrial sources of UV-absorbing DOM within their catchments (Vincent and Pienitz 1996). Therefore changes in UV would be expected to arise solely from changes in solar production, atmospheric transmission, ice and snow cover or lake depth. Using a similar pigment approach as above, Leavitt el al. (2003a) showed that shallow lakes in Antarctica have been exposed to variable levels of UV of the Holocene, and higher levels in the preceding interglacial (Hodgson et al. 2005). Their analyses of lake sediments indicated that photo-protective pigments (scytonemin and its derivatives) were relatively more abundant in sediments older than 4000 years. The reconstruction further indicated that receipt of UV irradiance by benthic cyanobacteria in antarctic lakes has varied by at least 400% during the past 13 000 years. At present, photoprotective pigments, including scytonemin, are common in algal communities in antarctic lakes that are shallow (< 4-6 m depth) and transparent, and their abundance has been shown to increase as a function of algal exposure to UV (Hodgson et al. 2005).

14.3.4 Deglaciation responses in a coastal subarctic lake, Hudson Bay

Saulnier-Talbot et al. (2003) used a diatom-based paleo-optical approach to estimate past depths of UV penetration in coastal Lake Kachishayoot (northwestern Québec, Canada; lat. 55°20.0' N, long. 77°37.4'W; 102 m a.s.l.) following its isolation from the marine waters due to glacio-isostatic rebound of Hudson Bay lowlands. Prior comparisons of optical environments in coastal systems have revealed that shifts from marine to freshwater conditions are accompanied by increased DOC, changes in C-specific UV attenuation and declines in UV penetration (Conde et al. 2000). Consistent with these modern observations, Saulnier-Talbot et al's (2003) multi-proxy investigation revealed abrupt increases in diatom-inferred DOC concentrations and water color that coincided with the retreat of postglacial marine waters and the arrival of spruce trees within the landscape and catchment of the study site. Their investigation also revealed large changes in the underwater irradiance environment over the course of the postglacial period, from extremely high UV exposure following the initial formation of the lake and its isolation from the sea, to an order-of-magnitude lower exposure associated with the development of spruce forests in the catchment. Furthermore, the use of additional macrofossil markers revealed that UV penetration remained low even following forest retreat due to the development of alternate DOC sources in the catchment such as *Sphagnum* wetlands.

14.3.5 UV-exposure in lakes during glacial retreat at Glacier Bay, Alaska

A final paleo-ecological example is based on a set of modern day ecosystems, but environments that span a gradient of different ages and degrees of maturity in successional development. Major variations in CDOM and in underwater UV radiation have been observed in the chronosequence of lakes associated with the retreat of ice over the last 12,000 years in the Glacier Bay area, Alaska. Lakes near the glacier face and up to a few decades old have high pH and low DOC. With the gradual development of alder, coniferous forest and peatlands, the lakes have become more acidic, more dilute and have accumulated DOC associated with the slow but continuous accretion of soil organic matter. This soil development has been accompanied by a shift in hydrology from groundwater flow to increased near-surface runoff resulting in increased flow through the peat and weathered soil horizons, increasing the efficiency of transfer of organic matter from soil to water (Engstrom et al. 2000). Measurements of UV penetration in some of these lakes showed that 1% of surface UV at 320 nm was correlated with DOC content, and ranged from 0.6 m in a 90-year old coloured lake to more than 14 m in a 10-year old clear lake. These disparate optical conditions also corresponded with major differences in zooplankton community structure, and transplant experiments confirmed that UV exposure had a strong effect on zooplankton survival, but to an extent that varied according to species (Williamson et al. 2001). These results provide strong evidence that climate effects on vegetation and hydrology are likely to have a major influence on underwater UV exposure and associated impacts.

14.4 Conclusions

There are many mechanisms linking UV exposure to climate in the aquatic environment. Some are caused by climate-induced changes in the stratosphere, while many are associated with temperature-related effects on the main UV-attenuating components of natural waters, notably changes in snow and ice cover, and in CDOM associated with shifts in terrestrial vegetation. There are also a variety of hydrological effects of climate with major implications for underwater UV such as changes in snow and rainfall (with runoff, vegetation and albedo effects), evaporation and cloud cover, pathways of runoff and degree of interaction between the soil and water. Finally, there are more subtle effects such as changes in wind-induced mixing and climate-induced shifts in species composition towards more or less UV-tolerant species. Many of these effects are likely to be especially pronounced in arctic, antarctic and alpine aquatic ecosystems where there is a precarious balance between freezing and melting throughout summer, and in which CDOM concentrations are often in a range where small changes have a large effect on UV transparency. As shown with the many examples and models summarized here, several of these climate change mechanisms can have much greater impacts on biological UV exposure than the recently observed human-induced changes in stratospheric ozone. The paleo-ecological examples provide several lines of evidence for the overriding control exerted by external catchment processes, in turn mediated by climate, on the underwater optical conditions in lakes. All arctic investigations to date converge on the conclusion that biotic exposure to UV should have been greatest early in lake history immediately after deglaciation or retreat of postglacial seas, prior to the development of terrestrial sources of UV-absorbing DOM. Because past episodes of UV exposure appear to have been greater than those arising from many modern processes, these analyses offer insights (potentially at annual resolution) into the unique impacts of UV on ecosystem processes, including those occurring immediately after lake formation when DOM inputs are lowest. In the Antarctic, the near absence of UV-absorbing CDOM means that the absorption and transmission characteristics of ice, snow and the atmosphere are likely to be more important. Finally, to what extent will the future warming of polar and alpine regions result in UV-mediated changes in biological and biogeochemical processes in the aquatic environment? Higher temperatures will mean longer open water conditions (more UV) but also more vegetation and CDOM input. The mobilisation of DOC within alpine and northern permafrost soils has the potential to cause a massive influx of CDOM, and substantial increases in UV-shading. However, the beneficial effects of these changes may be offset by the concomitant decrease in availability of light in the visible range for photosynthetic production. The future assessment of climate impacts in polar and alpine regions will require close attention to the net result of these opposing effects.

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15 Effects of UV radiation on seaweeds

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15.1 Introduction

Depletion of stratospheric ozone over the Arctic region (Müller et al. 1997; Rex et al. 1997) causes an increase of UV-B radiation (280-315 nm) and could affect algal distribution patterns in the unique marine ecosystem (Wiencke et al. 2000). To date, most of the recent investigations on biological effects of UV radiation on marine ecosystems have concentrated on the Southern Ocean due to the huge "ozone hole" over Antarctica (Holm-Hansen et al. 1993a,b). Increasing ozone depletion over the northern Hemisphere (Blumthaler and Ambach 1990; Wängberg et al. 1996) may also have the potential to change growth conditions for macroalgae and other organisms, especially in Arctic waters. Therefore, in recent years several studies on the distribution and the physiology of several algal species growing in the Arctic environment have been undertaken to investigate the effects of ultraviolet radiation on seaweeds (e.g. Hanelt et al. 1997a; Bischof et al. 1998; Karsten et al. 1998, 1999). In coastal sea waters, UV radiation (UV) and blue light are strongly attenuated (Björn 1993), and this depends largely on the input of dissolved organic matter (DOM) from terrestrial ecosystems. This occurs often during the warmer seasons due to rainfall or melt water from snow layers and glaciers. Moreover, the absolute UV irradiation depends also on the clouds, solar altitude or sun angle which is much lower in the Arctic than at temperate zones. That means that already double of UV-B radiation is impinging on the earth surface in a temperate latitude 20° lower, which needs to be considered for discussing the UV problem in polar regions. However, in comparison to temperate species polar algae are more sensitive to UV.

In spring, coinciding with low temperatures and clear water conditions, the harmful UV wavelengths penetrate deeply into the water column in Kongsfjorden (Svalbard; Hanelt et al. 2001). The threshold irradiance with the potential to affect primary plant productivity negatively was still found at about 5-6 m depth. With increasing temperature in summer, snow layers and glacier ice melt, resulting in a high discharge of turbid fresh water into the fjord overlaying the more dense sea water. This causes a stratification in the optical features, salinity and temperature of the water body, strongly attenuating solar radiation in the first meter of the water column. Consequently, organisms in deeper water are more protected against harmful UV-B radiation. Nevertheless, organisms growing in the intertidal are still exposed to high UV-B during low tide and high sun position also in summer. The possible impact of global climate change on the radiation conditions underwater and the effects on primary production of seaweeds can be higher during the spring season, as organisms in the eulittoral and upper sublittoral zone are affected by UV radiation throughout the polar day. In addition, melt water input is only a phenomenon during the warmer summer season. This applies to Arctic shorelines in half-open fjord systems where the water exchange with the clearer oceanic water is retarded. At open coastlines the melt water will be exchanged much faster with oceanic water which will diminish the observed turbidity effects on light penetration.

15.2 Effects on the molecular level

Due to the high energy of UV-B and the special absorption characteristics of aromatic and sulphur containing aminoacids (e.g. tyrosine, tryptophan, sulfhydril group of cysteine and nucleic-acids, especially pyrimidines), or by production of free radicals within the chloroplast and their reaction with nucleophilic amino acid side chains, UV can induce severe damage on the cellular level (Bornman and Teramura 1993; Jordan 1996). On the molecular level, proteins (e.g. destruction of C-C bonds, or the tertiary protein structure due to S-S bond cleavage) and lipids (e.g. peroxidations at C=C bonds), as well as nucleic acids (especially cyclobutyl pyrimidine dimers and pyrimidine (6-4) pyrimidone photoproducts) are particularly affected. Conformation changes of certain proteins involved in photosynthesis, such as the reaction center protein (D_1) of photosystem II or the CO_2 fixing enzyme in the Calvin cycle (ribulose-1,5-bisphosphate carboxylase/oxygenase, RubisCO) lead to an inhibition of photosynthesis, and consequently to a decrease in the productivity of the plants which will be demonstrated below (for review on the effects see Holm-Hansen et al. 1993b; Bornman and Teramura 1993; Jordan 1996; Franklin and Forster 1997; Häder and Figueroa 1997). Moreover, different life stages in the life cycle of an individual species may differ in its sensitivity to UV radiation (Wiencke et al. 2000). The small zoospores can be easily penetrated by damaging UV radiation. However, several macroalgal species may be able to protect themselves against UV radiation by synthesis and accumulation of photoprotective substances, e.g. of mycosporine-like amino acids (MAAs; Karsten et al. 1998, 2003). The capacity for formation of MAAs induced by UV radiation has been shown in particular for shallow water red macroalgae (Karsten et al. 1999; Hoyer et al. 2002, 2003).

Animals feeding on MAA-rich algae might be protected against UV radiation (Dunlap and Shick 1998; Cockell and Knowland 1999). Adams and Shick (1996, 2001) demonstrated in a feeding experiment with the red alga *Mastocarpus stellatus* and the sea urchin *Strongylocentrotus droebachiensis* that the sea urchin eggs became less sensitive to UV if sea urchins were previously fed with MAA-rich algae. The division of the eggs, normally delayed by UV, occurs faster, when the eggs were loaded with MAAs. A possible protective effect of the MAAs as UV filter in macroalgae was demonstrated by Bischof et al. (2000b) by a comparison of the UV sensitivity of the two space competitive red algae *Mastocarpus stellatus* and *Chondrus crispus* from Helgoland. Quantum yield of photochemistry as well as maximal electron transport rate in *C. crispus* were more strongly affected by UV-B radiation than in *M. stellatus* (Fig.15.1). But no negative effects of the respective radiation conditions were found on total activity of RubisCO. Total MAA content in *M. stellatus* was up to six fold higher than in *C. crispus* and the composition of MAAs in the two species was also different. The results indicate that, among others, UV-B sensitivity may be a factor restricting *C. crispus* to the lower intertidal and upper sublittoral, whereas *M. stellatus* is better adapted to UV radiation and is therefore more competitive in the upper intertidal.

Besides the MAAs, which mainly were found in red and a few green algal species (Karsten et al. 1998) other molecular groups may prevent damage by the establishment of a physical barrier to shield critical cellular components (e.g. the photosynthetic apparatus, DNA) against harmful radiation (Beggs et al. 1986; Karentz 1994). Previous research on marine macroalgae has stressed the induction of different UV screening components in various algal groups.

In the Mediterranean alga *Dasycladus vermicularis* an unknown UV absorbing compound is excreted into the surrounding water under UV stress and protects photosynthesis and enzyme activity against harmful UV-B (Gómez et al. 1998). Generally, cellular concentrations of algal UV

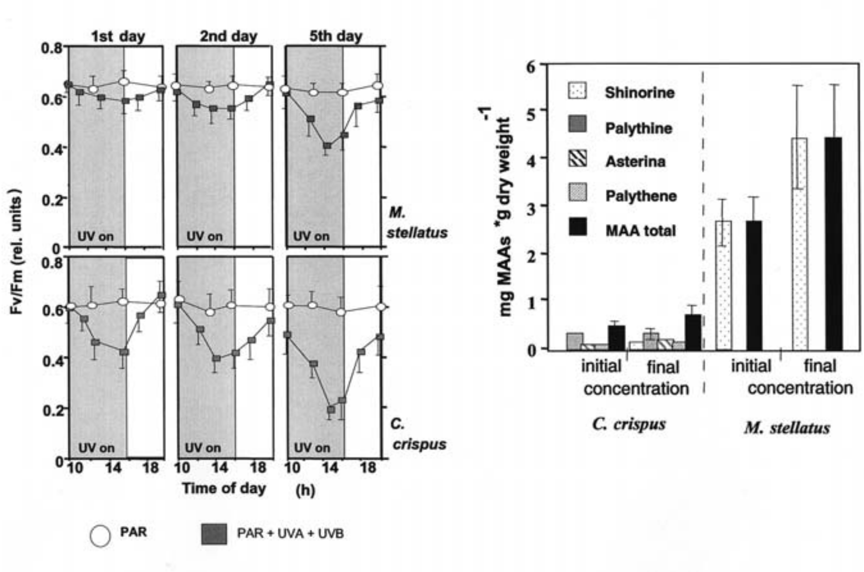

Fig. 15.1. Comparison of the photosynthetic activity and MAA content of two space competitive red algae *Mastocarpus stellatus* and *Chondrus crispus*. Left side: photosynthetic activity under UV stress was measured on five consecutive days by in vivo fluorescence (Fv/Fm). Additional to PAR, UV was irradiated always from 10 to 16 o'clock. The photosynthetic activity of *C. crispus* decreased much stronger under additional UV than in *M. stellatus*. One reason might be the different content of UV absorbing compounds (MAAs) within each species. The right side of the figure shows the content of different MAAs before and after the irradiation period. *C. crispus* possesses a higher diversity in these compounds but the concentration is much lower than in *M. stellatus*, which also means a lower UV absorption by these sunscreens (modified after Bischof et al. 2000b).

absorbing compounds seem to depend on the degree of exposure to UV, thus determined by the season, the algal position in the canopy and the respective growth depth. Wood (1987) described the UV induced production of unspecified UV absorbing compounds in the kelp *Ecklonia radiata* from Western Australia. More recent research indicate that especially in brown algae, phenolic compounds play a major role as UV sunscreens (Schoenwaelder et al. 2003). In *Ascophyllum nodosum* from the west coast of Sweden, Pavia et al. (1997) demonstrated that UV is an important factor related to intraspecific variation in phlorotannin content. In higher plants it is known that UV-B penetration through epidermal layers is much lower in conifer than in herbaceous species. It was concluded that the lower UV-B transmittance through the anticlinal cell walls is caused by the presence of more phenolic compounds (Jordan 1996). As brown algae contain a huge amount of phenolic substances, this may act as a possible UV-B screen in this algal class, comparable to the findings in higher plants.

Under UV stress there is an increased formation of reactive oxygen species such as oxygen radicals, which can induce an oxidation of many essential biomolecules susceptible to oxidative damage (Halliwell and Gutteridge 1989; Franklin and Forster 1997; Franklin et al. 2003). At a high reduction state of ferredoxin, due to high light exposure, electrons transferred from PS I to oxygen can generate superoxide radicals (similar to the Mehler reaction). Reactive oxygen species (ROS) would oxidize chlorophylls and proteins, for instance, the D_1 protein in the reaction center of PS II (Andersson et al. 1992). To prevent those high light damages, many marine organisms possess specific scavenging enzymes for detoxifying the damaging oxygen species (especially superoxide-dismutase, catalase, gluthation reductase, ascorbate peroxidase; Aguilera et al. 2002b; Dummermuth et al. 2003). However, the antioxidative enzyme system may also be inhibited under UV stress and the inhibition of the photoprotective xanthophyll cycle by UV-B may lead to an increase of the ROS production (Bischof et al. 2003). Beside these enzymological systems, various hydrophilic and lipophilic scavenging antioxidants are also present (especially vitamin E and C).

DNA damage can be repaired photoenzymatically in the presence of UV-A or blue light. This repair mechanism is known as photoreactivation or photoenzymatic repair, and it reverses the photodimer products (cyclobutane-pyrimidine dimers; CPDs) to its normal monomeric form. The dimers are cytotoxic because they block DNA and RNA polymerase and consequently inhibit genome replication and expression (Jordan 1996). Specific photolyases have been identified for thymine and 6-4 photoproducts. There is also another repair mechanism, which is independent of light, and it is called nucleotide excision repair or "dark repair". This mechanism, in which several enzymes are involved, consists of excising the damaged oligonucleotide and replacing it by a newly synthesized fragment. Whereas UV induced CPD formation can be rapidly repaired in light, the excision repair works in darkness but more slowly (Britt et al. 1993). CPD induction can exceed repair rates as sun radiation mediated CPD accumulation has been detected in phyto- and bacterioplankton and plants from a wide range of latitudes (Ballaré et al. 1996; Jeffrey et al. 1996a,b; Rousseaux et al. 1999; Boelen et al. 2000; Buma et al. 2000, 2001a, b; van de Poll et al. 2001). The accumulation of CPDs is accompanied by reduced growth rates in several phytoplankton and macroalgal species (Buma et al. 2000; van de Poll et al. 2001, 2002). The DNA damage burden in Arctic macrophytes mediated by ozone depletion may elevate and consequently depress productivity and alter species composition.

However, the ecological relevance of DNA damage as a stress factor for macrophytes is uncertain at high latitudes because relatively low irradiances of the DNA harming short wavelengths of UV-B reach the ground in the Arctic (Hanelt et al. 2001). Exclusion of UV radiation from the natural solar spectrum resulted in an elevated overall activity of RubisCO in *Ulva lactuca* (Bischof et al. 2002b), related to an increase in its cellular concentration. That means UV-B may cause an additional stress on the activity of the Calvin cycle, decreasing the CO_2 fixation rate. Among the photosynthetic pigments, lutein concentration was substantially elevated under UV exclusion and also the ratio of zeaxanthin concentration to the total xanthophyll content increased (Bischof et al. 2002b). Zeaxanthin is one of the important pigments which dissipate excess energy harmless by heat which will be further explained below. Therefore, these results indicate adverse effects of UV-B on the efficiency of photoprotection under high irradiances of PAR. The results confirm a marked impact already of present UV-B levels on macroalgal physiology under natural field conditions.

Marine animals living in the coastal ecosystem are often protected against UV radiation by UV impermeable shells or scales. Moreover, many animals are able to move vertically and thereby to withdraw from the influence of surface radiation (Obermüller et al. 2003). On the other hand, various animals are exposed to UV induced formation of toxic oxygen radicals and hydrogen peroxide, especially in places where - due to a dense algal vegetation or phytoplankton concentration - high oxygen concentrations are present. Hydrogen peroxide penetrates relatively easily through the body surface of soft-skinned animals and is therefore able to damage even organisms which are protected against UV radiation by their shells or the sediment tubes they inhabit (Abele-Oeschger and Oeschger 1995; Viarengo et al. 1998). As in algae, the relevant protecting mechanisms are antioxidants and antioxidative enzymes protecting the functional proteins and membrane lipids against photooxidative damage. By this way, the function of the cellular metabolism is generally maintained as long as the oxygen radical scavenging system is not overstressed.

15.2.1 Inhibition of the photosynthetic performance

Seaweed productivity depends strongly on the daily impinging photon fluences and this determines generally the lower distribution limit in the sublittoral (Gómez et al. 1997; Hanelt et al. 2003). For planktonic algae, generally a lower depth limit of 1% of the surface light is regarded as euphotic zone (Steemann Nielsen 1975). Brown kelps reach their lower growth limit at about 0.6 - 1.2 % of surface light, whereas for the deep growing red macroalgae a minimum of 0.001 - 0.05% was determined (Lüning 1985). Deepest crustaceous macroalgae seem to survive at an absolute light minimum of about 0.01 µmol $m^{-2}s^{-1}$ (Littler et al. 1986). In the intertidal and close below the water surface the survival of the organism depends, however, also on the capacity to cope with temporary high radiation stress. Sunny days can depress photosynthetic activity of marine macroalgae, especially in the intertidal and upper subtidal (Huppertz et al. 1990; Henley et al. 1991, 1992; Hanelt et al. 1993). First results of Larkum and Wood (1993) indicate that increasing UV levels of solar radiation also cause similar effects as observed under strong PAR. UV radiation depresses photosynthetic performance by impairing several target sites which absorb UV-B. It can be envisaged that an increase in the UV component of the light impinging on cells will increase their susceptibility to photodamage, and, hence, affect the kinetics of the recovery processes after high-light induced photoinhibition in the daily course (Hanelt et al. 1997a). Moreover, first data indicate also an effect of UV radiation on N-uptake in macroalgae (Döhler et al. 1995), a result which makes more intensive investigations necessary.

In the field, high irradiances of PAR are generally accompanied by harmful UV-B irradiation. Although the measurable effects (such as reduced photosynthetic efficiency) caused by both wavebands, are similar, the mechanisms behind PAR and UV induced inhibition of photosynthesis are very different. Therefore, both events should be carefully distinguished (Neale et al. 1993). To protect photosynthesis from high irradiances of PAR, plants activate different mechanisms. The increase of thermal energy dissipation removes excessively absorbed energy before generation of reactive oxygen species (ROS) can occur. The mechanism is proposed to include an increase in heat dissipation within the antennae, by the interconversion of violaxanthin to zeaxanthin within the xanthophyll cycle, which is also described for green and brown algae (Demmig-Adams 1990; Uhrmacher et al. 1995; Schofield et al. 1998). Zeaxanthin may act as a direct quencher of excited triplet chlorophyll, thus avoiding energy transfer to triplet oxygen (Frank et al. 1994). ROS may be scavenged by carotenoids and other antioxidants (as e.g. glutathione), or they may be enzymatically degraded by superoxide dismutase (SOD), catalase or peroxidase (Asada and Takahashi 1987; Barber and Andersson 1992). However, if PAR stress exceeds the protective capacity of the radical quenching enzymes and carotenoids, damage to the photosynthetic apparatus occurs, and plants bleach due to the photooxidation of their pigments (Björkman 1981; Krause 1988). This may be enhanced by the concomitant high UV irradiances as the down regulation of the photosynthetic activity due to dynamic photoinhibition seems to be negatively affected by UV-B. The recovery process from photoinhibition is delayed (Hanelt et al. 1997a) and the protective zeaxanthin content is diminished (Bischof et al. 2002b). Moreover, RubisCO activity is inhibited by UV-B exposure (Strid et al. 1990; Bischof et al. 2000a) and this is likely to be caused by protein degradation as well as inactivation of the enzyme.

Due to numerous effects of UV-B radiation to the respective biomolecules involved in photosynthesis, the effects of UV exposure are manifold (see Vass 1997 for review). The common consequences on photosynthetic function are decreased CO_2-fixation and oxygen evolution (Renger et al. 1986; Allen et al. 1997). This could be caused by several molecular events. While most studies have found that PS I is only minimally affected by UV-B (by inhibiting PS I-mediated cyclic photophosphorylation; Iwanzik et al. 1983; Renger et al. 1986), PS II seems to be a more important target (Bornman 1989; Jordan 1996). It is likely that UV-B causes an inhibition of energy transfer within the PS II reaction center by blocking the electron flow. This may be due to interactions with the electron transfer from phaeophytin to plastoquinone or by directly affecting the plastoquinones Q_A and Q_B, both showing a strong absorption within the UV-B region (Iwanzik et al. 1983). UV radiation may also cause structural modification of the Q_A and Q_B apoproteins. Furthermore, the function of the D_1 protein may be impaired by the UV-B induced fragmentation of the protein (Renger et al. 1989; Vass 1997). On the oxidizing side of PS II, the oxygen evolving system (water splitting complex) is another sensitive target of UV-B (Renger et al. 1989). Furthermore, it has been suggested that UV-B may affect the light-harvesting complex (LHC) by its functional disconnection from the photosystem, resulting in an impairment of energy transfer to the reaction center (Renger et al. 1986; Lorenz et al. 1997). In addition to the direct damage to PS II, structural disturbance of the membranes is likely to result in a reduced photosynthetic activity, e.g. due to dilation of the thylakoid membranes and rupture of the chloroplast double membrane (Iwanzik et al. 1983; Strid et al. 1994; Poppe et al. 2002, 2003). A decrease in photosynthetic activity may also be due to the photodestruction of pigments. Within the pigment group of chlorophylls, Chl *a* has been observed to be more affected than Chl *b* (Teramura 1983; Strid et al. 1990) and in brown algae Chl *c* seems to be more sensitive than Chl *a* (Roleda et al. 2004a). An additional effect of UV-B on reactions related to photosynthesis represents the inactivation of chloroplast ATPase (Strid et al. 1990). Impairment of any of the above-mentioned components can contribute to lower the photosynthetic activity during and following UV exposure.

Recently, the gene regulation of the CO_2 fixing enzyme RubisCO has been shown to be another critical component in UV induced inhibition of photosynthesis. The UV-induced decline in its activity is related to the decreasing amount of both subunits as well as the corresponding mRNA levels (Strid et al. 1990; Jordan et al. 1992; Bischof et al. 2000a). Transcripts encoding several other photosynthesis-related proteins were significantly reduced by UV-B radiation (Strid et al. 1994; Jordan 1996; Mackerness et al. 1999). These authors demonstrated that reactive oxygen species are a component in the signal transduction pathway leading to the down-regulation of gene expression in response to UV-B radiation. In contrast, cyanobacteria react to moderate doses of UV-B radiation with increased levels of psbA transcripts encoding the D_1 reaction center subunit of photosystem II (Campbell et al. 1998; Máté et al. 1998). We investigated firstly the effects of UV radiation on the regulation of photosynthetic proteins in marine macroalgae. The chloroplast-encoded psbA and rbcL RNA transcript levels, encoding for D_1 protein of the PS II reaction center and the large subunit of RubisCO, have been determined in Northern blot experiments, in samples exposed to higher UV-B irradiance (0.97 W m^{-2}) over the course of 11 days. psbA showed a rise of up to 400 % of the control after 11 days of UV exposure (Fig. 15.2). rbcL transcripts followed by an increase to 180 % of the control level. These results suggest that UV radiation affects a transcriptional regulation of proteins involved in photosynthesis. A stronger destruction of the D_1 protein due to UV-B induced chronic photoinhibition and a decrease of the RubisCO content may induce a higher transcription rate of the encoding genes for higher synthesis of both proteins to counteract the negative effects of UV-B.

In contrast to PAR, UV can not be regarded as being an "excessive energy input" in a proper sense. The maximal irradiance is much smaller than of PAR (1.8 Wm^{-2} UV-B compared to 368 Wm^{-2} PAR at 70^{o}S in Antarctica or 1.2 Wm^{-2} UV-B compared to 274 Wm^{-2} PAR at 79^{o} N on Spitsbergen; Hoyer et al. 2001; Svendsen et al. 2002). Thus, the UV wavebands do not contribute specifically to energy supply for photosynthetic chemistry.

As emphasized in this chapter, UV exhibits adverse effects on photosynthesis in a more direct way, such as its absorption by many aromatic and sulfhydril containing biomolecules leading to a direct molecular damage or by indirect evolution of reactive oxygen species. The high potential of UV to inhibit photosynthesis was firstly demonstrated by Jones and Kok (1966). Whilst within the PAR range, the action spectrum of photoinhibition runs in parallel with the action spectrum of photosynthesis (Nultsch et al. 1987; Hanelt et al. 1995), and therefore is directly related to photosynthetic pigment absorption, UV-B induced inhibition correlates much

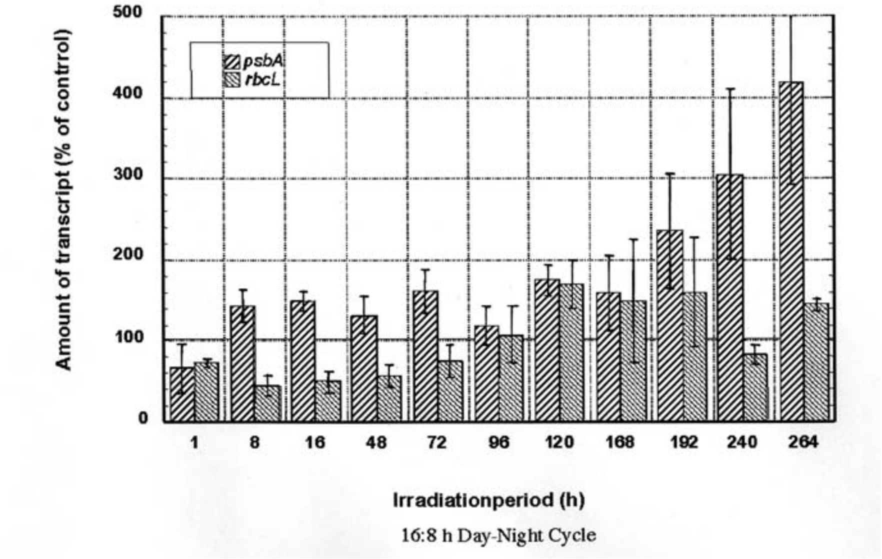

Fig. 15.2. *Palmaria decipiens*: Effect of UV-B on the amount of the mRNA encoding for the D_1 protein (psbA) and the large subunit of RubisCO (rbcL). Samples (n=5 ± SD) for RNA analysis were taken at the end of the respective exposure period (PAR + UV-A,B).

more to the absorption by DNA and proteins, conversely (Jones and Kok 1966; Setlow 1974).

15.3 Effects at the cellular level

UV-B radiation causes clear effects in cellular ultrastructure, especially in chloroplasts and mitochondria of marine macroalgae. In red algae from the Antarctic (*Palmaria decipiens*, *Phycodrys austrogeorgica)* and the Arctic (*Palmaria palmata*, *Bangia atropurpurea)* chloroplast thylakoids formed abnormal vesicles upon exposure to artificial UV radiation (Poppe et al. 2002, 2003). In *P. decipiens*, most vesicles were developed after 8 hours, in the less UV sensitive *P. palmata* after 48 hours of UV exposure. In *B. atropurpurea*, a strong vesiculation of thylakoids was observed after 72 hours of UV irradiation. In the highly UV sensitive red alga *Ph. austrogeorgica*, chloroplast envelope and thylakoid membranes were already strongly damaged and the phycobilisomes became detached from the thylakoids after 12 hours of UV exposure. UV induced changes in the membrane structure of mitochondria were observed in *P. decipiens* and *P. palmata*. However, in *P. decipiens* changes in membrane structure were reversible as was the damage in chloroplast fine structure after 12 hours of UV treatment. Protein crystals occurring in the cytoplasma of *Ph. austrogeorgica* showed a degradation after UV radiation. These findings gave first insight into the fine structural changes during and after UV exposure and confirmed the former results on inhibition of the photosynthetic performance by UV.

15.4 Effects on the early settlement stages

Early settlement stages are normally shade-adapted, as they live sheltered under adult canopies, crevices or even below stones. There is a high mortality in early post-settlement stages, and the specimens which can survive represent a gene pool for the subsequent generation (Coelho et al. 2000). The environment causes a conflict between maximum photosynthetic efficiency under low light conditions and a minimum of inhibition or even photodamage during possible exposures in high light periods. A large number of propagules are normally produced by macroalgae which disperse away from the parent population and colonize new sites. The settlement stages of subtidal macroalgae show, however, rather low light adaptations (e.g. low saturation point for photosynthesis and growth) which enable their survival in a low light environment, than under high light conditions (Lüning and Neushul 1978; Kain and Norton 1990; Franklin and Forster 1997). In many polar species growth rates and propagation are highest in spring, when the ozone destruction also occurs (Wiencke 1990a, b) and within a period when early settlement stages or young thallus parts are more sensitive to UV (Wood 1987; Dring et al. 1996). Spores seem to be the most light-sensitive life history stage found in the studied brown algae and are strongly affected by increased UV-B radiation, both with respect to their photosynthetic performance and their susceptibility to DNA damage (Wiencke et al. 2000). As already mentioned above, Schoenwaelder et al. (2003) demonstrated that zygotes and embryos of *Fucus spiralis* were less sensitive to UV-B than those of *F. serratus* and *F. distichus*. *F. spiralis* grows on the rocky shore at high light exposed positions in the upper intertidal whereas *F. serratus* is a species growing in the middle and lower intertidal, thus, is more protected against UV radiation. This is similar to *F. distichus* which grows only at higher latitudes under lower UV-B irradiances. In a recent study, Wiencke (2000) found that zoospores of several species of brown algae from Spitsbergen and southern Spain were damaged to a different degree. Their vulnerability was directly re-were damaged to a different degree. Their vulnerability was directly related to the depth distribution of their parental sporophytes, e.g. spores mortality of Laminariales is significantly caused in Spain when exposed to the radiation conditions in depths < 5m, restricting the growth to the middle and deep sublittoral. These results are supported in a subsequent study on all five kelp species from Arctic Spitsbergen (Wiencke et al. 2004). One prominent cytological feature of UV exposed spores from these species was the enlargement of phenolic vesicles (physodes), particularly seen in *Saccorhiza dermatodea* and *Alaria esculenta*, which may have a protective function against UV.

Carpospore photosynthesis and germination of the intertidal red algae *Mastocarpus stellatus* and *Chondrus crispus* are low light adapted. Roleda et al. (2004b) demonstrated that UV-A has low impact on the reproduction units of both species while a combined effect of UV-A plus UV-B with increasing exposure time is more pronounced in *C. crispus*. Photosynthetic recovery of *M. stellatus* progresses faster in carpospores when the algae were previously exposed to UV, suggesting a positive effect of UV on recovery processes. Dose-response relationship (BED_{50}) showed that *C. crispus* is more sensitive to UV as higher fluences were necessary to achieve 50% germination inhibition in *M. stellatus*. This corresponds to an efficient DNA damage repair capacity in this species. However, photosynthesis of young gametophytes was completely acclimated to UV after only three days and mature thalli of both species showed no DNA damage. The susceptibility of carpospores to UV was therefore regarded as an important feature which determines recruitment capacity in the upper intertidal apart from other factors already described above (Bischof et al. 2000b).

UV also affects the motility of unicellular algae or swarmers, e.g. for phytoplankton Ekelund (1990, 1994) reported effects on growth and speed of some dinoflagellates and diatom species. Motility of the flagellate *Euglena gracilis* was shown to be very sensitive to exposure to UV (Häder and Häder 1988). Photomovement of macroalgal zoospores is also affected. Flores-Moya et al. (2002) found that the response of photomovement of swarmers in the brown algae *Scytosiphon lomentaria* and *Petalonia fascia* declined linearly with the logarithm of the applied UV fluence. The zoospores of *Laminaria saccharina* ceased their movement after treatment with UV-B, although the spores retained their viability (Makarov and Voskoboinikov 2001). In addition to motility, this study showed that UV-B also affects the spore release and germination of *L. sacharina* negatively. A consequence could be, if the swarmers are the sexual gametes, fertilization is affected under UV-B and the life history may be blocked to a certain extent. But if they are non-sexual gametes at least recruitment of new thalli by asexual reproduction can be diminished as was demonstrated by Wiencke et al. (2000, 2004). According to Dring et al. (1996) the sensitivity of *Laminaria* species to UV is higher in the young sporophytes than in the older ones, and gametophytes are most sensitive. Already moderate photosynthetic active radiation (PAR) can reduce growth of the eulittoral germlings of red algae (Leukart and Lüning 1994) not considering that red algae are often already quite sensitive to UV.

Most studies on the adverse effects of UV, however, have been conducted on mature sporophytes, neglecting that during growth and development macroalgae undergo unicellular life history stages. It was previously stated by Lüning (1980) that depth distribution patterns of large kelps (Laminariales) reflect light requirements of their establishment stages (zoospores, germlings), but hitherto the question whether early developmental stages of macroalgae are more susceptible to UV than large sporophytes has received little attention (Dring et al. 1996; Hanelt et al. 1997b; Yakovleva et al. 1998). Houvinen et al. (2000) demonstrated the high susceptibility to UV in zoospores and gametophytes of *Macrocystis pyrifera*. They found that UV exposure is most dramatically affecting recruitment when interfering with DNA synthesis. Wiencke et al. (2000) showed a direct relationship between DNA damage and mortality of brown alga zoospores. Apart from that it is likely that UV has the ability to impair the motility of brown algal zoospores during their planktonic phase when they swim actively due to the action of two flagella as mentioned above. Altamirano et al. (2003) investigated the relationship between temperature and UV radiation with germlings of different *Fucus* species. High temperature in combination with high fluences of UV-B caused generally the death of the germlings, whereas at low temperature the rate of survival increased. All these manifold results showed that it is absolutely necessary to measure the effects of increased UV levels on the sensitivity of the early settlement stages when considering the future consequences for the marine ecosystem.

15.5 UV effects on growth

Growth-related studies have mostly been performed in the laboratory (Dring et al. 1996; Grobe and Murphy 1997; van de Poll et al. 2001, 2002) and natural sunlight was used only in a few long-term experiments (Grobe and Murphy 1998; Aguilera et al. 1999; Altamirano et al. 2000a, b; Pang et al. 2001; Michler et al. 2002). With a few exceptions, only a low number of species has been included in the studies so far, reflecting the lack of knowledge about individual responses of a broad variety of species. Generally, reduced growth activity may be caused by an inhibition of energy generating processes, such as inactivation or degradation of any component of the photosynthetic process or respiration. Also, an alteration of energy consuming processes, such as pigment synthesis, which are involved in protection mechanisms of the plant, could operate at the expense of growth (Altamirano et al. 2000b). Furthermore, UV radiation is assumed to influence cell division and cell elongation (Grobe and Murphy 1997). UV related damage on a molecular level could also directly affect genes responsible for growth. In a recent laboratory study on different marine red macrophytes, a reduction in growth was mostly attributed to the accumulation of DNA damage (van de Poll et al. 2001). However, growth is considered to be an integrative parameter (Altamirano et al. 2000b) since it integrates stress at multiple levels. All negative effects on physiological processes such as nutrient uptake, protein synthesis, photosynthesis, DNA repair or transcription would decrease the ability of a plant to use light energy and nutrients for primary production and growth. Therefore, growth is a useful indicator to assess UV effects in long-term experiments and should be used more often in combination with other parameters. Despite the high significance of growth data, only few results on UV effects on macroalgal growth of Arctic species are hitherto published. This applies especially to *in situ* experiments. Changes of *in vivo* fluorescence of photosystem II of macroalgae were not always consistent with the measurable changes in growth rate, indicating that physiological processes leading to an inhibition of growth may act independently of changes in photosynthetic activity (Dring et al. 1996; Michler et al. 2002). In numerous studies on higher plants and phytoplankton it was demonstrated that UV-B exposure has the potential to seriously affect growth, and, thus, reduce primary production rates (Holm-Hansen et al. 1989; Björn et al. 1999; McMinn et al. 1999). Macroalgae grown under laboratory conditions and exposed to artificial UV are strongly impaired in terms of gaining biomass. This was shown in a variety of species from the cold temperate to the tropical zone (Dring et al. 1996; Han 1996 a,b). In studies on the cold temperate red alga *Chondrus crispus* it was confirmed that UV induced reduction in growth rate was accompanied by a relatively small reduction in maximal quantum yield of photosynthesis and detectable levels of thymine dimer formation of the DNA (van de Poll et al. 2003). This shows, that reduction in growth might be due to the impairment of several physiological processes and not only by lowered photosynthetic activity. Grobe and Murphy (1994) found strong UV-B induced reduction in growth of the chlorophyte *Ulva expansa* from the Californian coast line and it was concluded that it is cell division which is inhibited by UV-B rather than cell expansion. On Spitsbergen, Aguilera et al. (1999) transplanted algae from deep to shallow waters. The samples exposed to the full solar spectrum mostly exhibit growth rate reductions related to its respective depth distribution in the field. Compared to specimens exposed to PAR only, UV-A also showed an adverse effect on algal growth rates, but was not as severe as UV-B. The only one of the investigated species without significant UV effects on growth was the intertidal brown alga *Fucus distichus*. Apart from these experiments, Aguilera et al. (1999) performed *in situ* growth measurements in summer under turbid water conditions. However, at their natural growth site, the investigated species of the *Laminariaceae* did not show any difference in growth rates due to natural UV. These results are in line with data from the same location obtained by Brouwer et al. (2000) who incubated older sporophytes of *Laminaria saccharina* for 3 weeks at 1 m water depth. As result, specimens did not show significant differences in growth rates when receiving the whole solar spectrum compared to those shielded from UV. Under the present radiation levels, UV impacts on growth of adult Arctic macroalgae might occur only under conditions of shallow water or during periods of extreme water transparency e.g. in Arctic spring after the break up of sea ice. Therefore, it remains open whether increased UV-B will seriously affect growth of the investigated older sporophytes in the field. However, reduced growth rates were also observed at ambient UV-B levels in a variety of other macrophytes (Grobe and Murphy 1994; Aguilera et al. 1999; Franklin et al. 1999; Makarov 1999; Altamirano et al. 2000a,b; Kuhlenkamp et al. 2001; Pang et al. 2001; Michler et al. 2002).

In conclusion, polar species show inhibition of growth, at least the young sporophytes, which is related to the natural vertical zonation pattern. However, polar species are exposed to solar radiation in their natural environment only for a limited time during the year (Kirst and Wiencke 1995; Hanelt et al. 2001), and adaptation time to higher UV irradiation due to thinning of the ozone layer could be a crucial aspect concerning tolerance towards UV. In contrast to polar species, species from mid-latitudes such as from the rocky shore of Helgoland, showed no clear relationship between vulnerability towards UV and depth distribution (Michler at al. 2002). Due to very low transmission of UV through waters around Helgoland (Lüning and Dring 1979; Franklin et al. 1999), the zonation of sublittoral red macroalgae may be also not affected by higher UV-B irradiation. However, observed sensitivities in species from the lower eulittoral such as *Codium fragile* or *Chaetomorpha* sp. indicate that changing UV radiation conditions have the potential to influence the structure and productivity of macroalgal communities in the mid latitudes. Apparently, long term UV effects are more evident on growth of sporophytes than on their photosynthetic processes. In order to elucidate ecological consequences of ozone depletion, future studies should concentrate more on the integrative parameters such as growth and reproduction.

15.6 Acclimation to seasonal increase of UV-B irradiances

Changes in UV-B irradiances are not only caused by anthropogenic effects or meteorological reasons but also occur in the normal course of the season, e.g. breakup of sea ice generate a strong increase of irradiance including the harmful UV-B waveband (Hanelt et al. 2001). Photosynthesis of certain macroalgae species are able to adapt to changes in the radiation environment within a few days (Bischof et al. 1999; Roleda et al. 2004b). However as discussed above, that does not necessarily induce concomitantly also an adaptation in their growth rate (Michler et al. 2002; Roleda et al. 2004b). Ability to acclimate and adjust photosynthesis and growth to the rapid changes in light climate must be one prerequisite for macroalgal life under strong seasonal changes in the Arctic. Increasing light availability after the break up of sea ice is linked to the increase of maximum photosynthetic rates in several Arctic species (Bischof et al. 2002a). This acclimation is reversible as soon as underwater radiation conditions are diminished due to decreasing solar irradiance and increasing water turbidity. A high ability to adjust photosynthesis to the respective radiation conditions may be due to a multitude of specific regulatory events including e.g. a de- and acceleration of dark reactions (Scheibe 1990; Schmid and Dring 1996), an adjustment of the absorption cross section (Hanelt and Nultsch 1991), antennae size and number of active reaction centers (Dau 1994) as well as pigment composition (Gómez and Wiencke 1997). Moreover, seasonal changes in pigment composition, a substantial increase in the concentration of UV absorbing mycosporine-like amino acids (MAAs), the antioxidative activities of the enzymes SOD and catalase and other biochemical defense systems are related to seasonal changes in irradiances as well as variation in nutrient levels (Aguilera et al. 1999, 2002a,b). This enables a flexible response of the algae to a highly variable marine environment.

15.7 Conclusions

Organisms living in the littoral ecosystem have to a certain extent developed the capability to adapt to an increasing stress factor, e.g. the increasing UV radiation. From the studies conducted so far, it can be concluded that the presently measured UV levels are not likely to seriously affect the macroalgal communities in Arctic coastal ecosystems. Although photosynthesis and growth were shown to be sensitive to UV exposure when algae were sampled or transplanted from their original location, all species studied exhibited sufficient acclimation potential to the respective variations in radiation conditions at their specific growth site. However, in combination with other stress factors, e.g. global warming, increased storm frequencies or pollution the impact on the plant will increase or may even become exponential so that the organism is strongly harmed and the species might become endangered. As a result, this will affect not only the plant community but also the grazers and carnivores which adopt a higher position in the respective biotic pyramid. In future, more attention has to be directed to the small developmental stages of the macroalgae. Zonation pattern depends mostly on this life history stage with the highest susceptibility to UV. Due to the tiny size or the delicate structure of the early developmental stages, UV penetrates easily and can produce strong damage to the young organisms. Due to the central role of macroalgae as primary producers at the Arctic coast line these investigations will provide important information on the function of this unique ecosystem.

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16 Climate and ozone change effects on UV-radiation and health risks

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16.1 Introduction

The stratospheric ozone layer effectively serves as a protective shield that reduces the most harmful part of the solar ultraviolet (UV) radiation reaching the earths surface. As a consequence, the depletion of stratospheric ozone observed over the last two decades has probably led to an increase in ambient UV radiation. An increase in UV at ground-level may induce a wide range of harmful effects like an increase in skin cancer, cataracts, a decrease in bio-mass production and crop yields, and suppression of the human immune system (UNEP 1999, 2003). Ozone depletion is probably related to the large scale emissions of halocarbons, among which the chlorofluorocarbons (CFC's), in the seventies and eighties of the previous century. The Vienna Convention in 1985 was the starting point for international policy agreements to protect the ozone layer by aiming at reducing the production and emission of ozone depleting substances, and by providing the framework for the restrictive protocols that were agreed upon later.

The Montreal protocol in 1987 provided the first restrictive countermeasures and in view of the compelling evidence that ozone depletion occurred, this protocol was subsequently strengthened in several more restrictive Amendments. In the latest Amendments the production of the most potent ozone depleting substances is completely phased out in 1996. A longer phase out period is allowed for the developing countries. These countermeasures are expected to lead to a slow recovery of the ozone layer over the next century.

To evaluate the consequence of ozone depletion in terms of health risks such as skin cancer incidence, the full source-risk chain has to be taken into account. The Assessment Model for UV Radiation and Risks

(AMOUR) developed at RIVM, in collaboration with NOAA, Utrecht/Leiden University and KNMI, incorporates the various aspects of the source risk chain, including: the link between production and emission of halocarbons, and the resulting depletion of the ozone layer, the consequences of ozone changes for ambient effective UV doses and the corresponding skin cancer risks. The effects of the agreed countermeasures in terms of a recovery of the ozone layer, the (future) UV-radiation levels and their effect on the excess skin cancer risks associated with ozone depletion were previously analysed for the USA and Europe (Slaper et al., 1996).

In line with other studies (UNEP, 1999) it was expected that a slow recovery of the ozone layer will occur with a return to ‘normal’ (1980) levels around 2050. Excess skin cancer risks, caused by ozone depletion, are in those scenarios expected to rise until 2050-2070. Slaper et al (1996) clearly showed the potential success of the countermeasures in reducing the future excess skin cancer risks associated with the chemical depletion of ozone.

A limitation of the previous analyses is the basic assumption that ozone depletion is purely chemically driven, and that no interaction with climate change occurs. Thus, it is assumed that the ozone layer will return to the “normal” 1980-levels as soon as the active chlorine levels in the stratosphere reach the 1980 levels. However, in view of the ongoing climate change this assumption might well be too simple, and especially polar regions might play a crucial role in the future developments.

This paper focuses on the possible effects of past, present and future developments in ozone depletion on UV-radiation levels and the skin cancer risks associated with these changes, using an updated version of the AMOUR-model with a first attempt to include possible effects of climate ozone interactions (Kelfkens et al. 2002). We provide an update of the previous analysis of skin cancer risks for various scenarios for ozone depletion in relation to countermeasures taken and possible effects of ozone-climate interactions. Special focus is given to the role of climate and ozone changes in the arctic region on the future risks at mid-latitudes in densely populated areas in Europe.

16.2 Effects of UV on human health

UV-exposure of skin and eye can lead to a wide variety of adverse health effects, among which the development of erythema (sunburn), photokeratitis (snowblindness), an impairment of the immune system, with possible suppressive effects on the resistance to infections and the effectivity of vaccination programs, skin ageing, cataracts and skin cancer. A positive effect of UV-exposure of the skin is the production of vitamin-D, which is important for bone-formation in humans. It should be noted however that only a relatively small amount of UVB exposure in every day life is adequate for the required vitamin D production. Vitamin D requirements can also be met by a proper diet with sufficient consumption of fatty fish (or food that is artificially supplemented with vitamin D).

In response to the cellular damages in the skin invoked by UV exposure a natural adaptive response occurs through thickening of the skin and an increase of skin pigmentation (tanning). Especially the skin thickening offers some protection against sunburn effects in new exposure situations simply by shielding the viable cells in the epidermis. Tanning is often acknowledged as a positive effect, but it is in fact a response to the damage and offers limited protection in caucasian skin.

Many of the adverse health effects associated with UV-exposure, like skin cancer, skin ageing and possibly cataracts, are related to doses received by individuals over prolonged time periods, i.e. exposure over many years up to a lifetime. Other effects like an impairment of the immune system can be related to doses received over a period of weeks to months. Some short term effects, like skin erythema (sunburn) and snow-blindness, are primarily related to doses received over a day, but are influenced by the exposure history of the previous days to weeks. Adverse effects to plants and terrestrial and aquatic ecosystems are also primarily related to doses received over at least days to months, or in case of ecological changes years. Effects of UV on materials, especially polymers, and paints are also related to prolonged exposure periods.

In order to evaluate risks associated with ozone depletion and changes in UV-exposure it is essential to acquire information on the dose-time-effect relationships for the effects under study and on the relative effectiveness of UV-exposure at different wavelengths, i.e. the determination of the biological weighting functions or action spectra. For many of the aforementioned adverse effects the relative effectiveness of radiation at different wavelengths varies considerably in the range of the solar UV-spectrum: in order to induce the same effect an exposure at wavelengths around 340 nm requires 1000-10000 times higher physical doses than exposure at wavelengths around 300 nm.

16.2.1 Skin-cancer and it’s relationship to UV-exposure

Skin cancer is the most common cancer type in light-skinned populations and the yearly incidence in mid-latitudinal regions like Europe and North

America is 1000-2000 new cases per year per million inhabitants. The incidence increases with lower latitudes and thus with higher solar radiation levels. Three major skin cancer types can be distinguished: basal cell carcinoma (BCC), squamous cell carcinoma (SCC) and malignant melanoma. Of all skin cancers around 70-80 % are BCC. This most common type is not very aggressive and the lethality rate is lower than 1%. The second most common skin cancer type is SCC (10-20%) with a lethality of around 2-3%. Melanoma are least common (around 10%) but they are the most aggressive type with a lethality of around 20-25%. BCC and SCC originate from the malignant transformation of keratinocytes, the major structural cells in the epidermis of the skin. BCC and SCC are together also referred to as non-melanoma skin cancers (NMSC). Melanoma results from malignant transformation of the skin's pigment producing cells in the epidermis, ie the melanocytes.

Evidence that UV exposure induces skin cancer comes from three main sources of information: epidemiology, animal experiments, and studies on the biological mechanisms of skin carcinogenesis.

16.2.2 Epidemiological evidence

Skin cancer occurs with higher probability in humans with a sun-sensitive skin, and especially light skinned people from Celtic origin like Irish or English are at highest risks. Risks for Asian and black populations are much lower. Risks are especially high in Xeroderma Pigmentosum (XP) patients, who lack the ability to repair solar induced cellular DNA-damage and who develop multiple skin cancers very early in life. Furthermore, among populations with a similar skin complexity incidences are higher in areas with higher ambient solar radiation levels, i.e. at lower latitudes, and skin cancer primarily occurs on sun-exposed areas. Non-melanoma skin cancers are primarily found on head, neck and hands, and melanoma also occur frequently on occasionally exposed areas like the trunk.

Within a population, those with highest exposure are at highest risks, i.e. groups with outdoor jobs. This holds for the NMSC, but not for the melanoma. For melanoma intermittent exposure is indicated as a risk factor, and highest risks are seen in indoor workers with relatively low overall exposure but excessive exposure in holiday-periods.

The evidence further suggests that SCC are primarily related to the cumulative UV-dose received by the skin, but for BCC and melanoma exposures early in life appear to be most relevant (de Gruijl et al. 2003). This could be an indication that the UV-related processes are early events in the carcinogenic process for the BCC and melanoma, whereas for SCC the specific order of events appears to be less relevant.

16.2.3 Animal experiments and action spectra

UV irradiation of the skin has been shown to lead to the incidence of SCC skin cancer in laboratory animals. Extensive dose-time-response studies have demonstrated the relationship between exposure and the incidence of skin cancers (de Gruijl et al. 1983). These studies provided dose-time-effect relationships which could be used in the analysis of epidemiological data and are the basis for quantitative risk models (see next section). The most common type produced by UV in laboratory animals, i.e. mice and rats, are SCC. The accumulated UV-dose over a life time appears to be the primary risk factor. Recently also melanoma mammalian models in transgenic mice and the opossum have been found for the induction of melanoma through UV-exposure. However, in contrast with the induction of SCC for melanoma the exposures early in life appear to be the dominant risk-factor (see de Gruijl et al. 2003).

In addition to the dose-time-effect information animal studies have provided essential information on the relative effectiveness of UV-radiation from different wavelength regions in the induction of skin cancers. Such information cannot be obtained from epidemiological data. The observed latitude dependency of the incidence does not give any insight in the relative importance of different wavelength regions, because the exposure is lower at higher latitudes for all UV and visible wavelengths in the solar spectrum. Most extensive information on action spectra from animal studies is available for SCC. De Gruijl et al. (1993) extracted an action spectrum for skin cancer development in hairless mice, SCUP-m. This murine action spectrum was transferred to humans by accounting for the differences in skin transmission between mice and human skin, and thus de Gruijl and van der Leun (1994) constructed the SCUP-h action spectrum, which is plotted in fig. 16.1. The SCUP-h action spectrum closely matches an action spectrum for pyrimidine dimer formation in cellular DNA following a correction for transmission of the epidermis.

16.2.4 Mechanistic evidence from molecular biology

UV radiation, and in particular the UVB region of the spectrum (280-315 nm) is capable of causing damage and mutations to cellular DNA. UVB is particularly effective in the induction of pyrimidine dimers. For a large majority of SCC and half of the BCC skin cancers specific mutations in the

P53 tumour suppressor gene are found, which have characteristics of UV-induced point mutations. The molecular evidence that UV is directly involved in the development of melanoma is not as apparent since the mutations regularly found in melanoma were not identified as specific UV-induced mutations. However, UVB induced DNA damage is not restricted to point mutations and can involve larger sections of DNA. Such defects can also be caused by other agents, and thus cannot be identified as specific UV-related defects (de Gruijl et al. 2003).

16.2.5 A quantitative risk assessment model for skin cancer in relation to UV-exposure

In order to provide risk assessments it is essential to use proper dose-time-response relationships and a proper action spectrum. We used the quantitative model that was used and described in Slaper et al (1996). The basic quantitative relationships were derived from detailed dose-time response studies in hairless mice (de Gruijl et al. 1983; Slaper et al. 1996). In case of continued exposure the cumulated number of skin cancer cases in a population is described by:

$$Y(a) = \gamma (Da)^{c} a^{d-c} \qquad (1)$$

where D stands for the daily (or yearly) effective UV-dose received, a for the time since the start of the exposure (or age), and γ, c and d are the basic model-parameters reflecting respectively the sensitivity of the population, and the dose and age dependency of the carcinogenic process. The parameter c is sometimes referred to as the biological amplification factor indicating the percent change in incidence related to a 1% increase in UV-doses received.

Epidemiological data relating ambient UV-radiation levels to the skin cancer incidences were used to fit the model-parameters for each of the three skin cancer types. Equation (1) requires additional interpretation in case of changing exposures over a life-time. Epidemiological data and animal experiments indicate that for squamous cell carcinoma the life time cumulative dose is the dominant factor. This implies that equation (1) could be used interpreting the factor Da as the cumulative lifetime dose ($\Phi(a)$). In terms of processes this implies that UV and time related changes can occur independently of each other. For melanoma and basal cell carcinoma epidemiological data suggest that UV-exposure early in life is more important than the cumulative dose, which is an indication that at least a part of the UV-related processes have to occur prior to the time related processes. In that case equation (1) is modified to (Slaper et al. 1996):

$$Y(a) = \gamma \Sigma D(x) (\Phi(x))^{c-1} (a-x)^{d-c} \qquad (2)$$

where the summation Σ is over all ages x from birth to age a.

In the presented analysis the SCUP-h action spectrum (fig. 16.1) is used as the biological weighting function. It should be noted that the SCUP-h action spectrum also roughly resembles the action spectrum for erythema, which is often used characterizing the ambient UV-radiation levels (for instance in the solar UV-index).

In addition to the SCUP-h action spectrum fig. 16.1 also provides an example of a solar spectrum measured at ground level (high overhead sun at mid-latitudes), and the two multiplied with each other which indicates the effective spectral irradiance, which peaks in the UVB range of the solar spectrum. The effective spectral irradiance integrated over the full wavelength range is referred to as the effective dose-rate (marked area in fig. 16.1) and integrated over time the effective dose is obtained. Also indicated in fig. 16.1 is the extraterrestrial spectrum which lacks the strong ozone induced cut off in the UVB range of the spectrum (below 315 nm) that occurs in the solar spectrum at ground level.

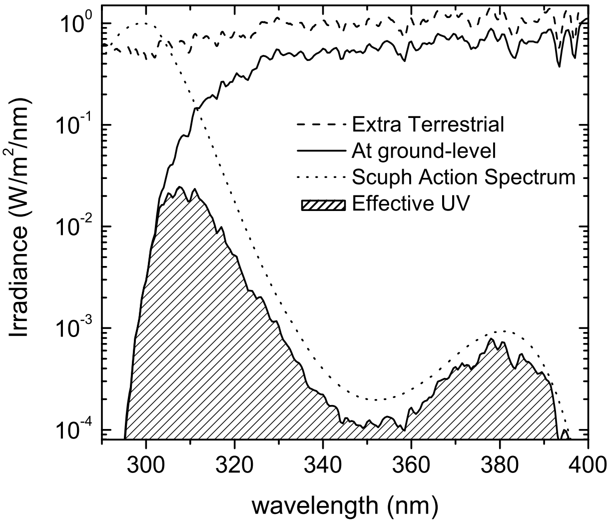

Fig. 16.1. Solar spectrum (extra terrestrial and at the ground (RIVM)), action spectrum for photo-carcinogenesis (SCUP-h), and weighted effective UV irradiance for skin cancer

For melanoma, previous studies in a fish model seemed to indicate that the UVA part of the solar spectrum could be more effective than UVB, however, recent evidence gathered in two mammalian models suggest that similar to the action spectra discussed above, UVB is indeed much more effective in producing melanoma. For the risk assessment, provided in this paper we use the SCUP-h action spectrum for all three skin cancer types (de Gruijl and van der Leun, 1994).

16.3 UV-exposure

UV-exposure of the skin is not restricted to solar exposure, since many artificial sources emit or can emit UV-radiation. Although detailed knowledge on the overall UV-exposure to the sun and artificial sources is lacking, it is highly likely that the sun dominates the effective UV-exposure of the overall population and estimated for the Netherlands amount to over 90% of the mean exposures. It should be noted however that for groups with excessive exposure to artificial tanning booths the yearly effective dose received using this equipment could well be equal or higher than the solar exposure. The same holds for psoriasis patients receiving UVB phototherapy.

The skin receives only a fraction of the solar UV that is measured on a horizontal plane, since not all time is spent outside, and the skin usually is not fully oriented towards the sun and open sky. In addition clothes and the use of sunscreens can influence the exposure received by the viable layers of the skin. Furthermore, the local environment like mountains, buildings, snow and trees can shade and reflect part of the UV and influence the radiation levels actually received.

It should be noted that in solar exposure roughly half of the effective UV comes directly from the sun and half from the sky. In situations where the ground is snow covered the reflectance from the ground can also considerably contribute to the exposure.

Indications of the exposure received in every day life are obtained using personal UV-dosimeters. Indoor workers receive on average around 2-3% of the available ambient effective dose on the most exposed skin parts (face, neck and hands). Holiday periods in the summer could double the year round exposure of indoor workers to 5%. For outdoor workers it is estimated that around 9% of the ambient dose is received. Large variations occur among different individuals depending strongly on the leisure activities.

It should be noted that changes in behaviour influencing the exposure would also alter the (excess) risks estimated in relation to environmental change. Excess risks are altered in two ways: first the excess dose received due to environmental change is changed in relation to a different exposure fraction, and second the non-linearity of the dose-time response relationships implies that excess risks due to a specific additional dose are depending on the “normal” exposure. In that respect it should be noted that skin cancer incidence has been reported to be increased over the past decades (de Gruijl et al. 2003). This increase is probably related to behavioural factors rather than the environmental change, simply because it is too soon to identify the influence of environmental change.

In the scenario-analysis we assume that exposure habits do not change over time, and assuming that the exposure received is a certain be it not exactly known fraction of the ambient dose, we can use equations 1 and 2 and use the ambient doses in stead of the actual dose received (the fraction received is accounted for in the parameter γ). Assessing the long term risks related to UV-exposure requires life-time analysis of the UV-exposure doses received.

16.4 Determination of the UV-climate combining measurements and modelling

The effective UV radiation received at the ground primarily depends on the solar height, the total ozone column, clouds, aerosols and snow cover. Skin cancer risk assessments require the life-time UV-dose received, and thus a long term assessment of the UV-dose is necessary.

The most direct way to assess changes in the UV-climate would be to use long-term data from highly accurate ground based UV-monitoring stations, however such long-term data are largely lacking at present (WMO, 1999). An assessment of changes over prolonged periods of time is therefore based on modelled UV-transfer, using ozone and other atmospheric data from either ground based or satellite based sources. Such model approaches can be at least partly validated by a comparison with ground based measurements for shorter time periods (den Outer et al. 2005, Slaper et al. 2001, den Outer et al. 2000). In the next sections we will first compare modelled and measured effective UV in relation to ozone and clouds, and then provide an assessment of the historical changes in UV-radiation levels combining models and measurements.

16.4.1 Ozone and cloud dependence of the effective UV radiation

The effect of an ozone change on the effective UV-dose received at the ground is illustrated in fig. 16.2a, which shows the clear anti-correlation between skin cancer weighted UV and ozone. The measured results, which are corrected for cloud effects, are obtained using daily integrated UV-measurements from the RIVM UV-monitoring system in Bilthoven for the period 1996-2000, and are compared with modelled results. On the vertical axis the relative deviation of the measured ratio of daily SCUP-h doses and daily UVA doses from the modelled ratio for the same day using an ozone value of 350 DU. This is plotted versus the measured ozone value, thus obtaining a view of the relative increase in effective UV related to a change in ozone. Measured data-points for 3 days with similar ozone values are averaged to obtain a smooth result, and in addition a modelled curve is provided for the same days, showing good agreement between modelled and measured ozone dependence of the effective UV-dose. From this plot a Radiation Amplification Factor (RAF), indicating the increase in effective UV-dose related to a one percent change in ozone, could be derived, which amounts to 1.3 for the SCUP-h weighted UV. This RAF for SCUP-h is slightly higher than the RAF for the erythemal action spectrum (1.1-1.2). Similar approaches for other locations are summarised in WMO (1999). In addition it has been shown that an upward trend in clear-sky UV-dose is correlated to a downward trend in ozone (Zerefos et al.1998; Mckenzie, 1999).

The effects of clouds on the UV-irradiance are highly variable and related to a broad range of cloud parameters like: cloud cover, cloud shapes, cloud optical thickness, water content etc. Previous studies have shown empirical relationships between the cloud induced reduction of global solar radiation and cloud effects on biologically weighted effective UV (Bordewijk et al. 1995, Bodeker and McKenzie, 1996). Fig. 16.2b illustrates the non-linear empirical relationship between the reduction of effective UV and global solar radiation. It should be noted that this relationship is depending on the solar zenith angle and becomes slightly more linear at high sun and more curved at low sun conditions. An extensive analysis of cloud induced reduction on UV and global solar radiation is given in den Outer et al. (2005).

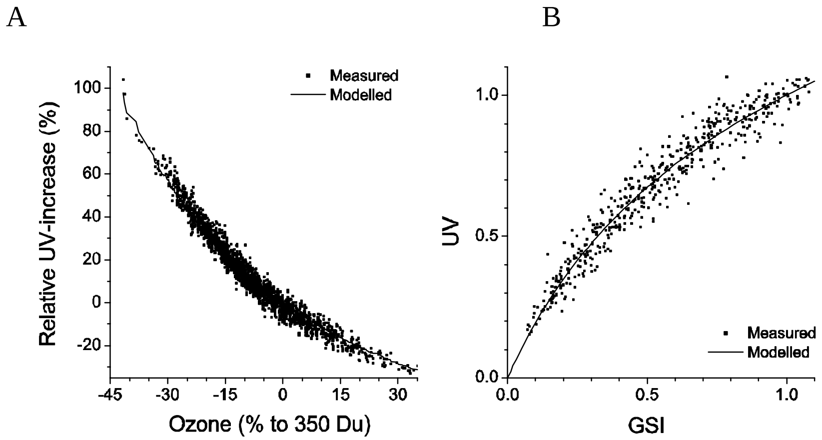

Fig. 16.2. Relation between changes in ozone and changes in effective UV-radiation levels (left hand panel 2A), relation between the cloud-induced reduction of global solar irradiation (GSI) and the reduction of UV-irradiance (shown for 45-60 degrees Solar Zenith Angle)(right hand panel 2B). Measurements from RIVM UV-monitoring spectroradiometer (den Outer et al. 2005).

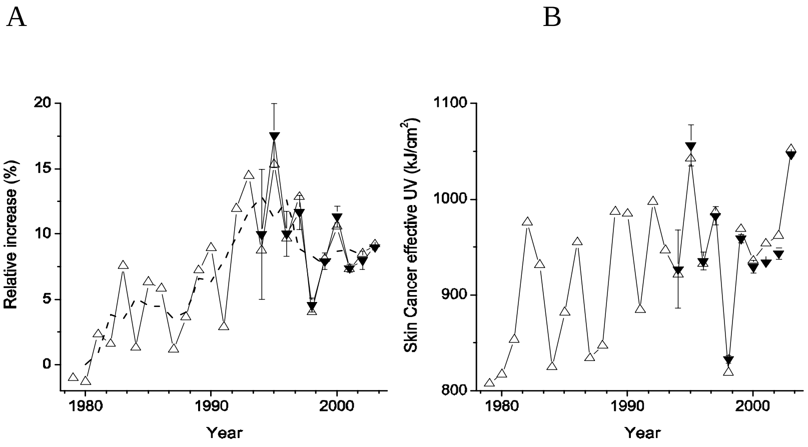

Fig. 16.3. Change in yearly effective UV-dose (SCUP-h weighted) in Bilthoven, the Netherlands (52 N, 5.2 E) related to ozone changes (left panel, 3A), and related to ozone and cloud changes (right panel, 3B). Filled triangles derived from RIVM ground based UV-monitoring, open triangles modeled UV-doses (method described in den Outer et al 2005).

16.4.2 Changes in ambient UV-radiation in the past decades

Using the above models and available data from ground based and satellite based measurements on ozone and global solar radiation it is possible to analyse the past UV-climate. Fig. 16.3 shows an analysis of yearly ambient effective UV-doses for the past 25 years for Bilthoven in the Netherlands (derived from den Outer et al. 2005). This modelled analysis is compared with ambient UV-measurements available from RIVM's UV-monitoring system since 1994. The left hand panel (3a) shows the ozone related changes in the UV relative to the average 1979-1981 yearly UV-dose. Here the measurements are corrected for cloud variations from year to year using the above illustrated empirical cloud model backwards. The results in fig. 16.3a show that highest UV-radiation levels are calculated for the period 1992-1995. These high levels are probably related to enhanced ozone depletion caused by heterogeneous chemical interaction of halocarbons with stratospheric dust from the volcanic eruption of the Pinatubo (WMO, 1999, 2003). The right hand panel (3b) shows the skin cancer effective dose actually received in the same period including the cloud variability. An upward trend is apparent in both figures, and using a linear least squares fit an upward trend of 3.4±0.7 % per decade for the ozone related changes and 5.7±2.0 % per decade for the overall trend including clouds and ozone changes (den Outer et al. 2005). It should be noted that the difference in these trends is not significant due to the high variability of the cloud effects from year to year. Highest UV-doses, over the past 25 years were received in the Netherlands in 1995 and 2003. Both years show relatively low ozone values and a low reduction by clouds, but in 1995 the effect of ozone depletion dominates, whereas in 2003 the low reduction by clouds dominates the deviation from other years.

Satellite data on ozone and (cloud) reflectance can be used to analyse the UV-climate at the ground, and previous studies comparing satellite and ground based modelling approaches have validated this (Matthijsen et al 2000, Williams et al. 2004, Kaurola et al 2000, Slaper et al. 2004). Using TOMS ozone data (version 7) we analysed the ozone related UV-trends for the European continent as shown in fig. 16.4. The figure shows that the largest increasing UV-trends related to ozone depletion are observed over large parts of central and western Europe and amount to a 3-4 % increase per decade. The area most affected includes all most densely populated areas on the European continent, including Germany, the Netherlands, Belgium, France and northern Italy, and ranging from the southeast of England to Poland, and from the southwest of France to former Yugoslavia.

The effects of clouds are also important with respect to climate change. Although no decisive evidence is available yet, climate change may well

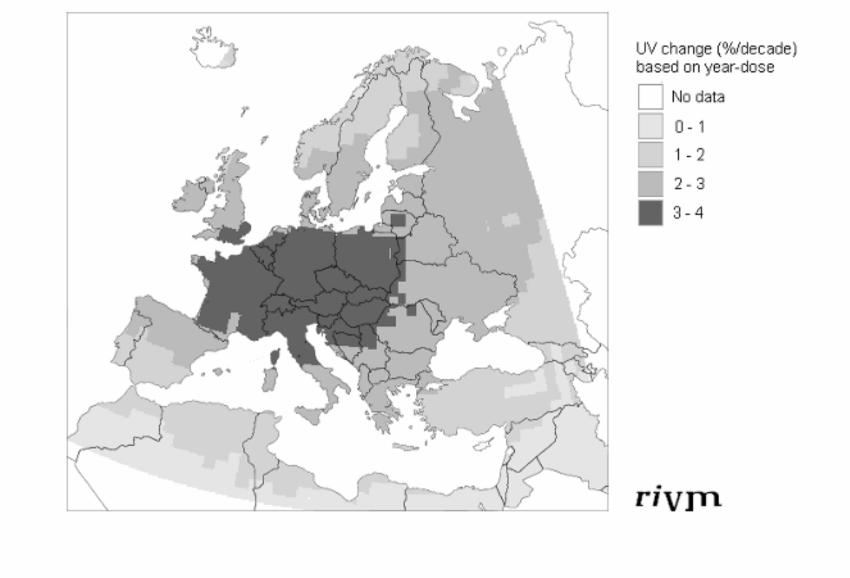

Fig. 16.4. Ultraviolet trends over Europe derived from satellite based changes in ozone in the period 1979-2000 (using TOMS ozone data; methodology described in Slaper et al. 2001)

affect cloud cover and cloud optical thickness in a way dependent on season and location. A change in cloudiness and temperature will, in turn, influence (recreational) exposure with potential impacts on the overall risk of the population. At the moment, effects of structural change in cloudiness or a change in human behaviour due to climate change are not incorporated in our scenario analysis for (future) human risks.

Although there is a lack of direct observations of UV trends in relation to ozone changes, it is highly likely that the yearly UV doses received in large parts of Europe have increased by 5-10% over the past two decades. Further monitoring is required to substantiate the analysis and to establish how the climate-ozone changes influence the future UV radiation levels at the ground. In view of the high year to year variability of clouds and vortex effects, one might argue that a prolonged observation period will be required to fully establish UV trends.

16.5 Ozone-depletion and Ozone-climate interactions

Ozone is found as a trace gas throughout the atmosphere, with highest concentrations in the stratosphere at heights around 25 km above the earths surface. At standard atmospheric pressure and temperature the total atmospheric amount of ozone consists of a layer of no more than 3 mm. Ozone molecules are constantly produced and destroyed in a series of (photo)chemical reactions in the stratosphere. Molina and Rowland (1974) were the first to predict that large scale emissions of halocarbons might lead to a disturbance of the natural photochemical ozone-balance leading to a decrease in ozone. CFC’s were widely and increasingly used during the sixties and seventies, and without countermeasures a further increase could have been expected. CFC’s are non-toxic and inert gases, which are not readily destroyed in the troposphere. They slowly diffuse to the stratosphere and are photo-dissociated there under the influence of the short-wave solar UV releasing effective chlorine which strongly enhances the destruction of ozone. The first evidence that ozone depletion occurred came from the discovery of, what is usually referred to as the Antarctic ozone hole: a strong decrease in stratospheric ozone during the early spring in the Antarctic region which was observed since the beginning of the eighties (Farman et al. 1985). The discovery of the Antarctic ozone hole came as a surprise because it had not been predicted that the Antarctic region would be exceptionally vulnerable.

It was found that the photochemical breakdown of ozone by active chlorine is strongly catalysed in the presence of Polar Stratospheric Clouds (PSC) and/or stratospheric aerosols, such as resulting from volcanic eruptions. The early Antarctic spring provides a stable polar vortex with very low stratospheric temperatures, and thus optimal conditions for the formation of PSC, which contribute to the catalytic breakdown of ozone by active chlorine. In the arctic region the polar vortex conditions are less stable and the temperatures in the stratosphere are higher. Ozone depletion, however was not restricted to the Antarctic and a decrease in ozone has now also been well established over mid-latitudes at the northern and southern hemisphere (WMO 2003).

The observations seem to indicate that ozone depletion started around 1980, which is surprisingly late in view of the fact that the stratospheric chlorine load at that time was al ready elevated compared to pre-industrial times (from around 0.8 ppbv to nearly 2 ppbv). Taking into account the information available on the emission of halocarbons and a scenario of future releases many efforts were made to analyse the past and future trends using predictive 2D and 3D modelling of stratospheric ozone. Fig. 16.5

provides a summary plot, adapted from Kelfkens et al. 2002, showing the range of calculated developments for mid-latitudes in the northern hemisphere, obtained with 2D and 3 D modelling efforts (grey band indicates the results). Two lines indicating results obtained with the AMOUR-model include an empirical fit of ozone depletion observed in the 1980-2000 period in NW-Europe and a scenario analysis for future developments taking into account the countermeasures to prevent further ozone depletion. It can be seen that the historical trend observed (represented by the AMOUR-model line) is underestimated by the 2D and 3D modelling approaches. Two different scenario-lines indicate the future developments with the AMOUR-model. The dashed line represents the situation assuming that ozone depletion is purely chemically driven and that no climate ozone interactions are involved in future developments. This evaluation closely resembles previous modelling attempts provided by Slaper et al. (1996), the difference being that the scenario for halocarbon releases has been updated to include the Montreal Amendments of the Montreal Protocol. The second scenario analysis, represented by the full line, attempts to include possible effects of climate-ozone interactions as discussed below.

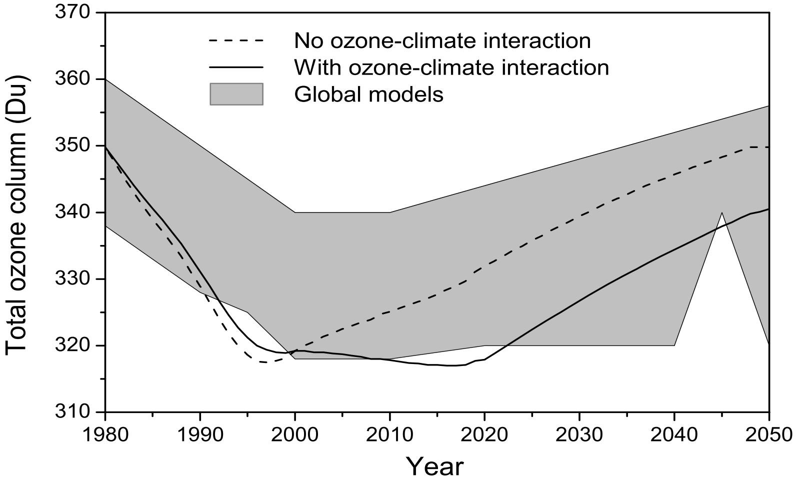

Fig. 16.5. Range in prognosis for the future development of the stratospheric ozone layer (grey modified from Kelfkens et al. 2002, including results from Shindell et al. 1998, Austin et al. 2001, 2000, and Dvortsov and Salomon, 2001). The curves are obtained using the RIVM AMOUR model for the NW-European region.

Most studies assuming ozone depletion to be purely chemically driven, estimate that the ozone layer will return to the normal 1980 levels as soon as the active chlorine levels in the stratosphere reach the 1980 levels. However, other relevant atmospheric parameters such as stratospheric temperatures and troposphere heights might change in relation to ongoing climate change and this on its term can have important implications for ozone. Polar regions might well play a crucial role in the future developments of the ozone layer and the effects of climate ozone interactions. As a consequence of global warming it is expected that temperatures in the stratosphere will decrease, and thus conditions in the arctic region might become more favourable for PSC formation and an enhanced ozone depletion. The implications however are not restricted to the polar regions, since the low ozone concentrations can be transported to mid-latitudes and thus affect the heavily populated areas in Europe and North America. We use results reported by Kelfkens et al (2002) to simulate the effects of such climate ozone interactions on ozone levels at mid-latitudes.

16.6 Ozone-climate change scenario-analysis

The calculated development of the ozone layer over Europe during the period 1980-2100 is based on a scenario for chlorine in the stratosphere resulting from the countermeasures taken in the Montreal Amendments of the Montreal Protocol (Madronich et al., 1999) and on the ozone trend over 1980-2000 observed by the NASA-TOMS satellite. Monthly ozone values enable us to calculate - with a UV-transfer model – the future effective UV-levels at the earth’s surface. These future UV-levels yield via a dose-response model for skin cancer, eventually the increased skin cancer incidence.

In this chapter the baseline risk, determined by the situation with no ozone-climate interaction, is compared with a scenario including ozone-climate interaction. The magnitude of the interaction is based on a literature survey, 2D model calculations for the Arctic vortex and on expert judgement. For the ozone-climate interaction we formulate the following preconditions:

- Chlorine scenario A1 (Madronich et al. 1999)
- Stratospheric temperature according to IPCC, IS92a (Velders, 1997)
- Stratospheric cooling results – via a shift in the chemical equilibrium for ozone production/destruction - in 0.9% extra ozone per one Kelvin drop in temperature.

- Splitting up of the arctic vortex induces a month and latitude dependent ozone depletion over the Northern hemisphere. The magnitude of the ozone loss is calculated by 2 D simulation (Velders, 1997).
- Of the observed ozone trend 25% can be attributed to non-vortex dynamical changes.

For details on the AMOUR model, the calculations and the interaction between the ozone layer and climate change the reader is referred to Kelfkens et al. (2002). The result of the AMOUR assessment can be given at a fixed location in terms of the increase in effective UV and skin cancer incidence with and without ozone-climate interaction. Finally AMOUR produces maps of the difference in effective UV and skin cancer incidence over Europe. Here, it should be noted that the excess risks due to ozone depletion are calculated for a population with the genetically determined skin sensitivity of the Northwest European population.

Fig. 16.6 shows the increase in effective UV for Bilthoven, the Netherlands. The triangles are three year running mean yearly doses derived from UV-monitoring at RIVM in the period 1994-2003, and the dash-dotted line represents the three year running mean for the modelled yearly UV-dose (from fig. 16.3a, den Outer et al 2005). The dotted curve shows the AMOUR model result if no countermeasures would have been taken to protect the ozone layer (scenario according to Slaper et al 1996). This curve shows a rapid upward trend, and the observed UV-radiation levels in the past six years do not follow this upward curve, indicating the success of the countermeasures in slowing down the ozone and UV trends. The dashed curve shows the AMOUR model result of the Montreal Amendments of the Montreal Protocol assuming that no climate ozone interaction occurs, and in that scenario the UV-radiation levels are estimated to slowly decrease from the year 2000 onward. The full line indicates AMOUR model results obtained using the same emission scenario, but now incorporating ozone-climate interactions. As can be seen in that scenario the UV-radiation levels will slowly rise until around 2020 and thereafter start a slow decrease.

The consequences of the latter two scenarios in terms of future excess skin cancer risks related to ozone depletion are shown in fig. 16.7, where it can be seen that without ozone-climate interaction future excess skin cancer risks might increase to around 2055 with 60 extra cases per million inhabitants per year, whereas including climate ozone interactions the risks will increase until 2065 and amount to 95 extra cases per million inhabitants per year. Thus the difference in terms of excess risks is considerable between the scenarios with and without climate-ozone interactions.

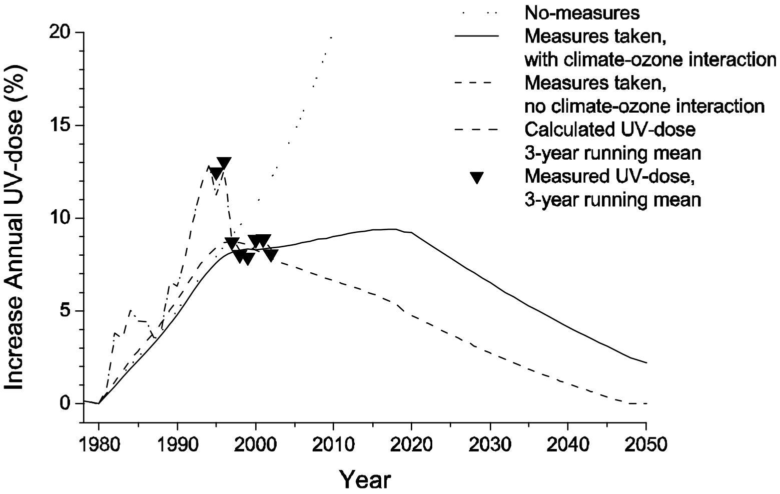

Fig. 16.6. Relative changes of yearly UV-doses for the Netherlands due to ozone depletion

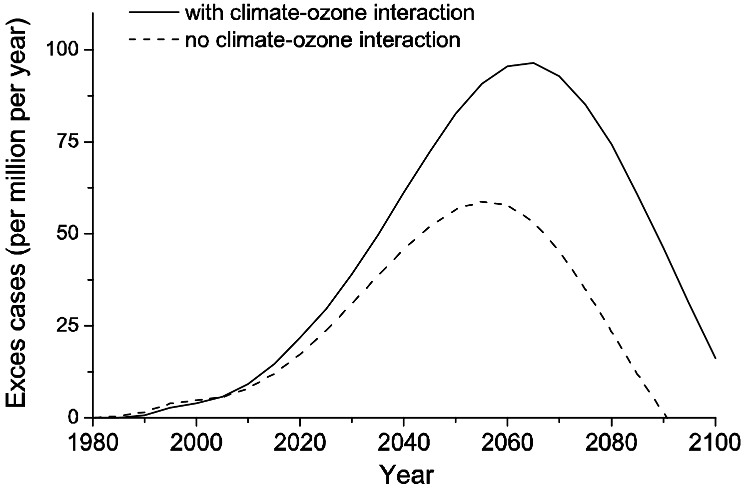

Fig. 16.7. Excess skin cancer incidence caused by ozone depletion calculated in relation to past and future ozone changes for the Netherlands (representative for large part of NW-European population).

Fig. 16.8 provides a map of excess skin cancer risks related to ozone changes in the ozone-climate interaction scenario. The map shows that the calculated excess risks for 2070 amount to 75-125 additional cases per year per million inhabitants for large parts in central Europe. The map is calculated for a population with the sensitivity of the Dutch population, and could be regarded as representative for NW-European populations.

The results given have a large uncertainty because the stratospheric ozone concentration at mid-latitudes is a subtle balance of chemical destruction of ozone, dilution by ozone poor air from the Arctic vortex, destruction/dilution by non-vortex dynamical effects and production of ozone due to chemical equilibrium shift as a consequence of temperature changes. Scientific understanding of these processes, especially of the non-vortex dynamics and of the Arctic vortex itself, is far from complete. The observed changes do presently not allow a distinction between the presented scenarios. In that respect it should also be noted that climate ozone interactions through changes in polar vortex might introduce a strong year to year variability which is not indicated in the scenario analysis. Thus, the analysis of future developments requires further knowledge on the climate ozone interactions, and further monitoring of changes and trends using satellite and ground based observations for ozone and UV.

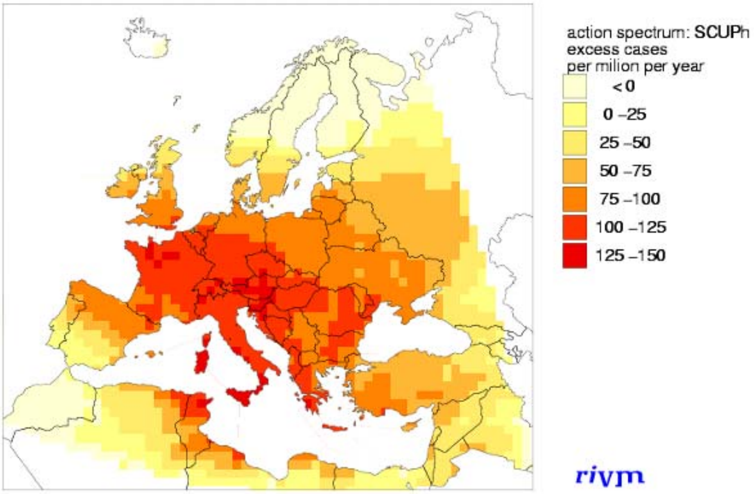

Fig. 16.8. Excess skin cancer risks due to ozone depletion calculated for 2070 with the AMOUR-model including climate and ozone interactions

16.7 Conclusions

Ozone depletion has occurred over large parts of the globe, with implications for the effective UV-radiation received on the ground. Over large parts of Europe the UV-radiation levels have probably increased by 5-10 % since 1980. As a consequence future skin cancer risks will probably increase.

A slow recovery of the ozone layer might be expected as a consequence of the countermeasures taken to restrict the emissions of ozone depleting substances. However, a substantial delay in ozone recovery, might occur due to ongoing climate change and the interaction between climate and ozone change. The arctic region might well play a crucial role in the future developments regarding ozone depletion and it's influence has been shown to involve large parts of the northern hemisphere including North-America and Europe.

Future developments however are regarded highly uncertain. This uncertainty arises from the fact that the stratospheric ozone concentration at mid-latitudes is a subtle balance of chemical destruction, dilution and production of ozone, and atmospheric dynamics. Scientific understanding of the underlying processes, especially of the non-vortex dynamics and of the Arctic vortex itself, is far from perfect. With this in mind we conclude:

- The ozone layer is expected to recover as a result of the implementation of the Montreal protocol. Based on the expected decrease in chlorine and bromine a recovery is expected around 2050. The full recovery is possibly delayed by increased concentrations of greenhouse gases with effects on atmospheric temperatures and atmospheric dynamics.
- The delay calculated by Chemistry-Climate models show a large variation, ranging from about 10 years to more than 20 years.
- A stronger winter Arctic vortex - triggered by lower stratospheric temperatures – results in more efficient (chemical) ozone loss. Thus, the Arctic vortex plays a crucial role in the future ozone levels, also at mid-latitudes, and possibly contributes substantially to the delayed ozone recovery. The mechanism underlying this enhanced ozone depletion, however, is poorly understood.
- Dynamic changes in the climate system, not coupled to the Arctic vortex, may also contribute substantially to a delay in ozone recovery. But, at present there is little consensus on the magnitude and relative importance of this contribution. Also dynamical changes could lead to substantial regional differences in ozone recovery.

- A delay in recovery of the ozone layer, induced by ozone layer - climate change interactions, leads to a higher and more persistent increase in effective UV-levels over Europe. In 2020 UV-levels over mid-Europe, accounting for ozone-climate interaction, are estimated to be 4-6% higher compared to the UV-levels without interaction.
- Elevated ambient UV-levels result in a higher and more persistent increase in skin cancer incidence. Under the assumption that other conditions, in particular cloudiness, are not affected and that climate change does not influence behaviour of the population, the excess risk due to ozone changes in the Netherlands (representative for large parts of the central-western part of Europe) increases from approximately 60 extra cases per million inhabitants per year (no ozone-climate interaction, 2055) to about 95 extra cases per million per year (ozone-climate interaction taken into account 2065).

Acknowledgement

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Long range pollutants transport and ecological impacts

17 Contaminants, global change and cold regions

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17.1 Introduction

Perhaps the first example of climate change and contaminants interacting with fatal consequences occurred during the Franklin expedition of 1845-1848. Franklin's group, which entered the Canadian Archipelago hoping to discover a Northwest Passage during a cool period of climate (the end of the so-called 'little ice age' (Bradley and Jones 1993)), was doomed to failure simply by poor ice conditions. They brought with them food that was contaminated by lead from soldering in early experiments with canning (Keenleyside, et al. 1997). The harsh environmental conditions, which stalled progress and prevented retreat, also made game hard to find leading to a strong reliance on the food they brought. Although there remains controversy over what role lead poisoning might have played in Franklin's demise, this example well illustrates how the environment and contaminants can operate together; toxicity is often a consequence of two or more factors, any one of which might not cause irreparable harm by itself, and sometimes there is a shortcut pathway, or vector, that provides a surprise.

How global change might impact semi-volatile organic contaminants was considered almost a decade ago (Harner 1997), but the focus was mainly on the effect of temperature rise. Intuitively, warmer temperatures enhance volatility, force chemicals back out of water, and perhaps increase degradation rates. This sounds like good news and McKone et al. (1996) concluded from model results that exposure of aquatic foodwebs to HCB (hexachlorobenzene) would be reduced should warming occur. However, in Alpine and Arctic regions, the important change is not likely to be temperature rise per se, but rather phase change (ice-water, snow-rain) and change in systems (foodwebs, organic carbon cycle, hydrological cycle, ocean/ice interaction). These system changes alter transfers between media and contaminant magnifying processes within the environment. Recent detailed reviews of change in the Arctic and inferences of what these changes might mean for contaminants reveal a surprising number of ways that climate variation and climate change can affect pathways, and how these pathway changes then alter risks to ecosystems (Macdonald, et al. 2003; 2005). Here, it is not my intention to repeat these lengthy reviews but rather to provide a synopsis of how global change may alter the risks to humans and ecosystems from semi-volatile contaminants in cold regions.

17.2 Transient Emissions of Global Contaminants

Semi-volatile organic contaminants have been released in large quantities predominantly by agriculture and industry in Northern Hemispheric temperate countries (Fig. 17.1). For example, the estimated cumulative pesticide usage up to the year 2000 was 10 Mt for HCH (hexachlorocyclohexane),

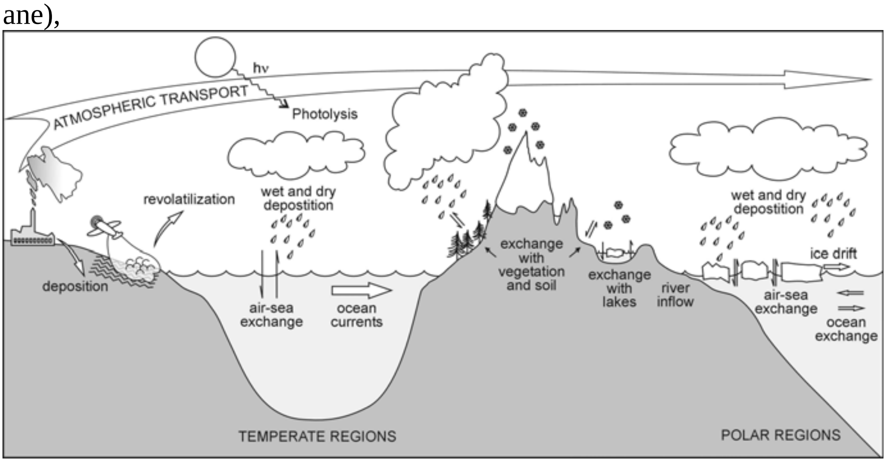

Fig. 17.1. The transport of contaminants from emission to receptor regions in the environment. On the left hand side, climate factors can operate on the transporting mechanisms including wind and water pathways and on the coupling between these two (snow and rain, air-particle partitioning, air-water exchange). On the right hand side, climate operates on the capturing mechanisms within the receptor region. Climate variation and change alters the balance between gaseous and particulate contaminant, the amount of precipitation and its type (snow/rain) or the amount of open water for air-water exchange.

4.5 Mt for DDT (dichlorodiphenyltrichloroethane), 1.33 Mt for toxaphene and 0.34 Mt for endosulfan (Li and Macdonald 2005). To these may be added industrial products such as polychlorinated biphenyls (PCBs; 1.2 Mt) or by-products such as PCDD/Fs (Macdonald, et al. 2000)
and, more recently, the poly-brominated diphenyl ether (PBDE) flame retardants (estimated demand in 1999 on the order of 0.2 Mt (de Wit 2002)).

With respect to global pathways and transport, it is important to note that semi-volatile contaminants have generally entered the environment in a transient pulse, which for the classic organochlorine contaminants started in about 1940-1950. An ensuing rapid rise in emission is eventually followed by a period of decline (after about 1970) when various countries banned or restricted the use of many of these substances, or found ways to eliminate them as by-products. Eventually, we have seen complete banning of some of these chemicals, at least in the industrialized world.

Initially, the atmosphere provides the major means for rapid, widespread dispersal as discovered by atmospheric measurements in remote regions (Ottar 1981). But as environmental reservoirs become loaded (e.g., surface water, soils, vegetation, snow and ice), these media then begin to exert a greater influence on distribution patterns and processes. When industrial or agricultural emissions are stopped, the environmental reservoirs then account for all of the circulating chemical. What this means, specifically, is that the transport of any given chemical and its loading into foodwebs evolves with time and is likely to be very different between early and late periods in a chemical's history. Furthermore, variations in physical and chemical properties (volatility, partitioning, degradation) between contaminants means that, even if the emission of two chemicals has been very similar (e.g., the CFCs (chlorofluorocarbons) and HCHs (hexachlorocyclohexane), they may behave very differently once they begin cycling in the environment. This is especially true late in a contaminant's history when phase partitioning and environmental cycles (temperature, precipitation) become dominant sources of transport and transfer.

17.3 Environmental Concentrating Processes

As soon as a contaminant is released to air or water, dispersion begins. If advection and diffusion were the only environmental processes at play, contaminants would become more dilute as they drifted away from their sources such that remote regions would exhibit far lower concentrations than close to emissions. Contradicting this, the distribution of HCH in the Northern Hemisphere ocean surface water in the early 1990s, which had higher concentrations in the Arctic Ocean than in North Pacific waters near Asian points of release (Li, et al. 2002; Wania, et al. 1999), clearly demonstrates that powerful processes in the environment may reverse the effects of dispersion. The environment actually contains several surprisingly effective concentrating processes, aquatic foodwebs providing perhaps the best-known example (Muir and Norstrom 1994). But, before discussing how global change can alter transfers and transports of chemicals, it is useful to consider the concentrating mechanisms, which come in two fundamentally different forms (Macdonald, et al. 2002). The first mechanism involves transfers between phases – often described and modeled with reference to partition coefficients (e.g., air-water, air-particle, water-particle, water-oil). These processes involve the spontaneous switching of a contaminant from one medium to another, often with an increase in concentration in one of the media. For example, the counter-intuitive distribution of HCH in surface ocean waters can be explained entirely by Henry's Law gas partitioning; HCH tends to partition strongly into water and especially strongly into cold water (Li, et al. 2002; 2004). The second mechanism involves the reduction of the volume of the phase in which the contaminant is contained. Unlike the switching mechanism, this process requires an input of energy and can, therefore, push a contaminant's chemical potential above thermodynamic equilibrium. Indeed, an observation of a contaminant in, for example, a marine mammal, at concentrations above thermodynamic equilibrium with the surrounding water points strongly to a solvent reduction process.

17.4 Recent Change in the Arctic

Perhaps one of the greatest surprises of the 1990s was how rapidly change could occur in the Arctic and how many forms that change could take (Macdonald 1996; Macdonald, et al. 2003; ACIA 2005). Although many of the observed changes have been linked to the Arctic Oscillation (AO), which is a variable, or cyclic, distribution of northern hemispheric atmospheric sea-level pressure (Wallace and Thompson 2002), there is evidence that long-term change associated with greenhouse gases and global warming may in fact produce changes similar to those we have witnessed under the strong positive phase of the AO during the early 1990s. A leading question is whether any of these changes will reverse themselves as part of a cycle or whether they portend a change toward a new Arctic Ocean that is seasonally clear of ice.

What were these changes? Following an atmospheric pressure drop over the North Pole during the late 1980s, the Arctic's atmospheric circulation became more cyclonic. Winds connecting the eastern seaboard of North America and the Nordic Seas became more intense, and the storm track to the east of Greenland penetrated more deeply into the Arctic delivering larger amounts of precipitation. At the same time, there were observations of loss of ice cover over the Arctic's shelves and a general shift from multiyear ice to seasonal (first-year ice). Freeze-up became delayed by weeks in some places, and spring advanced. Within the Arctic Ocean, the ice-drift pathways changed such that the Beaufort Gyre became smaller and disconnected from the rest of the Arctic Ocean and the Transpolar Drift diverted from its normal direct path over the Lomonosov Ridge to the Greenland Sea, to a path that placed sea ice from the Laptev Sea into the Canada Basin. Water masses changed as well. The domain in the upper ocean traditionally occupied by waters of Pacific origin became smaller as Atlantic water pushed itself across the Lomonosov Ridge to realign the Pacific/Atlantic front at the Alpha Mendeleev Ridge – this change entailed a displacement of perhaps 20% of the Arctic Ocean's surface water. The Arctic's hydrological cycle appears also to have changed in several ways possibly including more precipitation, a change in the relative amounts of snow and rain, higher river inflow from Russian rivers entering the Kara and Laptev Seas (Peterson, et al. 2003), a diversion eastward of the pathways of river water entering the Russian Shelves and an alteration of the storage of freshwater within the Arctic Ocean. Over land other changes have been reported; for example, snow cover has disappeared earlier in some locations, ice has melted earlier on lakes, permafrost is melting especially in discontinuous permafrost zones, and terrestrial vegetation has responded to these changes (Vörösmarty, et al. 2001). Other intriguing changes, which are likely to be highly significant but difficult to quantify, include extreme events (e.g., storms, rain, coastal erosion; (see Stirling and Smith 2004; ACIA 2005)).

These primary physical changes then produce change in biological systems and organic carbon cycling (Macdonald, et al. 2003; Tynan and DeMaster 1997). Clearly, changes altering the distribution of, or access to, biological resources will have enormous significance for humans living in the Arctic and depending on country foods.

17.5 Contaminant Pathways and Change

17.5.1 Transport from Emission to Receptor

The first opportunity for global change to affect contaminant pathways occurs immediately upon the release of a chemical from a source (Fig. 17.1, left side). It is now well recognized that large scale pressure changes in the atmosphere (e.g., the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), El Niño-Southern Oscillation (ENSO), Pacific North American (PNA) pattern) insert decadal or longer signals into wind pathways and the distribution of precipitation (Dickson, et al. 2000; Serreze, et al. 2000). On the large scale, general eastward atmospheric transport determines who is downwind from whom (e.g., see Wilkening 2001). Climate cycles then change these wind tracks to alter the length of time of transport and the connection between source and sink. Changes in precipitation along the atmospheric path alter the transfer to surfaces especially for contaminants that partition strongly into water (HCH) or strongly onto particles (highly chlorinated polychlorinated biphenyls (PCBs). The effect of climate cycles on contaminant transport is a neglected topic, largely due to the paucity of appropriate long-term observations; nevertheless, recent papers have begun to seek – and find – such connections (Ma et al. 2003; 2004). To disentangle the effects of the NAO or AO, for example, from other sources of variance requires the collection of coherent data over a climate cycle or two – that is, for a decade or longer. But there are examples where such effects may have been recorded. The decline of aerosol metal concentrations at Alert after about 1991, ascribed by Sirois and Barrie (1999) to the collapse of industry following the fragmenting of the former Soviet Union, could alternatively be explained by changes in wind and precipitation patterns at the end of the 1980s due to the strong positive phase of the AO/NAO at that time (Macdonald, et al. 2003), or to a combination of the two. More recently, Ma et al. (2004) have found correlations between climate variables (NAO, ENSO, PNA) and air concentrations of HCHs, HCB (hexachlorobenzene) and several PCBs over the Great Lakes and the Arctic. As these authors point out, the correlation may be a consequence of changed wind pathways or altered temperatures which then change upwind re-emission from soils. Finally, altered wind fields together with increased numbers of extreme events may produce a stochastic process of contaminant delivery – perhaps resulting in larger contaminant depositions at certain locations (Stirling and Smith 2004; Welch, et al. 1991) under climate change scenarios.

The ocean also provides a potent pathway of transport. In contrast to the atmosphere, which is quick to load and quick to transport contaminants (a few days for emissions to reach remote regions), the ocean is slow to load and takes years to decades to transport properties long distances. However, once the upper ocean becomes loaded with a contaminant, it can become the major reservoir and transporting mechanism (Gobeil, et al. 2001; Li, et al. 2002; Li, et al. 2004; Macdonald, et al. 2000) and, indeed, may delay atmospheric turndown subsequent to emission control by evading gas back out of the ocean (Jantunen and Bidleman 1995; Shen, et al. 2004). Accordingly, it is important to note that surface ocean currents and temperatures are important components of climate change as are connections between oceans – for example the passages at Bering and Fram Straits which allow the Arctic Ocean to exchange water with the Pacific and Atlantic Oceans respectively (Macdonald, et al. 2003). Changes in ocean currents, and the locations of fronts and surface temperature anomalies, while apparently important to budgets (Li, et al. 2004), have been little studied in the context of contaminant transport. One exception to this ironically involves artificial radionuclides: Smith et al. (1998) document the rapid transport of European coastal water into the Arctic Ocean and then around the basin margins using radiotracers like ^{137}Cs and ^{129}I which were disposed under license by the nuclear reprocessing industry.

17.5.2 Capture and Re-emission at the Receptor

The second opportunity for global change to affect contaminant pathways to cold regions occurs in the mechanisms by which contaminants are deposited (Fig. 17.1, right side). Capture may occur through precipitation (rain/snow), which removes contaminants through gas exchange (into rain or onto snow surfaces) or by removing particles onto which contaminants have exchanged. Contaminants can also deposit to surfaces through dry deposition (particles) or air-water exchange at the surface. There are three primary means by which climate change may directly alter this deposition. Firstly, there is temperature change, which alters partitioning onto particles, particularly important for chemicals with log K_{OA} values in the range of 11 to 14 (Macdonald, et al. 2003), and air-water exchange (McKone, et al. 1996; Wania 2003). Both of these affect the efficiency of removal of contaminants from the atmosphere by precipitation. Secondly, there is the amount of precipitation; the Arctic is practically a desert (20-30 cm/yr) and the efficiency of deposition for many contaminants may be rather low (e.g., see Akeredolu, et al. 1994) so that increases in precipitation as projected by change scenarios will be accompanied by increased capture of contaminants. Thirdly, the forms of precipitation (rain versus snow) have very different contaminant exchange characteristics (Macdonald, et al. 2000; Macdonald, et al. 2002; Wania and Halsall 2003; Daly and Wania 2005). For cold regions the change between snow and rain offers an enormous potential for altered pathways and for strong thermodynamic forcing when snow loses its surface area upon sintering or melting.

In addition to these primary changes, there are other climate-related variables that alter net capture. For example, the percent ice cover on lakes, rivers and oceans, which is affected by temperature and winds, controls air-water exchange. The cycle of soil temperature affects the re-emission of many contaminants (multi-hopping), and the timing and rate of melting in the Arctic affect the coupling of deposited contaminants into the hydrological cycle (see, for example Diamond, et al. 2003; Shepson, et al. 2003). Alteration in ice cover may affect primary production which then affects how the lake's sediments capture persistent organic pollutants (POPs) (Stern, et al. 2005). Change from tundra to vascular plants such as willows can also alter exchange between air and surfaces (Wania and McLachlan 2001) either upwind from cold regions or within these regions themselves. Other climate-related impacts on contaminant cycling at the site may affect the distribution after deposition; for example, deposition during climatically cold periods may store contaminant in permanent snow fields only to be released during a subsequent climatically warm period (Blais, et al. 2001).

17.5.3 Concentration Processes at the Receptor

Concentrating processes – often involving the reduction of solvent (Fig. 17.2) – offer subtle means to change the exposure, and hence risks, of contaminants to biota. Several of these processes are unique to the cryosphere and, thus, may make such regions especially vulnerable to long-range contaminant transport. In particular, snow provides an important exchange surface for many contaminants. Once snow deposits, it weathers, which may involve a slow loss of surface during sintering or a complete loss of the surface during melting. These losses of surface provide an opportunity for very large thermodynamic forcing (Macdonald, et al. 2002; Wania 1998); upon melting the sorbed contaminant must go somewhere else, either back into the atmosphere or into other media such as soil or biota.

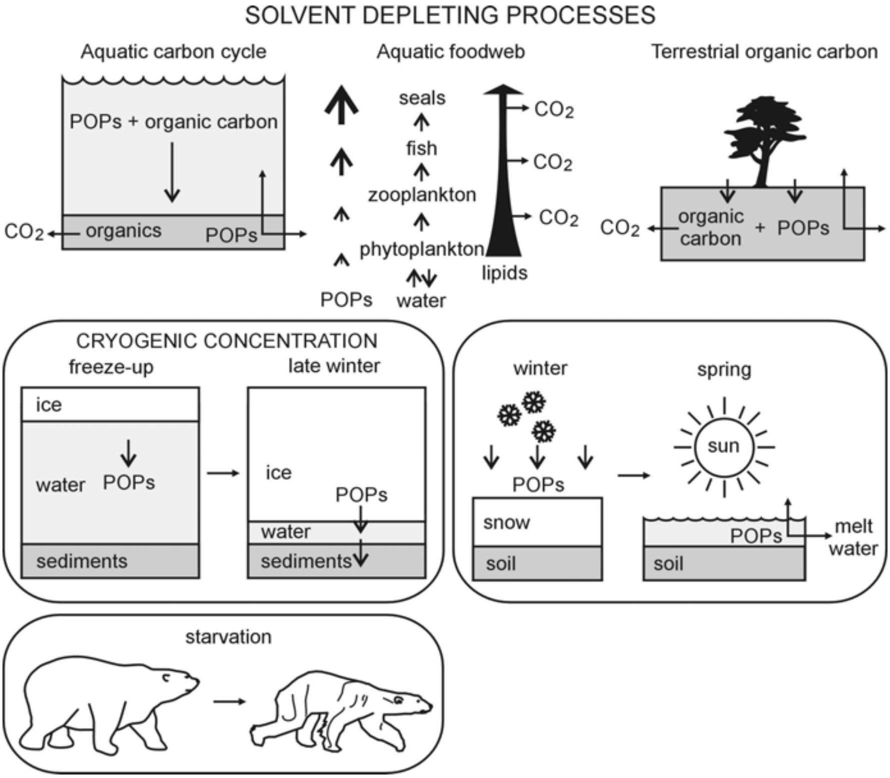

Fig. 17.2. Examples of processes in the environment that lead to high concentration of organochlorine contaminants through the removal of solvent. These include the metabolism of organic carbon in aquatic sediments and terrestrial soils, the aquatic food chain (inefficient lipid transfer up food webs), the exclusion of contaminants into a dwindling volume of water under ice as it forms, the loss of snow surfaces during melting and the loss of lipids in animals that undergo starvation cycles.

If snow is an important contributing factor to the cryosphere's attraction for contaminants, then climate change, which alters the seasonality of snowfall and snow melt, and which may alter the frequency and timing of important random events such as freezing rain, will have a great opportunity to alter that attraction. We do not understand post-depositional processes in snow sufficiently to say how these changes might occur – only to say they are likely to be important (Shepson, et al. 2003). As is the case for scavenging of contaminants by precipitation within the Arctic, it appears that most of the contaminants that enter the hydrological cycle do not get captured by the lakes they enter but, rather, pass under the ice cover in a stratified layer in spring to exit in the lake's outflow (Macdonald, et al.

2000). Inefficient processes of capture like these offer great leverage for change in that efficiency, and such changes delivered by either the hydrological cycle or the biological cycle, can be recorded in lake sediments (Stern, et al. 2005).

Aquatic systems tend to be among the most sensitive to fat-soluble contaminants due to the mechanism of biomagnification. The process of contaminant amplification depends on the inefficient transfer of fat between trophic levels (Macdonald, et al. 2002) and the presence of a large number of trophic steps – often as many as five (Kidd, et al. 1998). Climate change can impact aquatic foodwebs, sometimes radically and often rapidly (Hare and Mantua 2000; Macdonald, et al. 2003). Such changes can lead to an alteration of the number of trophic steps, which then changes the contaminant exposure of apex feeders. Alternatively, ecosystem structure and function can be changed in several ways, for example by altering the balance between pelagic and benthic coupling, by altering the availability of food (growth dilution) to a particular trophic level, or by changing the age structure of populations within the system. This latter would have particular significance, for example, for predatory lake fish where age correlates directly with mercury burden. Change can also come in the form of altered fat cycles within animals that undergo periods of starvation (i.e., solvent depletion) during which fat-soluble contaminants may be released depending on how severe the fasting has been (cf. De Swart, et al. 1996). Fat cycling and starvation cycles are common to most aquatic animals including anadromous fish (Ewald, et al. 1998; Krümmel, et al. 2003), polar bears (Stirling, et al. 1999), gray whales (Le Boeuf, et al. 1999) and gray seals (Reilly 1991) to name a few.

Change in biological systems can occur through bottom-up forcing initiated by oceanographic or limnological properties such as ice cover, nutrient supply, temperature, salinity or stratification. But change can also be effected by changing the distribution or prevalence of dominant species at the top of the foodweb (Parsons 1992; Pauly, et al. 2003). The Arctic is especially sensitive to such top-down changes because many of the dominant species depend in some way on the ice (e.g., bowhead whales, belugas, walrus, polar bears, seals, eiders, arctic cod). These top-down changes then have great potential to alter trophic structure (Tynan and DeMaster 1997) and diet of humans who depend on many of these species for food (ACIA 2005).

Change in foodwebs can also be produced by shifts in the distributions of species in response to climate change (e.g., Gaston, et al. 2003) or because exotic species are introduced accidentally into regions where they can then expand as did the zebra mussel in the Great Lakes (Morrison, et al. 1998). Other changes mediated by human activities can also be envisioned – for example the introduction of new species (e.g. the rainbow smelt into the Hudson Bay drainage (Remnant, et al. 1997)) which is now displacing indigenous species, or heavy predation on selected species such that age or trophic structure changes (Myers and Worm 2003). An ice-reduced climate in the Arctic Ocean enhances all of these possibilities.

17.5.4 Vectors and Surprises

Perhaps the most interesting – and threatening – interactions between climate change and contaminants will occur due to combinations of unforeseen circumstances. In such cases there are likely to be two components to the threat – the setting of the stage and a triggering event. Recently, it has been shown that mass mortality in marine mammals occurs due to several factors including population stress, population size, population immunity (or naïvety) to specific pathogens, condition of animals, contaminant burdens, and disease vectors (cf. Ross 2002; Daszak, et al. 2000). Each of these can be affected by climate change (e.g., Harvell, et al. 1999) and it is the complexity of this interaction that provides fertile ground for surprises. Some disease outbreaks have been observed following migrations associated with large-scale ecological change while others have derived from the introduction of viruses from domestic animals. But the addition of immunotoxic chemicals, like many of the POPs, may further set the stage for an epidemic to occur (Ross, et al. 2000). The widespread distribution of phocine distemper virus (member of Genus *Morbillivirus*) in seals from Greenland, led Dietz, et al. (1989) to speculate that a long migration of a harp seal or seals (*Phoca groenlandica*) from the Norwegian Coast to north-western Europe in 1986-87 might have provided a disease vector. The co-factors of a European seal population naïve to this virus and also manifesting a suppressed immune system due to PCB contamination would then produce an epidemic (Ross, et al. 1996; De Swart, et al. 1996). In northwestern European waters, these factors conspired to kill 20,000 harbour seals (*Phoca vitulina*; up to 60% of some populations), and a further 400 grey seals (*Halichoerus grypus*) (cf Ross 2002; Dietz, et al. 1989).

Within the Arctic, top predators would be at greatest risk to such an epidemic due to their relatively high exposure to contaminants. Marine mammals like polar bears face the added stress of change in ice climate which alters their expenditure of energy and ability to find food (Stirling and Derocher 1993; Stirling, et al. 1999). Therefore, evidence of immunosuppression in polar bears, northern fur seals and glaucous gulls (de Wit, et al. 2003) should be viewed with concern, and it seems that the polar bears of the Kara Sea, Franz Jozef Land, East Greenland and Svalbard are especially vulnerable. First, they exhibit inordinately high contaminant burdens (Norstrom, et al. 1998) and these high burdens may very well derive partly from the enhanced connectivity between this region and Europe/North America under the high AO/NAO indices of the 1990s. Second, change in ice climate and in marine ecosystems may have provided the added stress of malnourishment and a change in pathogen transmission pathway via migration (e.g., Daszak, et al. 2000). Finally, it seems these bears already have sufficient contaminant burdens to exhibit health effects (Skaare, et al. 2001).

Sea ice provides another pathway that is subject to climate change. Although the potential in the Arctic for sea ice to transport contaminants has long been recognized (Pfirman, et al. 1995), detailed studies are still lacking. Material transport by ice involves three main steps including incorporation into the ice, concentration at the ice surface during seasonal cycling and, finally, release from the ice when it melts. Suspension freezing over the middle shelves occurs when cold winds blow over open seawater at its freezing temperature; sediments are resuspended while at the same time frazil ice is produced and this scavenges suspended particles and incorporates them into the newly forming ice cover (Eicken, et al. 2000). This process, which can account for a large off-shelf transport of shelf sediment and organic carbon (Stein and Macdonald 2003), also incorporates contaminants associated with the sediments. As the ice drifts across the ocean in time scales that span two to six years (Rigor, et al. 2002), ice melts at the surface during summer but more ice is formed at the bottom of the ice in winter. This process tends to push particles and contaminants toward the surface of the ice where they may concentrate in mud balls. Additionally, as the ice drifts across the Arctic Ocean, contaminants deposit from the atmosphere depending on processes discussed above such as precipitation. Finally, when the ice travels far enough south (to the Polar Front near Fram Strait, for example), it melts and drops its load back into the water column. Climate can change the intensity of the suspension freezing process, the length of time ice takes to transport across the Arctic Ocean (and accumulate contaminants), the intensity of scavenging by snow or rain, the rate of ice export from the Arctic and the location at which the ice finally melts. Clearly, this pathway offers some ‘shortcut’ surprises. For example, depending on the ice-drift trajectories, radionuclide contaminants in sediments of the Russian Shelves could be transported to the Greenland Sea or into the Canadian Archipelago, becoming concentrated in a dirty surface layer along the way. Similarly, under high Arctic Oscillation index, oil spilled over the Beaufort shelves would tend to drift around in the ice of the Beaufort Gyre whereas oil spilled during low AO index would be rapidly exported into the East Siberian Sea within the ice drift.

Among the most important vectors for contaminant transport are high-trophic level aquatic biota. These are the carriers of biomagnified fat-soluble contaminants like the organochlorines and, through long migration or very dense migrations, focus these contaminants to particular locations or into human diets. Anadromous fish provide perhaps one of the clearest examples; by returning in millions to natal streams and lakes, they deliver sufficient contaminant to affect the fish native to these lakes (Ewald, et al. 1998). For lakes exhibiting high sockeye returns, this pathway can account for up to eight times the amount of PCB delivered through the atmosphere (Krümmel, et al. 2003) and the focusing of this contaminant within the salmon's life cycle may put eggs and fry at risk. Interestingly, anadromous fish are not the only means by which organochlorine contaminants can 'vector' into lakes. Evenset et al., (2004) have shown that bird guano has, likewise, impacted the nutrient and contaminant cycles within a lake on Bear Island in the Barents Sea, and birds are well-known vectors for contaminants accumulated during long migrations (Braune, et al. 1999). Biological vectors are exceptionally sensitive to climate change which is well known to alter migration pathways (Babaluk, et al. 2000; Moore, et al. 2003) and intensities (Finney, et al. 2002).

17.6 The Special Case of Mercury

Mercury has a natural biogeochemical cycle with a high level of complexity that allows the operation of climate change at many points (see Fig. 17.3). Human activities have mobilized mercury during the past two centuries such that we presently account for as much as one half to two thirds of the cycling mercury (Lamborg, et al. 2002; Pacyna and Pacyna 2001). The long atmospheric residence time (~1-2 years) easily distributes mercury globally, but it is the phenomenon of the mercury depletion event (MDE) that provides a deposition pathway unique to polar regions. MDEs are associated with polar sunrise and are initiated by photochemistry that oxidizes halogens and produces an oxidized, bioavailable form of mercury (see Fig. 17.3), which is then rapidly deposited to the surface (Lindberg, et al. 2002; Lu, et al. 2001). The marginal seas of the Arctic Ocean appear to be the prominent location for this process, which requires ice surfaces, snow, freezing temperatures and sea salt. However, it is not at all clear what conditions of ice, snow and water are optimum for this process and it has been argued that MDEs may actually be a recent phenomenon associated with change in the Arctic (Lindberg, et al. 2002). It is certain that the intensity of the process is related to climate variables including the distribution of open water, the types of ice (multi-year, first year) and the amount of primary production. In this context, the increase in first-year ice over the past decades (Yu, et al. 2004), especially in the marginal seas, may

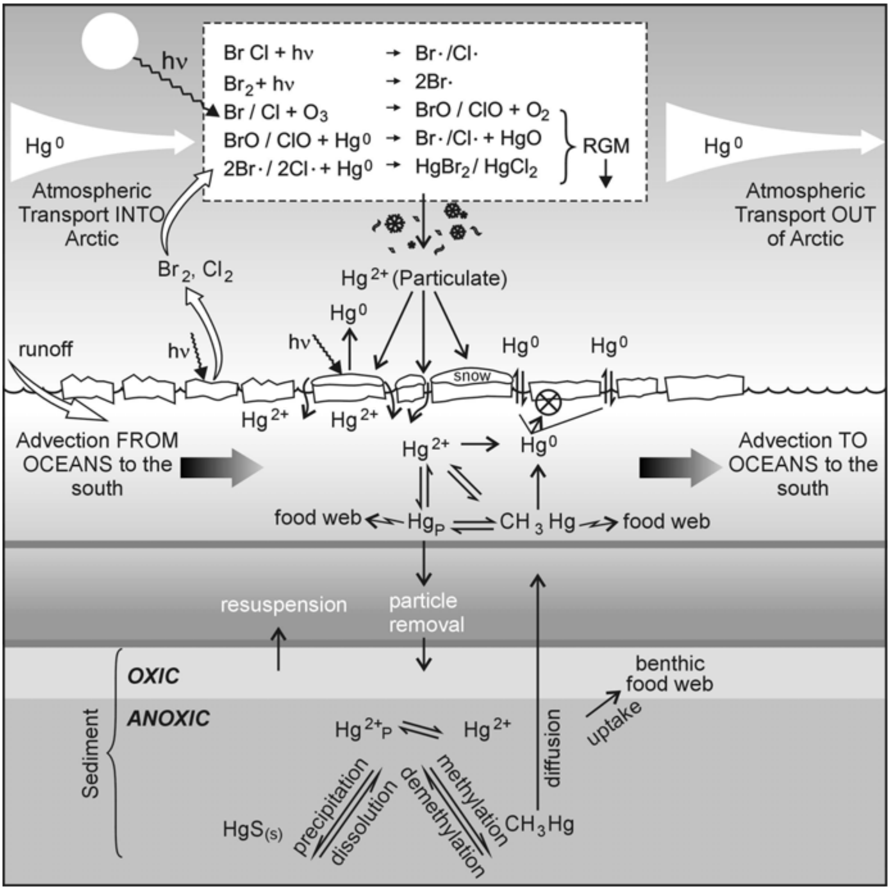

Fig. 17.3. The mercury cycle showing the many processes subject to climate variation and change. In particular, mercury depletion events are affected by ice and snow cover and the presence of sea salts, and the methylation of mercury can be enhanced by flooding land or, possibly, by melting permafrost.

have led to more intense MDEs which might then explain why mercury concentration has been increasing in some biota counter to atmospheric trends and emissions (Lindberg, et al. 2002; Pacyna and Pacyna 2001; Steffen, et al. 2003). Nevertheless, there remains much uncertainty about how much of the deposited mercury actually enters aquatic systems and how much returns to the atmosphere (Macdonald, et al. 2003; Shepson, et al. 2003), a process also subject to climate variation. Recent findings suggest that MDEs play almost no role in Hg(II) loading in the Arctic marine system (Kirk and St. Louis 2004; Stern and Macdonald 2004) and, therefore, do not provide a mechanism that can explain observed increases in Hg in marine mammal tissue (cf. Wagemann et al. 1995; Fisk et al. 2003).

Methyl-mercury is the predominant toxic form that accumulates in fish and other animals. It seems clear, therefore, that processes altering the production, accumulation or destruction of methyl-mercury are of greater concern than MDEs (Fig. 17.3) and yet we know little about what controls methyl mercury concentrations spatially and temporally. As is well known from the release of methyl mercury in response to flooding of reservoirs (Bodaly and Johnston 1992), change in hydrology may lead enhanced mercury fluxes from terrestrial soils. For the Arctic, where permafrost is melting, there is likely to be a patchwork of responses within terrestrial systems including flooding and drying. Exactly how these changes will alter the balance of methyl-mercury fluxes remains to be seen, and there are likely to be other processes that control the production and destruction of methyl mercury in the ocean about which we presently know little.

17.7 Time Series and Climate Variability

Time series provide unique insight into contaminant sources, sinks and the effects of emission controls. There are relatively few long time series available, and those we have often span a decade or less or are sporadic, containing relatively few points. For example, atmospheric measurements of organochlorines and mercury at Alert (Hung, et al. 2001; Steffen, et al. 2003) are rich in detail but span less than a decade. On the other hand, Addison et al. (1998) have measured organochlorine contaminants in seal blubber collected between 1972 and 1991 at Holman Island, but there are only four sample intervals, and Lockhart et al. (2004) have collated Hg date from belugas hunted between 1981 and 2002. Given the Arctic Oscillation's time scale of 5-7 years, it would be difficult to sort out the effects of emission controls and factors of climate change based solely on these records. Proxy measurements, which have been extracted from sediment, ice and snow cores, tooth samples, tree rings, peat bogs and museum collections can do better in terms of producing a longer record but these, too, are subject to climate variation and change. Very little concern has been paid to the potential influence of climate cycles on such records and, where it has, evidence of cycles has been found (Hung, et al. 2001; Ma, et al. 2004; Stern et al., 2005). The lesson here is clear. To understand contaminant time series we need to collect data for periods that span more than one climate cycle (e.g., decades), the interval of sampling should be at least annual, ancillary measurements (e.g., isotopic composition) should be made to help interpret the record, and trends should be collected for a set of media (e.g., air, water, sediment, low-mid-high trophic level). Furthermore, we should be archiving samples in properly funded and maintained repositories or tissue banks such that emerging issues can be studied with new tools.

17.8 Conclusions

Contaminants enter natural cycles which include transfers between media (air, water, soil, biota), magnification due to loss of phases (snow surfaces, organic carbon, fats), and permanent burial or degradation. Climate variables can impact all of these processes. In particular, each contaminant responds differently in the environment depending on its physical and chemical properties, which often act to produce contaminant separation during long-range transport similar to a global chromatography or global distillation. Air and water, the Earth's two dominant moving phases, pass over and interact with soils, vegetation, and sediments, the Earth's dominant stationary phases. Initially, the transport process is dominated by the atmosphere, but as the other media become loaded, these then dominate future transport once the emissions have been turned off. At this point, the transport, magnification and burial of chemicals occurs on time scales set by the sizes of the environmental reservoirs and the natural processes occurring within and between them. This cadence of turndown is then very much subject to change in climate systems – especially those that alter the balance between phases or exchange between reservoirs.

Nowhere in the world are there regions more sensitive to change than the poles and the mountain alpine and it is these regions we need to observe carefully in the coming decades. Recent reviews of climate change have found that temperature rise is but one manifestation of change. Others include alterations to hydrological cycles, potential stalling of thermohaline circulation, more frequent extreme events, alteration to organic carbon cycles, change in global food webs, and adaptation by humans (Houghton, et al. 2001; ACIA 2005). For contaminants distributed by long-range transport, it is the interaction with these elements of change that will produce inevitable surprises.

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18 Modeling of long-range transport of contaminants from potential sources in the Arctic Ocean by water and sea ice

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18.1 Introduction

The geographical position and climatic features of the Arctic seas mean that their ecological balance is sensitive to disturbance by inputs of man-made pollutants. The Arctic seas represent zones where pollutants naturally accumulate and pollutants are transported between regions where there is active exploitation of natural resources and pollution, and the ecologically clean regions of the central Polar Basin. The processes involved in the transport, transformation and accumulation of contaminants from different possible sources are important in assessing whether we are to forecast the fate of potential pollutant releases. These sources and potential sources are described by several reports and papers (Yablokov Commission Report 1993; Aarkrog 1993; Pavlov and Pfirman 1995; Duursma and Carroll 1996; ANWAP 1997; AMAP 1997; AMAP 1998; Champ et al. 1998; Yablokov 2001). In some Arctic seas, such as the Barents and Kara seas, there were earlier local sources of anthropogenic origin, connected with the nuclear trials at the test site of Novaya Zemlya and dumping of radioactive waste over their areas. Extensive dumping of nuclear materials in the Kara and Barents seaы marine environment is listed in the Yablokov Commission Report (1993) and in Yablokov (2001). Low level liquid radioactive wastes are stored in the following regions of Russia in large volumes: by the northern fleet in the Kola Peninsula in the Murmansk and Severodvinsk regions, and by the Pacific fleet in the Russian Far East in the naval ship yards at Vladivostok. The combined capacity of all Northern Fleet containers amounts to 10,000 m^3 and annual production is estimated to be about 20,000 m^3. Approximately 30 to 40,000 m^3+ of solid radioactive waste is stored at different sites in the Russian Far East and Northwest

(ANWAP 1997; AMAP 1998; Champ et al. 1998). The discharges of fresh water from the large Arctic rivers that have huge catchment areas draining water from land areas and industrial zones also contribute to the input of pollutants into the Arctic Ocean.

Ocean currents and drifting ice are among the most important mechanisms of pollutant transport (Nürnberg et al. 1994; Emery et al. (1997); Pfirman et al. 1997; Nilsson 1997; Rigor and Colony 1997; Smith et al. 1998; Smith and Ellis 1999; Zhang et al. 2000; Rigor et al. 2002; Zhang et al. 2003; Pfirman et al. 2004a; Pfirman et al. 2004b). Severe natural conditions and the year-round presence of drifting ice make direct full-scale observations of currents difficult and expensive. Numerical modelling, supported and validated by in situ field observations, is therefore the only practical possibility for gaining an understanding of water circulation in the Arctic Ocean on different spatial and temporal scales. Many models describing transport and transformation of various pollutants in the water environment of the Arctic have appeared in recent years inspired by increasing anthropogenic effects, especially in coastal zones (Preller and Cheng 1995; Pavlov et al. 1995; Harms 1997; Scott et al. 1997; AMAP 1998; Nies et al. 1999; Harms and Karcher 1999; Harms et al. 2000; Karcher et al. 2004 and others). In these papers, modelling results for the spreading of contaminants from individual sources, mostly located in the Nordic seas and Kara Sea, were discussed. For example, Harms (1997) has described the application of 3-D, baroclinic circulation models to study the dispersal of radioactivity in the Barents and Kara seas. Release is expected to occur at underwater dump sites for radioactive waste in the Kara Sea, used by the former Soviet Union. To cover the wide range of a possible radionuclide dispersion, two different spatial scales were considered: i) the regional scale, which covered the shelves of the Barents and Kara seas and ii) the local scale, which is focused on the bay where some of the dumping took place. The regional-scale model results have suggested that, even for a worst case scenario, the radioactive contamination of Siberian coastal waters would be relatively small compared to observations in other marine systems (e.g. the Baltic Sea and the Irish Sea). Realistic gradual release scenarios show very low concentrations in the central and eastern Kara Sea. Significant contamination of shelf seas such as the Laptev Sea, the Arctic Ocean or the Barents Sea by radioactive waste dispersion from the Kara Sea seems unlikely.

Nies et al. (1999) presented a review of results from a joint project carried out in Germany in order to assess the consequences to the marine environment from the dumping of nuclear waste in the Kara and Barents seas. The project consisted of experimental work on measurements of radionuclides (^{137}Cs, ^{90}Sr, $^{239+240}$Pu, ^{238}Pu, ^{241}Am) in samples from the Arctic marine environment, and numerical modelling of the potential pathways and dispersion of contaminants in the Arctic Ocean. The role of transport by sea ice from the Kara Sea into the Arctic Ocean was assessed. This transport process might be considered as a rapid contribution of pollutants due to entrainment of contaminated sediments into sea ice, followed by export from the Kara Sea by the Transpolar Ice Drift, and subsequent release in the Arctic Ocean in the region of the East Greenland Current. Numerical modelling of pollutant dispersion from the Kara and Barents seas was carried out both on a local scale, for the Barents and Kara seas, and for long range dispersion into the Arctic and Atlantic oceans. 3-D baroclinic circulation models were applied to trace the transport of pollutants. Modelling results show no significant pollution even for worst case scenarios from the radioactive waste dumped in the Kara Sea to other seas in the Arctic or North Atlantic (as in Harms 1997). The results from the dispersion models suggest that, even for worst case scenarios, the contamination of Arctic waters and North Atlantic areas is relatively minor compared to pre-contamination from Sellafield, or global fallout from nuclear weapon testing in the 1960s. Long range simulations of Sellafield discharges of ^{137}Cs since the 1960s correlates well with measured levels. Harms et al. (2000) investigated the role of Siberian river runoff for the transport of possible river contaminants in the Arctic Ocean. 3-D coupled ice-ocean models of different horizontal resolution were applied to simulate the dispersion of river water from the Ob, Yenisei and Lena. Circulation model results explain the main pathways and transit times of Siberian river water in the Arctic Ocean. Kara Sea river water clearly dominates in the Siberian branch of the Transpolar Drift, while the water from the Lena dominates in the Canadian Branch. The model confirms that contaminant transport through sediment laden sea ice offers a short and effective pathway for pollutant transport from Siberian rivers to the Barents and Nordic seas. Karcher et al. (2004) have compared the simulated dispersion of ^{99}Tc in surface water from the sources to the Nordic Seas and the Arctic Ocean as calculated by a hydrodynamic model and in assessment box model with field-observations from 1996 to 1999 to study concentrations, pathways and travel times. The observations cover the northern part of the Nordic Seas. The main sources of ^{99}Tc are global fallout from nuclear weapon testing, and discharges from reprocessing plants for spent nuclear fuel in Northwestern Europe. Radioactive wastes have been discharged from the reprocessing plant at Sellafield (UK) into the Irish Sea, and at La Hague (France) into the English Channel since 1952 and 1966 respectively. The model results were consistent with the observations and have shown typical pathways of dissolved radionuclides from the Irish Sea via the North Sea along the Norwegian coast. The results of the hydrodynamic model have indicated a large variability of surface concentrations in the West Spitsbergen Current.

The importance of sea ice for the climate has led to many efforts to develop different models which study sea-ice morphology, dynamics and thermodynamics of sea ice. Many papers, e.g. Zwally and Walsh (1987), Barry et al. (1993), Zhang et al. (2003), give very good overviews of sea ice modelling. Some comparisons between different modelling approaches and results are given in Pavlov et al. (2004). Large-scale sea ice modelling requires effective use of commensurate observational data sets (sea ice concentration, sea ice extent, sea ice motion) on daily to inter-annual timescales for initialisation and verification. Recent sea ice observation data, measured by satellites, combined with sea ice motion derived from buoys in the International Arctic Buoy Programme (IABP), initiated a large number of studies of ice motion and variability of ice conditions in the Arctic Ocean. This also includes the problem of pollutant transport by sea ice, and provides a good opportunity to develop, compare and verify sea ice models (Pfirman et al. 1997).

Here we discuss the results of our simulation of the transport of passive non-conservative tracers by currents from a number of possible sources in the Arctic Ocean and Nordic seas. For simulation vectors of ocean currents we used a 3-D baroclinic ocean model developed at the Arctic and Antarctic Research Institute (AARI, St.Petersburg, Russia). Model is documented in Pavlov (1995) and Pavlov and Pavlov (1999).

We also include the possible transport of contaminants via sea ice. To estimate the transport of passive tracers by sea ice from potential sources of contamination in the Arctic Ocean we used the Ice Statistical Model (ISMO) developed at the Norwegian Polar Institute (Korsnes et al. 2002; Pavlov et al. 2004). The main approach of ISMO is to reveal the statistical relationship between atmospheric forcing and sea ice conditions derived from satellite imagery, in order to reconstruct the ice drift and ice concentrations, estimate the sea ice fluxes through the main straits in the Arctic Ocean and Arctic marginal seas and calculate forward and backward trajectories of the ice drift from any point in the Arctic Ocean.

18.2 Methods and data

18.2.1 Model of the dispersion of contaminants by ocean currents

To model the dispersion of a soluble contaminant we use the 3-D Eulerian transport equations for a non-conservative passive tracer with properties corresponding to anthropogenic radionuclides such as ^{137}Cs and ^{90}Sr.

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=-\lambda c+\frac{\partial}{\partial z}\eta\frac{\partial c}{\partial z}+\mu\Delta c+Q\delta(r-r_0) \tag{1}$$

where c is the contaminant concentration; u,v,w are the components of the current velocity in the x, y and z directions; λ is the decay constant; η is the vertical diffusion coefficient; μ is the horizontal diffusion coefficient; $r_0=(x_0,y_0,z_0)$ gives the co-ordinates of the source; δ is Dirac delta function; and Q is the source strength.

Initial conditions are $c=0$ at $t=0$ and the boundary conditions are:

$$\frac{\partial c}{\partial n}=0 \qquad u_n \geq 0; \qquad\qquad c=0 \qquad u_n<0 \tag{2}$$

where u_n is the projection of the current speed vector to the external normal to the surface S, restricting the calculation area. These conditions allow for the transport of a contaminant out of the model domain. In general Eq. (1) describes two different physical processes. The first is the transfer of a substance, with its conservation along the trajectory (LHS Eq. (1)) and is described by the equation:

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=0 \tag{3}$$

The second physical process is connected with the diffusion of the substance and its disintegration in the process of spreading from the source (RHS Eq. (1)) and is described by the equation:

$$\frac{\partial c}{\partial t}=-\lambda c+\frac{\partial}{\partial z}\eta\frac{\partial c}{\partial z}+\mu\Delta c+Q\delta(r-r_0) \tag{4}$$

Marchuk (1982) has shown that splitting the initial Eq. (1) into the two Eqs. (3) and (4), by physical processes, gives a form more suitable for numerical application. Eq. (4) is discretized as finite differences on an Arakawa C-grid and Eq. (3) is solved by the “Flux-Corrected Transport” (FCT) method (Boris and Book 1973) which has low viscosity whilst preserving the monotone and conservative character of the tracer field.

Horizontal and vertical velocities of currents for Eq. (1) were simulated using a 3-D baroclinic ocean level-type model (Pavlov and Pavlov 1999). The model is based on the Boussinesq approximation of the non-linear primitive equations of motion. Model equations including the sea ice parameterisation and numerical methods are in detail described in Pavlov and Pavlov (1999). The Arctic Ocean model has 22 layers in the vertical scale. We used a spherical rotated grid with a spatial resolution of 55 km. The model was driven with monthly mean climatologic atmospheric pressure and wind calculated from NCEP/NCAR gridded data (http://dss.ucar.edu/datasets/) and 3-D seasonal mean potential density calculated from data in the US-Russian atlas (US-Russian Joint Atlas 1996). The climatologic annual cycle of the discharge of the major rivers into the seas of the Arctic Ocean (Ivanov 1976; Omstedt et al. 1994) and data on water exchange through the Bering Strait and straits of the Canadian Archipelago were used to assign boundary conditions at open boundaries. Mean water exchange values through Bering Strait are sufficiently well known and estimates by different authors for different times are very close. For this model the water transport through Bering Strait was prescribed to be 1.2 Sv in summer and 0.7 Sv in winter (Pavlov and Pavlova 1999). The water transport from the Arctic Ocean through the Canadian Archipelago straits is taken from Coachman and Aagaard (1988) to be 2.0 Sv. The water exchange at open boundaries in the straits between Greenland and Iceland and between Iceland and the European continent were not prescribed, but the emission condition for the vertical-averaged horizontal velocity $\bar{u}$ was assumed to be $\bar{u} = \xi(g/h)^{1/2}$, where ξ -sea level elevation, g - Earth gravity acceleration and h-depth.

The annual cycle of all forcing and boundary conditions was not changed during the simulations and as a result after about 30 years we obtained a stable annual cycle of the 3-D water circulation in the Arctic Ocean. Harms et al. (2000) using a similar approach achieved a stable seasonal cycle in the ice and the upper ocean circulation after 35-years running their coupled ice-ocean model of the Arctic Ocean. The annual cycle of the water circulation obtained is used in the integration of Eq. (1).

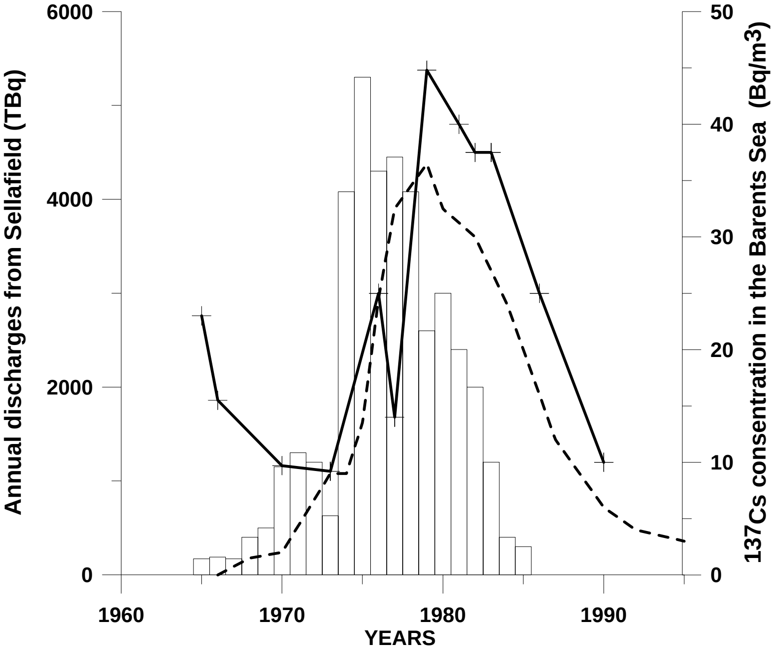

Fig. 18.1. Annual discharge (TBq) of ^{137}Cs from Sellafield (bars); ^{137}Cs concentration (Bq m^{-3}) in the Barents Sea surface waters. Observations from Kershaw and Baxter (1995)-solid line, and modelling results-dashed line (Kulakov and Pavlov 1999)

Kulakov and Pavlov (1999) have verified this model using data on the release of ^{137}Cs from the Sellafield reprocessing plant into the Irish Sea on the Cumbrian coast of England. The discharge from Sellafield started in 1952 (Dahlgaard 1995; Israel et a1. 1993; Matishov et al. 1994; Smith et al. 1990, 1998; Smith and Ellis 1999) and peaked in the mid- to late-1970s (Fig. 18.1). Almost all ^{137}Cs entering the sea with waste from Sellafield was transported from the Irish Sea to the North and Norwegian seas and then via the North-Atlantic Current to the Barents Sea and the Arctic Ocean. This passage has been well described previously; summary is presented in Kershaw and Baxter (1995). Using this model the redistribution and transformation of ^{137}Cs from the source in coastal water of the British Islands was calculated for 30 years from 1965 to 1995 with a time interval of one day. The strength of the source was prescribed in accordance with the real discharge volumes (Fig. 18.1). For the calculations the coefficients of the vertical and horizontal diffusion were assumed to be equal to 5 and $2\cdot10^5$ cm^2/s respectively. Kulakov and Pavlov (1999) reported that the calculated ^{137}Cs distribution is both qualitatively and quantitatively close to that in the Nordic seas (Kershaw and Baxter 1995; Vakulovsky et al. 1993).

Fig. 18.1 shows the comparison of the observed and the calculated time variations of the levels of ^{137}Cs concentrations in the surface water of the Barents Sea. Good agreement suggests that the model describes well the processes of transfer and transformation of ^{137}Cs.

18.2.2 Model of the sea ice transport

Sea ice trajectories have been simulated by the ISMO which was well documented in Korsnes et al. (2002) and Pavlov et al. (2004). In the development of ISMO, a multiple linear regression model was used to establish the statistical relationship between: 1) ice motion and the spatial structure of the sea level atmospheric pressure (SLP); and 2) sea ice concentration and both sea surface temperature (SST) and the spatial structure of the sea level pressure (SLP) in the each point of simulating domain.

The following observational data was used for statistical analysis: Monthly mean sea ice concentration and ice drift from the Special Sensor Microwave /Imager data set from the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center, University of Colorado, Boulder, CO. Monthly mean gridded sea level atmospheric pressure (SLP) fields and sea surface temperature (SST) from the NCEP/NCAR data set.

This model was verified by comparing simulated and observed ice conditions such as ice drift, ice concentration, ice fluxes through the main straits of the Arctic Ocean and ice tracks. The comparisons showed quite good agreement between the ISMO results and the observational data, and also with results of other models (see Pavlov et al. 2004). Using the ISMO we have computed the vectors of ice velocity for the period 1899-2000.

18.3 Contaminant Transport

18.3.1 Dispersion of passive tracers by water from potential sources of contaminants

Numerical experiments simulating the transport of contaminants from possible sources in different parts of the Arctic Ocean have been performed using calculated 3-D current fields. For these simulations potential pollut-

ant sources have been located in the vicinity of river-mouths of major rivers flowing into the Arctic Ocean, as well as in the Bering Strait, in the bottle-neck of the White Sea, in the Faeroe-Shetland Channel and also in the region of the wreck of the “Komsomolets” nuclear submarine.
What is the reason of such chooses?

The Faeroe-Shetland Channel (not far from the Sellafield reprocessing plant), the nuclear submarine wreck “Komsomolets” as well as the Kara Sea with the Ob and Yenisei river mouths, are chosen due to the public, political and scientific concern, and because there are many papers and reports already published from these sites.

The cumulative, and decay corrected total ^{137}Cs radioactivity released in Sellafield amounts to approximately 40 PBq, 14 PBq of which entered the Arctic regions mainly through the Faeroe-Shetland Channel. Maximum releases from Sellafield occurred in 1975. Releases of ^{137}Cs have been continually reduced since that time (Kershaw and Baxter 1995).

Radioactive sources dumped in the Kara Sea mainly include 17 nuclear ship reactors, seven of them still containing spent fuel. The total radioactive inventory at the time of dumping was 37 PBq (Yablokov Commission Report 1993; NPRA 1996; AMAP 1998). By 1994 this had decayed to approximately 4.7 PBq. The dominant nuclides are ^{137}Cs, ^{90}Sr, ^{63}Ni and ^{241}Pu. The amount of ^{137}Cs is estimated to be approximately 1 PBq for 1994 (IAEA 1997).

The sunken submarine “Komsomolets” contains one nuclear reactor with an inventory of long lived radionuclides comprising of 2800 PBq of ^{90}Sr and 3100 PBq of ^{137}Cs. Two nuclear torpedoes with mixed uranium/plutonium warheads, situated in the forepart of the hull contain about 16 PBq of weapons-grade plutonium (AMAP 1998).

The Kara Sea is distinguished from the other Siberian shelf seas by the strong influence of continental discharge. It receives about 55 % (1290 km^3/year) of the total river runoff discharged to the entire Siberian Arctic. The annual discharge from the Ob River is 400 km^3 and from the Yenisei River is 630 km^3 (Soviet Arctic 1970; Pavlov and Pfirman 1995). The nuclear fuel reprocessing plant Mayak is situated around the headwaters of the river Techa, which ultimately drains into the Kara Sea via the Ob River. The waste management system has been developed on a series of natural and artificial reservoirs and drainage canals. A total of 4000 PBq (decay corrected to 1994) comprising mainly of ^{90}Sr and ^{137}Cs has been released to this restricted system (NRPA 1997). Tomsk reprocessing plant also enters the drainage basin of the Ob. The plant’s storage ponds contain an estimated 4800 PBq. The storage ponds at Krasnoyarsk reprocessing plant are believed to contain an inventory of about 2 PBq. As at the other sites, there is a risk of contaminated groundwater migrating into the rivers, in this case the Yenisei river. (AMAP 1998). The observations carried out by Roshydromet, Russia (Vakulovsky et al. 1993) indicate that the amount of ^{90}Sr transported by the Ob during 1961-1989 is about 1 PBq, and 0.1 PBq ^{137}Cs.

In contrast to the possible sources of contamination mentioned above, information about contaminant levels at other possible sources such as the Lena, Kolyma and Mackenzie river mouths, the bottle-neck of the White Sea and the Bering Strait are fragmental or practically absent.

The large rivers of Siberia such as Lena and Kolyma, and Mackenzie in Canada transport large amounts of water over long distances and on their way to the Arctic seas. The annual discharge of the Lena and Kolyma is 525 km^3 and 132 km^3, respectively, and the Mackenzie runoff is 333 km^3/year (AMAP 1998). These areas include agricultural and industrial regions, and also regions of mining, and oil and gas explorations in Siberia and Canada. So, these rivers are expected to be a key source for considerable quantities of several different contaminants

About 1 Sv enter the Arctic Ocean from the Pacific Ocean with the Pacific current through the Bering Strait (Pavlov and Pavlova 1999). These waters wash the industrial regions of the Russian Far East and Northern America where possible sources of contamination are located, such, for example, as the large shipyards for nuclear-powered submarines near Vladivostok, and the regions of drilling activity in Alaska.

The bottle-neck of the White Sea was chosen because the city of Severodvinsk lies on the delta of the Dvina River, close to Archangelsk, and has one of the largest shipyards for nuclear-powered submarines in the former Soviet Union. It is also a disposal site for military nuclear waste (Nilsen and Bøhmer 1994; Champ et al. 1998). Severodvinsk is potentially a major source of radioactive contamination in the White Sea.

However, even if we do not have information about contaminants from these regions, the selected sources could release large amounts of contaminants in the future. For example, release of contaminants through accidents during production, transport, waste disposal and storage, oil and gas exploration and exploitation, and also nuclear submarine waste generated from operations in the Northwest and Far East, or accidents involving nuclear weapons. Potential contaminant release that may occur in the Arctic in the future and source related assessments of potential release are well documented in AMAP (1998).

As we do not have information about a possible release volume, pollutant concentration in all these sources has been set to 100 arbitrary units. The non-conservative parameter has been prescribed to 30 years, this being approximately equal to the averaged half-life of the dangerous anthropogenic long-life radionuclides, such as ^{137}Cs and ^{90}Sr.

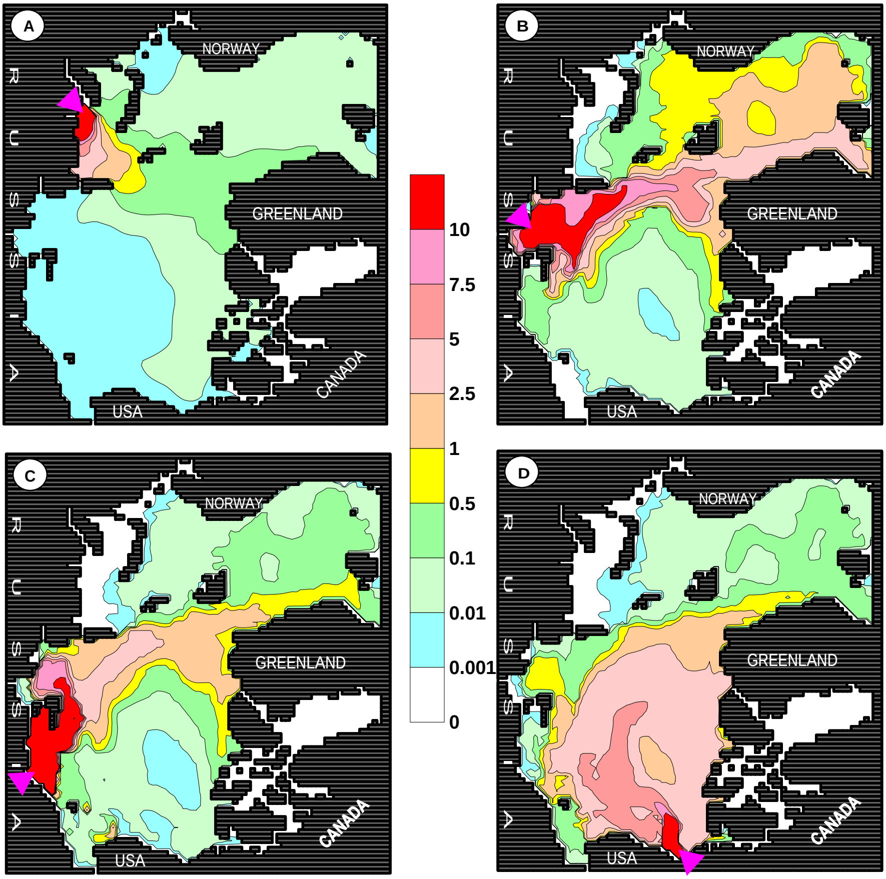

Fig. 18.2. Distributions of pollutant concentration in the surface layer of the Arctic Ocean after 15 years of release from sources in the river-mouths of the major rivers: A - Ob and Yenisei rivers, B - Lena river, C - Kolyma river, and D - Mackenzie river. The scale shows % of pollutant in relation to its concentration at source. ▲ - source location.

Distributions of the pollutant concentration from all the permanently acting sources in the river-mouths of major rivers in the surface layer of the Arctic Ocean after 15 years from the beginning of the release are presented in Fig. 18.2. Depths of the sources near the river-mouths have been set equal to 5 m.

Pollutant spreading from sources in the river mouths of the Siberian shelf is directed predominantly to the north-west. Pollutants from the source in the Kara Sea in the region of the Ob-Yenisei river mouth (Fig. 18.2a) cover a greater part of the Nordic seas, the Laptev Sea and the area near the northern coast of Greenland. However, pollutant concentrations exceeding 5% of the source concentration in the surface layers of the ocean are only observed within the Kara Sea area. The most rapid spreading of the pollutant is observed from the source near the Lena river mouth (Fig. 18.2b). The pollutants entering the Transpolar Drift are transported to the coast of Greenland, spreading later over the region of the Nordic seas. Pollutant concentrations of 5% are observed in the Fram Strait and near the northern coast of Greenland.

The structure of the pollutant transportation from the source near the Kolyma river mouth (Fig. 18.2c) is in many ways similar to the previous one. However, in this case contamination of the Nordic seas significantly decreases, and contamination of the coastal zone of the East Siberian and Chukchi seas increases. As this takes place concentrations exceeding 5% are registered along the continental slope and in the south-eastern part of the Laptev Sea and in the coastal zone of the East Siberian Sea. Pollutants from the source near the Kolyma river mouth are transported also along the continental slope to the east in the sub-bottom layer. They reach the sea surface in the Chukchi Sea to the north of Wrangel Island and near the north-east coast of Alaska. A pollutant concentration of 5% of the source is registered in this region, whereas on the surface of the northern part of the East Siberian Sea, along the transportation route of the pollutants, their concentration is less than 3%. A completely different situation occurs in the case where the pollutant spreads from a source located in the Mackenzie river mouth (Fig. 18.2d). The pollutants in this case essentially fill the region of the anticyclonic gyre, and only an insignificant part of them enters the Laptev Sea and Nordic seas. Pollutant concentrations exceeding 5% are observed in the surface layers in the anticyclonic gyre in the Canadian Basin.

In the second set of numerical experiments, pollutant with 100% concentration are released in the region of the wreck of the “Komsomolets” nuclear submarine in the sub-bottom layer at the depth 1700 m, in the bottle-neck of the White Sea, in the Faeroe-Shetland Channel and in the Bering Strait in the streams of the Atlantic and Pacific currents, respectively, at the depth 5 m. The pollutant-spreading from these sources after 15 years from the beginning of their activity is given in Fig. 18.3.

The pollutants from the “Komsomolets” wreck region crop out at the surface mainly in the area of the central part of the Barents Sea and the north-western part of the Kara Sea (Fig. 18.3a). Regions with concentrations higher than 5% are located near the north-western part of Norway. The pollutants from the source in the surface layer near the bottleneck of the White Sea (Fig. 18.3b) spread to the east along the coasts of the Barents and Kara seas and to the north along the western coast of Severnaya Zemlya.

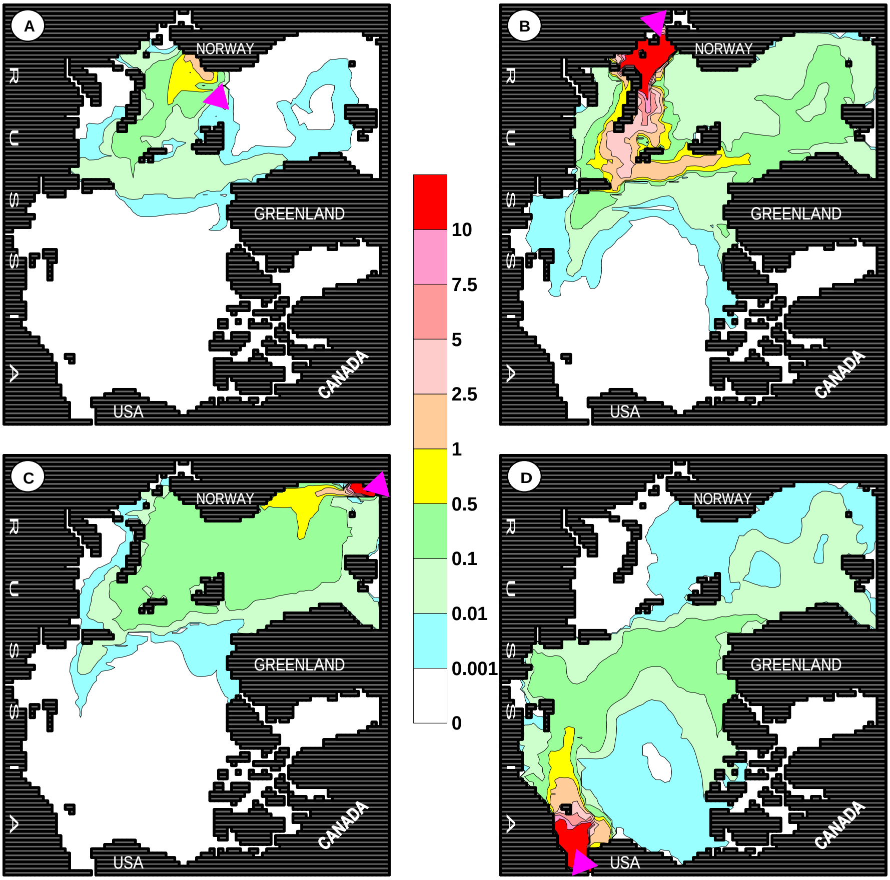

Fig. 18.3. The spread of a pollutant with ocean currents, 15 years after the beginning of a hypothetic pollutant release, from sources located in the following regions: A - the wreck of the “Komsomolets” nuclear submarine, B - the bottle-neck of the White Sea, C - the Faeroe-Shetland Channel in the stream of the Atlantic current and D - the Bering Strait. The scale shows % of pollutant in relation to its concentration at source. ▲ - source location.

Having entered the Transpolar Drift Stream in the northern part of the Kara Sea the pollutants subsequently reach the Greenland Sea. Pollutant concentrations exceeding 5% are registered in the eastern and south-eastern parts of the Barents Sea, in the Kara Sea and in the stream of the Transpolar Drift.

The pollutants from the possible source in the stream of the North Atlantic Current in the Faeroe-Shetland Channel (Fig. 18.3c) spread predominantly in the Norwegian and Barents seas and in the northern part of the Kara Sea. A region with concentrations higher than 5% in the surface layer is observed in the Norwegian Sea, in the western part of the Barents Sea and near the southern and western coasts of Spitsbergen.

The pollutants from the possible source in the Bering Strait (Fig. 18.3d) spread mainly to the west. The zone of possible contamination covers the Chukchi Sea, the northern part of the East Siberian Sea, the greater part of the Laptev Sea and the region of the Transpolar Drift Stream. Pollutant concentrations exceeding 5% are registered in the Chukchi Sea and in the north-eastern part of the East Siberian Sea. Concentrations of 10% and above are located in the Bering Strait and in the Chukchi Sea near the coasts of Alaska and Chukotka.

The numerical experiments performed revealed that the anticyclonic gyre zone in the Canadian Basin would be the least polluted area of the Arctic Ocean for the contamination sources located in the coastal zone of the Siberian shelf seas, the Barents and Norwegian seas.

There are some regions that would become contaminated in nearly all possible variants of location of the possible sources in the coastal zone of the Arctic seas. Among these are the Laptev Sea and the northern and eastern coasts of Greenland. This could explain measured increased concentration of the anthropogenic radionuclides in the Greenland coastal waters, for example a sharp increase in the concentration of ^{137}Cs near Danmarkshavn from 1986 (3.5 Bq m^{-3}) to 1989 (>8 Bq m^{-3}) (Dahlgaard 1995; Pavlov and Stanovoy 2001).

18.3.2 Sea ice transport from potential sources of contaminants

Here we continue the analysis of the simulation results described by Pavlov et al. (2004). In Pavlov et al. (2004), in order to estimate the drift route of the sea ice from the areas containing potential sources of pollution in the Arctic Ocean, trajectories of the ice drift were simulated. The following regions were chosen: in the Kara Sea–the regions of the Ob and Yenisei river mouths; in the Laptev Sea–the region of the Lena river mouth; in the East Siberian Sea–the region of the Kolyma river mouth; in the Chukchi Sea–the region near the Bering Strait; and in the Beaufort Sea–the mouth of the Mackenzie River. For these simulations reconstructed ice drift data for the period 1899-2000 were used. Trajectories were started for each month that the ice concentration at the starting position was more than 10%. Most of the trajectories were launched in the arctic winter time. In this work, based on trajectories simulated in Pavlov et al. (2004) from different potential sources in the Arctic Ocean, we analyse and discuss interannual variability of the travel time (TT) from all selected sources, and

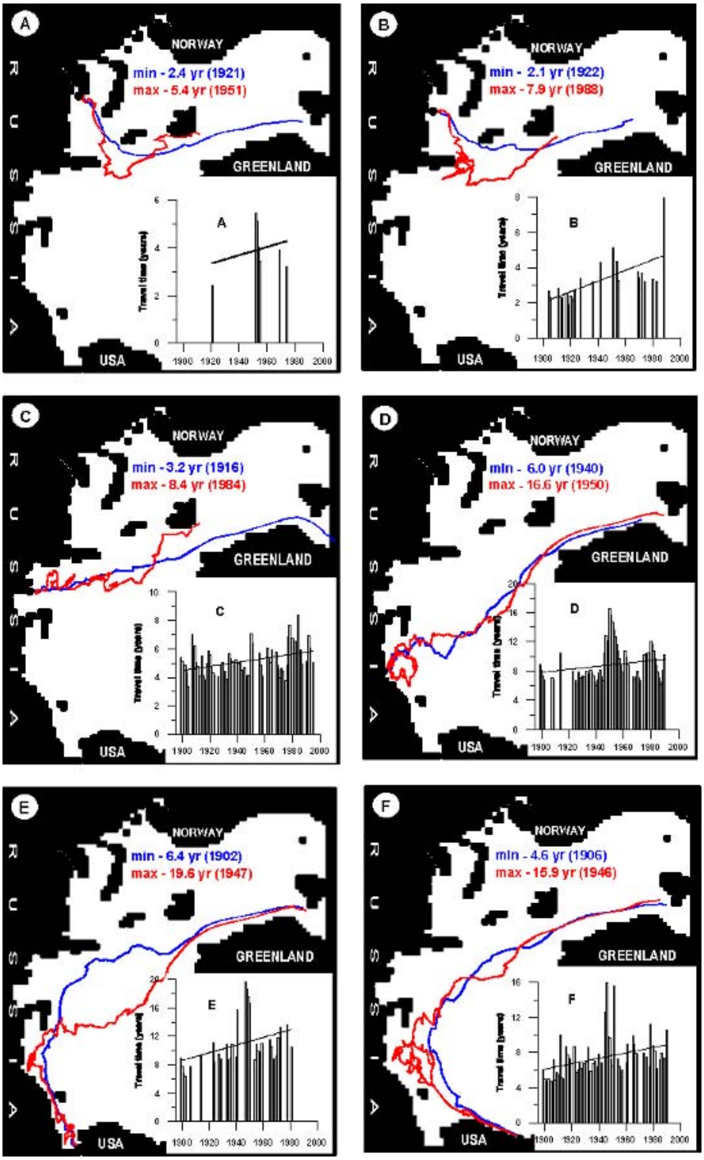

Fig. 18.4. Trajectories for sea ice drift with the minimum (blue) and maximum (red) travel time from selected potential sources to the Fram Strait region (80ºN). A-Ob River, B-Yenisei River, C-Lena River, D-Kolyma River, E-the Bering Strait and F-Mackenzie river. Bar diagrams show the travel time to the Fram Strait for sea ice starting in different years in the last century (1899-2000).

estimate the shortest and longest trajectories of ice drift.

Fig. 18.4 shows maps with trajectories and the travel time from selected potential sources to the Fram Strait (FS) for sea ice starting in different years in the last century (1899-2000). Trajectories with the minimum and maximum TT are also shown. For example, sea ice from the sites in the Kara Sea reaches the FS after 2-4 years (Fig. 18.4a, b). The probability of ice from the Ob Gulf region reaching the FS is only 0.7%. From the Yenisei Gulf region the probability is increased to 27%. The most probable route from these sites to the Barents Sea is through the strait between the islands of Novaya Zemlya and Franz Josef Land (Pavlov et al. 2004). Ice starting from the Ob Gulf in 1921 has the shortest TT to the FS. It drifts from the Ob Gulf to the north and around the northern coasts of Franz Josef Land and Svalbard to reach the FS in 2.4 years (Fig. 18.4a).

Ice starting in 1954 has the longest TT (5.4 years). The ice from this area drifts to the north-east, then west near the northern coast of Severnaya Zemlya, and then along the northern coast of Svalbard through the eastern part of the FS. A similar configuration of trajectories with the minimum and maximum TT was simulated for ice drifting from the Yenisei Gulf in 1922 (TT 2.1 years) and in 1988 (7.9 years). The trajectory starting in 1988 reached the north-western part of the Laptev Sea and the ice drifted for a long time near the northern coast of Severnaya Zemlya (Fig. 18.4b). The sea ice from the Laptev Sea (Fig. 18.4c) takes roughly 4-8 years to reach the FS and the probability of this happening is 71%. The trajectory with the shortest TT (3.2 years) started in 1916, when the ice drifted directly to the western part of the FS (Fig. 18.4c). The trajectory with the longest TT (8.4 years) started in 1984. This trajectory has the same general direction but a very complicated configuration, ending up in the eastern part of the FS (Fig. 18.4c). The longest TT is from the Kolyma river mouth (Fig. 18.4d) and the Bering Strait region (Fig. 18.4e).

The TT of the sea ice drift from the Kolyma River ranges form 7-17 years with a probability of reaching the FS of 71%. The ice drift trajectories with the shortest (6.0 years) and the longest (16.6 years) TT are both from the area of the Kolyma river delta. They both pass the North Pole and continue to the south and the western part of the FS. However the trajectory with the longest TT, starting in 1950, has a much more complicated configuration (loops at the shelf of the East Siberian Sea) than the trajectory with the shortest TT, starting in 1940. For ice starting from the Bering Strait, TT ranges between 5-19 years (Fig. 18.4e) and the probability of reaching the FS is decreased to 41%. The trajectory with the shortest TT (6.4 years) started in 1902. It runs along the coast of Siberia, through the De Long Strait and to the northern part of the Laptev Sea along the continental slope. From Severnaya Zemlya island the ice drifts west and southwest to the FS. The trajectory with the longest TT (19.6) started in 1947 and it has a more eastern position in the centre of the Polar Basin (Fig. 18.4e). Ice drifts a long time at the shelf zone of the Chukchi and East Siberian seas. From the site near the Mackenzie River (Fig. 18.4d) sea ice can reach the FS in 5-16 years with a probability of 68% of this happening. Trajectories with the shortest (4.6 yr) and longest (15.9 yr) TT have nearly the same position, but the configuration of the trajectory with the longest TT is much more complicated. Based on analysis of the patterns of the atmospheric circulation (not shown) we can conclude that the shortest TT of ice drift to the FS is connected with the extreme development of anticyclonic circulation above the Arctic Ocean. During the longest TT the atmospheric circulation is in an extreme cyclonic regime.

In the light of climate change in the Arctic it is interesting to consider the inter-annual variability of the TT of ice drift through the Arctic Ocean. We have obtained a generally positive trend (Fig. 18.4). The minimum TT was in the first two decades of the last century. In the last four decades the TT has increased. Maximum values of the TT were obtained at the end of the 1940s and mid 1950s, except for ice drifting from the Lena River where the maximum was at the end of the 1970s and beginning of the 1980s.

These calculated trajectories and TT estimations are in good agreement with the results of Pfirman et al. (1997; 2004a).

The studies of Pfirman et al. (1997) have indicated that drifting Arctic sea ice plays an important role in the redistribution of sediments and contaminants. It was also shown that forward and backward trajectories of sea ice can be calculated to identify regions influenced by sea ice from different source areas and reconstruct the drift path of individual ice floes with some confidence over a period of several years. Authors have demonstrated that ice from the Kara Sea has a strong influence on the Laptev Sea, Barents Sea, Svalbard, the southern portion of the Transpolar Drift Stream, and eastern FS. Ice from the Laptev Sea is mostly advected through the FS and to a lesser degree into the Barents Sea. Ice from the East Siberian Sea is either advected through the FS or is caught up in the Beaufort Gyre and is transported along the northern North American coast. Pfirman et al. (2004a) have analysed sea ice drift from 1979 to 1997 based again on fields of ice motion obtained from IABP. The analysis of potential trajectories of sea ice incorporated in the central Arctic pack between 1979 and 1997 showed extensive changes in the fate of sea ice exported from the Arctic shelves. TT of ice within the central Arctic Basin decreased by at least 1 year, at the same time that the fraction of ice with 4 year TT exported through the FS increased. Ice from distant sources that formerly recirculated in the Beaufort Gyre under lower NAO/AO conditions of the 1980s, was exported more directly through the FS in higher NAO/AO conditions of the 1990s. It was recognised that changes in trajectories of ice with different origins are important, because they affect advection and release of any transported material.

However, in contrast to the ISMO approach for simulation of sea ice trajectories, Pfirman et al. (1997; 2004a) have calculated trajectories based on historical drift data from IABP. Buoy positions have high spatial accuracy and temporal resolution. But the spatial distribution is generally rather coarse, so that buoy data provide only a highly restricted view of the temporal and spatial variability of the large-scale sea ice drift patterns. Buoy data provided by the IABP cover mostly the central part of Arctic Ocean, so in significant areas of the Siberian seas, where there are potential sources of pollution, the buoy data are absent.

18.4 Conclusions

The most rapid spreading of the pollutants and largest contaminated areas result from possible sources located near the Lena and Mackenzie river mouths.

There are two regions, the northern and eastern coastal zone of Greenland and the Laptev Sea, that are contaminated in nearly all variants of location of the possible sources in the coastal zone of the Arctic and Nordic seas.

The calculated trajectories of ice drift from areas of potential sources of pollution allow us to evaluate the character of pollutant transport and the areas of redistribution. From that we can conclude that sea ice from most potential sources of contaminant can reach the open Polar Basin and the FS. Contaminated sea ice from potential sources in the Kara and Laptev seas can reach FS within 2-4 years and from the East Siberian, Chukchi and Beaufort seas within 6-11 years.

Analysis of the inter-annual variability of sea ice TT from different sites to FS has shown a significant positive trend in the last century.

The results of the simulation can also give useful information for the selection of the most representative areas for monitoring contaminants in the Arctic Ocean. Based the structure of passive tracer spreading we obtained and our simulated trajectories of ice drift from different potential sources in the Arctic Ocean we conclude that the most important regions for monitoring of contaminants are FS and Laptev Sea.

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19 Long-term atmospheric contaminant monitoring for the elucidation of airborne transport processes into polar regions

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19.1 Introduction

Present levels of anthropogenic contaminants found in the polar environments cannot be explained by known use and/or release from sources within the region. Based on continuous monitoring and surveillance, atmospheric long-range transport from lower latitudes is known to be the most important source for the presence of many persistent organic (POP) and inorganic pollutants in the Arctic environment today. During the past decades, international long-term atmospheric monitoring programs have proven to be versatile tools for the demanding task of identification and evaluation of hazardous chemicals in the environment. Modern tools for atmospheric monitoring especially in background regions like the polar regions, are designed to:

- control and assess international regulatory measures
- determine “natural” background levels as well as the concentration thresholds when counter measures are required.
- collect information on environmental behaviour (spatial and temporal trends) and serve as “early warning tool”. Even minimal changes in levels and distributions may be a first signal for larger global changes expected at a later stage.

This concept has proven highly effective and useful. Many examples illustrate the importance of continuous atmospheric monitoring for surveillance of anthropogenic contamination in the cold polar regions.

The principles and pathways of global atmospheric long-range transport of persistent semi-volatile contaminants across several climate zones into the polar regions have been revealed and confirmed by long-term monitoring of persistent organic pollutants from the temperate zones of the globe into the polar atmosphere (Bindler *et al.* 2001, Macdonald *et al.* 2000, Macdonald *et al.* 2003, Wania 2003b).

The atmospheric burden of lead caused by emissions from fuel combustion increased continuously during the first 70 years of the 20th century, affecting even the Arctic regions (Bindler *et al.* 2001, Hopke *et al.* 2001, Riget *et al*. 2000, Rosman *et al.* 2000). International governmental agreements and regulations lead to considerable reduction of lead additives in standard fuels for vehicles worldwide (Riget *et al*. 2000). Subsequent monitoring of the lead distribution in the Arctic background air documented the continuous reduction of atmospheric lead globally (DeWit *et al*. 2004)

Polychlorinated biphenyls (PCB) have been used and applied as industrial chemicals and as oils in transformers as well as in capacitors. About 1 000 000 tons have been produced and applied since the 1940s. In the 1960s evidence for the presence of PCBs in the biological environment was presented. In the 1970s the presence of PCBs in the Arctic atmosphere was reported from Norwegian and Canadian research groups. The highly toxic effects of PCBs in the Arctic environment (e.g., on top predators and indigenous people of the arctic lead consequently to the international ban of these chemicals as industrial products in the 1980s. Modern monitoring programs are tracking this type of atmospheric contaminants and contribute to the evaluation of suitable regulatory measures and have shown that even more than a decade of continuous monitoring reveals no clear general trends are observed. In the European Arctic as well as Antarctica no decreasing tendency/ trend are observed for POPs in air. (Berg *et al.* 2004, Bignert *et al.* 1998, DeWit *et al.* 2004, Macdonald *et al.* 2000), whereas decreasing trends are reported for the Canadian Arctic (Hung *et al.* 2001, 2002).

The occurrence and detection of the stratospheric “ozone hole” in the Antarctic region is an additional example of the effectiveness of continuous pollution monitoring in the Antarctic. Only through long-term monitoring of high volatile chlorofluoro-carbons (CFC) and other related volatile chemicals, the devastating result of their depletion effects on the stratospheric ozone layer was made visible and adequate countermeasures on an international levels were conducted.

As a direct result of the above-mentioned international efforts on atmospheric contaminant monitoring, large monitoring programs covering also the polar background regions, have been established. A comprehensive “list of action” focusing on national and international initiatives directed towards elimination/ reduction of contaminant burdens in the environment is summarized in UNEP’s master list of actions (UNEP, 2000).

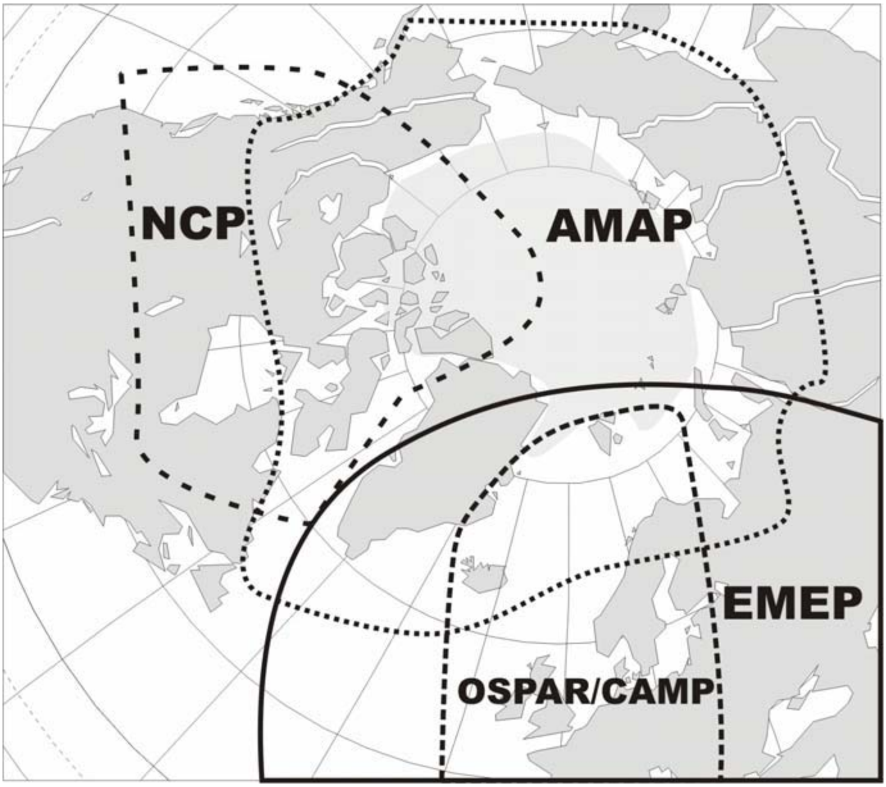

Fig. 19.1. Four major international and national long-term monitoring programs with specific interest in Arctic environments. Abbreviations are explained in Table 19.1. **) NCP is also performing atmospheric monitoring at two stations in the Russian Arctic (Amderma and Dunai)*

A selected number of international atmospheric monitoring programs with focus on Arctic and Alpine environments is shown in fig. 19.2.

All circum-Arctic countries as well as numerous southern nations with interest in the Antarctic, maintain national monitoring and scientific screening initiatives in order to control and survey levels and distribution of priority contaminants. Thus, during the past decades a wealth of scientific information on transport, levels, distribution and fate of priority contaminants was produced and reported to the respective authorities, institutions and stakeholders. However, the availability and transparency of validated monitoring information for scientific purposes represents often a major challenge for environmental sciences. The access to the majority of the collected data is often restricted due to national regulations or simply due to the fact that reports are not officially registered and, thus, not available in open accessible literature databases for environmental studies.

19.2 Contaminant monitoring today

One immediate result of the past decade with continuous comprehensive atmospheric monitoring of priority contaminants is that atmospheric contamination and atmospheric long-range transport is not just considered anymore as a local or a regional challenge restricted to developed industrialized regions and countries. All priority contaminants prone to atmospheric long-range transport must be considered as global problems regardless of their sources or transport routes.

A multinational program such as AMAP, has defined as its main goal: "providing reliable and sufficient information on the status of, and threats to, the Arctic environment, and providing scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions relating to contaminants" (www.amap.no). This statement can be seen as a general description for the overall goal of many other regional and international contaminant monitoring programs. National and international programs like NCP, AMAP, CAMP, EMEP etc. have achieved highly valuable results by highlighting and documenting distribution and fate of anthropogenic contamination. Through this type of surveillance, long-range transport of persistent pollutants and, thus, the global transport phenomenon of this type of chemicals has been revealed and brought into the political agenda. Persistent organochlorine pesticides (e.g, chlordane, toxaphene, DDT, HCH), highly important as crop protection agents in North America, Europe or developing countries in Africa and Asia, are transported as atmospheric burden throughout several climate zones into the Arctic regions with significant implications for the health and well being of the indigenous people of the North (Bidleman et al. 1993, Bridgman et al. 1994, Macdonald et al. 2000). Short-term monitoring programs performed in the Antarctic regions, revealed similar patterns for atmospheric long-range transport as already identified for the Northern hemisphere (Kallenborn 2000, Lakaschus et al. 2002).

The main antropogenic sources of heavy metals are various industrial sources, foundries and smelters. Relatively volatile heavy metals and those that become attached to airborne particles can be widely dispersed. Emission data indicate that reductions occurred from 1983 (Nriagu and Pacyna 1988) to the mid-1990s (Pacyna and Pacyna 2002) on a hemispheric scale.

Long term monitoring in the Arctic, however, have revealed no significant increasing or decreasing trends for many metals derived from antropogenic sources (Department of Indian Affairs and Northern Development 2003; Berg et al. 2004). Temporal trends with regard to increasing mercury levels in marine birds and mammals have been observed in some Arctic areas (Bignert *et al.* 2004a, Braune *et al.* 2001, Kim *et al.* 1996, Riget *et al.* 2000). There is also evidence that current mercury exposures pose a health risk to some people and animals in the Arctic. Cadmium levels in some seabirds are high enough to cause kidney damage (Chavez *et al.* 1991, DeWit et al. 2004, Holmes *et al.* 1996).

19.2.1 Restrictions and challenges

19.2.1.1 Data access

Several regional and international long-term monitoring programs are established nowadays focusing on global aspects of contaminant distribution and transport into polar regions (table 19.1). Except for monitoring of aerosols, ozone and CFC, practically no long-term atmospheric monitoring initiative have been established for Antarctica (with a monitoring period over 5 years).

In addition to regional and international initiatives, all circum-Arctic countries as well as a selection of southern nations with interest in the Antarctic, maintain national monitoring initiatives in order to control and survey levels and distribution of priority contaminants. Thus, during the past decades a wealth of scientific information on transport, levels, distribution and fate of priority contaminants was produced and reported to the respective authorities, institutions and stakeholders. However, the availability of validated monitoring information collected during long-term atmospheric monitoring is often restricted due to national regulations or simply due to the fact that reports are not officially registered and, thus, not available in open accessible literature databases. With these restrictions in mind, the Arctic Monitoring and Assessment program (AMAP) as well as the EMEP initiative have established joint data centers collecting and administrating all available data within the monitoring programs.

AMAP's assessments are based to a large extent on information and results from recent (largely unpublished) monitoring and research work (including atmospheric contaminant information). Data from such activities are compiled together with routine monitoring data within AMAP's thematic data centers. Data are made available from the data centers to scientists engaged in AMAP assessments under strict conditions that protect the rights of data originators. These conditions are described in AMAP's Data Policy documentation (see www.amap.no). AMAP Thematic Data Centres have been established to meet the following objectives:

- to provide access to data from recent monitoring and research activities conducted as part of the AMAP National Implemention Plans (NIPs);
- to provide a means to ensure that data are treated in a consistent manner, undergo uniform statistical analysis, etc., including application of objective quality assurance procedures;
- to begin the process of establishing a long-term archive of Arctic-relevant monitoring data, for use in future assessments of, e.g. temporal trends, etc.;
- to meet the terms of reference of Ministerial declarations, charging AMAP with establishing databases of sources, types, and levels of contamination of the atmospheric, aquatic and terrestrial environments of the Arctic and northern areas.

As already mentioned, similar data centers are established within the LRTAP-EMEP monitoring initiative with the potential for comprehensive co-operation and data transfer. However, no official communication/ efforts directed towards the ultimate goal to combine the data centers or allow inter-comparison for common monitoring parameters are established yet. In addition, no long-term atmospheric monitoring of persistent contaminants neither on a national or an international basis is established yet for pristine high-altitude, alpine environments.

19.2.1.2 Quality and comparability

Quality assurance issues are normally an integral component of most monitoring programs and research works. However, national and international monitoring programs (including atmospheric monitoring) have different demands with regard to data quality, priority criteria for contaminant selection, documentation, sampling frequency and methodology (AMAP 2000, Manø *et al.* 2003, Perkins 1995). These simple discrepancies often severely hamper the opportunity to compare monitoring data and perform scientific elucidations of temporal and spatial trends beyond the borders of the assigned region in an effective way. As an additional consequence, effective implementation and source elucidation by comparing the information collected within the arctic monitoring with monitoring information from possible source regions is severely restricted or even impossible due to the above-described differences.

As already stated, atmospheric long-range transport of anthropogenic contaminants is currenlty recognized as a global process with severe implications for ecosystems, wildlife and human populations of the northern regions (Brunstrom *et al.* 2000, Hansen 2000a, Hoekstra *et al.* 2003, Law *et al.* 2003, Muir *et al.* 1999a, Pereg *et al.* 2003, Ross *et al.* 2003, Skaare *et al.* 2002). Since the sources and possible solutions for this challenge are mostly located in the middle latitude temperate zones, the hitherto regionally restricted monitoring efforts of priority contaminants is not sufficient anymore to cope with the challenge of estimating global atmospheric transport and distribution processes. Joint strategies for and co-operation between regional and global atmospheric monitoring programs are necessary to raise the widely scattered scientific efforts on monitoring and surveillance of atmospheric contamination in the Polar Regions onto a global level with strong linkages between the national and international initiatives.

However, not just sampling and method differences restrict the comparability of monitored data. Local characteristic meteorological and climate conditions as well as varying content of particulate materials (including snow formation) might lead to significant differences in the capacity of air masses to adsorb and transport specific contaminant burdens (Daly *et al.* 2004b, Graham 2003, Guo *et al.* 2004, Mandrioli *et al.* 1984, Moore *et al.* 2003, Pacyna 1995, Prospero 1999, Wania 2003a, Zhuang *et al.* 2001). These differences restrict severely the comparability of datasets collected under different meteorological conditions. Based on these conclusions, the Canadian meteorological services have developed a statistical time-series tool (digital filtration = DF) in order to normalize monitoring data based on statistical trend analysis. DF is developed as a statistical trend and seasonal cycle development tool based on time-series development theories (Nakazawa *et al.* 1997). DF will definitively develop into a very useful tool for large-scale data analysis in atmospheric monitoring and consequently allow a better comparison of otherwise different datasets (Hung *et al.* 2002).

Thus, a strong and high priority commitment for co-operation between long-term monitoring programs in order to develop general guidelines in terms of sampling techniques, quality control measures, monitoring parameters (priority contaminants, sampling frequency etc.) is overdue in order to allow investigating and evaluating global aspects of atmospheric contaminant distribution. In order to allow better data comparison across the regional borders, annual laboratory intercomparison excercises should be established.

The official lists of target compounds for the four most important international monitoring initiatives with interest in Arctic environments are

Table 19.1. Main parameters covered by the four major international atmospheric monitoring programs with specific interest in Arctic environments.

Acronym	**Name**	**Sample types**	**Chemical parameters**
LRTAP-EMEP	European Monitoring and Evaluation Program	Precipitation, particles/ aerosol, gaseous phase	Gaseous phase: Particles/aerosols: SO_4^{2-}, Cd, Pb, Cu, Zn, As, Cr, Ni Gaseous + particulate phase: SO_2, NO_2, O_3, VOC (C_2-C_7), Carbonyl-compounds, Hg, HNO_3+ NO_3^- , NH_3+NH_4^+, PAH, PCB, HCB, chlordane, γ–, α-HCH, DDT, DDE Precipitation : SO_4^{2-}, NO_3^-, Cl^-, pH, NH_4^+, Na, Mg, Ca, Hg, Cd, Pb, Cu, Zn, As, Cr, Ni, PAH, PCB, HCB, α–, γ–HCH, DDT, DDE.
AMAP	Arctic Monitoring and Assessment Program	Precipitation, aerosol, gaseous phase	Gaseous + particulate: PAH, PCB, HCB, mirex, toxaphene, aldrin, dieldrin, α–, β–, γ–HCH, DDT, DDD, DDE, chlordanes, TBT, endosulfan, Hg, Pb, Cd, As, Sn, Zn, Cu, Ni, Cr, Precipitation: PAH, PCB, HCB, mirex, toxaphene, aldrin, dieldrin, α–, β– and γ–HCH, DDT, DDD, DDE, chlordanes, TBT, endosulfan, Hg, Pb, Cd, As, Sn, Zn, Cu, Ni, Cr,
OSPAR / CAMP	Comprehensive Atmospheric Monitoring Program	Precipitation, aerosol, gaseous phase	Precipitation: Cd, Hg, NO_3, NH_4^+ optional: As, Cr, Cu, Ni, Pb, Zn, organo-halogens. Aerosol + gaseous phase: Cd, Hg, α-HCH, γ-HCH, HNO_3, NO_3^-, NO_2, NO, NH_3, NH_4^+ Optional: As, Cr, Cu, Ni, Pb, Zn.
WMO-GAW	Global Atmospheric Watch	Gaseous phase	CO_2, O_3, CH_4, N_2O, CFCs, NO_2, H_2O, CH_3CCl_3, $^{14}CO_2$, SO_2

listed in table 19.1. The below presented overview demonstrates clearly the strong potential for joint and harmonised monitoring strategies.

Atmospheric monitoring programmes usually monitor contaminants in ambient air (gaseous and particulate phase) as well as in precipitation (incl. meteorological data). LRTAP-EMEP, OSPAR/CAMP and AMAP report on gaseous and particulate compartments whereas WMO-GAW concentrate on the gaseous phase only. A comprehensive list of target contaminants is presented. Many programmes are concentrating on inorganic pollutants like “greenhouse gases” (incl. NO_x, NH_4^+ etc.) and a variety of trace metals. However, as substantial contaminants chloro-fluoro carbons (CFC) and related compounds are usually included. Only AMAP and LRTAP-EMEP have included a substantial monitoring programme for a suit of priority persistent organic pollutants. However, also OSPAR/CAMP included a few (two) organochlorine pesticide compounds in the monitoring program, whereas WMO/GAW only focuses on greenhouse gases incl. methane, carbon dioxide, CFC etc.

Generally about 60% of the priority target chemicals are included in all major monitoring programmes and, thus, a basis for mutual interest in data exchange and joint quality criteria for analytical procedures and reporting is obvious. In the light of newly ratified international conventions and agreements (e.g., EU- Water frame work directive, Stockholm POP convention, etc.) a close co-operation between modern contaminant monitoring programs is also important from a political point of view.

National and international regulation and control authorities have recognised the here-described urgent needs for harmonisation and cross-linking of international monitoring initiatives as an essential step towards globalisation of contaminant monitoring efforts (AMAP 1998, Prandle 1991) Therefore, the joint initiative of the European Commission and the European Space Agency: “Global Monitoring for Environment and Security (GMES)” has the ambition to develop a joint strategy for global atmospheric observations, which also includes Arctic atmospheric background monitoring. Thus, a cluster of several EU-projects has been established focusing on ozone (O_3) and greenhouse gasses as a first step to co-ordinate monitoring and surveillance initiatives (“Global Atmospheric Observations“, GMES-GATO-cluster: http://www.nilu.no/gmes-gato/). The GATO cluster enables the space agencies and atmospheric scientists working in this area to communicate effectively. Coordination of EC and nationally-funded research occurs within GATO through workshops, meetings and working papers.

LRTAP-EMEP has recognised the need for integration and compatibility of local and global initiatives (Tørseth and Hov, 2003, Tørseth, 2004). The program officials acknowledge the need for integration and communication between regional monitoring initiatives aiming at monitoring atmospheric chemical composition. LRTAP-EMEP, therefore, emphasises strong co-operation linkages between the regional monitoring initiatives listed in table 19.2.

The general need is, thus, to establish more formal monitoring requirements for those participating in these co-ordination efforts in order to improve the compliance between the programs. It is those important to ensure data comparability with respect to site location, representativity, network

Table 19.2. List of regional monitoring programmes on atmospheric chemical composition with already established communication linkages.

Regional monitoring Programmes
- European Monitoring and Evaluation Programme (LRTAP-EMEP)
- CLRTAP Working Group on Effects
- World Meteorological Organisation - Global Atmosphere Watch (WMO-GAW)
- Marine Conventions (OSPAR, HELCOM)
- Arctic Monitoring and Assessment Programme (AMAP)
- EC AQFD (EIONET)
- UNEP Global POPs network
- EANET

density, parameters to be requested, temporal resolution, method and future co-operation opportunities.

19.2.2 Interdisciplinary linkage and coordination

The produced monitoring information shows its full potential and value for the evaluation of regional and global distribution processes when combined with other scientific information. Only in combination with various related scientific information such as modelling tools and chemical evaluations, meteorological information and climate data will environmental scientists hopefully be able to unravel the still highly complex challenge of global atmospheric transport and distribution of anthropogenic pollution including pesticide chemicals from tropical regions into the polar climate zones.

19.2.2.1 Modelling

The use and availability of monitoring data for scenario assessments and/or monitoring purposes is one of the most important features of today's international atmospheric monitoring programs. However, advances in modelling have been enhanced by a growing database of physico-chemical properties as a function of temperature. Models of precipitation scavenging of contaminants from air have advanced our understanding of deposition processes (Dethloff *et al.* 2002, Felzer *et al.* 2000, Furevik *et al.* 2003, Groves *et al.* 2002, Holland 2003, Kattsov *et al.* 2000, Proshutinsky *et al.* 1999, Serreze *et al.* 2003, Serreze *et al.* 2000, Walsh *et al.* 2002). Modern multi-compartmental models contribute today significantly to the interdisciplinary efforts to investigate compound-specific atmospheric distribution and transport processes (Beyer *et al.* 2000, Breivik *et al.* 2003, Christensen *et al.* 2004a, Daly *et al.* 2004c, Hansen *et al.* 2004, Karcher *et* *al.* 2004, Ma *et al.* 2004, Mackay *et al.* 1995, Muir *et al.* 2004, Scheringer *et al.* 2004, Toose *et al.* 2004, Wania *et al.* 1996, Wania 1998, Wania *et al.* 1999b, Wania *et al.* 1999a, Wania *et al.* 2003). However, for calibration and evaluation of new models, empirically derived and quality controlled monitoring data are highly important. Therefore, continuous communication between scientists involved in maintaining atmospheric monitoring, and modellers is essential in order to provide relevant scientifically sound information needed for the development of transport and distribution models.

Already today, a large number of versatile models exist with the potential for joint scenario assessment. Under the LRTAP-EMEP umbrella, six lagrangian and Eulerian models exists already as assessment tools for global transport processes of POPs and trace metals, acid deposition, fate of photo-oxidants and particulate matter (Andersson-Skold *et al.* 1999, Andersson-Skold *et al.* 2001, Bartnicki 1994, Derwent 1993, Jonson *et al.* 1998, Jonson *et al.* 2001, Kahnert *et al.* 2004, Kangas *et al.* 2002, Kruger *et al.* 1997, Olendrzynski *et al.* 2000, Tuovinen *et al.* 2004).

However, as an important measure for optimisation, harmonisation and quality assurance, model inter-comparisons must be performed. In this context currently, model intercomparsions are on the way to elaborate harmonisation and combination of established models. The EMEP Meteorological Synthesising Center East (MSC/E) is evaluating a first comparison of 16 regional and global atmospheric transport model for POPs (Shatalov *et al.* 2003). Many other comparative initiatives are on the way to evaluate and combine model approaches in order to improve the today available tools for scenario and transport evaluations.

19.2.2.2 Compound specific evaluations

One example on interdisciplinary linkage is the Mercury Depletion Phenomenon (MDE's): The Arctic Council encouraged, expanded and accelerated the comprehensive research and recent knowledge on critical aspects of the mercury cycle and budget in the Arctic. Based on the recent state of knowledge, future monitoring initiatives on atmospheric mercury distribution should contribute to investigation of long-range transport, elucidation of mercury deposition mechanisms, as well as to the evaluation of processes leading to biological exposure and effects, and the influence of climate variability and change on these processes (Allengil *et al.* 1995, Bjerregaard *et al.* 2000, Gauthier *et al.* 1998, Landers *et al.* 1995, Macdonald *et al.* 1996, Riget *et al.* 2000). The current finding of photochemical degradation of elementary mercury during the Arctic and Antarctic sunrise gives raise to considerable concern, since degradation products are assumed to be bioavailable and toxic for polar ecosystems (Ariya *et al.* 2004, Asmund *et al.* 2000, Berg *et al.* 2003, Berg *et al.* 2001, Christensen *et al.* 2004b, Ebinghaus *et al.* 2002, Hansen 2000b, Lindberg *et al.* 2002, Lu *et al.* 2001, Poissant *et al.* 2002, Power *et al.* 2002, Schroeder 2002, Schroeder *et al.* 1998, Skov *et al.* 2004, Sommar *et al.* 2004; Sprovieri *et al.* 2002; Temme *et al.* 2003, Wagemann *et al.* 1998; Wängberg *et al.* 2003).

During the atmospheric mercury depletion events (MDE's) gaseous elemental mercury (GEM) disappears almost completely from the atmosphere (Fig. 19.2). During these episodes GEM is transformed to more reactive species of mercury, which have significantly higher deposition rates than GEM.

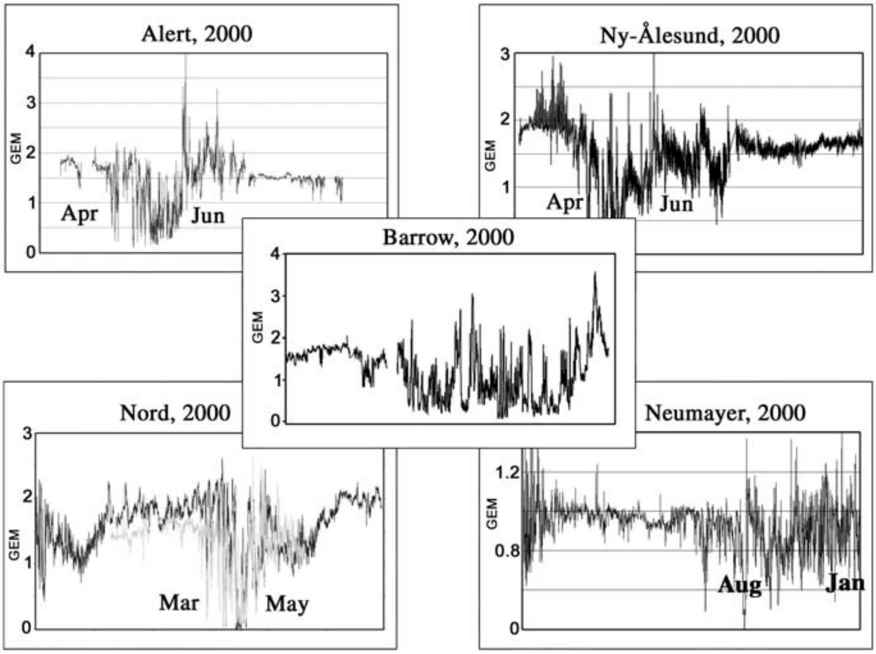

Fig. 19.2. "Polar Spring" mercury depletion events documented during mercury measurements campaigns in the year 2000 Atmospheric monitoring stations presented: Alert (Arctic Canada) (Schroeder *et al.* 1998), Point Barrow (Alaska) (Lindberg *et al.* 2002), Ny-Ålesund (Svalbard) (Berg *et al* 2003), North (Greenland) (Skov *et al.* 2004), Neumayer (German Antarctic station) (Ebinghaus *et al.* 2002) Concentrations are given in [ng/m^3].

19.2.2.3 Meteorology and source elucidation

Atmospheric long-range transport episodes can only be revealed and elucidated by combining unusual contamination patterns in atmospheric samples with meteorological air mass back trajectory calculations (Bailey *et al* 2000, Brankov *et al.* 1998, Eneroth *et al.* 2003, Gebhart *et al.* 2001, Hung *et al.* 2002, Kallenborn *et al.* 1998, Stohl 1996, Subhash *et al.* 1999, Traub *et al.* 2003, Vaughan *et al.* 2002). New scientific studies have also shown that the circulation pattern of air masses in the Arctic influences the long-term distribution trend of atmospheric contaminants (Rinke *et al.* 1999, Stone 1997, Stone *et al.* 2002, Zhao *et al.* 2004). These results implies that even a region with a constant emission could result in an oscillation contribution to the Arctic in a 4-14 years cycle, which may either weaken or amplify contributions of the changes in the anthropogenic emissions to the Arctic (CACAR 2003; Kahl *et al*. 1999).

Seasonally dependent distribution patterns have been found for POPs (Borga *et al.* 2004, Daly *et al.* 2004a, Dietz *et al.* 2004, Fellin *et al.* 1996, Halsall 2004, Hargrave *et al.* 1997, Hung *et al.* 2002, Pavlov *et al.* 2004), volatile organic contaminants (Blake *et al.* 2003, Gautrois *et al.* 2003) as well as for several heavy metals (Berg *et al.* 2004, Bignert *et al.* 2004b, Klungsoyr *et al.* 1995, MacDonald *et al.* 2000, Muir *et al.* 1999b, Muir *et al.* 1992, Riget *et al.* 2004, Thomas *et al.* 1992, Wagemann *et al.* 1996, Zheng *et al.* 2003) and arctic haze compounds (Heidam 1994, Hopke *et al.* 1995, Rasmussen *et al.* 1983, Weber *et al.* 2003) at Arctic monitoring sites. Highest levels of heavy metals were found in winter whereas the lowest concentrations were reported for the summer period. This situation is mainly due to the character of major weather systems: In winter and spring, a high pressure system over Siberia pushes the Arctic front far to the south, so that important polluted areas are within the Arctic air mass.

For some of the POPs, highest levels are found in summer and the lowest concentrations are reported for the winter period. As major reason for this typical distribution pattern, remobilisation from secondary sources (e.g., re-evaporation from open sea surface), which is considerable reduced during wintertime due to low temperature and ice-coverage, is identified (Berg et al. 2004)

19.3 Perspectives and future needs

The major challenge for future atmospheric monitoring of long-range transported contaminants is identified as the need for expansion from regionally restricted atmospheric monitoring towards global monitoring initiatives implementing locally, regionally and continent-related specific parameters. Two possible strategies are identified as promising scientific approaches for effective future global atmospheric monitoring of anthropogenic persistent contaminants with the aim to survey and study atmospheric long-range transport of anthropogenic contaminants into polar regions.

- International and national agreements concerning priority compounds, sample collection, methodology, quality control and data access will lead to global network of regional atmospheric monitoring programs with similar priority compounds and monitoring strategies. This approach will allow an easy comparability of monitored data. All data will be available for multidisciplinary studies and evaluations as well as for regulatory purposes.
- Within the frame of a global intergovernmental environmental organization, a global atmospheric monitoring program will be established or an already ongoing atmospheric monitoring program (e.g., GAW) will be expanded.

Reflecting on today’s situation in atmospheric monitoring of relevant persistent contaminants and other pollution, “strategy 1” seems to be the strategy of choice for international monitoring programs. National and international regulatory institutions recognised already a decade ago the importance for harmonisation and standardisation of monitoring initiatives (Oei *et al.* 1994). Thus, already in 1991, the Danish National Environmental Research institute (NERI), department for atmospheric research, launched an initiative on "Harmonisation within Atmospheric Dispersion Modeling for Regulatory Purposes". This initiative still serves as a national and international tool for increased cooperation and standardisation of atmospheric dispersion models for regulatory purposes (http://www.harmo.org/).

19.3.1 Quality control measures

The general need for harmonisation and quality assurance of the collected data within large monitoring and surveillance programmes is recognised by all major international environmental monitoring programmes (e.g., LRTAP-EMEP, AMAP and others). LRTAP-EMEP has recently documented needs and requirements for comprehensive international monitoring programmes (EMEP 2001). In order to meet the requirements of scientific based quality assurance (QA) and harmonisation between the stations, LRTAP-EMEP recommends (EMEP 1988):

- Appointment of a QA Manager in each of the participating units (countries, laboratories). These persons will be responsible for implementing harmonized quality assurance systems within the units, including documentation of standards and reference materials.
- Development of standardized operating procedures based on recognised QA recommendations (e.g., AMAP 1994, EMEP 2001).
- Co-location experiments and instrument comparisons in the various units to document precision and quantify internal network differences.
- Continuation of efforts towards site characterization.

Very comprehensive and up-to-date guidelines on the issues of harmonisation and quality assurance measures are also given in a recently published US-EPA report (US-EPA 2001). On the basis of this documentation, continuous discussions and co-operation on QA and harmonisation are necessary as an integrated part of future integrated atmospheric monitoring co-operations.

In addition, the Arctic Monitoring and Assessment Programme (AMAP) developed already in 1995 a collection of method performance criteria and quality control measures for Arctic environmental samples (AMAP 1994). The quality control criteria developed include recommendations considered having significant influence on the reliable determination of contaminants (particles, pollutants etc.). This includes both sampling and fieldwork. In this context, a tight cooperation between the all laboratories, researchers, modellers and regulatory authorities involved is needed and required.

19.4 Conclusions

The role of long-term atmospheric monitoring in Polar Regions as a versatile tool for the evaluation and assessment of compound specific distribution and transport processes, is today fully recognised by the international scientific community as well as by regulatory authorities. Important phenomena like polar springtime depletion of mercury, POP and trace metal atmospheric long-range transport, as well as “Arctic haze” have been studied in detail through circum Arctic atmospheric monitoring programs.

However, the today ongoing monitoring initiatives (including Arctic and Antarctic monitoring initiatives) are mostly regionally oriented and, thus, face considerable challenges in adapting and harmonising monitoring programs to the aspects of global transport processes.

The need for close co-operation between international atmospheric monitoring programs is recognised and will be a priority task for future monitoring initiatives. Topics like sample and method harmonisation, joint quality control criteria as well as continuous inter-comparison, will be issues to be discussed and implemented in co-operation programs between international and regional atmospheric monitoring initiatives.

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20 Levels and effects of persistent organic pollutants in arctic animals

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20.1 Introduction

Despite the fact that the Arctic is far from the industrialized world the presence of persistent organic pollutants (POPs) in arctic food webs shows that man-made substances are transported over long distances to these remote areas. Several international reports (AMAP 1998; 2004; EEA 2004) and reviews (Muir et al. 1999; Gabrielsen and Henriksen 2001; Fisk et al. 2003; de Wit et al. 2004) list and document threats to the Arctic ecosystem from long-range transported contaminants such as POPs.

POPs are a diverse group of anthropogenic pollutants that are of industrial and agricultural origin. POPs are rarely used in the Arctic, but they have been documented in arctic wildlife since the beginning of the 1970s. Substances such as polychlorinated biphenyls (PCBs) and chlorinated pesticides (e.g., dichlorodiphenyltrichloroethane (DDT), toxaphenes) were reported in arctic seals, polar bears *(Ursus maritimus)* and glaucous gulls *(Larus hyperboreus)* in the early 1970s (Bogan and Bourne 1972; Bourne and Bogan 1972; Holden 1972; Bowes and Jonkel 1975). Although low levels of POPs have been reported in terrestrial Arctic species, the problems are mainly related to marine organisms. While some POPs (e.g., DDT and PCBs) have decreased in levels during the last 10-20 years, following the introduction of bans and restrictions in use, new persistent pollutants are increasing in the environment due to the fact they are currently being produced in large quantities. Some of these new chemicals include chlorinated naphthalene (PCN), brominated flame retardants (BFRs) and perfluoro-octane sulfonate (PFOS) (AMAP 2004).

Most POPs found in the Arctic are transported from distant industrial and agricultural sources by atmospheric and oceanic currents, as well as river discharges (AMAP 2003). The most important transport route is atmospheric circulation bringing contaminants from the lower latitudes to the Arctic within days (Macdonald et al. 2000). The contaminants are deposited and taken up mainly in the lipid rich food chains of the arctic marine ecosystem (Muir et al. 1992; Borgå et al. 2001; 2004; Fisk et al. 2003). As a result of processes of bioaccumulation and biomagnification, POPs can reach very high concentrations in apex predators such as polar bears, arctic fox (*Alopex lagopus*) and glaucous gulls (Wang-Andersen et al. 1993; Gabrielsen et al. 1995; Bernhoft et al. 1997; de Wit et al. 2004).

The concern about POP levels and possible effects in arctic wildlife increased with the comprehensive surveys performed in the 1980s and 1990s (AMAP 1998; 2004). POPs are known to elicit a range of detrimental effects on biota. For POPs the effects are related to the enzyme-, immune-, hormone- and vitamin systems. Of great concern are contaminants that may have reproductive effects and those that can mimic and disrupt the hormone system (Colborn et al. 1993; Giesy et al. 2003). During the last 5-10 years, a number of field studies have been performed on polar bears and glaucous gulls from Bjørnøya and Svalbard in order to study the relationships between contaminant levels and effects. The levels documented in glaucous gulls and polar bears are high enough to raise concern about the effects on the health of these species.

The present article summarizes some recent studies on the levels and biological effects of POPs in arctic animals. A special emphasis has been put on effect studies on polar bears and glaucous gulls from Svalbard and Bjørnøya.

20.2 Persistent organic pollutants (POPs)

Environmental contaminants include both industrial chemicals, such as PCBs, hexachlorobenzene (HCB), chlorinated pesticides, such as DDT, chlordanes, hexachloro-cyclohexane (HCH), aldrin/dieldrin, polychlorinated boranes (Toxaphenes) and industrial byproducts such as polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs) (Muir et al. 1992). Most of these contaminants were developed and put into production more than 50 years ago. The highest production of most of these contaminants was at the end of the 1960s and the start of 1970s (Blus 1995). For some of the new contaminants (e.g., PBDEs) the use has increased drastically in the past decade. Most of the use is in industrial areas of the northern hemisphere that are potential source regions to the Arctic.

20.2.1 PCBs

PCBs are mixtures of chlorinated hydrocarbons that have been heavily used since 1930 for many industrial purposes such as dielectrics in transformers and large capacitors, heat exchange fluids, paint additives, in carbonless copy paper and plastics (Fisher 1999). At present, the major source of PCB exposure seems to be environmental recycling of PCBs from former usage. There are 209 possible PCBs (congeners), of which about 100 have been found in biological samples (McFarland and Clarke 1989). The properties of PCBs depend on the number of Cl-atoms and their position and include low water solubility, high stability, and semi-volatility, which favour long-range transport. Worldwide PCB production in 2000 was estimated at 1.3 million tonnes (Breivik et al. 2002).

20.2.2 DDTs

DDT and its metabolites (1,1-dichloro-2,2-bis ethane (DDD) and 1,1-dichloro-2,2-bis ethylene (DDE)) have been found in biota since the 1940s. After the war, DDT was used extensively as a pesticide on a variety of agricultural crops (i.e. cotton and peanuts) and to prevent the spread of diseases to humans by insects (e.g., malaria and typhus). The total global usage was estimated at 2.6 million tonnes up until 1992 (Voldner and Li 1995). DDT and related compounds are very persistent in the environment and their half-lives in soil range from 10 to 15 years. DDT has been declining in the temperate regions of the northern and hemisphere since the 1960s and especially since the mid-1970s when production and use were banned by many western nations (Mellanby 1992).

20.2.3 PBBs and PBDEs

PBBs, PBDEs and tetrabromobisphenol are the three main classes of brominated compounds used as flame retardant additives (Renner 2000). They are used at high volume in electric equipment such as computers, television sets, textiles (clothing), cars, airplanes and other applications (de Boer et al. 1998). Humans may absorb PBBs and PBDEs when they are emitted from electronic circuit boards and plastic computers and cabinets (Zelinski et al. 1993). PBBs and PBDEs show high lipophilicity, high resistance to degradation, and are expected to bioaccumulate effectively in the aquatic and terrestrial food chains. The annual usage of the flame retardants have drastically increased during the last few years. The annual world production in 1998 was estimated at 150 000 tonnes (Sellstrøm and Jansson 1995).

20.2.4 Perfluorinated alkyl substances (PFAS) and PFOS

In recent years environmental concern has arisen as PFAS have been reported in seabirds and marine mammals in the Arctic (Giesy and Kannan 2001; Smithwick et al. 2005; Verreault et al., submitted). The most pervasive PFAS reported in arctic biota has been PFOS (Kannan et al. 2001). PFOS is used as a refrigerant, surfactant, and as a component in pharmaceuticals, flame retardants, lubricant, paints, adhesives, cosmetics, paper coating, and insecticides. PFOS has been manufactured for over 50 years and has steadily increased its use. The annual US production was 3000 tonnes in 2000 (AMAP 2004).

20.2.5 PCN

PCNs exist as 75 congeners that are structurally similar to the PCBs and have many similar applications. These include electrical equipment, lubricants, solvents, dyes and sealants. They are also present as impurities in technical PCB and are formed during anthropogenic combustion processes. In the 1920s the worldwide annual production was approximately 9000 tonnes. One of the largest PCN producers voluntarily ceased production in the late 1970s. At the present, information about the world production is limited. Although the use of PCNs has declined over the past few decades, they are not prohibited in most countries and are still being used in many PCB-like applications (AMAP 2004).

20.3 Levels of POPs in marine food chains

The arctic environment is among the least polluted ecosystems in the world. The POP levels are low in most lower trophic level marine species from the Barents Sea area compared to the Baltic and the North Sea. The POP levels at lower trophic levels in the Barents Sea, are very similar to what is found in Alaska and Canada. High POP levels and possible biological effects are mainly associated with species at the top of the food webs (AMAP 1998, 2004). However, few studies to date have examined the potential effects of various POPs on the lower trophic level of the polar ecosystems.

There are large differences in POPs levels in Arctic animals. These differences may be attributed to several factors such as exposure, ability to metabolize contaminants, ability to excrete compounds, seasonal variation in body mass, age and sex (Bignert et al. 1993; Henriksen et al. 1996). For example, the sex difference in POP levels often seen in birds partly reflects the fact that female birds are able to deposit lipophilic compounds into the egg. In polar bears and other marine mammals, considerable amounts of POPs are also transferred to the foetus and via milk from the mother to the cub. This is one of the main reasons for lower levels of some POPs in sexually mature female polar bears than in males (Bernhoft et al. 1997).

Several detailed studies of the Arctic marine food webs and POP accumulation were carried out in the 1990s in different Arctic regions (e.g. Borgå et al. 2001; Fisk et al. 2001; Muir and Strachan 2003; Hoekstra et al. 2003). These are summarized along with factors of importance for POP flux and food webs in Borgå et al. (2004).

20.4 Marine invertebrates

Marine invertebrates provide the trophic link from phytoplankton to fish, seabirds and marine mammals in the arctic marine food web. These species do not only carry nutrients and energy, but also POPs. In general, marine invertebrates have low POP levels. In most marine species investigated at lower trophic levels in the Barents Sea area (Borgå et al. 2001; 2002 a-c), the POP levels are low compared to species at lower trophic levels from the sub-arctic and temperate areas (0.01-0.2 µg/g, lipid weight concentrations) (Borgå et al. 2001). In a comparison of the marine food web of the Barents Sea and the Canadian Arctic (Northwater Polynya), POP levels were relatively similar in copepods (*Calanus* spp.), euphausiids (*Thysanoessa* spp.), amphipods (*Themisto libellula*) and polar cod (*Boreogadus saida)* (Borgå et al. 2005a). This in contrast to what is found in higher trophic levels, where these POP levels are higher in the Barents Sea than in the Canadian and Alaskan marine food webs (Norstrom et al. 1998; Muir et al. 2000a; Borgå et al. 2005a). In the same species only hexachloro-cyclohexane (HCH) were higher in the Canadian Arctic marine food web than in the Barents Sea food web due to the proximity to point sources in eastern Asia. In all fish species from the Barents Sea the POP levels are lower than the levels found in the North- and Baltic Seas

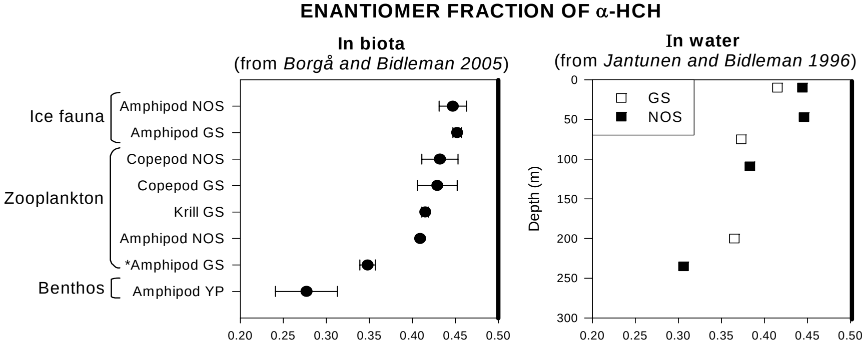

Fig. 20.1. Enantiomer fractions of α-HCH (mean ± 95 % confidence interval) in invertebrates and water from the Greenland Sea (GS), north of Svalbard (NOS and the Yermak Plateu (YP). * refers to predominantely pelagic amphipods that were collected with a bottom trawl. For details see Jantunen and Bidleman 1996 for water data, and Borgå and Bidleman 2005 for invertebrate data.

(AMAP 2004).

Despite low levels in invertebrates, they differ in POP levels according to diet, size and habitat (Borgå et al. 2002 a-c; Fisk et al. 2003). This has recently also been seen for chiral chlorinated pesticides in ice fauna, zooplankton and benthos (Borgå and Bidleman 2005) (Fig. 20.1), as well as in invertebrates from the Great Lakes (Wong et al. 2004). In addition, ice fauna differ in levels for some POPs reflecting the sea ice drift route across the Arctic Ocean (Borgå et al. 2002b; Borgå and Bidleman 2005).

Analysis of brominated flame retardant in polar cod has shown low levels compared to fish from other areas. Liver concentrations of PBDEs in herring (*Clupa harengus*) and cod (*Gadus morua*) were 15-60 times higher, respectively than the levels found in polar cod from Svalbard (Wolkers et al. 2004).

20.5 Seabirds

Seabird species living in the Arctic are contaminated by the same POPs as seabirds living in the south although their levels and proportions may occasionally differ to a certain extent (AMAP 1998; 2004). The POP levels in seabirds are mainly determined by their feeding habits and ability to biotransform contaminants (Borgå et al. 2005a). Common eider (*Somateria mollissima*), which feed on benthic organisms, and little auk (*Alle alle*), which mainly feed on copepods, have low POP levels (0.5-1.0 µg/g) (Savinova et al. 1995). However, in fish-eating species such as black-legged kittiwakes (*Rissa tridactyla*), common and Brünnich's guillemots (*Uria aalge* and *Uria lomvia*) and puffins (*Fratercula arctica*), the POP levels are somewhat higher (1.0-5.0 µg/g). The highest POP levels (1.0 to 40 µg/g) are found in herring gull (*Larus argentatus*), glaucous gull, great black-backed gull (*Larus marinus*) and the great skua (*Stercorarius skua*) (Savinova, Skaare and Gabrielsen, unpublished). The POP levels in gull species are 5-10 times higher than the other seabird species in the same area. In seabirds, PCBs comprise the majority of POP in all species, followed by DDT, chlordanes, HCB and HCHs (Savinova et al. 1995; Borgå et al. 2001). The high POP levels in herring gull, glaucous gull, great black-backed gull reflect their position on the top of the arctic food web. The levels of POP in different seabird species may also be explained by their migration pattern during the winter. Guillemots from low arctic colonies in Canada have shown higher PCB and HCB levels than guillemots from high arctic colonies (Braune and Donaldson 2000). Most seabird species from Svalbard, which migrate south to the North- or Norwegian Seas during the winter, have higher POP levels than seabirds that live in the Arctic throughout the winter (Borgå et al. 2005a; Savinova, Skaare and Gabrielsen, unpublished). A comparison of POP levels in 5 species of seabirds (black-legged kittiwakes, little auk, black guillemot (*Cepphus grylle*), common guillemot and glaucous gull), between the Barents Sea and the Canadian Arctic, show higher contaminant levels in species from the European Arctic (Barents Sea) (Borgå et al. 2005a).

Analysis of brominated flame retardants (e.g. PBDEs, hexabromocyclododecane (HBCD), PBBs), PFOS and PCN in seabirds have shown concentration in, e.g. glaucous gulls from Bjørnøya that were among the highest reported in any arctic seabirds, although generally lower, occasionally by many fold, compared to species from lower latitudes (Verreault et al. 2005a, 2005b). PFOS levels in glaucous gull plasma were comparable to levels of legacy POPs such as DDTs (Verreault et al., submitted).

20.5.1 Glaucous gulls

The glaucous gull has a circumpolar distribution in the Arctic. It is one of the largest gulls breeding in the Arctic and the only numerous avian predator in Svalbard, Frans Josef Land and Novaya Zemlya (Bakken and Tertitski 2000). The glaucous gulls breeding in the Barents Sea area do not migrate long distances. They winter mainly in the northern part of the Atlantic Ocean and remain there from November to March (Yudin and Firsova 1988). In Svalbard, the glaucous gull is both a predator and a scavenger (Løvenskiold 1964). On Bjørnøya, its diet consists mainly of eggs, chicks, adult birds, and crabs *(Hyas araneus*), as well as offal from fishing boats (Bakken and Tertitski 2000).

PCBs and DDT are the most common POP measured in Glaucous gulls. PCBs and DDT constitutes on average 72 and 22 %, respectively, of the total pollution load measured in plasma (Verreault et al. 2005a). This is mainly due to the efficient bioaccumulation potential of PCBs and DDT and the ability of glaucous gulls to metabolize other POPs, although lower levels relative to marine mammals such as polar bear.

On Bjørnøya the sum PCB concentration in brain tissue of glaucous gulls found dead vary from 1 to 30 µg/g (wet weight (ww)), while healthy individuals vary from 0.5 to 10 µg/g (ww). In other tissue (muscle, liver and fat) the sum PCB varies from 0.5 to 23 µg/g (ww) (Gabrielsen et al. 1995; Sagerup et al. 2000). In blood from healthy glaucous gulls of normal body condition from Bjørnøya, the sum PCB were 0.6 µg/g (ww) in male gulls and 0.3 µg/g (ww) in female gulls (Bustnes et al. 2001; 2003; Verreault et al. 2004). At Bjørnøya, the POP levels vary within the population. Bustnes et al. (2001) studied two colonies, a few kilometers from each other, and found a large variation in POP concentration. Birds, which nested on the cliffs, had higher POP concentration than birds that nested at sea-level. While the birds on the cliffs were eating seabird eggs and chicks, the birds at sea-level fed more on fish, and thus were feeding at a lower trophic level. The concentration of sum PCB and sum DDT in glaucous gull were higher in the Barents Sea and Jan Mayen area than in Baffin Bay. The highest concentration was found around Frans Josef Land (Savinova, Skaare and Gabrielsen, unpublished data).

In glaucous gulls from Bjørnøya the levels of PCN ranged from 1.3 to 126 ng/g (lipid weight (lw)) in plasma and 1.8 to 162 ng/g (lw) in eggs (Verreault et al. 2005a). Of the PCB metabolites the hexa-chlorinated methylsulfonyl ($MeSO_2$)-PCB congener (range 13.5-551 ng/g (lw) was found in the plasma whereas the penta-chlorinated congeners 3’- and 4’-$MeSO_2$-CB101 (range 4.5-38.1 ng/g (lw)) dominated in the eggs from glaucous gulls (Verreault et al. 2005a). Of the PBDEs the plasma levels in glaucous gulls varied between 8.2 and 67.5 ng/g (ww) (Verreault et al. 2005b). The levels of PBDEs were 10 times lower than the concentration of sum PCB (sum 47 congeners). Of the brominated compounds that have been reported as naturally-occurring in the marine environment and/or metabolites of PBDEs, the methoxylated (MeO) and hydroxylated (OH)- PBDEs were found in plasma of glaucous gulls (Verreault et al. 2005b). The level of perfluorooctane sulfonate (PFOS) in plasma (48.1-349 ng/g (ww)) was the most pervasive perfuorinated alkyl substance (PFAS) found in glaucous gulls. The levels of PFOS in glaucous gulls are also the highest reported in any arctic seabird (Verreault et al., submitted).

20.6 Arctic fox

The arctic fox is an opportunistic feeder, which eats cached food, scavenged carcasses of seabirds, terrestrial birds, seals, Svalbard reindeer and Svalbard ptarmigans (Fuglei 2000). Some arctic foxes follow polar bears on the sea ice, feeding on remnants of seals killed by polar bears (Hiruki and Stirling 1989). The levels of PCBs in arctic fox show a great variation (1.0-45 µg/g), which probably reflects what they feed on (Wang-Andersen et al. 1993; Severinsen and Skaare 1997). Foxes sampled on the coast, which are feeding on marine species, have higher POP levels than foxes living inland, which feed on reindeer carcasses and terrestrial birds. Foxes in Canada, inland Iceland, and Alaska have lower POP levels than foxes along the coast of Iceland and on Svalbard (AMAP 2004). The reason for this may be that foxes from the coast of Iceland and Svalbard eat more marine species than foxes in Europe and in Canada.

20.7 Seals

The POP levels in different seal species from the Barents Sea area are low (10-50 times lower) when compared to seal species from the North Sea and the Baltic Sea. The PCB levels in ringed seal (*Phoca hispida*), harp seal (*Phoca groenlandica*), bearded seal (*Erignathus barbatus*) and Atlantic walrus (*Odobenus rosmarus*) are found at concentrations averaging 1.0-5.0 µg/g (ww) (AMAP 1998; 2004). The PCB levels in blubber of harp seals from the East Ice (Russian area) were three times higher (3.0 µg/g) (ww) than the levels in West ice (Greenland area) (Espeland et al. 1997; Kleivane et al. 1997). However, this comparison is confounded by a significant difference in blubber thickness between the two areas (less blubber in the East Ice seals), which could have increased the pollution levels in seals from the east. A geographical study of PCBs and DDTs in ringed seal blubber has shown higher levels - in samples from the Yenisey Gulf in the Russian Arctic, Svalbard and eastern Greenland compared to western Greenland and the Canadian Arctic (Muir et al. 2000). The ringed seal from Svalbard has PCB levels four times higher than seals from the western Canadian Arctic and Alaska (Wolkers et al. 1998; Muir et al. 2000). The highest levels of toxaphene, a chlorinated pesticide, have been found in harp seal collected east of Svalbard. The levels of toxaphene (Tox 26 and Tox 50) were 20 times higher than in ringed seal samples west of Svalbard (Wolkers et al. 1998; Wolkers et al. 2000).

In ringed seal, the levels of PBDEs were 10-20 times higher than Canadian seals. However, the levels were substantially lower than in seals from more southern latitudes (Wolkers et al. 2004).

20.8 Whales

The levels of POPs in different whale species also reflect their feeding habits. Beluga (*Delphinapterus leucas*), narwhal (*Mondon monoceros*) and harbour porpoise (*Phocoena phocoena*), which feed mainly on fish, have higher POP levels (5-6 µg/g) (ww) in their blubber than minke whales (*Balaenoptera acutorostrata*) (2-4 µg/g) (ww), which feed on krill and amphipods. Levels of POPs increase with age and there are large differences between males (highest level) and females. There are also geographical differences in the POP levels in whales. PCBs and DDTs increase from the west to the east in minke whales (Hobbs et al. 2002). In minke whales, the levels of POPs are also higher on the coast of Lofoten Island in northern Norway compared to the Svalbard and the Kola areas (Kleivane and Skaare 1998). In beluga whales most POPs are lower in southern Alaska than in eastern Canada and Svalbard (Wolkers 2002). The levels in recent measurements from the northeast Atlantic are 2-3 times lower than those made in the 1990s. This may be explained in part by changes in feeding habits to almost exclusively krill after the collapse of the capelin (*Mallotus villosus*) stocks in 1986 (AMAP 2004). Geographical differences in POP levels can also be explained by differences in migration pattern.

In killer whales (*Orcinus orca*) from Lofoten, which feed on herring, the highest PCB and DEE levels have been found of all whale species studied so far (Wolkers, pers. com.). The PCB levels were comparable to the levels found in polar bears from Svalbard.

Levels of PBDEs in beluga whales from Svalbard were 10-20 times lower than beluga whales from Canada. In addition, the levels in beluga whales were lower than in whales from more southern latitudes (Wolkers et al. 2004). The reason for higher levels in seals and whales in the European Arctic compared to the Canadian Arctic is probably due to a more effective PBDE transport from lower latitudes to the European Arctic.

Very high PCB levels (20-30 µg/g) (ww) have been found in harbour porpoise blubber samples from northern Norway. The levels of PCBs and DDTs are comparable to the Baltic Sea and North Sea and are the highest measured in any whale species from the Arctic (Berggren et al. 1999). The levels in harbour porpoises from Greenland are much lower. The reason for the high PCB levels in harbour porpoise from northern Norway is not fully understood. The levels of PCBs in pilot whales (*Globicephala melas*) from Faeroe Islands are higher than most other whales. Levels of other POPs are also comparably high (Dam and Bloch 2000). For example, the levels of brominated compounds in pilot whales are an order of magnitude higher than in other arctic marine mammals examined to date (van Bavel et al. 2001). Narwhal from west Greenland and the Canadian Arctic have similar POP levels. The levels in narwhal from Svalbard were considerably higher (Wolkers 2002).

20.9 Polar bears

Polar bears are widely distributed throughout the Arctic. They move south with the ice in the autumn and winter and then north as the pack ice melts in the spring and summer. Their primary prey are ringed seal and bearded seal (Stirling et al. 1982). Kleivane et al. (2000) also showed that polar bears from eastern Svalbard feed upon harp seals. Polar bears eat almost exclusively the blubber of seals. Polar bears have a very good capacity for oxidative biotransformation (e.g. via cytochrome P450 (CYP) 1A enzymes) of most POPs, as evidenced by high levels of PCB metabolites (i.e. OH-PCBs and $MeSO_2$–PCBs) found in plasma and tissues (Letcher et al. 1996; Sandau et al. 2000; Sandala et al. 2004; Verreault et al. 2005c).

Two studies (Andersen et al. 2001; Lie et al. 2003) investigating PCB and pesticide concentrations in polar bears from Svalbard, Frans Josef Land, Kara Sea, East Siberian Sea and Chukchi Sea (samples collected between 1987 and 1995) combined with earlier findings (Bernhoft et al. 1997; Norstrom et al. 1998) indicated that polar bears from Frans Josef Land and the Kara Sea have the highest sum PCB, sum chlordane and sum DDT levels among arctic animals. A decreasing trend was seen both east and west of these regions. At Svalbard, 35 mother/cub pairs were sampled between 1995 and 1998 (Lie et al. 2000) and the sum PCB geometric mean concentrations in plasma were 12 300 ng/g (lw) in cubs, 5820 ng/g (1w) in females with cubs, 6820 ng/g (1w) in yearlings, and 2945 ng/g (1w) in females with yearlings. In cubs, the sum PCB concentrations were significantly higher than in the other three groups. The reason for a higher sum PCB concentration in cubs was due to lactational transfer from their mothers.

In a recent circumpolar study (1996-2002) of polar bears from Alaska, Canada, Greenland and Svalbard the PCB and DDT levels were highest in the East Greenland and the Svalbard population (Fig. 20.2). In this study the levels of PCB and DDE levels were 6 and 3 times higher, respectively, in polar bears from east Greenland and Svalbard when compared to polar bears from Alaska and Canada (Verreault et al. 2005c). In polar bears from Svalbard the levels of PCNs ranged from 1.2 to 52 ng/g (lw) in fat samples. Compared to other marine species (e.g. the beluga whale, 0.04-0.4 ng/g (lw)) the PCN concentration is much higher (Gabrielsen et al. 2004). Of the PCB metabolites, a sum $MeSO_2$-PCB (ranging between 162 to 279 ng/g (lw)) was found in the fat samples of polar bears (Verreault et al. 2005c). The concentration of sum OH-PCB in Svalbard polar bear plasma from females ranged between 4.15 and 394 ng/g (ww) (Verreault et al. 2005b)(data for East Greenland polar bears see Sandala et al. 2004). PCB-metabolites are transferred from the polar bear females to the cubs via milk, resulting in concentrations that are approximately three times higher in the cubs than in the mother. While polar bears in the European Arctic usually have the highest levels of contaminants, the levels of PBDEs are low compared to Alaska, Canada and Greenland (Muir et al., in prep.).

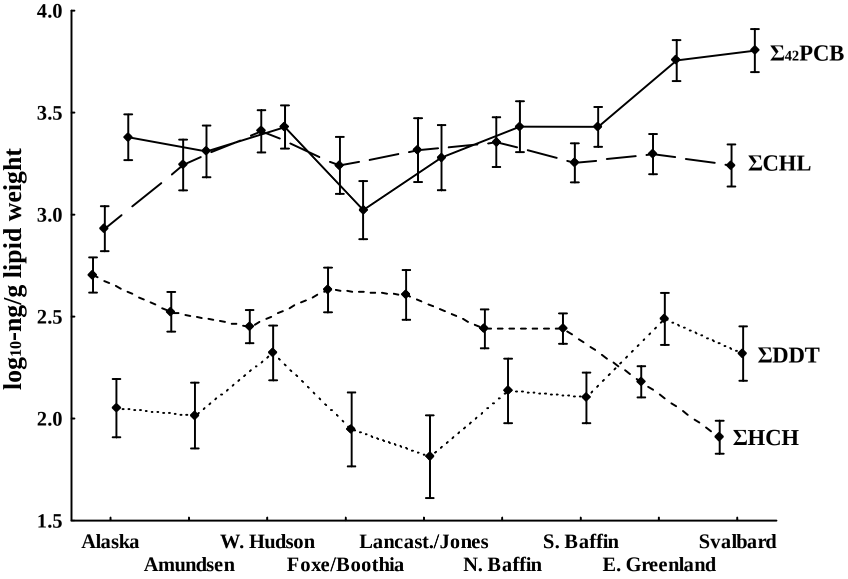

Fig. 20.2. Age-adjusted mean Σ (chlordanes) CHL, ΣHCH, ΣDDT, and Σ_{42}PCB concentrations ($\log_{10}$- transformed ng g^{-1} lipid weight) plotted with 95% confidence intervals (vertical bars) in adipose tissue of female polar bears from nine Arctic and Subarctic populations listed in order of longitude (Verreault et al. 2005c).

PBDEs in polar bear from Svalbard varied between 2.7 and 9.7 ng/g (ww). Of the brominated metabolites both the MeO and OH PBDEs (partly natural components in the marine environment, e.g. found in algae and sponges) were found in plasma of polar bears (Verreault et al. 2005b). Because the PBDE congener profile in the polar bear is comprised almost uniquely of PBDE 47, this may indicate that the polar bears have an effective metabolism of most PBDEs. The levels of PFOS (range 56.7 to 150 ng/g (ww)) were the most pervasive PFASs found in plasma from polar bears (Gabrielsen et al. 2004). In a geographical trend study, the PFOS concentration in liver samples of polar bears from south Hudson Bay and east Greenland were significant higher than in polar bears from Svalbard, high Arctic and the western Northwest Territories (Canada). The high concentration in polar bears from south Hudson Bay and east Greenland was suggested to be due to the proximity to sources in Europe and eastern North America (Smithwich et al. 2005).

20.10 Temporal trends in POPs in arctic seabirds and marine mammals

In general, the levels of most POPs- (i.e. PCB, DDT and HCB), which have been taken out of production and use in the 1970s and 1980s, show a decline. However, the decline has occurred with varying rates in different regions of the Arctic (AMAP 1998; 2004). This is also an explanation why animals differ in regional trends. Trend studies of DDT and PCB levels in seabird eggs and marine mammals (polar bears, seals and whales) from the Arctic and sub-Arctic show a clear reduction during the last 15-20 years (Braune and Donaldson 2000; Barrett et al. 1996; Henriksen et al. 2001; Verreault et al. 2005c; Muir et al. 2001; Stern and Addison 1999). In seabird eggs from northern Norway, there is a reduction in DDT and PCBs of 80-90 % between 1973 and 1993 (Barrett et al. 1996). In the Canadian Arctic, a similar reduction has been shown in eggs from guillemots, northern fulmars and black-legged kittiwakes (Braune and Donaldson 2000). In marine mammals (seals and whales), the reduction in DDT and PCBs are not great as those observed in seabirds (AMAP 2004). In polar bears from Svalbard, both PCB and HCB decreased significantly during the 1990s (Henriksen et al. 2001). The shape of the decline for polar bear suggests a levelling off in the latter part of the sampling period. Data from beluga also indicate that decline will be slow during the coming decade.

While PCBs and pesticides seem to be declining in the environment, the PBDE concentrations in arctic wildlife are increasing. Although the levels in the Arctic are still relatively low, a study in Canada showed a dramatic increase over a period of 15 years. In samples from blubber of ring seal and beluga, the levels increased by 3-9 times since the beginning of 1980s (Ikonomou et al. 2002). Generally, a doubling every five years seems to be the rule. Herring gull eggs from the Great Lakes in North-America show a similar increase as seen in ringed seal (Norstrom et al. 2002). The sources of environmental PBDE contamination include leakage from consumer products and industrial facilities that manufacture PBDEs as well as from disposal sites of products containing PBDEs. There are no temporal trend data from the European Arctic. If nothing is done to the “PCB of the 21st century” (i.e. proper restriction) the PBDEs may reach the same levels as PCBs in a few decades.

20.11 Effect studies

Ecological risk assessment of contaminants in arctic animals comprises assessments of exposures and effects, and risk characterization. In order to identify possible effects of contaminant exposure in free ranging animals from remote areas, two approaches are generally used. The first involves extrapolation and comparison. Possible effects are determined by comparing levels of contaminants in the species of interest to levels known to cause toxic effects in laboratory species (e.g., rats) or from observations on affected animals in the wild (AMAP 2004). The second approach investigates biological and potential toxic effects by studying biomarkers (indicators of biological responses) of contaminant exposure (AMAP 2004). Such studies may reveal subtle biological changes/disturbances associated with low and sub-lethal concentrations of contaminants. However, the significance of such effects for the health of the individual is often not obvious, and validity of extrapolating between biomarker responses measured in individuals and population level effects is not easily established. Thus, ecological risk assessment of contaminant exposure in free-ranging species will always be rather difficult without captive studies to demonstrate direct cause and effects (AMAP 2004).

Ecological risk assessment of contaminants in animals in the Arctic comprises assessments of exposures and effects, and risk characterization.

20.12 Effects of POPs in arctic animals

In field studies of Arctic free-living wildlife, it is difficult to prove a causal relationship between a suspected effect and specific contaminants. Thus, assessments of possible effects are based on associations between biological parameters and tissue contaminant concentrations. Some biological responses (or *biomarkers of exposure*) are quite specifically related to contaminant exposure (*e.g.* cytochrome P450 enzyme activities, accumulation of highly carboxylated porphyrins and thyroid hormone disruption), but are difficult to interpret in terms of consequences for the health of the individual, and populations (Peakall 1992). Other responses may be more directly coupled to the survival or reproduction of the individual, but influenced by a large variety of confounding factors.

Sometimes it is possible to compare the levels of POPs found in wildlife with effect thresholds derived from laboratory studies or environmental levels that are believed to have been implicated in observed effects (e.g., declines in bird populations). Such a process is not simple. For many arctic species, laboratory studies do not exist and comparisons should be made with caution since there are problems with extrapolating data across species. Also, unlike most laboratory studies, animals in the wild are exposed to a suite of different contaminants. They are also usually exposed to lower concentrations than laboratory animals. Furthermore, wild species are exposed to weathered mixtures of contaminants due to changes in composition of many POPs caused by abiotic degradation, metabolism, and filtering through the food web. Differences in species sensitivities to the effect of POPs also make it difficult to know which laboratory species best represent those in the Arctic. Arctic species differ from laboratory animals due to their fat dynamics, differences in life styles and life strategies, and differences in toxicokinetics (AMAP 2004).

In studies, which investigate biological and potential toxic effects by studying biomarkers of contaminant exposure, there are also limitations. It is not possible to determine causality, only that a statistical association has been found between a biomarker and the contaminant in question. Most POPs co-vary, and thus, it is not possible to state equivocally that the biomarker response has been caused by a particular contaminant. There may be other contaminants not analyzed, or biological parameters, that are just as important, or the response may be a result of synergistic, additive or antagonistic effects of contaminant mixtures. Biological variables such as age, sex, body condition, and presence of disease, or other stresses may also act as confounders, as they can cause similar biological effects as those seen from POPs. Therefore, for most reported biological effects in wildlife, the evidence for a causal link with a specific chemical contaminant is weak or non-existent. This is mainly due to the complexity of contaminant mixtures, the lack of data on chemical exposure, species sensitivity and mechanisms of action. Understanding the linkage between contaminants and health effects (e.g., reduced fitness or immunosuppression) is most likely to come from studies in laboratory animals. Crucial in establishing causal evidence for chemical-induced wildlife effects are semi-field or laboratory studies using the wildlife species of concern. Semi-field studies represent a useful approach to bridge the gap between the controlled conditions of laboratory experiments and environmental-exposure conditions in the field (AMAP 2004).

In the following assessment, results are presented in which associations have been reported between biological parameters and contaminant levels in glaucous gulls and polar bears from the Svalbard area. Levels of specific POPs are compared to no-observed adverse effect levels (NOAEL) or no-observed effect levels (NOEL), and the lowest observed adverse effect level (LOAEL) or lowest observed effect levels (LOEL) known to cause subtle effect in sensitive species. The purpose of these comparisons are to assess the likelihood that glaucous gull and polar bears may be at risk for effects of some POPs and to identify the contaminants associated with these effects.

20.12.1 Glaucous gulls

The NOEL range for sum PCB was 1.3 to 11.0 µg/g (ww) for effects related to reproductive success in seabirds. The LOEL range for various endpoints of reproductive success (hatching success, egg mortality, deformities, and parental attentiveness) ranged from 3.5 to 22 µg/g sum PCBs/g (ww) in eggs. For adults, sum PCB concentrations in brain tissue higher than 300 µg/g (ww) were associated with mortality. For dioxin-like compounds, the NOAEL range for reproductive effects was 1.5 to 200 pg toxic equivalency quotient (TEQ)/g (ww) in eggs, and the LOAEL range for various reproductive endpoints (deformities, hatching success, and mortality) ranged from 10 to 2200 pg TEQ/g (ww) in eggs (Barron et al. 1995; Giesy et al. 1994; Bosveld and van den Berg 1994). In eggs from peregrine falcons, DDE residues of 15 to 20 µg/g (ww) would result in eggshell thinning (Peakall et al. 1990).

In glaucous gull eggs from Svalbard/Bjørnøya, the sum PCB is close to or above NOEL and LOEL levels found for reproduction effects. Glaucous gull eggs from Bjørnøya are close to or above LOEL levels which have effects on hatching success in chickens and NOEL levels for hatching success in Foster terns (*Sterna forsteri*). The sum PCB in eggs from Bjørnøya is not above the levels that are related to increased egg mortality. The sum PCB found in liver from glaucous gulls from Bjørnøya is above levels reported to cause toxic effects in birds (AMAP 2004). The TEQ concentration was calculated to 2500 µg/g in glaucous gulls (Daelemans et al. 1992). These TEQ levels exceed all NOAELS and LOAELS for reproductive effects and LD_{50} in the range of other bird species (AMAP 2004). Sum DDT levels in eggs and liver exceed Canadian and U.S. Environmental Protection Agency (EPA) guideline levels for protecting wildlife. Thus glaucous gulls that prey on seabird eggs, chicks and adults have intake of sum PCB, sum DDT and TEQs high enough to cause effects.

20.12.1.1 Reproductive effects

Glaucous gulls from Bjørnøya with high levels of sum PCB were more often away from the nest and spent more time away than birds with low levels. Increased time away from the nest in glaucous gulls with high PCB levels may indicate that they needed more time to search for food than individuals with low PCB levels (Bustnes et al. 2001). Thus, chick survival may decrease for parents with elevated PCB exposure due to the fact that their parents spend less time protecting the chicks.

In glaucous gulls from Bjørnøya, the females with high POP levels (HCB, oxychlordane, DDE and PCBs) had a greater possibility for embryo mortality or unfertilized eggs than females with low POP levels. Also, the body condition at hatching was poorer in the first chick in a clutch (glaucous gulls normally lay 2-3 eggs) compared to the other chicks in females with high POP levels, suggesting that the female shunts a larger percentage of POPs to the first chick in the clutch. A negative relationship was also found between chick body condition (e.g., body mass) and the parents' blood concentration of HCB, β-HCH and PCB 28 for the second chick in a clutch. Except for the negative relationship found between the concentration of some POPs and date of egg laying no relationship was found toward other reproductive parameters (e.g.; clutch size, egg size, number of days incubating, predation of eggs and early chick survival) and the level of POPs (Bustnes et al. 2003).

Many POPs can disrupt endocrine function (Colborn et al. 1993). Female glaucous gulls from Bjørnøya, with high POP levels, produced more male chicks compared to females with low POP levels (Erikstad et al. 2005), strongly indicating that POPs are acting as endocrine disruptors in these birds.

In glaucous gulls from Bjørnøya, a significant relationship was found between levels of POPs and asymmetric wingfeathers. The effects were stronger for HCB than PCB and DDE (Bustnes et al. 2002). Asymmetric wingfeathers are an indication of stress and the observation of asymmetry may indicate that gulls with elevated POP concentrations are under increased stress during moulting.

20.12.1.2 Cytochrome P450 activity

In glaucous gull liver samples (Henriksen et al. 2000), a weak positive association was found between hepatic 7-ethoxyresorufin-O-dethylase (EROD) activity and PCB-levels. This may indicate enzyme induction by PCBs, but the EROD activities were low compared to other studies on fish-eating birds. Microsomal testosterone hydroxylase activity was only observed at the 6β-position and could not be related to levels of POPs. The low P450 associated enzyme activities in glaucous gulls suggests that they have a low capacity for metabolizing POPs, which may contribute to the high accumulation of POPs in this species.

In a laboratory study of glaucous gull chicks on Svalbard, a significantly higher level of CYP 1A enzymes was found in the liver in males from a group that were feed a diet of POPs (a natural diet they receive in the wild) compared to a group of males which were feed clean food (hen egg with little or no POPs) (Østby et al. 2005). Evaluation of blood POP levels demonstrated that the chicks fed a natural diet had higher POPs than the clean diet and there was also a positive correlation between blood POP levels and CYP 1A enzyme induction.

When making comparison of the TEQ value in glaucous gulls and several arctic seabird species (little auk, Brünnichs guillemot, kittiwake and black guillemot) the EROD levels were higher in little auk and lower in Brünnichs guillemot, kittiwake and black guillemot compared to glaucous gulls (Borgå et al. 2005b). Since the TEQ values in arctic seabirds were 100-200 times lower than the LOEL for CYP induction in common tern, it is assumed that most birds are below threshold levels for biological effects (Borgå et al. 2005b).

20.12.1.3 Effects on the hormone system

In male glaucous gulls from Bjørnøya a significant negative correlation was found between the PCB and HCB levels, and thyroxin (T4) levels and T4- to T3-ratios in the blood (Fig. 20.3). HCB, oxychlordane and PCB 118, 114 and 105 were the contaminants that had the strongest correlation to the decrease of the T4/T3-ratios in these glaucous gulls. The levels of T4 and T4/T3-ratio were lower in glaucous gulls from the colony that had highest levels of POPs when compared to the colony with low POP levels

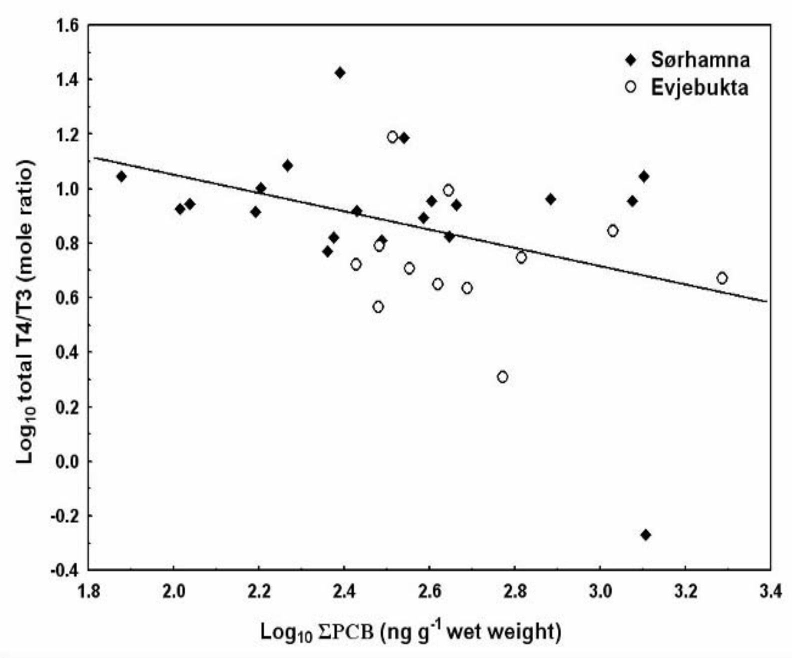

Fig. 20.3. Relationship between the total T4:T3 (thyroxin:triiodothyronine) ratios ($\log_{10}$ mole ratio) and blood levels of $\sum$ PCB ($\log_{10}$ ng/g wet wt), corrected for extractable plasma fat (%) and day of capture, for male glaucous gulls (n = 32) breeding in two colonies (Evjebukta and Sørhamna) at Bjørnøya (Norwegian Arctic) ($r = -0.40$, $p = 0.031$) (ng g^{-1} w.w.: nanograms per gram wet weight) (Verreault et al. 2004).

(Verreault et al. 2004).

20.12.1.4 Effects on the vitamin system

Many POPs, in particular 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) and dioxin-like PCBs, can interfere with vitamin A homeostasis in experimental animals (Zile 1992). Vitamin A is mainly stored as retinyl palmitate in lipid droplets of liver stellate cells (Blomhoff 1994). In herring gulls from colonies in eastern Canada, liver retinoid concentrations were inversely related to TCDD-concentrations in eggs from the same colonies (Spear et al. 1986; Anonymous 1991). In the sample of forty glaucous gulls from Bjørnøya, no significant relationships were found between liver retinoid concentrations and PCB levels (Henriksen et al. 2000). The hepatic vitamin A stores in glaucous gulls from Bjørnøya were larger than in herring gulls from contaminated locations in North America (Anonymous 1991) suggesting that the present contaminant levels do not influence vitamin A in gulls from Svalbard.

20.12.1.5 Genotoxic effects

In a laboratory study of glaucous gull chicks from Svalbard, a significant increase in levels of DNA-adducts (a measure of genetic mutations) was found in the group receiving a diet of POPs compared to a clean group. However, no clear relationship was found between levels of DNA adducts and POPs between the exposed and clean group (Østbye et al. 2005). The small sample size of birds included in this study may be one reason for the lack of statistical significance.

The frequency of chromosome abbreviation in lymphocytes was also higher in the POP-exposed group, when compared with the clean group. Although, no correlation was found for frequency of chromosome abbreviation and concentration of some of the POPs analyzed (Krøkje et al. 2005), suggesting that the present contaminant levels have genotoxic effects in gulls from Svalbard.

20.12.1.6 Effects on the immune system

Suppressed immune function has been associated with exposure to POPs in herring gulls from the contaminated Great Lakes area (Grasman et al. 1996). If establishment and/or survival of intestinal macroparasites are limited by host immune function, we would expect increased parasite intensities in animals with high organochlorine burdens, such as the glaucous gull. In a sample of 40 glaucous gulls from Bjørnøya in the western Barents Sea, numbers of intestinal macroparasites were compared with hepatic levels of selected POPs (Fig. 20.4) (Sagerup et al. 2000). After controlling for nutritional condition, no single parasite species was significantly associated with concentrations of PCBs or chlorinated pesticides. However, the intensity of all nematodes grouped together was positively correlated with all the 14 POPs measured, and significantly with 10 of them. The strongest correlations were with p,p’-DDT, Mirex, sum PCB, and PCB congeners 28, 118, 153, 138, 170, and 180. Although correlative, no immunological data were collected. However, these results suggest that POPs might affect immune function in the glaucous gull.

In glaucous gull from Bjørnøya a correlation was found between blood levels of POPs and increased levels of white blood cells. Females with high levels of HCB and oxychlordane have less possibility to initiate immune responses than glaucous gulls with low levels of these contaminants (Bustnes et al. 2004).

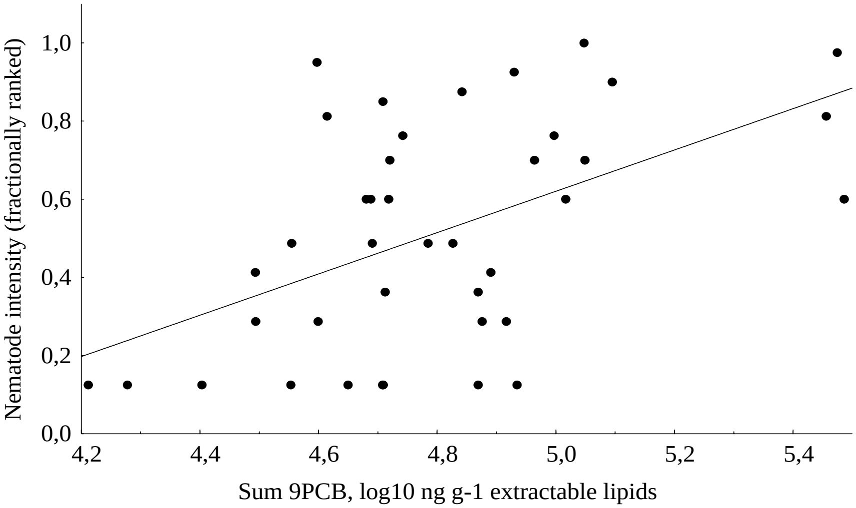

Fig. 20.4. Correlation between intestinal nematode infection intensity (fractionally ranked) and $\sum$ 9 PCB concentrations ($\log_{10}$ ng/g lipid weight, liver) in glaucous gulls from Bear Island (n = 40, $R^2 = 0.26$, $P = 0.001$) (Sagerup et al. 2000).

In a Svalbard laboratory study of glaucous gull chicks (56 days old chicks) fed a diet of POPs, a negative effect was found between POP levels in the diet and immunoglobulin (both IgG and IgM) concentrations when compared to a control group fed a clean diet (Larsen et al. 2004). The exposures of POPs through their diet appeared to cause a decrease in the immuno-competence and resistance of these chicks, which could impact their resistance to disease and infection.

20.12.2 Polar bears

In mink (*Mustela vison*), levels of 1230 ng/g (ww) of Aroclor 1254 in liver, was associated with impaired reproductive success (Platonow and Karstad 1973). Reduced growth and survival of mink kits were observed in female mink with 2000 ng/g (ww) Aroclor 1254 in liver tissue (Wren et al. 1987). An EC_{50} (effective concentration causing a response in 50 % of the treated organisms) in adult females for litter size was calculated to be 40 000 to 60 000 ng total PCB/g (lw) (approximately 1200 ng total PCB/g (ww) in muscle) and 2400 ng/g in muscle for kit survival (Leonards et al. 1995). Captive harbour seals (*Phoca vitulina*), exposed to PCBs via different fish diets, had reduced reproductive success at sum PCB levels of 25 000 ng/g (lw) in blood (Reijnders 1986). The EC_{50} for dioxin-like compounds was calculated to be 160 pg TEQ/g (ww) (5300-8000 pg/g (lw)) in mink muscle for litter size and 200 pg TEQ/g (ww) (6600-10000 pg/g (lw)) for kit survival (Leonards et al. 1995). Assessment based on subtle neurobehavioural effects in offspring of rhesus monkeys treated with PCBs and human mothers eating PCB contaminated fish, have resulted in an estimated LOAEL for effects on short term memory of 500-1000 ng/g (lw), and a NOAEL for effects on visual memory of 1000 ng/g (lw) in offspring or cord blood serum (Ahlborg et al. 1992). The LOAEL for immunosuppression is 21 000 ng sum PCB/g (lw) in rhesus monkeys (Tryphonas 1994).

In some polar bears from Svalbard, sum PCB concentrations are above the NOAEL and LOAEL levels for neurological-behavioural effects on their offspring, based on information studies of monkeys and humans and NOEL levels for kit survival in minks. The sum PCB in polar bears from Svalbard is also above NOEL and LOEL for reduced vitamin A in otters. Some individuals of polar bears above 3 years of age are above reported LOAEL levels for reduced immune function (based on information from monkeys). Some polar bears also have elevated levels of PCBs, which is correlated to low reproduction in seals and EC_{50} for reduced kit survival in mink (de Wit el at. 2004).

20.12.2.1 Reproductive effects

A negative effect on the reproduction and survival rate of young seals as result of PCB contamination has been shown in the Baltic (Olsson et al. 1992). Epi-zoological studies of polar bears indicate a reduced reproduction and survival of cubs at Svalbard compared to other arctic areas (Wiig 1995; Wiig et al. 1998), although the relationship between cub survival and POP levels has not been established. From laboratory studies on mammals, it is shown that high intake of PCB in a critical period may have an influence on the fetus and decrease in the survival of the offspring.

In Canada it was found that polar bear mothers with high levels of POPs (in the milk) had a greater chance for loosing the cubs than mothers with low POP levels. Mothers, which lost their cubs, had levels of PCBs, which were 3 times higher than females that did not lose their cubs (Nordstrom 1999).

In polar bears from Svalbard, the age composition in the population was different from the Canadian population. Female polar bears, which were more than 16 years old, constituted 12.7 % at Svalbard compared to 40.3 % in Canada (Wiig et al. 1998; Derocher et al. 2003), signifying that POPs may have an influence on the polar bear population at Svalbard.

It has also been hypothesized that PCBs and other POPs may be involved in the relatively high incidence of female pseudohermaphroditism in polar bears from Svalbard (Wiig et al. 1998). In polar bears from Svalbard, pseudohermaphroditism was found in 3 % of the total amount of female polar bears caught (Wiig et al. 1998). In female polar bears from Canada and Alaska, no such malfunction has been found (Andrew Derocher, pers. com.). Because POPs cause endocrine disruption, high POP levels in polar bears at Svalbard may be one reason for the observed pseudohermaphroditism.

20.12.2.2 Cytochrome P450 activity

Many planar halogenated hydrocarbons (e.g., dioxin-like compounds, which include some of the PCBs) have a common pattern of toxic effects that is associated with affinity to the aryl hydrocarbon (Ah) receptor and induction of isoforms from the CYP1A subfamily (Poland and Knutson 1982). Preliminary results from 13 polar bears from Svalbard show a positive correlation ($P = 0.026$) between CYP1A and total PCB concentration in white blood cells (Skaare et al. 2000).

In male polar bears from Canada, CYP 1A1 levels were correlated to mono-*ortho* and non-*ortho* substituted PCBs. CYP 2B was correlated to the concentration of chlordanes (mainly oxychlordane and nonachlor) and total mono- and non-*ortho*-substituted PCBs (de Wit et al. 2004).

20.12.2.3 Effects on the hormone system

The thyroid hormones are important for regulating metabolism and heat production. For arctic species thyroid hormones are very important for their adaptations to a cold climate. In young animals, the thyroid hormones are also important for the growth and development of the central neural system. Hormone data from polar bears at Svalbard (high POP levels) and Canada (low POP levels) show that the levels of thyroid hormones (e.g., T4) are negatively correlated to PCBs (Skaare et al. 2001). In polar bears from Svalbard, high levels of POPs, were negatively correlated to thyroid hormone levels (total T4/free T4) with POPs explaining 30 % of the variation in these ratios (Skaare et al. 2001). The correlation was strongest for sum PCBs and HCB. In another study of polar bears from Svalbard, a negative correlation was found between sum PCBs and total (t) T4, free (f) T4, fT3, tT4/tT3, tT3/fT3 and fT4/fT3. More thyroid hormone variables from female polar bears were affected when compared to males (Braathen et al. 2004). This may indicate that female polar bears are more vulnerable to effects of PCB on thyroid hormones than males.

Testosterone is an important male hormone, which is involved in sexual development. In males of polar bears from Svalbard, a negative relationship was found between the levels of sum PCB/sum pesticides and testosterone levels. The sum of PCB and sum of pesticides explained 57 % of the variation in testosterone levels (Oskam et al. 2003).

In female polar bears with cubs from Svalbard, a positive relationship was found between sum PCB and the level of the sex hormone progesterone (Haave et al. 2003). This may indicate that the exposure of PCB might disturb the timing of ovulation (release of eggs) in female polar bears and thereby impacting the possibility for fertilization. No relationship was found between sum PCB and estrogen in female polar bears from Svalbard (Haave et al. 2003).

Cortisol is involved in the body metabolism and is released during stress in animals. In polar bears from Svalbard a negative relationship was found between POP levels and the level of cortisol in the blood. The sum PCB and sum pesticides explained 27 % of the variation in cortisol levels (Oskam et al. 2004). This may indicate that the exposure of PCB can disturb metabolism and the release of stress hormones.

Female polar bears from Svalbard and the northern part of the Barents Sea, with and without cubs, had significantly higher progesterone levels than polar bears from other areas. However, no relationship was found between PCBs and progesterone levels within the Svalbard and Barents Sea bears (Haave et al. 2003).

Taken together, these findings strongly indicate that the present level of POPs may have an influence on the endocrine system on polar bears from Svalbard.

20.12.2.4 Effects on the vitamin system

Vitamin A homeostasis can be severely altered by exposure to POPs, and several vitamin A deficiency-like symptoms are associated with intoxication by poly-halogenated aromatic hydrocarbons (Zile 1992). Some PCB metabolites can disturb the formation of the protein complex responsible for retinol (vitamin A) and thyroxin transport (Brouwer et al. 1986). In harbour seals, which were fed fish from polluted waters, retinol and thyroid hormones in blood plasma were depressed, compared to seals fed fish from less polluted waters (Brouwer et al. 1989). In polar bears from Svalbard, the level of PCB, HCB and HCH was negatively correlated to the level of plasma retinol. POPs explained 12 % of the variation in retinol levels (Skaare et al. 2001). In another study from Svalbard, no relationship was found between the levels of PCB and retinol levels (Braathen et al. 2004).

When data from Svalbard (high POP levels) and Canada (low POP levels) were compiled and compared, a negative relationship was found between PCBs and retinol. A positive relationship was found between OH-PCBs and retinol levels (de Wit et al. 2004).

20.12.2.5 Effects on the immune system

Many studies have demonstrated adverse effects of PCBs and dioxin-like compound on the immune system of experimental animals (see *e.g.* review by Tryphonas 1994). In captive harbor seals fed fish highly contaminated with POPs, several measures of cell-mediated and humoral immune function were depressed compared to seals fed less contaminated fish (de Swart et al. 1996). Immunoglobulin G (IgG) is the most abundant class of antibodies in mammals, and consequently an essential part of the humoral immune system. In a sample of 52 polar bears from Svalbard, age- and sex-corrected levels of IgG were negatively correlated with sum PCB and HCB (Bernhoft et al. 2000). The PCB levels in bears were within in the range found to give immunotoxic effects in experimental animals (Bernhoft et al. 2000). In a subsequent study from Svalbard, which included more animals, the same negative relationship was found between IgG and PCBs. The sum PCB and sum pesticides explained 53 % of the variation in IgG levels (Lie et al. 2004). In polar bears from Svalbard, the ability to produce anti-bodies against flu- and rheo-virus and tetanus toxid after vaccination is 40-60 % explained of the sum PCB and sum of pesticides (Lie et al. 2004). The ability to produce anti bodies against *Mannheimia haemolytica* (earlier *Pasteurella* sp.) is 59 % explained by sum PCB and sum of pesticides (Lie et al. 2004). The lymphocyte function after *in vitro* stimulation by mitogens (PHA, Con A, PWM, LPS and PPD) and antigens (tetanus toxsoid and KLH) is 45-72 % explained by sum PCB and sum of pesticides (Lie et al. 2005). The association between POPs and IgG could indicate a contaminant-induced immunosuppression in Svalbard polar bears, with possible consequences for susceptibility to infectious diseases. This may indicate that the present contaminant levels may affect the health and the status for the polar bear at Svalbard.

20.13 Conclusion

The levels of POPs in the arctic environment are generally lower than found in more temperate regions. The present article shows that, while the levels of some POPs are decreasing (e.g., PCBs and DDTs), the levels of other POPs (brominated flame retardants and fluorinated) are increasing in the arctic animals. The main reason for this increase is the increase in the global production and use of these contaminants. The POP levels found in polar bears and glaucous gulls from these areas exceed the effect thresholds as demonstrated by laboratory and field studies, which indicate present POP level influence behavioural-, biochemical-, physiological- and immunological parameters. Today there is enough evidence to suggest that the contaminant levels affect the health of polar bears and glaucous gulls from Svalbard and Bjørnøya. Further monitoring and research is needed to get a better understanding of the relationship between POP exposure and biological effects in arctic animals.

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21 Arctic health problems and environmental challenges in Greenland.

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21.1 Introduction

The traditional diet in Greenland is to a large extend based upon marine animals and fish (Deutch 2004). Today the Greenlandic diet is a mixture of traditional food and imported food, this is the way it has been for some generations. Due to weather conditions most of fresh food come from wild animals or fish. Greenland has a production of lamb and a limited supply of vegetables but most produced foods are imported from outside. A large part of the diet still stem from seafood, fish or sea animals, but imported fabricated foods are expected to continue to take over an increasing part of their energy consumption (Deutch 2004, Mulvad 1996).

In any community it is important how food is produced, how it is prepared and how it is consumed. These things are important to the individual and for the way people come together. That is why food is more than just getting the necessary nutrition, it is also essential for social life and the ways families function. Since food is increasingly imported and come in full or almost full fabricated forms the quality of nutrition changes. Along with this public health may be affected as well as the social aspect of eating and preparing the meals. Still the traditional diet is very important to the population culturally and financially. It is also of importance in order to get sufficient nutrients, because in many places imported food is available mostly in poor quality (Deutch 2004, Pars 2000).

High levels of long range transported contaminants to the Arctic have been documented by (AMAP 2003). In Greenland high contents of organic contaminants are found in people (Hansen et al 2002, Deutch 1998, Deutch et al. 2000) and the pollution has reached a level of concern. However, the replacement of traditional food by substandard, imported food is of significant concern.

Pollutants that accumulate in this part of the food chain can best be studied in the Inuit population. Other dietary studies focusing upon a diet rich in fat, like n-3 fatty acids, have been subject to study (Dyerberg 1975). However, much more could be done. The partly isolated Inuit population with its ethnic background provides new opportunities for genetic studies, as well as studies on the health impact of unique social circumstances, light and extreme cold weather.

Greenland is now in a transition between a disease pattern characterized by acute diseases, mainly infections, and chronic diseases, diabetes and cardiovascular diseases. This transition took place in Europe many decades ago but now we have a chance to study the process with modern technology. Organization and logistic of the health care system in sparsely populated Arctic regions is of great interest. Further more Greenland has public health problems which more than anything require a long term strategy for prevention.

21.2 Contaminants, diet and health effect in the Arctic

21.2.1 Organic environmental contaminants in the Arctic

A common problem for some environmental contaminants is that they have natural half lives of many years. They are also long range transported and can cause problems for generations. Contaminants examined by the Arctic Monitoring and Assessment Program, (AMAP), are PCBs, pesticides such as DDT, HCB, HCH, chlordane, dieldrin and toxaphene, and heavy metals. The persistent organic pollutants (POPs), are accumulated in the food chain in fatty tissue, creating the highest levels in orsoq/blubber from seals and tooth whales. Barleene whales, however, have a lower place in the food chain and are therefore less contaminated. The highest levels are also found in the oldest individuals. Humans and polar bears are at the top of the food chain, and are thus highly exposed to these chemicals (NERI 2004). Generally the levels are low in fish from Greenland and it is not a problem to eat Greenlandic fish. In the Baltic there has been found levels in seals up to 100 times higher than along the coasts of Greenland, but in the countries around the Baltic, seals are not eaten.

Table 21.1. Chlorinated organic contaminants in adipose tissue. (Mulvad, Pedersen et al.)

	Greenland n = 42	Canada	USA	Finland
Fatty acids	1993	1983	1983-84	1983
PCB(mg/kg)	15,8	2,1	1,2	0,3
DDT(ug/kg)	4450	2630	1670	330
HCB(ug/kg)	752	10	31	20

Currents in the sea and in the air spread the contaminants unevenly so that seals and people along the East coast of Greenland are more exposed to most POPs (Deutch 1998, Deutch et al. 2000).

21.2.2 Heavy metal in the Arctic

In Greenland, research on mercury is extensive. Mercury is a heavy metal that has always been in the environment, it also constitutes a pollution without borders. Mercury levels in blood from Greenlandic people are some of the highest measured in human samples (Hansen et al. 1990).

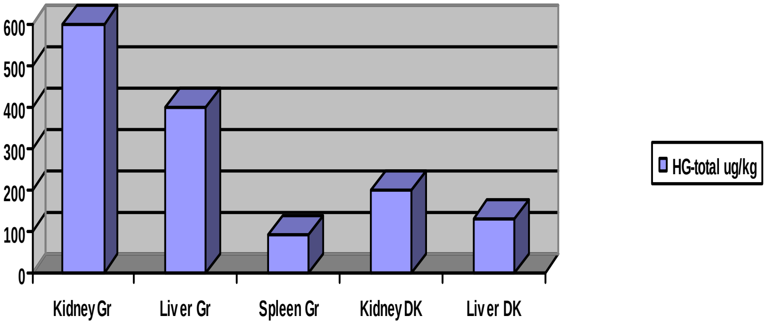

Fig. 21.1. Mercury in organs from Greenland(Gr) and Denmark(DK). Mercury level are some of the highest measured in human samples. (Mulvad, Pedersen, Hansen et al. 1996)

Lead is a well known contaminant that may stem from hunting bullets (NERI 2004) or from petrol and gasoline. Cadmium comes mostly from smoking cigarettes. The high smoking frequency in Greenland creates rather high blood levels in Greenlandic people in general. Heavy metals are accumulated on their way through the food chain and are also accumulated in human tissues.

21.2.3 The possible effect of the contaminants?

It is not dangerous for adults to eat the traditional food and the change from traditional diets to westernized MacDonalization may be a poor option concerning health. It is in relation to pregnant women and especially unborn babies that contaminants cause concern.

Clinical studies have shown an effect on the ability to learn and on memory, as a function of exposure to e.g. mercury early in life (Weihe et al. 2004). Some surveys indicate that the hormone balance and the immune system may be affected, i.e. the ability to fight infections (AMAP 2003). Some of these effects may perhaps be counteracted by the fatty acids in sea mammals.

As the woman accumulates contaminants throughout her life, contaminants will be present in the body even if the diet is changed during pregnancy (Deutch 1998). Some surveys also suspect POPs for affecting the quality of sperm (Abell et al. 2000).

21.2.4 Omega-3 fatty acid a gift from the sea

The traditional Greenlandic diet, where sea mammals are dominant, provides heat, energy and a healthy diet, at least for physical active people (Pars 2000, Dyerberg et al. 1975); the well known fat from sea mammals protects against coronary heart diseases and possibly also immune and inflammatory diseases.

A great amount of evidence from epidemiological studies and clinical trials support a theory of protective effect against coronary heart disease for fish consumption and intake of marine omega-3 fatty acids (Jul et al. 1994, Pedersen 2000, Pedersen et al 2003). Biological pathways for this risk reduction include membrane stabilization in the cardiac myocite, inhibition of platelet aggregation, favorable modifications of the lipid profile, decrease in blood pressure and reduction of the inflammatory response of the endothelium. Results from epidemiological studies suggest a threshold effect for the consumption of fish and omega-3 fatty acids.

Table 21.2. Relative contrations of fatty acids in plasma phospholipids among Inuit Women from Greenland, aged between 49 and 65 years, and women from Quebec, Canada. (Cote, Mulvad, Pedersen et al, 2004)

Fatty acids	Greenland Women (N=153) Mean	Quebec Women (N=93) Mean
Eicosapentaenoic:		
EPA (C20:5 n-3)	4,7	0,6
Docosahexaenoic:		
DHA (C22:6 n-3)	7,2	1,4
EPA+DHA	12,0	2,0
PUFA, n-3 series	13,8	2,8
PUFA, n-6 series	22,8	28,3
EPA/AA ratio	0,90	0,09
n-3/n-6 ratio	0,67	0,10
MUFA, n-9 series	18,0	15,7
Saturated	45,0	53,0

Relative concentrations are expressed as the percentage of total acids in plasma phospholipids.

This number represents all women who were within the same group of age

Risk reduction is especially important for cardiac sudden death. Nevertheless, protection against non-fatal coronary heart disease has also been observed (Pedersen et al 2003). Menstrual discomfort in Danish women reduced by dietary supplements of seal oil capsules. Shown in a trial done in Aarhus University (Deutch et al. 2000). Omega 3 fatty acid may also help prevent pre-term births (Olsen et al. 2002). Selenium is an important vitamin which limits the effect of mercury. A number of other vitamins and trace elements are well represented in the traditional diet and at the same time it is a diet which is high in protein and low in sugar. It is a diet well suited for physical active hunters living in the cold Arctic environment.

21.2.5 Health impact of light and extreme cold weather provides opportunities in Greenland of special studies.

Vitamin D is obtained from dietary sources and from endogenous synthesis in the skin. Dietary sources rich in vitamin D are fat fish and sea mammals. Ordinary meat, milk and eggs contain less vitamin D and vegetables are void of vitamin D. The endogenous synthesis occurs in the skin under ultraviolet light B (UVB) stimulation. The endogenous production depends on sun exposure, age, clothing, skin pigmentation, and use of sun protection. The exposure to UVB depends again on latitude, solar height, absorption in ozone layer and atmosphere, and reflection from clouds.

In Greenland, protective clothing is customary, and summer is short with a low solar zenith altitude Thus, yearly exposure to UVB-sunlight is limited. However, the traditional Inuit diet is rich in sea mammals that contains large quantities of vitamin D. During the last decades, significant cultural changes have occurred in Greenland. Today, many Greenlanders are living on a westernized Danish diet that is low in natural dietary sources containing vitamin D Furthermore, Danish food is not fortified with vitamin D. Changes from a traditional- to a westernized-fare are associated with a reduced vitamin D status in Greenlanders, especially in winter time. (Rejnmark et al. 2004). The influence of age, gender, latitude, season, diet and ethnicity on plasma 25-hydroxy-vitamin D 25 OHD was studied showing that in addition to ethnicity (Danes versus Greenlanders), 25 OHD levels were influenced by age, season (summer > winter), and diet (a traditional Inuit diet > westernised diet).

A longitudinal study on osteoporosis was conducted in Nuuk, in September 2002. The objective was to evaluate risk factors of osteoporosis and changes in parameters of ultrasound densitometry, after two years, among perimenopausal Inuit women who previously participated in a cross section study. After two years, the prevalence of osteoporosis has doubled. Moreover, the study suggests an association between smoking and change in stiffness, and mono-ortho PCB congeners concentration was strongly and negatively associated with bone stiffness (Cote et al. 2003).

21.2.6 Ethnic background and genetic influence

The first known immigration was by Eskimos who came from the west more than 6.000 years ago, and since then there has been 4 immigrations by Eskimos and their descendants - Inuit - the latest only about 150 years ago. From the east came the Vikings 1.000 years ago, but they disappeared after a few hundred years, perhaps without leaving any genetic trace.

Until the 1960s, only 2-3% of the Greenlandic population were non-Greenlanders, so a major genetic influence on the Inuit tribe has only taken place during the last decades, where especially in the 1970s and 1980s a stream of laborers, employers and academics invaded the country and with an overweight of younger virile men that made significant marks not only on the color of the kids today, but also resulted in relative depletion of Greenlandic females. In spite of common beliefs these bureaucrats and

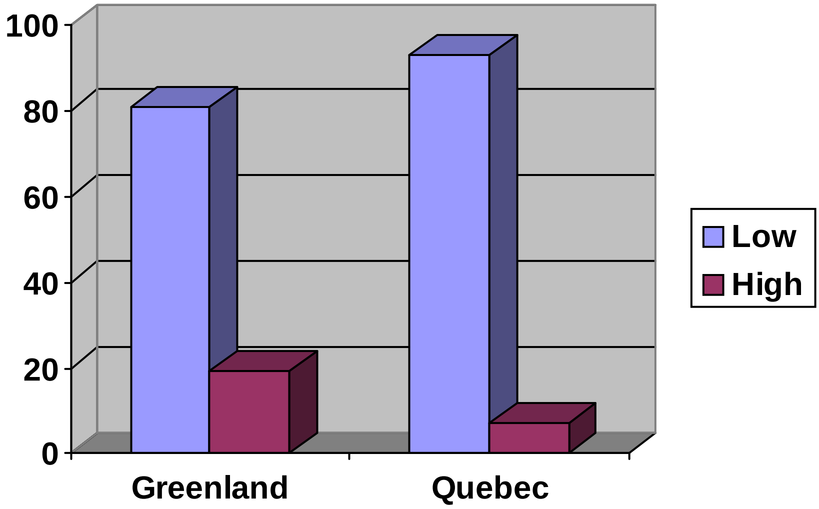

Fig. 21.2. Prevalence of risk of osteoporotic fractures among Inuit women from Nuuk, Greenland (N=153) and women from Quebec City Canada (N=2972). (Cote, Mulvad, Pedersen et al. 2004)

craftsmen were more successful in spreading their genes than the Vikings. More than 20% of the population were foreigners at that time. Since the late 1980's, the ratio has slowly decreased. Looking at the diversity in samples of Greenlandic Inuit shows 58% of the y chromosomes have been assigned to European origin in contrasts with a complete absence of European mitochondrial DNA, it indicates a male-biased European admixture. (Bosch et al. 2003).

21.2.7 Other diseases

Greenland is now in a transition between a disease pattern characterized by acute diseases, mainly infections and chronic diseases, diabetes and cardiovascular diseases. After World War 2 measles epidemic, tuberculosis, sexual transmitted diseases and hepatitis has been described. The lifestyle of the Inuit is in the same period undergoing a rapid transformation, like in most other countries that are not isolated from the rest of the world. These transitions also influence health parameters in Greenland. Infections are still frequent, especially acute respiratory infection, HIV, chlamydia,

Fig. 21.3. Infection are still frequent in Greenland

tuberculosis and hepatitis (Koch 1999, Homoe 2001). We also se an increase in the food born infections due to the increase of imported food.

The effect of the western lifestyle, obesity and central fat pattern are associated with several cardiovascular risk factors including diabetes, hypertension and dyslipidemia. Central fat patterns and obesity are more prevalent among the Inuit compared to the Danish population (Bjerregaard et al 2002, Jorgensen et al. 2002).

21.3 Organization and logistics of the health care system

For obvious reasons, experience in how to establish an efficient and competent public health system in sparsely populated Arctic regions is of great interest in the northern part of North America as well as in northern Europe and Russia. It is also a well known fact that technology from one area cannot necessary be transferred from one area to the next. Since most of health technology is developed by means of research in technically advanced settings we face a shortage a knowledge for how best to modify and transfer this technology to quite different settings.

Greenland is the largest island in the world covering 2.2 million sq. kilometers of which 90% is covered by ice, and 10% is a narrow strip of land along the coastline. The climate is Arctic. About 56.000 inhabitants are settled in 18 towns and 60 settlements along a coastline of 4.000 km. The towns have 600-6.000 inhabitants with the exemption of the capital, Nuuk, that has 14.000 inhabitants. About 20% of the total population live in settlements with 50 to 500 inhabitants.

21.3.1 Health Care Centers

Health care takes place in 17 district medical centers, one for each town including its settlements. Nuuk has a central hospital for specialized treatment, and one of the University Hospitals in Copenhagen (Rigshospitalet) is used for more intensive care or specialized treatment. The district medical centers are basically autonomous units. Depending on the population, there are 1-5 physicians, nurses, midwifes, health care assistants, lab-technicians, translators, secretaries and others. Typically, the doctors and nurses are Danish and the rest Greenlanders. In the smallest district, a doctor and a nurse are the only medically trained personnel. A district has from 1 to 10 surrounding settlements to look after, and the distance can be 300 kilometers. Boats and dog sledges can be used for transport, but in many emergency cases only helicopter is an option, and a helicopter is often placed far away. The cost for an emergency transportation can be very high.

The advantage of the health care system is the very close contact between the health care staff and the patients. The staff members are themselves part of the local communities and usually know their patients well. This contact is key to optimize immunization programs pr treatment modalities for venereal diseases, diabetes and mental diseases. Also the close relation to the social care system, police and institutions has advantages. The staff should be in a good position to implement prevention and more comprehensive public health programmers when such programmers are formulated by the health care authorities.

21.3.2 Telemedicine

To strengthen the connections between remote units to the main hospital and to specialists outside Greenland, the implementation of telemedicine is now of growing importance. Telemedicine is the use of information technology for electronic transmission of information, pictures, sound and other health-related data that is needed to make appropriate diagnosis and treatment plans. Based on the experience already obtained with telemedicine in Greenland, , there are good reasons to implement telemedicine on a

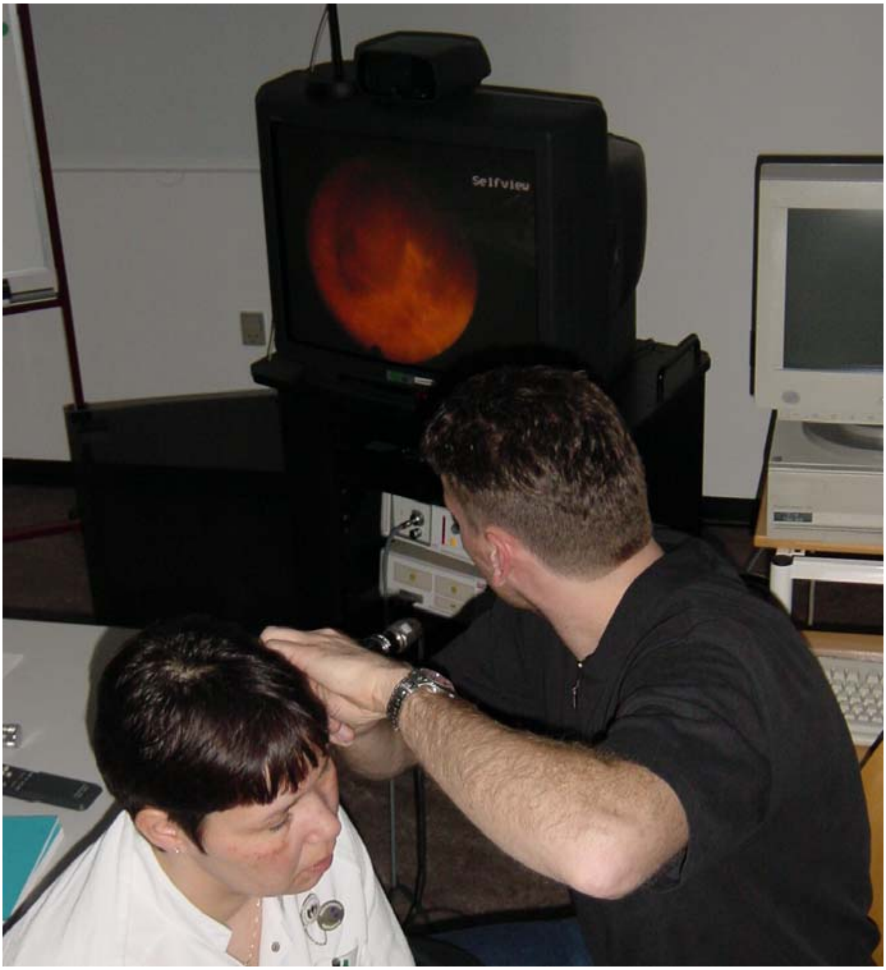

Fig. 21.4. Telemedicine is important between remote units.

larger scale (Stensgaard 2000).

It is important that the results are registered and analyzed currently throughout the period in order to ensure that the experience gained will support the continued use of telemedicine in Greenland and also be published to the benefit of others. Video-consultations can be established and X-ray photos and electro- cardiograms can also be transmitted. sonography of heart, dermatology and psychiatry are other areas. A common record system will also help provide updated information about each patient.

21.3.3 Strategy for improved health

The major characteristic of recent health and social problems in Greenland are (compared to Denmark): low mean lifetime expectancy, high infant mortality, increasing rates of diabetes, cardiovascular diseases and cancer, high rate of infectious diseases (tuberculosis, HIV, hepatitis B virus infection, Helicobacter pylori infection, meningitis), high rate of suicide, high rate of lethal accidents, high rate of legal abortions, domestic violence, tobacco, alcohol and drug abuse, mental health are stressed by unstable family relationships, contamination of the traditional diet (Chief Medical Officer 2000). The health of the population does not match the amount of money spend on health care. Health expenditure/GDP (per cent) Greenland: 9,2, Denmark: 8,2 Norway: 7,6. (Health Statistic in the Nordic Countries 2001).

Social studies and public health science have to take into consideration the conditions under which people live, e.g. health standards and housing, schools and education as well as social relations should be studied further. We need research in Greenland for the people not only on the people, and with the people.

Lifestyle diseases, the incidence of dental diseases, mental health, various forms of cancer, as well as infectious diseases are important in relation to the well-being and health of the population (Lynge 1997, Bjerregaard et al. 2002).

Social studies and studies on public health are to a great extent designed to accommodate the specific need for research in Greenland (Bjerregaard et al. 2003, Commission for Scientific Research in Greenland 2003), covered by this strategy within the framework of the effort.

To promote Health, well-being and economy of the Greenlandic population, it is suggest that, within this broad framework, social studies and public health science together encourage research which includes health hazards as an integral part of cultural aspects as well as research on social behavior in general. Since many of the problems related to problems that

Fig. 21.5. Children in Greenland - Greenland for children.

accumulate during a life time, a life course aspect should be implemented. Many results of studies indicate that prevention should start early, at the time when susceptibility is shaped or programmed and when habits are still modifiable. The effort should, in a broad sense, concentrate on the conditions under which children grow up under the theme: Children in Greenland- Greenland for children.

21.4 Conclusions

Global pollution has reached a level where the environment is affected and there is concern for people and animals that seat on the top of the food chain. Replacement of traditional food by substandard, imported food is also of significant concern. Any food recommendation must be structured to the community and take into consideration the available sources of food. For this reason it is important to keep monitoring the pollution that accumulates in the food chains and to take this information into consideration together with other available information concerning nutrition. These recommendations have to be well balanced and to incorporate all health aspects of diet and the social and economic consequences of our diet and how we get the food we need to eat. The pattern of disease will be increasingly influenced by chronic diseases being developed over long periods of time. The causes for this may be found early in life; during pregnancy, when all organs are formed, and during early childhood, where habits and

Table 21.3. Estimated daily intake of traditional and imported foods in East Greenland in 2001 by semi-quantitative food frequency questionnaire (n=180). (Deutch, Pedersen 2004)

Food	Daily intake
Seal meat and blubber	41g/d
Polar bear	23g/d
Walrus	14g/d
Whale meat and blubber	37g/d
Fish	78g/d
Reindeer, hare, muskox	50g/d
Imported food	638g/d

circumstance may have lifelong influence. In Greenland too, it is necessary to understand the social, cultural and environmental causes better in order to ensure a better preventive effort.

The conditions for children form the basis for the future of Greenland both economically, socially and for health. The position of the family and the definition of its responsibilities are central matters in this process. Time has come to concentrate the effort where it will have the greatest and longest lasting effect. A research program like this one should focus on families who are just starting to have children. Research should include genetic, social and cultural aspects on one hand and disease, behavior and cognitive development on the other. Research should have a longitudinal angle and should provide possibilities of trying out theory through interventional projects. Time has come for the policy makers to think ahead and to make decisions that span more than time periods of election.

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