OCEANOGRAPHY AND MARINE BIOLOGY SERIES

SEAS AND OCEANS SET

Tools for Oceanography and Ecosystemic Modeling

Edited by
André Monaco and Patrick Prouzet

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WILEY

Tools for Oceanography and Ecosystemic Modeling

From the ***Seas and Oceans*** Set

coordinated by
André Mariotti and Jean-Charles Pomerol

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Contents

Foreword

We have been asked by ISTE to stimulate work in the area of the environment. Therefore, we are proud to present the “Seas and Oceans” set of books, edited by André Monaco and Patrick Prouzet.

Both the content and the organization of this collection have largely been inspired by the reflection, initiatives and prospective works of a wide variety of national, European and international organizations in the field of the environment.

The “oceanographic” community in France – which is recognized for the academic quality of the work it produces, and is determined that its research should be founded on a solid effort in the area of training and knowledge dissemination – and internationally was quick to respond to our call, and now offers this set of books, compiled under the skilled supervision of the two editing authors.

Within this community, there is a consensus about the need to promote an interdisciplinary “science of systems” – specifically in reference to the Earth’s own “system” – in an all-encompassing approach, with the aim of providing answers about the planet’s state, the way it works and the threats it faces, before going on to construct scenarios and lay down the elementary foundations needed for long-term, sustainable environment management, and for societies to adapt as required. This approach facilitates the shift of attention from this fundamental science of systems (based on the analysis of processes at play, and the way in which they interact at all levels, and between all the constituent parts making up the global system) to a “public” type of science, which is finalizable and participative, open to decision-makers, managers and all those who are interested in the future of our planet.

In this community, terms such as “vulnerability”, “adaptation” and “sustainability” are commonly employed. We speak of various concepts, approaches or technologies, such as the value of ecosystems, heritage, “green” technologies, “blue” chemistry and renewable energies. Another foray into the field of civilian science lies in the adaptation of research to scales which are compatible with the societal, economic and legal issues, from global to regional to local.

All these aspects contribute to an in-depth understanding of the concept of an ecosystemic approach, the aim of which is the sustainable usage of natural resources, without affecting the quality, the structure or the function of the ecosystems involved. This concept is akin to the “socio-ecosystem approach” as defined by the Millennium Assessment (http://millenniumassessment.org).

In this context, where the complexity of natural systems is compounded with the complexity of societies, it has been difficult (if only because of how specialized the experts are in fairly reduced fields) to take into account the whole of the terrestrial system. Hence, in this editorial domain, the works in the “Seas and Oceans” set are limited to fluid envelopes and their interfaces. In this context, “sea” must be understood in the generic sense, as a general definition of bodies of salt water, as an environment. This includes epicontinental seas, semi-enclosed seas, enclosed seas, or coastal lakes, all of which are home to significant biodiversity and are highly susceptible to environmental impacts. “Ocean”, on the other hand, denotes the environmental system which has a crucial impact on the physical and biological operation of the terrestrial system – particularly in terms of climate regulation, but also in terms of the enormous reservoir of resources it constitutes Oceans covering 71% of the planet’s surface, with a volume of 1,370 million km^3 of water.

This set of books covers all of these areas, examined from various aspects by specialists in the field: biological, physical or chemical function, biodiversity, vulnerability to climatic impacts, various uses, etc. The systemic approach and the emphasis placed on the available resources will guide readers to aspects of value-creation, governance and public policy. The long-term observation techniques used, new techniques and modeling are also taken into account; they are indispensable tools for the understanding of the dynamics and integral functioning of the systems.

Finally, treatises will be included which are devoted to methodological or technical aspects.

The project thus conceived has been well received by numerous scientists renowned for their expertise. They belong to a wide variety of French national and international organizations, focusing on the environment.

These experts deserve our heartfelt thanks for committing to this effort in terms of putting their knowledge across and making it accessible, thus providing current students with the fundaments of knowledge which will help open the door to the broad range of careers that the area of the environment holds. These books are also addressed to a wider audience, including local or national governors, players in decision-making authorities, or indeed “ordinary” citizens looking to be informed by the most authoritative sources.

Our warmest thanks go to André Monaco and Patrick Prouzet for their devotion and perseverance in service of the success of this enterprise.

Finally, we must thank the CNRS and Ifremer for the interest they have shown in this collection and for their financial aid, and we are very grateful to the numerous universities and other organizations which, through their researchers and engineers, have made the results of their reflections and activities available to this instructional corpus.

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For a Systemic and Transdisciplinary Approach to the Environment

1.1. Introduction

In terms of research and technologies, the last ten years have been marked by an undeniably increased awareness of the problems posed by the evolution of our natural environment and societies. In the face of the visible changes of the dynamics of systems and the uses of resources, we called upon science to provide the elements necessary to understand these changes and to pave the way for the future by providing those tools that can help us make decisions.

Furthermore, the researchers working in the wide field of the environment have become familiar with the several initiatives, methods, and programs resulting from the reflection of the international community on the notion of “earth system research for global sustainability” (ESRGS); [REI 10] identify five “great challenges of future earth” which link global change to sustainable development. In France, the research and development programs follow the main directions of public policies, especially those of the National Research and Innovation Strategy (NRIS, Paris, 2009) of the Ministry of Higher Education and Research, to cope with and adapt to the accelerated development of economic, social and environmental pressures.

Internationally, programs are deeply rooted in several bodies and actions, including the international council for science (ICSU) and the joint programming initiative (JPI), which focus on water, climate, agriculture or

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Chapter written by André MONACO, Patrick PROUZET and Patrick VINCENT.

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the sea, and the International Group of Funding Agencies for Global Change Research (IGFA)/Belmont Forum[1], a group of funding agencies for global research on environmental change. The "Belmont" challenge aims at "providing the knowledge necessary to action aiming to adapt to and reduce harmful changes in the environment and extreme events". The priorities of collaborative research action (CRA) have to do with the safety of water resources and the vulnerability of coastal areas. These organizational concepts and priorities can be found in national research institutions in Europe as well as in the United States. We could even start to worry about the standardization of the research calls from authorities concerned.

Whatever the research field may be, every one of these programs advises a multi- inter- transdisciplinary approach which details the historical development of environmental sciences. This transversality represents and denotes, quite simply, an increasing amount of disciplines being integrated and applied to the environment, in particular social studies and finally, an interaction with the users and policy makers who use the research results in management strategies (see section 3.1). There is even talk of a "co-design" of research programs involving all the actors and participants to the projects. This stage really still seems out of reach. Nevertheless, the literature offers such a variety of terms, concepts and paradigms that it has become difficult for the lay person to get his or her bearings (Figure 1.1).

Figure 1.1. *Semantic proliferation of environmental research. See color section*

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[1] http://www.igfagcr.org/index.php/belmont-forum.

After this quick reminder about the development of environmental research, and while there is an increasingly wider range of occupations and professions in the environmental field, we have to make this observation: the future practitioners, i.e. students at different stages in their education, who are increasingly specialized in their sector, seem almost completely dissociated from these national and international considerations and projects. This explains the current difficulties faced when attempting to concretely apply the scientific knowledge into the complex problems posed by changes in the environment (Figure 1.2).

This remark constitutes the basis for the "Seas and Oceans" collection, which draws from the most recent reflections and national and international directives in terms of earth and environmental sciences to propose: i) a systemic approach to the ocean and its interfaces; ii) an order in which the volumes are published, which simulates the strategies advised for the organization of environmental studies; in other words, starting with the way the marine system works and ending with ocean governance, passing by various cases of vulnerability (Figure 1.3). To ensure this transition between the environment and the socio-economic sector, we have focused on the living resource which best integrates the functions and the changes in the natural environment and its usages.

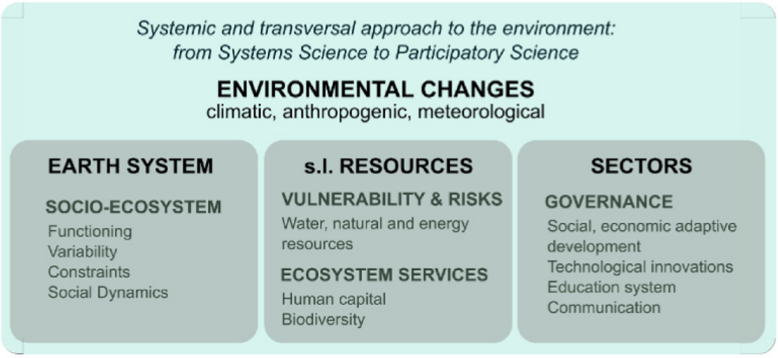

Figure 1.2. *Conceptual framework for a systemic and transversal approach (from ANR-ESS SSC). See color section*

This transition, through the resources that make up a vulnerable human capital, is essential and raises awareness among the public with less scientific knowledge since it is closely linked to society and its uses. For example, the “earth overshoot day”, when our planet has consumed more than what it produces yearly, makes it possible to raise public awareness about the pressure that our societies exert on these resources and somehow represents the degree of pressure that we exert on the environment. In French, this is called *jour du dépassement global*, i.e. the date on which theoretically the Earth’s renewable resources have been depleted[2]: the first “earth overshoot day” dates back to the December 31, 1986, when the world first consumed in a year more than the planet could offer. However, in 2015 it was on August 3 that we consumed the renewable resources of a whole year.

1.2. A complex and vulnerable ocean system

The *Seas and Oceans* set of books that we have coordinated has been defined by an editorial board[3] of experts in different scientific domains covering a wide range of subject fields, making it possible to tackle the complexity of marine ecosystems but also their vulnerability[4]. The contribution of experts in economics and social studies has also allowed us to see how human societies have exploited, but also sometimes destabilized, marine resources and how these societies could adapt to the change factors resulting from different natural and anthropogenic pressures. The value of resources has not only focused on traditional activities like fishing, aquaculture or maritime transport; it is also derived from the exploitation of the diversity of goods and services offered by the marine environment: renewable forms of energies, pharmacology of marine organisms, microalgae and biotechnology. Figure 1.3 describes the structure of the set schematically.

Its goal is to provide a body of work that allows us to get a better grasp of how the ocean system works in order to more precisely analyze the vulnerability of ecosystems and become more aware of the risks run by a

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[2] This date is calculated by the ONG, or Global Footprint Network, which came up with the concept of the ecological footprint (Wikipedia).

[3] The members of the editorial board were P. Bertrand (CNRS/INSU), G. Boeuf (MNHN/UMPC), J. Boncoeur (UBO/AMURE), P. Cury (IRD/CRHMT), L. Eymard (UMPC/LOCEAN), P. Gros (Ifremer/DM), Y. Henocque (Ifremer), M. Heral (ANR/Envt-Ress. Biologiques), R. Kalaydjian (Ifremer), M. Lafaye (CNES), L. Legendre (UMPC/LOV), A. Mariotti (UMPC), A. Monaco (CNRS/INSU), J.-C Pomerol (UMPC), P. Prouzet (Ifremer/DS), P. Roy-Delecluse (CNRS/INSU), and M.-H. Tusseau-Vuillemin (Ifremer/DS).

[4] Combination of the probability of exposure to a pressure, of the sensitivity to pressure, and of the restoration potential.

liquid environment that covers more than two-thirds of our planet, the resources of which are increasingly being constrained by the global change. The latter does not only take into account the effects induced by climate change, but also those caused by the increasingly harmful consequences of our formidable technological power, which we find difficult to control [LAR 01, JON 97].

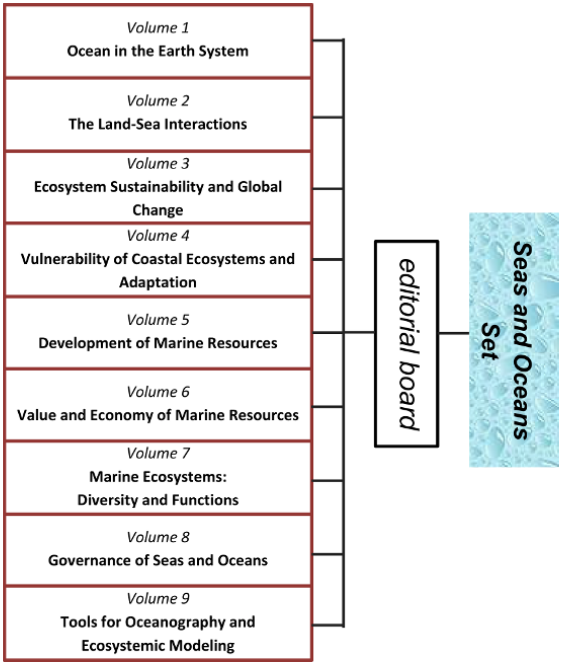

Figure 1.3. *Schematic overview of the structure of the Seas and Oceans set*

Our actions, usually performed in an exceedingly sectorial context (not much thought is given to the synergy of the effects of our actions upon the functioning and quality of the environment), have consequences and impacts on different levels – local, regional or global – which are illustrated in the various chapters of this set of books[5].

The authors have been chosen in relation to the general subject treated: each contributes in his or her own specialty, creating a work of

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[5] Hans Jonas, quoted by [LAR 01], mentions an actual cosmic power of man: “Technology places man in a role which only religion has sometimes assigned to him: that of steward or guardian of creation”.

multidisciplinarity across several chapters and volumes. Nonetheless, if interdisciplinarity is difficult to implement, it is perhaps more effective when it comes to oceanography, due to the necessary pooling of large and expensive means of exploration (ships, satellites, etc.), analysis and modeling platforms, multi-parametric and long-term networks and observation stations, often gathered in working sites or research networks. In total, the contributions of more than 120 specialists in the most diverse fields in relation to the marine environment – physics, chemistry, biogeochemistry, biology, ecology, economics, sociology, fishing, public policy analysis, resource exploitation and technology – have been addressed while making sure to link them together to show that the approach is not only pluri- or interdisciplinary, but also and necessarily, transdisciplinary.

All temporal and spatial scales are considered, since they are often inseparable if we want to understand the dynamics of an environment with no boundaries but whose exchange interfaces are very significant areas. The interest of long-term observations and measurements is well-established when it comes to evolution; if models and scenarios are often marred by uncertainties, it is often because of a lack of references in the past. This necessity is understood and acknowledged, but it implies the commitment of institutions and communities, which is not especially compatible with administrative rules and political actions.

Therefore, in the logic of the transversal approach ranging from the functioning and state of the ocean system to its management (Figure 1.3), 8 volumes, which provide an overview of the latest developments, have already been published. However, this accumulation of data would not have been possible without the development of observational techniques on all scales of the system. This is the subject matter of this last volume (9), which is concerned with the tools linked most closely to the themes dealt with in the set, including modeling strategies for ecosystem dynamics and supporting management of living resources and fisheries.

Volume 1: *Ocean in the Earth System* addresses the interactions of this system with the atmosphere and the biosphere. Seawater chemistry is seen from the perspective of the exchanges of heat flows, fluids, terrigenous and biological elements. The interactions between the marine components of biogeochemical cycles are described in great detail.

Volume 2: *The Land-Sea Interactions* covers the hydrological and geochemical exchanges that maintain a natural land-sea sytem. The intensification of human pressures on this interface increasingly leads to physical and chemical disequilibria (radioactive pollution, plastic waste) and ecological misfunctions (eutrophication) which, along with climate warming, are major components of global change.

Volume 3: *Ecosystem Sustainability and Global Change* deals with the ocean as a source of amazing biodiversity and an important reserve of food resources. The activity of marine organisms affects the concentration of chemical elements in the biosphere, hydrosphere and geosphere, as well as affecting biogeochemical mechanisms. The book analyzes the state and evolution of these resources, by defining some indicators as well as the impacts of global change on the dynamics of the living exploited resources.

Volume 4: *Vulnerability of Coastal Ecosystems and Adaptation* highlights different examples and types of risks: chemical, biological, climatic or linked to extreme events. It mentions the importance of the toxic chemical and biological pressures particularly exerted on estuary, littoral and coastal waters. These environments, whose quality has strongly deteriorated, are subjected to changes, at various speeds, linked to natural catastrophes (storms and tsunamis) or sea-level rise. All of this makes the coast a heritage site that is undergoing a transformation and a system study that's significant particularly for the assessment of the vulnerability and adaptation of societies to change factors.

Volume 5: *Development of Marine Resources* sketches a relatively comprehensive outline of what marine resources can contribute in the future through the development of marine biotechnologies, the pharmacology of marine reef organisms and renewable forms of marine energy channeling the force of currents or winds. This work also mentions some perspectives that can be more or less unrelated.

Volume 6: *Value and Economy of Marine Resources* presents the diversity of goods and services provided by the ocean and proven to be indispensable to human communities. Use of these services and exploitation of goods will have to be developed in a responsible and sustainable manner. New approaches and scenarios based on the analysis of the aquaculture and fishing production chain are developed to ensure an ecological economy linked to the use of living marine resources. An overview of EU maritime economy and policies is also presented.

Volume 7: *Marine Ecosystems: Diversity and Functions* illustrates biological diversity and the variety of habitats, structures and foodwebs in different oceans and systems: the phytoplankton, the first level of ecological and climatic dynamics via the carbon cycle; the coral ecosystems and their associated coastal seagrass, among the most diverse on the planet; and the deep ecosystems, oases around hydrothermal vents on mid-ocean ridges. In addition, the authors address the problem of preservation of resources, living and non-living and the services rendered to our societies endangered by environmental change. Thus, concepts and strategies emerge as ecological resilience.

Volume 8: *Governance of Seas and Oceans* tackles how society participates in making decisions about the marine environment from a legal perspective mainly, presenting Law of the Sea as key determining factor. It deals, therefore, with matters of ship transport, marine pollution, management and exploitation of renewable and non-renewable resources, legal or socioeconomic stakes linked to the development of forms of renewable marine energy or to the implementation of protected marine areas. The sustainable development of seas and coastlines is also dealt with by mentioning the integrated management of these areas in a context of globalization which has resulted in the increased importance of maritime issues in terms of flows and resources. In this context, importance of the partnership among the actors of the maritime sector and the awareness of their knowledge and expertize are vital to ensure the sustainable development of the maritime sector.

The objective of the present volume (9) is not to describe all the tools employed in oceanography or the history of their development, but to provide an overview of the tools, technologies and strategies developed before assessing the complexity and vulnerability of the marine environment to global change. It focuses on the observation and study of living organisms: the use of acoustics to assess the abundance and behavior of schools of fish, the instrumentation of marine animals enabling us not only to study their migration, but also to see some characteristics of the environment they explore. A chapter is also dedicated to the technological and experimental methods developed to study and sample fishing stocks, the reliability and performances of which have to be tested to gauge how qualitatively or quantitatively representative the samples taken are. It deals with the strategies employed to model marine ecosystems, for example by laying the metabolic foundations for population dynamics and showing how to model the complexity of food chains. The ecosystemic approach to fisheries is exhaustively described through its history and goals but also the content that characterizes it. Lastly, it raises the question of how to model the complexity and shows the interest in combining models coming from different domains in a systemic approach.

1.3. Suitable observation tools

Research, technology and innovation are inseparable and their development has gone hand in hand with the emergence of issues linked to the environment. Since 1977, the international council of scientific union (ICSU) and its scientific committee on problems of the environment (SCOPE) have defined monitoring as "the collection for a predetermined purpose of systematic, inter-comparable measurements or observations in a space-time series of any environmental variables which provide a synoptic view or a representative sample of the environment (global, regional, national or local). Such a sample may be used to assess existing and past states and to predict probable future trends in environmental features" [HOL 77]. No changes need to be made to this definition of a monitoring strategy triggered by problems of pollution, especially marine pollution, caused by the most diverse products of human activity. [QUE 11] examined the question of chemical monitoring exhaustively in 2011; the same author is updating the study within the framework of the *Seas and Oceans* set currently.

Step by step, the strategies and technologies devoted to the survey of the chemical quality of water and of marine organisms have evolved to adapt to an ecosystemic and more global approach to the environment, with respect to the new challenges associated with climate, but also in conjunction with public policies. In any case, the development and diversification of observation technologies have kept up with the increasing awareness of the demand of society and demand for decision support with the development of the concepts of vulnerability, social acceptability of risk, adjustment to change and sustainable management. To address all these issues, research will have to take into account the complexity of conceptual models integrating at the same time life sciences and social sciences and humanities.

As a consequence of this evolution, we have seen a proliferation of conventions, jurisdictions and scientific programs too numerous to go through but traceable throughout the volumes of the collection. [QUE 11] makes an inventory of these protection instruments and of a certain number of international conventions and treaties. As for the marine environment, we will mention the global network global ocean observing system (GOOS) and, on a European level, the water framework directive (WFD) and the marine strategy framework directive (MSFD). Decision-making tools have led to a regional organization of long-term observations, so that the planet Ocean has been divided into Regional Seas United Nations environment program (UNEP).

In the last volume of the set, after a presentation of the vast panoply of observations, measurement technologies and strategies that support the progress of research and its applications, we chose to prioritize the tools employed in ecosystem approaches that have do with living organisms and to the operational transition closest to the socioeconomic demand.

1.3.1. *For a systemic vision of the ocean*

The systemic approach that takes shape in a modeling process relies on four basic concepts: complexity (together with its notions of haziness, uncertainty, unpredictability, etc.), system (the set of elements interacting dynamically and organized around a purpose: ranging between physical and social systems), globality (the interdependence and coherence of the elements of the system), interaction and feedback (the relationship between the components of the system taken two by two). Through the remaining seven chapters of this volume, we will show that the systemic vision requires a 4D approach that includes long-term observation.

It is important to take complexity into account as it goes beyond the mere description of the set of elements making up the system studied. Complexity means that “the whole is more than the sum of its parts”. According to Edgar Morin, “complexity not only includes interacting quantities of unities which challenge our calculating capabilities; it also includes uncertainties, indetermination and random phenomena”. As a result, our societies will have to learn (or re-learn) how to live in an uncertain world.[6]

In this context, one of the roles of science will consist of assessing the nature of the risk involved and its plausibility. Given the complex nature of the system, this will only be feasible with an approach which is at least interdisciplinary to guarantee that the methods of one discipline will be

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[6] After the French Revolution, the perception of risk for our “modern societies” has shifted from divine fate to right to security [SÉB 06].

transferred to another. It will also be necessary to go even further by developing a transdisciplinary vision that can allow us to better grasp this complexity and the assessment of the risk involved by opening all disciplines “to that which they share and to that which lies beyond them”[7]. We will have “to piece together the knowledge acquired to overcome the crazed myopia of the retreat into oneself”, since, according to Edgar Morin, “a piece of knowledge is only pertinent if able to find its place within a context and the most sophisticated knowledge, if completely isolated, stops being pertinent” [MOR 98].

As for environmental management, we are still far from adopting this systemic vision since, in terms of research, we hesitate to leave our disciplinary perspective behind and, in terms of expertise, our approach still remains too sectorial. Hans Jonas[8] highlights this last point: “We control the technological operations on nature, but we have no control on the whole of the process, which raises the problem of the mastery of our (technological) mastery”.[9]

1.3.2. *To assess our vulnerability to global change*

System approach constitutes the conceptual framework for the socio-ecosystem approach defined by the Millennium Assessment[10]. This requires an articulation between research, assessment, decision and management, according to an outline which may be based on the one set up for the protection and restoration of the North Sea (Figure 1.4)[11].

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[7] Article 3 of the Chart of Transdisciplinarity – CIRET – November 1994 – http://ciret-transdisciplinarity.org/chart.php.

[8] Quoted by [LAR 01].

[9] On a political level, according to [LAR 01]: “When we want to introduce nature into politics and more generally to draw the attention of human communities to the fact that our relationships are not merely a matter of technological objectification, but involve moral and even philosophical problems, we refer to catastrophes”.

[10] The Bergen declaration in March 2002 adopts the following definition of an ecosystem approach: “integrated management of human activities based on the knowledge about the ecosystem dynamics in an effort to achieve a sustainable use of the goods and services associated with the ecosystem, and to maintain its integrity”.

[11] Drawn from the OSPAR Commission report, 2006: Report on North Sea Pilot project on Ecological Quality Objectives, p. 22.

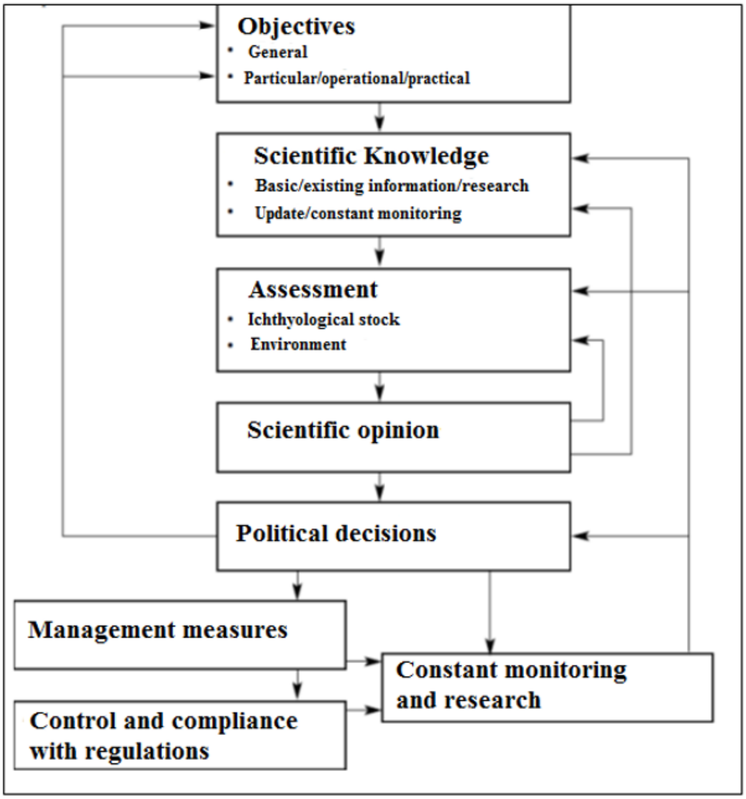

Figure 1.4. *Conceptual framework proposed for the management, protection and restoration of the North Sea [OSP 06]*

This framework changes our perspective on management by turning it from a mono-specific vision in a stable system to a multi-specific one in a complex and changeable system. It also incorporates decision support, which refers to the notion of expertise as well as to the notions of risk prevention and social acceptability of risk.[12]

Decision support requires the availability of operational tools which allow us to assess the state of ecosystems, to analyze their evolution as a result of global change, and to predict the impacts in response to different societal scenarios.

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[12] See Volumes 3 and 4 [MON 14a, MON 14b].

1.3.3. *The contribution of operational oceanography*

Operational oceanography (see section 1.3.3.1), which enables us to integrate large volumes of data derived from different observations[13] to supply digital models, constitutes a significant component of the control panels devised in accordance with DPSIR structure.[14] It makes it possible to provide a more realistic view of the characteristics of the oceans and of their development.

1.3.3.1. *Summary of operational oceanography and its development*

Operational oceanography (OO) allows us "to predict the state of the ocean system; to produce instantaneous values and realistic statistics of the target parameters, even in the absence of direct measurements of these parameters; to rerun past events while integrating data unavailable in real time, so as to generate in a deferred fashion the best possible descriptions of phenomena and situations; to simulate future situations according to several scenarios with the potential to support public decisions".[15]

OO expanded during the early 1990s and has stimulated research in different fields: treatment of *in situ* observations and satellite imagery, digital modeling and data assimilation[16], validation and oceanographic interpretation of the information produced, technological development of several physical, chemical and biogeochemical sensors.[17]

Satellite networks generate significant streams of data. For example, the altimetric measurements taken by the TOPEX/POSEIDON satellite since 1992, then by its successor JASON-1, launched in 2001 and finally by JASON-2, put into orbit in 2008, have covered more than 90% of the surface of the oceans with data streams of 50,000 pieces of information per day and a local altimetric precision of less than 5 centimeters. This enables us to monitor with precision the evolution of sea levels.

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[13] See Chapter 2.

[14] Driving Forces, Pressures, States, Impacts, Responses: framework adopted by the European Environment Agency.

[15] For more detailed information, one should read the final report on Operational Oceanography Foresight dating back to 9/10/2013 written by Bahurel *et al.*, [BAH 13] p. 40.

[16] A method that allows us to combine a model with observations.

[17] See Chapter 2.

These considerable streams of data and observations (in 2007 the network of profiling floats Argo[18] with 3,000 active floats took 100,000 temperature and salinity profiles) have favored the development of digital calculation abilities in relation to the modeling and assimilation of data, which has made it possible in France, since 2001, to produce a first forecast thanks to MERCATOR Océan (www.mercator-ocean.fr).

In 2007, the PREVIMER project (www.previmer.org) made it possible to make coastal forecasts (Figure 1.5) on metropolitan and ultramarine littorals.

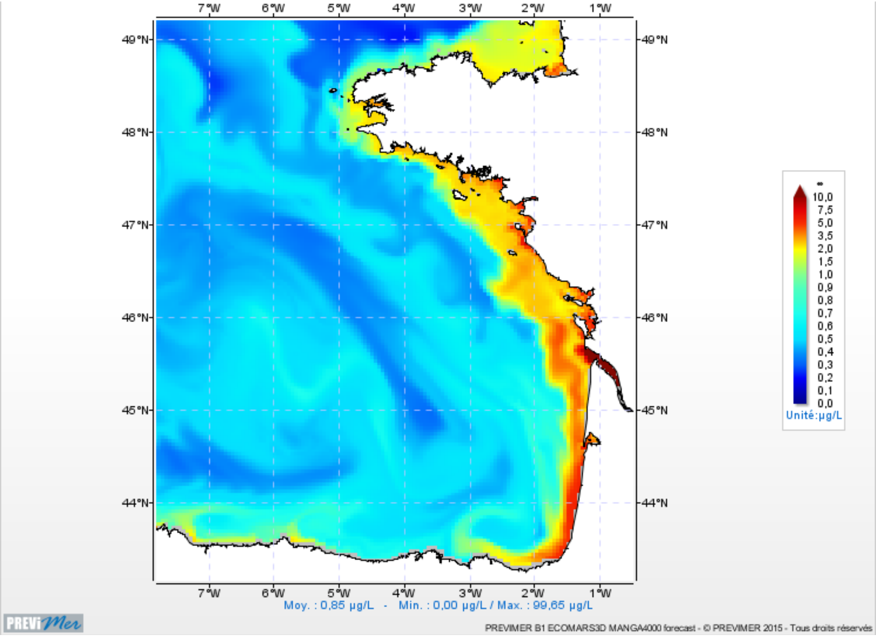

Figure 1.5. *Example of PREMIVER cartographic output showing the concentration of chlorophyll-a in surface waters (2/10/2015). See color section*

On a European level, EuroGOOS, set up in 1994, allows the development of OO on a European scale. The European program COPERNICUS/GMES (global monitoring for environment and security) aims at assessing the

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[18] In 2001, this network of floats enabled the launch of CORIOLIS (www.coriolis.eu.org) which allowed us to obtain the satellite and *in situ* data provided by oceanographic research and aimed at physical oceanography.

impact of its environmental policies. In this framework, the objective of the MyOcean consortium consists of setting up the “monitoring and forecast” component of European marine services.

Globally, global ocean data assimilation experiment (GODAE) and then the 2008 GODAE ocean view, have to favor scientific exchanges about OO.

1.3.4. *New technologies applied to the living world*

The development of satellites and the automation of data collection do not make the set-up of *in situ* monitoring superseded and obsolete, as is evident. Chapters 3, 4 and 5 of this volume provide examples that illustrate how population sampling and the assessment of their abundance or behaviors have only been able to progress thanks to the implementation of reliable catching techniques and investigations by means of acoustics or imaging. More and more behavioral observations are, therefore, coupled with the physical structures of the aquatic environments on different scales. Certain fish, mammals or marine reptiles are instrumented with beacons and sensors that allow us not only to detect very precisely their movements in water but also their reactions to physical or chemical structures. This ultimately consists of making certain marine animals indispensable collaborators to man to investigate in an ecosystemic way the quality and alterations of habitats (Figures 1.6 and 1.7).

Figure 1.6. *Salmon instrumented with an acoustic beacon allowing us to find out its location in the body of water in 3D (source Bégout-Ifremer)*

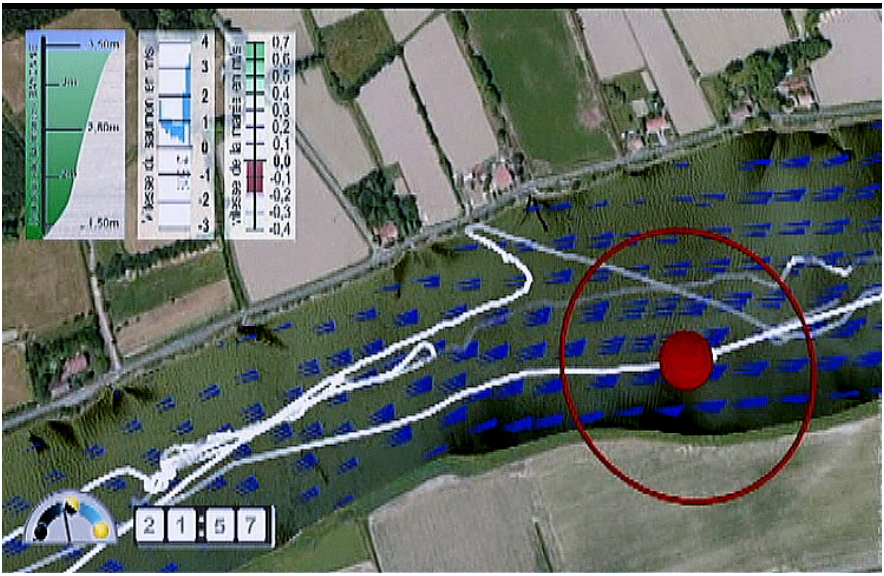

Figure 1.7. *Interaction between a hydrodynamic model (arrows) and a reconstruction of the salmon's journey (white line) in the estuary of the Adour [MAH 10]. See color section*

The different gauges inserted in the image show that it is nighttime (on the left below), that the tide is high at the mouth of the Adour (at the top, by considering the three indicators from left to right), that the salmon is moving upstream (positive velocity) and that the river current is starting to move downstream (negative velocity).

1.4. Conclusion

Data collection is, thus, extremely diverse as much in its content as in its form, and tackles several problems that future researchers, actors and managers will have to deal with. The ocean actually is and will be the regulator of climate and consequently of its variability. As for its uses, we can be confident that they will do nothing but multiply, as we can see with the planned development of maritime transport (industrial, military and touristic) and the dimensions of ships, coastal tourism, aquaculture, renewable forms of energy, biotechnologies, etc.

In these conditions, it becomes necessary to reinforce the links between sciences and societies, and to develop the ways in which knowledge is passed on and acquired. This is the first goal of this series of works, which has to be considered as a whole for a global vision of current knowledge and future challenges. The collection is aimed at higher education students who will have to work in the field but, more broadly, at an informed public of actors, managers and policymakers.

So sea or ocean? At the end of the set of book throughout the chapters and including specialists who use both terms, we can give the following advice: the difference between the two words remains valid according to the respective dimensions of the systems considered. However, the word *Sea*, as it has been historically used, is most often associated with a space close to man and his uses.

1.5. Acknowledgments

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2

Vulnerability to Global Change: Observation Strategies for the Marine Environment

2.1. Introduction

The Ocean, a mystical and sometimes hostile space, remained unknown for a long time and, to a good extent, this still holds true (the deep sea, biodiversity and so on). Though man has managed to move on its surface quickly, what was going on deep inside remained a mystery. Even though the development of maps, including those of marine currents, hydrologic probes and of fishery data, date several centuries back, it was in the 1870s that the exploration of the oceans became a significant scientific issue. This was historically linked to great oceanographic expeditions led to systemically explore the environmental features (physical, chemical and biological) of the oceans, as well as the characteristics of the seafloors (topography, temperature, sediments and currents).

For nearly a century, ships were the only means that allowed us to measure oceanic parameters. The need for precise measurements appeared during the first decade of the 20th century, but it was only at the end of WWII, at the instigation of meteorological observation programs and because of issues concerning the acoustic detection of submarines, that more systematic high-quality observation programs could be started. Since the late 1960s, thanks to electronics, their miniaturization and robotics, it has been possible to develop autonomous vehicles (buoys, floats, remotely operated

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vehicles (ROVs) and autonomous underwater vehicles (AUVs), in particular) which complement the measurements performed onboard the research vessels and which carry out measurement tasks without interruption.

2.2. Marine environment observation strategies

Oceanographic observation was initially associated with a kind of research aimed at understanding air–sea interactions or the connections between physical oceanography, the habitat of living organisms and fishing. Currently, oceanic monitoring is also employed to understand and monitor the evolution of the ocean within a climate context heavily influenced by anthropogenic changes: changes in the heat content, inflow of fresh water into the ocean, variations in primary production, evolution of sea levels, carbon storage and ocean acidification, evolution of de-oxygenated regions off the major upwelling areas and the impacts on fisheries. On the seasonal level, there is also the issue of obtaining ‘physical’ data about the upper ocean to set up seasonal forecasting models for climate evolution (El Niño, for example). Other issues are more specific. This is the case for the detection of hydrocarbon pollution, toxic algal blooms with the potential to provoke viral or bacterial contamination of shellfish (and therefore, entailing their temporary withdrawal from sale), the monitoring of drifting objects, sea searches, gravitational or seismic unpredictable events, etc. All these matters require targeted observation systems.

These “parameters” are more or less significant depending upon the focus on climate change, its effects, fishing, water quality or natural calamities (storms, floods, etc.). Climatologists are more interested in temperature and salinity. As far as the coastal and halieutic ecosystems are concerned, the focus required is not only on temperature and salinity, but also on turbidity, acidification, dissolved oxygen, nutrient salts or plankton. With regard to water quality, focus is required on contaminants, besides taking into account classic parameters such as temperature, salinity, turbidity or nutrient salts. In terms of natural risks and their respective impacts, the observation deals with the condition of the sea, swell, tides and storm surges.

Observation strategies for physicochemical and biological parameters, described hereafter, will vary according to the scale considered. For example, oceanic circulation and its variability are typically considered on a scale ranging from a few hundred to a few thousand kilometers for global circulation and on a scale of less than 100 km for the so-called mesoscale phenomena (turbulence, eddies, filament fronts, etc.); some of these phenomena can even develop on a scale of less than 10 km (sub-mesoscale). The strategies used to approach these phenomena require some realistic computer simulation analysis first, followed by a combined analysis integrating observations and computer simulations.

2.2.1. *Parameters to measure*

These parameters have to do with the physical and dynamic ocean, chemistry and biogeochemistry, but also with those involving living resources and biodiversity, all at once. Consequently, their measurement, done as precisely as possible, is a necessary step in perfecting our knowledge about the ocean and predicting its evolution.

The main parameters measured with respect to the physical and chemical ocean are discussed below.

2.2.1.1. *Temperature and salinity*

These are the basic parameters that need to be measured for the deep sea as well as for the coastal sea, even if in general we can settle for a slightly lower precision in the coastal domain, where variation ranges are the most important factor.

It is essential to know temperature (T) and salinity (S) to dynamically model the flow in the deep sea and coastal areas, hence, the importance of observatories. Water density is strongly linked to sea temperature and salinity, as well as pressure, and it is calculated with empirical equations called the equations of state of seawater. T and S are the parameters that are commonly quantified on the basis of conductivity (easier to measure), temperature and pressure measurements. Temperature is measured with a precision thermometer or with a thermistor sensor. By definition, salinity is “the weight in grams of solid residue contained in a kilogram of sea water, after its filtration and the evaporation of water molecules”. Salinity is more or less linked to the conductivity of seawater, which can be measured directly or indirectly.

2.2.1.2. *Pressure*

A good knowledge of the ocean requires us to work in three directions. Therefore, temperature and salinity measurements are also necessary in the water column. The pressure measurement, in addition to those of temperature and salinity, is also required to determine the volumetric mass density of the oceans. In practice, the measurement of pressure is closely linked to immersion depth, which will also involve the use of pressure sensors to obtain the immersion information associated with the parameters measured. Pressure is often measured in hectopascals, atmospheres or PSI's[1].

2.2.1.3. *Dissolved oxygen*

The dissolved molecular oxygen content is a parameter linked to the majority of ecosystemic biological processes. The concentration of dissolved oxygen results from the following physical, chemical and biological factors:

– exchanges at the air–ocean interface;

– diffusion and mixing within the body of water;

– reactions of chemical oxidation (natural or anthropogenic);

– the aquatic organisms' use of oxygen to breathe;

– *in situ* production of oxygen by photosynthesis.

Oxygen balances through gas exchange at the air–sea surface. Its concentration is influenced by biology, on one hand through the production of oxygen during oxygenic photosynthesis and through the consumption of oxygen during the living organisms' oxidative respiration of organic matter, on the other. We must point out first that anaerobic respiration (when oxygen is depleting) contributes, as much as aerobic respiration (when oxygen is present), to the consumption of oxygen in an indirect way, since the reduced metabolic products are oxidized further. Outside the layers closest to the surface and the upper areas of the thermocline, oxygen is also an interesting tracer of oceanic circulation. Dissolved oxygen is also an indicator of biological activity: the rate of O_2 dissolved in water can be interpreted as the result of the photosynthetic or respiratory activity of aquatic organisms or as potential for the development of aerobic or anaerobic organisms. However, it is also a gauge of pollution: small organic or mineral matter is oxidized biologically or chemically in water, which involves the consumption of dioxygen and the decrease in the concentration of dissolved O_2. In the context of certain kinds of environment where the anthropogenic pressure is heavy, an O_2-impoverished body of water can consequently be considered unhealthy.

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[1] Pounds per square inch. 1 PSI = 6.8948 103 Pascal.

2.2.1.4. *Carbon dioxide*

The precise quantification of the air–sea exchanges of CO_2 is essential if we want to predict the intensity of future global warming and the impact of climate change. The ratio between the CO_2 emitted and absorbed by the ocean has been imbalanced by the onset of the 20th century due to increased industrial activity and the resulting increase in CO_2 in the atmosphere. Consequently, the ocean absorbs more CO_2 than it loses. The ocean is not an acid environment, its pH being more than 7, but we are witnessing a decrease in the pH as a consequence of the ocean's net absorption of atmospheric carbon dioxide; whereas the average surface pH had been around 8.2 since the end of the last deglaciation, in a few decades it has changed to around 8.1. The knowledge of H is crucial to understanding the evolution of this acidification, which we estimate to increase about 0.4 between now and the end of the century. This acidification could affect some calcifying organisms, as well as certain submarine limestone structures, such as the coral reefs.

Most carbon is inorganic and dissolved and can, therefore, be monitored with targeted measurements: for example, the measurement of total inorganic carbon, alkalinity, or pH. Two of these parameters allow us, at a first glance, to determine the set marine carbon parameters. The measurement of the partial pressure of CO_2 (pCO_2) in seawater is therefore linked to the pH measurement.

While CO_2 fluxes at the air–sea interface start being assessed in the oceanic environment, the knowledge of CO_2 fluxes in coastal environments (continental margins, marginal seas, estuaries, lagoons, etc.) is much less advanced and requires research aimed at assessing the role of the coastal ocean in the global atmospheric CO_2 pump. Thus, CO_2 is a significant parameter in the measurement system employed to understand climate evolution and its consequences on ecosystems.

2.2.1.5. *Nutrient salts*

Nutrient salts are dissolved mineral salts that contain, among other things, phosphor (P), nitrogen (N) or silica (Si). Nitrates (NO_3), nitrites (NO_2) and ammonia (NH_3) are nitrogen salts. They provide plants with the nitrogen necessary for the synthesis of amino acids, which are essential components of proteins. The phosphor usable by plants is in the form of dissolved phosphate (PO_4). The silica dissolved in water is 95% silicic acid (or silicate) $Si(OH)_4$. It is crucial to silicic algae such as diatoms and silicoflagellates.

The major nutrient salts, i.e. nitrates, phosphates and silicates, are essential elements of phytoplankton production. They often limit this production in the surface layers (in more than 60% of cases), since their main source is the deep ocean through the vertical flows of oceanic circulation or vertical mixing, through turbulence or by means of diffusion, whereas the main sink consists, as a result of gravity, of the transport of organic matter specific to surface layers towards the bottom of the ocean. The measurements of at least one of these parameters (often the nitrates) is clearly an important issue in terms of partially grasping primary production (photosynthesis) in the oceanic surface layers, even if it depends on other factors (light, temperature, other nutrients, etc.) as well.

2.2.1.6. *Geostrophic currents and thermohaline circulation*

The ocean is subjected to a constant mixing that generates exchanges of all sorts: thermic, gaseous (CO_2 and oxygen among others), biological, etc. These exchanges can only take place because the ocean is in perpetual movement, especially through major surface currents like the Gulf Stream or the Kuroshio Current, but also because of a global circulation in three dimensions called thermohaline circulation.

The overturning areas of thermohaline circulation, where warm surface water sinks down to deeper waters, are part of meridional overturning circulation (Figure 2.1).

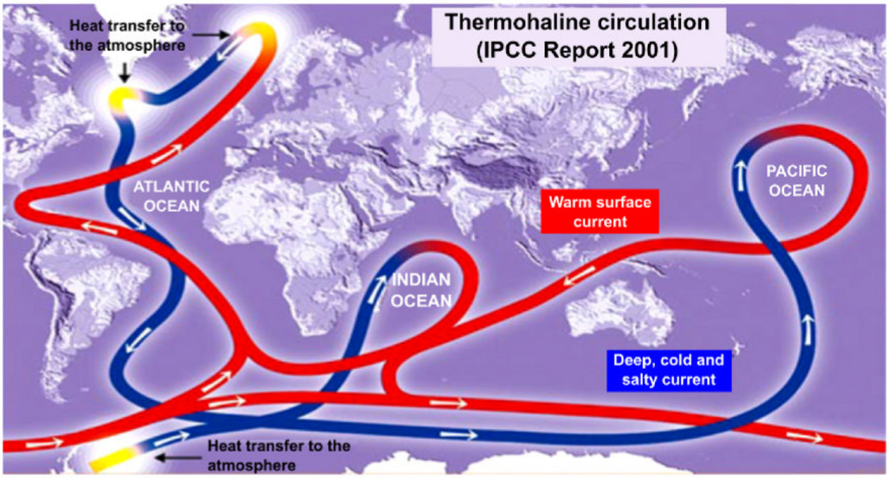

Figure 2.1. *Simplified pattern of thermohaline circulation [GIE 10]. See color section*

2.2.1.7. *Sea levels*

Ocean thermic warming contributes, through expansion, to the slow but steadily accelerating rise of average sea levels. The melting of continental glaciers and of certain ice caps also plays a significant part in the elevation of sea levels. The consequences of this rise may be dire for coasts, especially if they are associated locally with subsidence (coastline retreat, especially in the areas of large deltas, threatened loss protection dunes, flooding of inhabited areas), but also for the deep sea (flooding, even disappearance of flat islands, degradation of barrier reefs, etc.).

2.2.2. *Measurement techniques with wide-ranging applications*

Several techniques are available to assess ocean parameters. The principal ones have to do with physical (by means of thermometry, currentometry, etc.), electrochemical, acoustical, seismic and bio-optical measurements. We have already broached certain measurement techniques concerning the physical and chemical ocean. Let us now go back and examine some of those with a wide range of applications.

2.2.2.1. *Acoustical measurements*

The submarine environment can hardly be explored by the use of electromagnetic waves since water, because of its dissipative nature linked to its strong conductivity, quite significantly weakens them and quickly makes them ineffective. On the other hand, acoustic waves can propagate much further through the ocean. The propagation of sound in water has been the subject of much research aimed at defining its speed and direction, following the simplified formula:

$$C \approx 1410 + 4.21{*}T - 0.037{*}T^2 + 1.10{*}S + 0.018{*}P$$

where C is the speed of sound in m/s, T is the temperature in °C, S is the salinity in psu and P is the pressure in Pa.

These researches have made it possible to create generators of acoustic waves (generally called SONAR, for Sound Navigation and Ranging) or mechanical vibrations of the propagation medium. These vibrations, characterized by their frequencies (number of vibrations per second in Hertz), propagate easily in seawater, since water is a practically incompressible material. The damping of sound in water increases very rapidly with frequency, hence the lower the frequency, the higher its propagation. The facility with which acoustic waves propagate themselves in water was observed long ago, but their effective use is fairly recent. The first practical uses date back to the beginning of the 20th century with Paul Langevin's experiments.

Sonars and echo-sounders of all kinds are based on this principle and, depending on the frequency, allow us to measure phenomena in the water column, to chart the floor of the oceans or to study geological strata. So-called passive acoustics allow us to listen to the propagation of sounds generated by man or living organisms, including marine mammals[2], but also to the natural sound of the ocean, especially the sound of breaking waves, which can determine, among other things, the amount of air injected. This information is useful for the community of scientists working on ocean–atmosphere exchanges.

2.2.2.2. *Seismic measurements*

Seismic measurements are a specific instance of acoustics since they deal with very high-energy sources with very low frequencies. They allow us to identify the interfaces of different subsoil strata, up to more than 30 km deep.

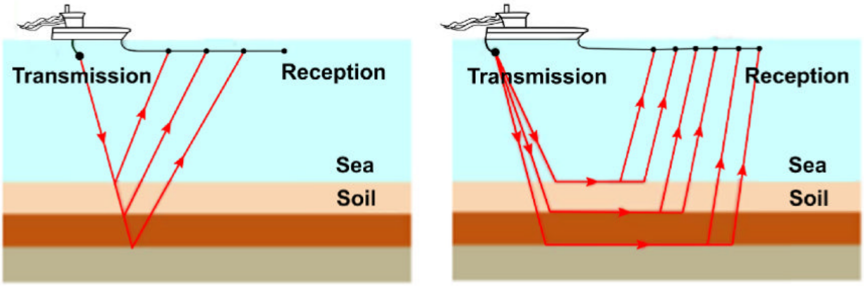

Figure 2.2. *a) Reflection seismology records the echoes of the waves reflected by different subsoil strata; b) seismic refraction records the echoes of the waves refracted on the interfaces of different subsoil strata*

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[2] See Chapter 3: Acoustic Technology to Detect and Estimate the Living Resources.

There are also passive seismic sensors called ocean bottom seismometers (OBSs) located on the floor of the oceans, which “listen to” natural vibrations (earth noises generated, for example, by earthquakes or tsunamis) or artificial vibrations (generated by a seismic source).

With higher frequencies (from 20 kHz to 1.2 MHz), when damping plays a more significant part, it is possible to use the reflection of waves emitted by a source and their Doppler[3] shifts to assess, for example, the distribution of certain particles or living organisms (zooplankton, ichthyoplankton or even fish), as well as the speed of marine currents.

2.2.2.3. *Bio-optical measurements*

Particles and compounds dissolved in seawater affect its optical properties and, consequently, the transmission, diffraction and absorption of light. Certain organic molecules of dissolved compounds and the pigments within the cells of phytoplankton, in particular chlorophyll-A, can be monitored using fluorescence. By illuminating them with a wavelength (for example, in the blue range towards 430 nm), they can re-emit some light in a longer wavelength (less energetic; for example, in the red range around 669 nm for chlorophyll-A). This fluorescence can be measured if cells have not already been saturated by natural light. Several small and autonomous sensors have been developed over the past 30 years, allowing us to monitor the optical properties of seawater to characterize particles, phytoplankton cells indicating primary production, but also colored dissolved matter resulting from biological activity. We can also use fluorimeters, used to measure fluorescence, transmitiometers (we illuminate with a light source, then we look at the light transmitted at the same frequency), turbidimeters (we illuminate with a light source, then we look at the light diffracted in a precise direction, to give us an idea of the concentrations of small particles) or simply those sensors that allow us to measure the light spectrum or natural light. Other sensors are built to measure the spectrum of particle sizes (for example by considering multi-frequency diffraction)[4]. Lastly, more

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[3] Doppler effect is the change in frequency of a wave observed between the emission and the reception measurements, as the distance between the emitter and the receiver varies over time.

[4] Measurement of the granulometric distributions of particles through the assessment of the angular variation of the intensity of light emitted when a laser beam goes through a sample of dispersed particles.

sophisticated sensors are going to be miniaturized, enabling automatic use software analysis. High-resolution photographic (or even video) measurements using dedicated measuring tools like the ZooScan[5] allow us to monitor and identify particles bigger than 100 µm, whether they are mineral, detrital or biological (large phytoplankton, heterotrophic plankton or zooplankton, up to the larval and juvenile stages of fish). We also can use of flow cytometric[6] measurements, where illumination in a thin ray of monochromatic light which allows us to characterize (through diffraction and fluorescence) small cells the size of pico- or nanoplankton but also, for example, bacteria or viruses.

2.3. Some large observation domains

2.3.1. *The open sea*

A first observation domain with respect to the open sea to be recognized by the international climate research programs as well as by those of operational oceanography (GODAE) regards the physical environment: heat, haline and steric content, but also currents and sea level. These variables are not independent within certain ranges of time and space scales. Thus, on a time scale of more than one day (or a few days near the equator) and on a spatial scale of more than a few kilometers (or 100 km near the equator), marine currents are mainly subjected to the geostrophic balance relationship which links them to “horizontal” pressure gradients. These gradients are, at a given depth, linked to “sea level” gradients (referenced with respect to a geoid), counterbalanced by a “steric” effect associated with the integral of seawater density on the vertical water column. The ocean is also the main reservoir of the changes in heat content associated with climate change (more than 90% of the increase in the heat content of our planet over the last 50 years has been stored in the ocean; [LEV 05]). Let us point out that the measurement of the speed of sound, which is a parameter that depends mainly on temperature, lets us gain indirect knowledge about the oceanic temperature (for example, through tomographic networks).

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[5] Licensed by CNRS and originally developed by the Villefranche-sur-Mer oceanographic laboratory in 1987 by G. Gorsky’s team. It combines an optical sensor with image processing software.

[6] Optical measurements at very high frequencies in a very thin stream of water (typically 10 µm).

Oceanic salinity is also a reflection of the great hydrological cycles [SCH 08]. Outside of the surface layer subjected directly to exchanges with the atmosphere or sea ice, temperature and salinity evolve under the influence of medium- or large-scale three-dimensional oceanic circulation, as well as under the influence of the vertical mixing due to the dissipation of small eddies (turbulent energy). Temperature can also evolve (slightly) with the supply of hydrothermal heat or chemical energy fluxes (for example, during the oxidation of organic matter) and in the euphotic layer illuminated from above with the absorption of radiative flows of solar origin. This absorption depends on the optical properties of water but also equally significantly on the content of particles (and on their nature, especially phytoplanktonic) or colored dissolved matter. Radiative fluxes and their absorption profile in the ocean are, thus, parameters whose measurement will be very useful both on a physical and on a bio-geochemical level.

At the air–sea interface, the ocean is subjected either to the direct action of the atmosphere (wind and heat, water vapor, gaseous exchanges) or indirectly to the presence of ice (water and salt [brine] exchanges with ice, ice tension on water, etc.). The exchanges of momentum through the action of wind take place with the creation of a wave (excluding sea ice), whose momentum is itself transferred quickly to the superficial part of the ocean below (turbulent movement after short waves), even if a small part is taken away by long swells up to coastal environments. The mixture caused by this turbulent wave movement, as well as by the heat or freshwater (evaporation, rain) exchange at the surface, entails the formation of a superficial layer, named the oceanic boundary layer, separated from the deeper parts of the ocean. This layer prevents, in a large part of the oceans, the surface turbulence penetrating towards the bottom, but it can also lead to the creation of internal waves (variations in the thickness of the boundary layer) which propagate in the distance. Wind, waves and air–sea flows (heat, water), as well as the presence of sea ice and its characteristics (thickness, age), are part of those significant parameters that need measuring to understand and monitor the physical and dynamic evolution of the ocean.

The chemical composition of the ocean is evidently a very complex subject. Research has focused mostly on the carbon cycles and on the oxygen and major nutrient cycles. We know that the ocean, thanks to the chemistry of the inorganic carbon contained in seawater, has absorbed nearly half of the CO_2 injected into the atmosphere by anthropogenic activities over the last century, without leading (on average) to seawater pH variations of more than 0.1.

Life in the oceans includes the first trophic levels, i.e. phytoplankton (vegetal or bacterial), which can synthesize organic matter through photosynthesis by employing pigments, in particular chlorophyll. The large categories of these pigments can be measured on the basis of the optical properties of sea water, allowing the concentrations of phytoplankton to be indirectly monitored. This measurement can be made by multi-spectral image analysis of the color of the sea (in the visible range). Some gene probes can be used to assess microbial or viral compartments, which play a significant part (microbial loop) in the re-mineralization of organic matter and its evolution. We can also perform imaging analysis or analyses of the size and characteristics of the particles (for example, fluorescence or epi-fluorescence) to obtain the distribution of species present, ranging from large plankton to large zooplankton and ichthyoplankton. The precise parameters measured can vary quite a lot and the selection of the most appropriate ones is still being assessed. Besides measuring primary production, in some cases these are parameters that describe the biodiversity that we are attempting to measure. For some kinds of zooplankton and ichthyoplankton, acoustical measurements, made thanks to the sounders of research ships, can be used to define their abundance. In different frequency ranges, these sounders can also be used to monitor shoals of fish[7]. Lastly, at low frequencies, some acoustical measurements (Acousonde) allow us to define the sounds produced by living organisms and, consequently, their presence or behavior (for example, those of marine mammals: pinnipeds or whales).

2.3.2. *The coastal and littoral ocean*

The coastal ocean is an interface between the open ocean and coastline, drainage basins and river estuaries. These interconnections are regulated by processes such as tides, which lead to the rising and falling of water in coastal areas and are created in the deep sea, waves which break on beaches and could have been generated thousands of kilometers from there, and the mixtures of fluvial water, that are low in salt content but rich in nutrient salts and contaminants (organic molecules or heavy metals) which come from continental drainage basins via estuaries or deltas. The coastline is globally

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[7] See Chapter 3.

significantly affected by human activities. From these characteristics we can deduce the significant need to understand how ecosystems (flora and fauna) respond to the evolution of the physical, biological and chemical parameters of these rich areas, which are exploited (they represent around 8% of the surface of the oceans but 50% of biological production) but also in danger[8].

The coastal environment is often characterized by interrelated parameters. For example, the concentration of phytoplankton biomass is strongly related to temperature, the concentration of dissolved oxygen, dissolved nutrient salts and turbidity.

The observation of the coastline is complicated by the number of parameters that need to be monitored to understand the processes, their impacts on biological populations and their potential feedback on the environment, but also because of the high spatial and temporal variability of these parameters. An optimized observation strategy requires us to place in relevant and representative areas some observation points that are temporally and spatially close; and to take into account several parameters measured regularly so as to better understand the processes at work in the coastal environment. In a second phase, this strategy must be extended to satellite-centered means of observation, to be able to observe processes on a larger spatial scale and even develop an operational monitoring system for coastal environments.

2.3.2.1. *Common ocean parameters (temperature, salinity, oxygen and nutrient salts)*

The salinity of coastal waters is generally less than that of open ocean due to the inflow of fluvial freshwaters. Besides, shallow waters can present significant temperature gradients. Thus, unlike the more homogeneous open-sea environment, in the coastal and littoral one we notice high variability in terms of temperature and dissolved oxygen, particularly in the mixing phenomena that take place in rivers. Pockets of water with low levels of salinity, originating in the Loire region, have been observed in the western part of the Channel after they have "circumnavigated" the Finistère promontory. These areas are generally subjected to quite strong tides and currents, which lead to transport dynamics entailing strong temporal variations of T and S.

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[8] See [MON 14a].

The diversity and concentration of nutrient salts are more significant aspects to monitor in littoral and coastal areas as they are carried by rivers and drainage basins and constitute, among other sources, the result of human activity: agriculture, urban life, industries, etc. They are studied simultaneously as nutrients for plants (like macroalgae and phytoplankton), which constitute the basis of the food web, as chemical tracers of coastal circulation since they are carried by coastal currents, and finally as potential contaminants in confined areas in danger of eutrophication.

The measurement of oxygen allows us to identify anoxic environments or sites where dissolved oxygen is depleted in coastal areas. The threshold of dissolved oxygen content below which the aerobic ecosystem suffers from deficiencies is generally set at 5 mg/l, whereas 2 mg/l marks the beginning of dire hypoxia which can lead to the death of marine invertebrates and even fish.

2.3.2.2. *Other parameters measured in the coastal environment*

These parameters, sometimes also measured in open-sea environments, are nonetheless operationally more important in the coastal areas because they often have direct applications to maritime security, the quality of littoral waters, the monitoring of the evolution of pelagic and benthic ecosystems, and consequently human health.

2.3.2.2.1. Currents and tides

Coastal areas are often characterized by currents that are much stronger than the offshore ones. Permanent currents, due to natural forces (pressure, winds and the Coriolis force) can lead to the intensification or weakening of tidal flows.

Currents influence oceanic circulation, the transport of sediments, species, nutrients or contaminants. It is, therefore, essential to know them thoroughly and to model them to understand their impact on ecosystems.

Astronomical tides are easily modeled in the long-term on a literal level (without taking into account external effects like meteorology). Nonetheless, the predictive modeling of the annual report on tides does not take into account the effects of atmospheric pressure and the weather on tide flow and height. More developed models now allow us, among other things, to assess storm surges, linked to tide gauges located in set positions and paired up with meteorological models and precision bathymetric maps to produce very good forecasts.

2.3.2.2.2. Swell and sea state

Waves are oscillations of the sea surface, generated by wind and involving gravitational forces. They transport a significant quantity of energy that they draw from wind force, which is partially dissipated by offshore and coastal breaking. The wave trains thus generated constitute the "wind sea". This "wind sea" is stronger as the wind is more intense or blows for a long time or over a significant distance (fetch). These waves turn into a swell when the wind abates. The swell can propagate a long way from the area where it was generated. It is characterized by a significant height, period and direction.

2.3.2.2.3. Water clarity or turbidity

Depending on its origin (karstic networks, fissured terrains), continental water in its natural state can be more or less full of suspended particles or colloidal matter (clay, silt, organic and mineral matter, metallic oxides, plankton, etc.). The cloudiness of water caused by these particles is termed turbidity, its unit is the NFU[9] and the tool commonly used to measure it is the turbidimeter.

Water turbidity does not pose a direct health hazard in itself, but it has the drawback of offering shelter to micro-organisms within the particles. It can also cause the water to change color. The consequences of turbidity have to do with the weak penetration of light and ultraviolet rays into the water, which entails an interruption of photosynthesis in deep waters and the development of bacteria. The absorption resulting from sunlight also affects temperature and the oxygen content.

Turbidity is a significant ecological factor, which can result in:

– a significant amount (normal or abnormal) of suspended matter (for example following erosion, leaching of fragile, damaged or cultivated but bare soils);

– a high plankton content;

– pollution or eutrophication of water, which may asphyxiate (through anoxia) the environment or clog the gills of fish.

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[9] Nephelometric formazine unit.

2.3.2.2.4. The indicators of phytoplankton biomass

Phytoplankton is the vegetal part of plankton, the latter grouping together small-sized animal and vegetal organisms which move mainly under the influence of currents. Phytoplankton constitutes the basis of the food web in the marine environment and is an indicator of the ecological quality of bodies of water. It can develop very quickly and provokes blooms which occur when the environmental conditions are favorable.

This biomass can be assessed by means of fluorescence measurements, which allow us to find the concentration of chlorophyll and chromophoric dissolved organic matter or dissolved organic matter. The other indicators are abundance of species and the presence of pests, which require field measurements[10].

2.3.2.2.5. Contaminants[11]

There are several contaminants identified as risks. Among them are metals such as cadmium and mercury, volatile substances such as benzene, hydrocarbons, biocides like TBT, pesticides, organic contaminants such as the PCBs (pyralene), the polycyclic aromatic hydrocarbons often resulting from incomplete combustion, cosmetic molecules and residues of pharmaceutical products, without taking into account plastic and micro-plastic, which result from the un-ecological management of our waste. These contaminants are typical of human and industrial activity. They are mostly transported by rivers and can be found in water or in coastal sediments.

2.3.2.3. *Continental inputs and the freshwater–seawater continuum*

The coastal ocean can be defined as the part of the ocean influenced by the continental shelf and land, which is therefore strongly affected by human presence[12]. In coastal areas, most nutrient and contaminant inputs (estimated at more than 80% of the total inflow) originate from rivers which themselves retrieve the supply of drainage basins. The good ecological management of coastal waters implies a good knowledge and constant monitoring of the evolution of these land intakes. On the coasts of metropolitan France, inputs derive mostly from the four big rivers which channel a significant surface of

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[10] See [MON 14a].

[11] See [MON 14a].

[12] See [MON 14c] and [MON 14a].

drainage basins: the Seine, the Loire, the Gironde-Garonne-Dordogne and the Rhône rivers. Monitoring how their water spreads, from the estuary up to the complete "dilution" in the coastal ocean, is therefore fundamental to understanding the dispersion and/or concentration of nutrients and contaminants, all the more so as the near-shore region is subjected to strong currents which accelerate dispersion and transport.

The temperature and density of fluvial freshwater differ from those of seawater. Mixing between these freshwaters and seawater is faster as the sea is stratified. Strong whirlpool currents and the force exerted by the wind accelerate this blending. It is not rare to identify bodies of water with low-salinity content deriving from rivers hundreds of miles from their estuary. This is the case for the waters of the Loire, which can be found in the western part of the Channel. The water framework directive has administratively determined a survey of the quality of freshwaters and near-shore waters up to 2 miles away from the coast. Surveys farther off are taken over by the marine strategy framework directive (MSFD).

2.3.2.4. *Coastal morphodynamics*

Oceanic circulation on the continental shelf and in the littoral environment, the contents and nature of suspended particles and turbidity heavily depend on the morphological nature of the ocean floors and, in particular, on the characteristics of the superficial sediments that lie on them. Some of these floors are relatively stable, but others evolve more rapidly under the influence of currents and phenomena of re-suspension or deposition. It is, thus, important to monitor these properties by means of bathymetric analyses carried out through acoustical multi-frequency sounders which penetrate to a greater or lesser extent into the superficial sediments, potentially using satellite imagery analysis for shallow floors. Satellite imagery analysis as well as some optical measurements (for example cameras) also allows us to assess the evolution of beaches and lagoon bars. Currents and the properties of waves are measured through analyses performed by means of high/very high frequency radars with typical horizontal resolutions of a few kilometers. Current measurements can also be made from anchoring points, for example with high-frequency Doppler echo-sounders to obtain a good vertical resolution; the amplitude of the signal is also sensitive to the properties of suspended particles. Lastly, pressure measurements at the bottom of the ocean allow us to monitor storm surges or long waves and swells.

2.3.2.5. *Benthic habitats, populations and resources*

On a regional or local scale, the ocean floors are ecosystems that give rise to other scientific questions and operational necessities. To characterize certain benthic populations and resources, we need to know their habitats. The notion of habitat is employed to describe the characteristics of the environment in which a population of organisms of a given species (or of a group of species) can normally live, feed and reproduce.

The habitat is the geographical environment where a set of animal or vegetal species live. Abiotic environmental factors are mainly temperature, salinity, pressure and the nature of the floors. To define these habitats, apart from the physicochemical parameters, we need to know their topography and nature. To this end, we employ laser or video airborne imaging to measure them on the foreshore or through very shallow waters or we use bathymetrical data (produced by a multibeam sounder or sonar) in addition to *in situ* optical imaging with towed cameras.

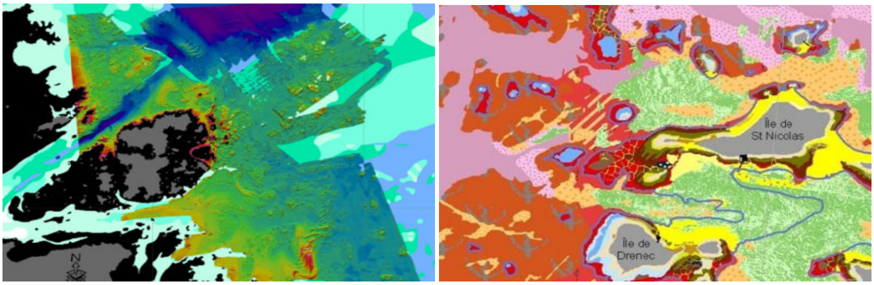

Figure 2.3. *Examples of bathymetric maps (on the left) and of marine habitats (on the right). Source: MESH project (Mapping European Seabed Habitat). See color section*

2.3.3. *The ocean floors: substratum and population*

Ocean floors represent no less than 70% of the solid surface of our planet. They can be seen from several perspectives in relation to different scientific and/or operational questions.

On a large scale, seabeds are evidently the interface between the "solid earth" (core, mantle, crusts and sediments) and the ocean, one of the fluid layers of the Earth's system. Several major scientific and operational questions have to do with them.

2.3.3.1. *The geodynamic functioning of the planet: plate tectonics*

Because of the way they stretch on the earth surface, ocean floors are natural archives that are useful to the understanding of geodynamical phenomena that result from plate tectonics, a theory that established itself in the 1970s. The discovery of the great mid-ocean ridges and their volcanic nature revealed the mechanism through which the oceanic crust was formed and how oceans expand. At the same time, the discovery of oceanic trenches adjacent to continental volcanic ridges revealed the collision between oceanic and continental plates, the disappearance of the oceanic crust by subduction and the creation of the continental crust. However, our understanding of local phenomena is still rather partial and must be tackled on an increasingly finer spatial scale, each zone being different from the other. Bathymetric data are the source data for these studies. Acoustic methods allow us to go back to the nature of the substratum, its density or the presence of faults in the upper crust. These measurements do not need to be made every other day, but there are areas that are still insufficiently charted or must be mapped with more spatial resolution.

2.3.3.2. *Seismic and volcanic monitoring*

The field of seismic and volcanic observation is the one in which the interests of research and those of operational monitoring are linked most closely. This holds true as much for dry land as for areas at the bottom of the ocean, especially when they are close to inhabited areas (islands and coastlines).

On one hand, observation has a warning function for civil security, as well as for research aiming to set up plans for a local and meticulous analysis of the processes occurring during the phenomena of paroxysm. On the other hand, frequency analysis of observation data reveals new information on the temporality of these phenomena (Figure 2.4).

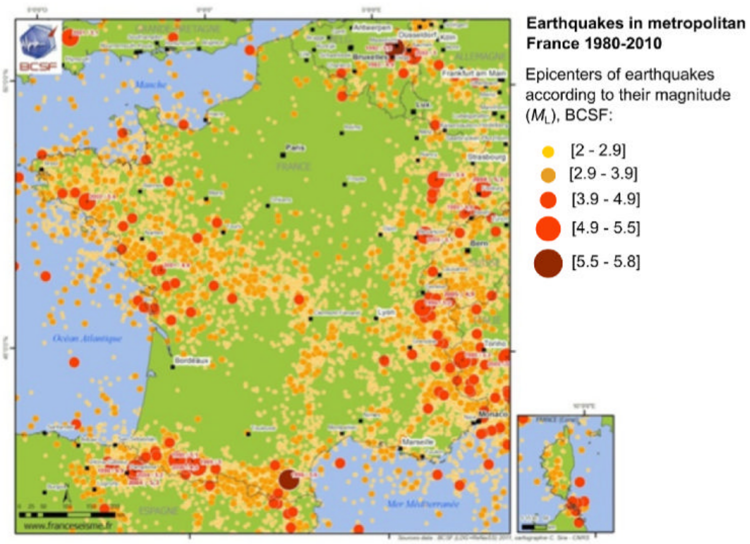

Figure 2.4. *Earthquakes in metropolitan France (source: RESIF network, www.resif.fr)*

2.3.3.3. *The monitoring of gravitational phenomena*

Gravitational phenomena are those catastrophic submarine events linked to destabilization of material on a slope. For example, it could be a significant sedimentary mass accumulated on the edge of a continental platform which, after becoming unstable, may detach itself during an earthquake (weak or strong) or a climate event originating from a submarine sedimentary avalanche (potentially canalized through a canyon). As a result of oceanic global warming, the thawing of methane clathrates (water and methane ice) contained in certain sediments on the continental slopes can also produce gravitational destabilizations. Another phenomenon has to do with the fragility linked to faults affecting the stability of the slopes of some large oceanic volcanos, as is the case in the Canary Islands, which bring into play very significant volumes of matter (hundreds of km^3). Like submarine earthquakes, such events can potentially give rise to tsunamis, which is why we should, as far as we can, have monitoring networks available that allow acoustical monitoring (hydrophone) and geodesic measurements (tri-axial geophone) integrated in seabed stations in areas where unpredictability is more significant (Figure 2.5).

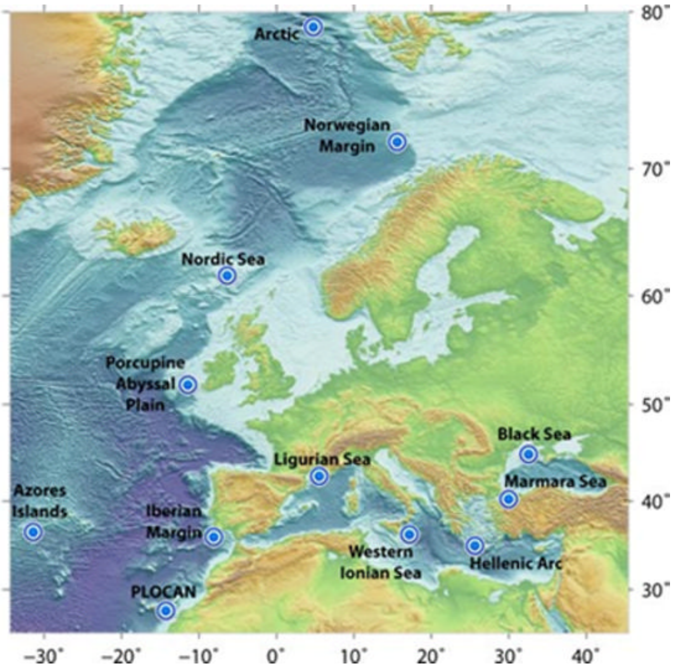

Figure 2.5. *The European Multidisciplinary Seafloor Observatory network*

2.3.3.4. *Exchange flows and mineralization*

The floors of the oceans are where significant matter exchanges, which contribute to the regulation of the Earth system[13], take place. Mid-ocean ridges are areas of tectonic expansion and oceanic crust formation, where the related volcanic phenomena link the newly-formed basalt to the external terrestrial environment. This contact, established either directly with seawater or indirectly through porous waters circulating in the sediments and the superficial oceanic crust, causes the recycling of some elements which play a significant role in certain regulations of the Earth's system. This is for example the case for the regulation of the main properties of seawater (pH, salinity, alkalinity, buffer power), which constitute the basis on which the properties of the Earth's living world and climate have been progressively adapting. This source of matter deriving from the earth mantle is evidently matched by a well. This is essentially the phenomenon of plate

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[13] See [MON 15].

subduction, which drags with it the crust as well as a part of the sediments that lie on it and the associated interstitial water, which gives rise to a well. Without this form of long-term regulation (the average length of a tectonic cycle is about 70 million years), life on the planet would have most likely been unable to continue and would have taken a very different shape. In particular, no living organisms using skeletons or calcareous shells would exist.

The ocean floor collects flows of solid particles (sedimentation) resulting from continental erosion and the primary biological production of the ocean (photosynthesis), which only takes place in the superficial layer exposed to sunlight. As sediments contain certain elements indispensable to life (N, P, Fe, trace elements, etc.), it is quite fortunate that the tectonic cycle can give rise to a kind of recycling without which life would not have developed. Naturally, these great phenomena are not observable in the way we mention in this chapter. However, they give rise to particularly interesting local phenomena that may require observation.

The interstitial waters circulating in the sediments and in the upper part of the oceanic crust dissolve elements and face strong contrast in physicochemical conditions (redox gradients) at the interfaces with free seawater. Some dissolved elements can then go back to their solid phase as mineral concretions, either by entering oxidized conditions (relatively insoluble oxide concretions) or by entering reduced conditions (concretions of barely soluble reduced compounds, especially sulfides). This is for example what happens near deep hydrothermal sources in the mid-ridge ocean areas, or at the surface of certain sediments (polymetallic nodules, encrustations, formation of pyrite, etc.). Such concretions constitute deposits with economic potential. However, sustainable exploitation of these deposits requires a thorough knowledge of the mechanisms of their natural formation and a good understanding of the ecosystems in which they are positioned in order to be able to assess the ecological consequences before any decision is taken.

2.3.3.5. *Methane clathrates*

The thawing of methane clathrates has already been briefly mentioned as a possible cause of gravitational destabilizations (section 2.3.3.3). Apart from this particular unpredictable occurrence, the potential large-scale melting of submarine methane clathrates poses a great risk in terms of acceleration of the intensification of the greenhouse effect and, consequently, global warming. This is a matter that requires the elaboration of an *ad hoc* observation strategy. As we cannot work on the set of continental slopes (out of reach given our abilities), we should focus on some sentinel areas on the basis of our knowledge about deep-sea dynamics and their known variations.

2.3.3.6. *The water–sediment interface*

The water–sediment interface is where sometimes intense matter exchanges between the sedimentary column and the water column take place. These exchanges are affected by several types of processes: sedimentary, macrobenthic, bacterial, and physicochemical. In a short timescale, they are particularly significant in coastal or near-shore areas where they partly determine the quality of the overlying waters and benthic ecosystems, especially through the capture or liberation of toxic chemical species (heavy metals and organic molecules). At longer timescales, these exchanges, together with those taking place on the slopes of continental platforms, play an important part in the assessment of CO_2 and the greenhouse effect. This state, for a sedimentary flow settling in a given place, depends on the proportion of organic carbon in relation to inorganic carbon (essentially carbonate).

Thus, several research problems arise in relation to the processes occurring at the water–sediment interface as well as in the superficial part of sediments which is affected by the biological processes of bioturbation and bacterial degradation. These degradations are aerobic (when dissolved oxygen is still available) or anaerobic (when other chemical species have to be employed instead of oxygen for bacterial respiration). The trapping or liberation of dissolved chemical species (and their diffusion towards the surface) also depend on the redox conditions. Redox gradients therefore play a very important part in these processes. They are quite evidently heavily affected by the flow of metabolizable organic matter which settles and degrades while consuming first the available oxygen and then the other oxidants (nitrate, sulfates, iron or manganese oxides or hydroxides, the oxidant functions of the organic matter itself, etc.). However, they are also determined by macrobenthic activity which not only depends on the presence of oxygen for its own respiration but also serves as an oxygen carrier in the sediments through bioturbation.

Nowadays the observation of sedimentary, biological and biogeochemical processes at the water–sediment interface essentially focuses on research problems which aim to understand their interactions. It is a matter of more precisely predicting the purifying and resilience abilities of shallow marine ecosystems, and of understanding the role played by the margins with large biological production in terms of wells or CO_2 emissions.

From a logistical perspective, observation is carried out by means of core-sampling operations, the deployment of benthic chambers allowing us to measure the rate of breathing and other flows, and vertical instrumentation of the sedimentary column (physicochemical measurements, image analysis).

2.4. Satellite contribution to observation strategies

Satellites are vital tools for the observation of the marine environment and it is impossible to imagine, at least in superficial oceanic layers, systems that do not take into account the measurements contributed by satellites. The range is very wide: from the estimation of surface winds, waves, the cover of sea ice and its properties, the temperature of the sea surface, chlorophyll-A and other optical properties of surface waters, to the measurements of sea levels and, more recently, the gravitational field (of the marine geoid) or salinity. These satellite measurements are all characterized by the fact that they define the surface (a relatively shallow layer, according to the sensor) and not the depths of the ocean. It is somehow a boundary condition for the inner ocean, which can only be directly observed through *in situ* measurements.

Let us briefly recall the characteristics of the different satellite observations of the sea and its surface so as to illustrate how they complement *in situ* observation. Measurements of oceanic temperature obtained by radiometers with different frequency ranges (from infrared measurements sensitive to the presence of clouds, to microwaves used by multi-frequency radiometers with more continuous ranges but less precise spatial resolution, typically in the range of several tens of kilometers) have been taken since the beginning of the 1980s and with increasing precision since the 1990s. These different observation interplays require *in situ* temperature measurements close to the surface in order to be calibrated. The definition of superficial layer is certainly tricky, because of the potential presence of strong temperature gradients in the first microns (skin effects for infrared measurements) up to the first centimeters (stratification between sub-surface and deeper layers, in particular during the day with solar heating).

Measurements of sea ice are also fairly diverse. The most common are concentration measurements obtained at high spatial resolution with different sensors (infrared and visible, or microwaves). One of the difficulties entailed by these measurements consists of properly separating seawater from the melted water on the ice at the end of spring and in summer. Other satellite measurements, which are more complex to analyze and on a shorter timescale, allow us to find some properties of sea ice (depth, age, etc.).

Satellite wind measurements, especially since the beginning of the 1990s, have been measuring the properties of short waves or sea roughness on different spatial scales. These measurements are taken with passive (radiometric in microwaves) or active (for example C band radars) instruments, the respective properties of which can be quite different, despite all being related to the wind close to the sea surface and depending on the displacement of the sea surface. Some of the difficulties involved in relating these measurements to those obtained through *in situ* observation lies in removing the effect of surface currents and the stratification between measurement level and the surrounding sea surface. *In situ* measurements play a very significant role in calibrating the different sensors and making them interoperable. Measurements of wave/swell heights have also been available for two decades, taken with several instruments (typically altimeters). Besides, the properties of wave displacement (which also constitutes a source of information about surface currents) can be assessed by means of synthetic aperture radar radar measurements, even if this information is not being used systematically.

Altimetric measurements of sea levels, whose precision has typically been in the order of centimeters since 1992, have provided oceanographers, physicists, and dynamic experts with essential information about average- and large-scale (100 km or more) oceanic variability. As we have mentioned, the slope of the sea surface is linked to the surface “geostrophic” current (slightly less directly at the equator). Sea levels include a heavy contribution of the density of oceanic (steric) seawater. In certain areas of the planet on scales ranging from the mesoscale to the gyro-scale[14] (1000 km or more) this steric signal is the main contributor to the variability of sea levels on timescales ranging from several days to a few years. We therefore have an integrated measurement of local density and an estimate of surface “geostrophic” currents. One of the limitations of altimetric satellite measurements, besides those linked to the precision of the reproduction of sea levels, consists of the fact that data are temporally and spatially limited at the nadir[15] of the satellite. Therefore, ocean variability is not sufficiently sampled by such an instrument. Ever since the beginning of the era of precise altimetric missions (end of 1992), several of them have been carried out in tandem, providing an increased resolution. By cleverly combining the data from different missions, it is therefore possible to chart the variability of the sea surface on scales sometimes smaller than 200 km and 10 days, and, consequently, to indirectly get a mesoscale overview of the surface circulation (by means of the geostrophic relation between the areas measured).

On a statistical basis, we have been able to associate the observations of surface sea levels with vertical density profiles and, by assuming an average relationship between temperature and salinity, with some profiles of these variables T and S. This statistical relationship has been established in relation to *in situ* profiles. *In situ* data can also provide us with information on the deviations in the temperature-salinity relationship, at least on larger scales, and on the deviations of the profiles obtained by altimetric measurements. Up until very recently, altimetric satellite observations only allowed us to directly obtain information about the variability of sea levels and altimetric circulation; the average was obtained by analyzing *in situ* data from the same period (mainly data on buoy drifting or density profiling).

Only recently, gravimetric measurements of several satellite missions have allowed us to put a geoid (a surface of iso-gravity) more directly in relation with a reference ellipsoid, which enables us, in combination with altimetric measurements, to obtain a direct measurement of the sea level associated with this geoid and, consequently, an absolute estimation of oceanic circulation.

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[14] It corresponds to an enormous whirlpool of oceanic water formed by a set of marine currents and caused by the Coriolis force.

[15] The point on the celestial sphere representing the descending vertical direction.

Lastly, multi-frequency observations in the visible range have allowed us (when there are no clouds) to obtain different pieces of information about the optical properties of the sea, enabling us to obtain estimates of chlorophyll pigments as well as of coccolithophore blooms, colored organic matter, and even the distribution of large phytoplankton groups.

These observations necessitate concomitant *in situ* measurements in order to calibrate the data and to interpret them quantitatively in terms of the concentration of these variables in the ocean or primary production (for the pigments). Since 1997, they have revolutionized our understanding of oceanic primary production and, despite being sensitive to overcast conditions, have allowed us to obtain a spatio-temporal vision unmatched by classic means of observation. Even if phytoplankton production tends to concentrate close to the surface in a significant portion of the ocean, the vertical structure of this production, below the layer a few meters deep observed by satellite measurements in the visible range, varies considerably and relies on the availability of nutrient salts and on oceanic stratification, particularly in the oligotrophic regions of the ocean. *In situ* data therefore play an essential role in providing information about this vertical dimension.

2.5. *In situ* observation

The other way of studying the ocean is direct: at the surface and in the water column, in order to measure, observe, and obtain information, which is what an *in situ* observation is. We can distinguish several types of measurements depending on whether we move in the environment with the body of water (Lagrangian measurement) or we remain in a geographically fixed position to analyse the evolution of the environment at this site (Eulerian measurement).

2.5.1. *Lagrangian measurements at the surface and in the water column*

2.5.1.1. *Buoys and profilers*

The observation of the ocean through Lagrangian measurements has been long established, both at the surface and below it, a passive way and as a “tracer” of oceanic circulation. Since the mid-1970s, GPS systems have allowed the monitoring and transmission of data form instruments located at the surface of the oceans (first with the Argo system). This has enabled the development of drifting buoys fitted with floating anchors to monitor surface currents as well as to take measurements of meteorological or oceanic interest, such as surface temperature, atmospheric pressure, winds, the partial pressure of carbon dioxide dissolved in seawater, surface salinity, the wave spectra, or sub-surface temperatures along instrumented chains suspended below the buoys (Figure 2.6). These buoys, together with the Global Drifter Program, now form an important component of the networks that structure observation of the oceans and the meteorology of the surface (around 1000 buoys are in operation in the oceans), a privileged area for the exchanges between atmosphere, ocean, and ice, which heavily affect the climate system.

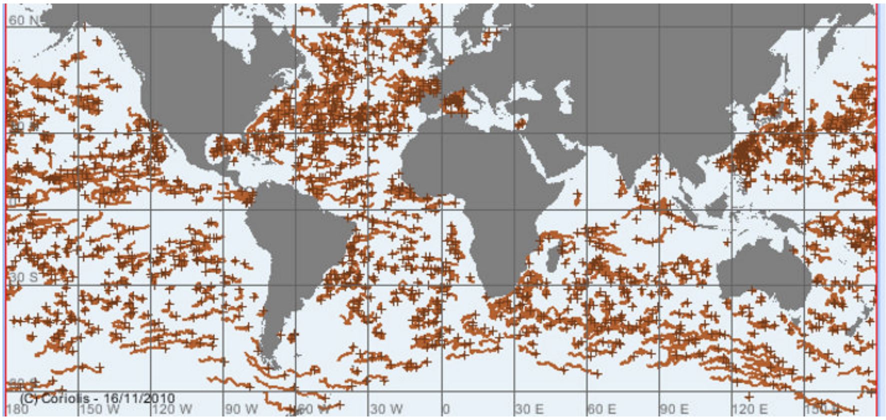

Figure 2.6. *A map of the distribution of surface floats (Argos system)*

In addition to these buoys, merchant ships are fitted with thermosalinographs that allow us to enhance the resolution for commercial sea lanes (Figure 2.7).

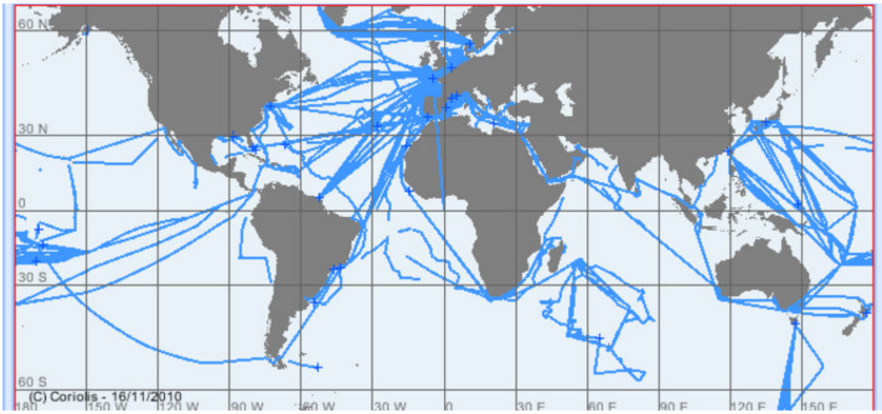

Figure 2.7. *Networks of measurements taken by merchant ships fitted with thermo salinographs (source: http://www.coriolis.eu.org)*

The ability to transmit via satellite (initially limited in terms of output and volume, but recently offering more potential) has also been very useful for the development of other Lagrangian vehicles. Since the 1950s, we have been able to acoustically monitor, by means of sources/receivers located on moorings, floats set up to reach a prescribed pressure level. This technology was difficult to implement, since it was necessary to retrieve the acoustical sources to access the data. At the end of the 1970s, when we acquired the ability to make use of surface positioning and data transmission, new floats were developed which retrieved the acoustic signals emitted by sources installed in the sea on moorings and relayed the data at the end of their cycle while they resurfaced (Rafos floats). From these initial floats, other systems have been progressively conceived. This is the case for multi-cycle floats, which go back down after transmitting the data, developed at the beginning of the 1990s (MARVOR systems in France, and ALACE system in the United States for the World Ocean Circulation Experiment international program). For practical reasons and due to experimental costs related to the moorings of acoustic devices, the United States chose ALACE systems to discard acoustic tracking while calculating the estimate of the drift between two surface trackings. In the mid-1990s, it seemed wise to take advantage of this regular transit ability between the drift level and the surface to place instruments on floats and gather profiles during these phases of rising and diving (the first implementations involved the measurements of parameters T and S). These developments gave birth to the ARGO program floats, whose most used data have to do with profiles, even if the drift information is always considered interesting (Figures 2.8 and 2.9).

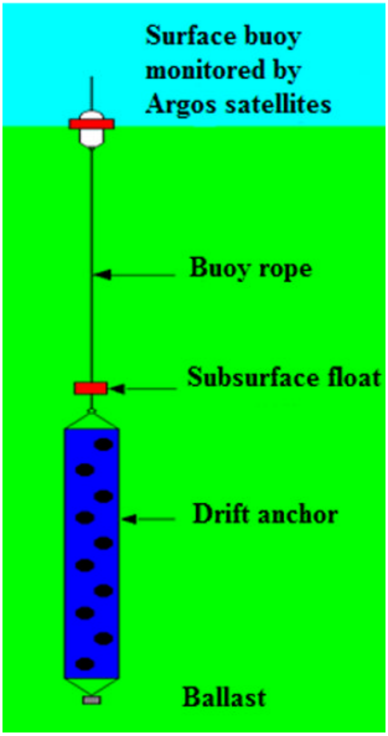

Figure 2.8. *Simplified diagram of a drifting buoy followed by the Argos satellite*

Since the beginning of the 2000s, the ARGO international program has instrumented oceans all over the planet (with the exception of some ice-covered regions and shallow seas) with a flotilla of more than 3000 floats, taking profiles every 10 days and up to 2000 m deep. These instruments are fitted with precise and reliable pressure, temperature, and salinity sensors, and are subjected to particularly intensive monitoring in order to identify potential bias in the data (Figure 2.10).

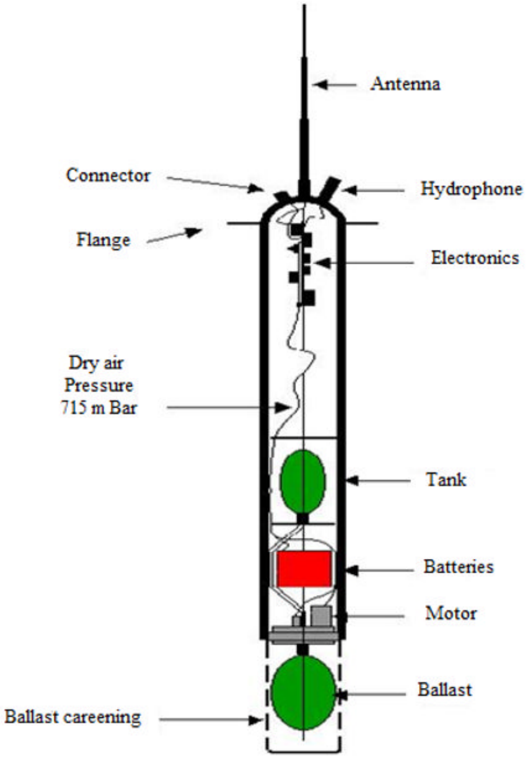

Figure 2.9. *An example of the structure of an ARGO deep-sea profiler*

Individual floats have a lifespan of at least 5 years but their slight drawback, considering this good longevity, is the fact that we obtain a stable conductivity measurement (which constitutes the basis on which we estimate salinity by taking into account temperature *T* and pressure *P*). This measurement evolves, leading to bias which is hard to correct. For the parameters *T*, *S*, and *P*, there was a wide range of different low-consumption sensors. The abilities of these sensors have grown to include other parameters like dissolved oxygen and, more recently, bio-optical measurements of fluorescence in two wavelengths (to estimate Chlorophyll-a and chromophoric dissolved organic matter) and profiles of light irradiance, absorption, and transmission, or even the concentration of nitrates (see section 2.2.2.3).

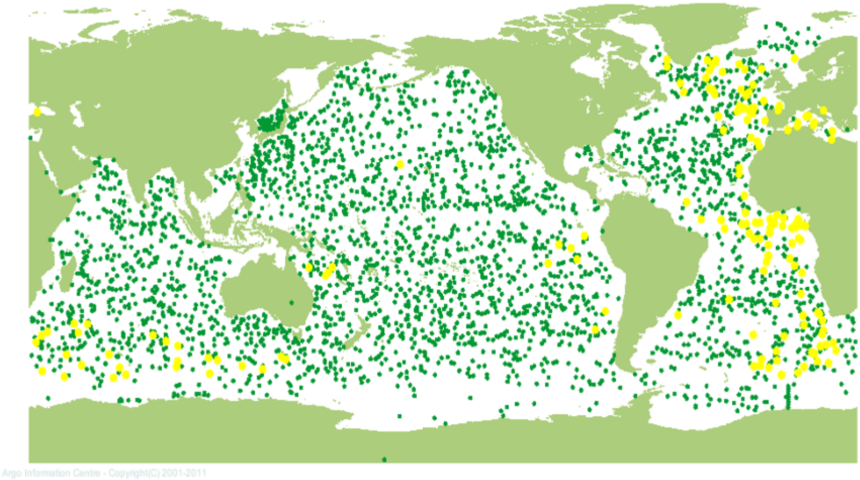

Figure 2.10. *ARGO floats in operation at the end of 2010 (those submerged by France are shown in yellow). See color section*

An original source of information on the environment can be obtained by taking advantage of the behavior of some marine animals that have been instrumented. Measurement programs generally combine research goals concerning the ecology of these animals and the oceanographic description of deep water bodies. We cannot define these living vehicles as either Eulerian or Lagrangian. They have fishing and living behaviors that dictate their movements, just as much as the physical or alimentary conditions. The most regular and numerous measurements have been taken on marine mammals, whose instinct to return where they were born or mate allows us to retrieve certain instruments, but also to recover the data after locating these animals during their prolonged presence at the surface. Elephant seals, but also other species of seals, have been instrumented since they travel long distances in the sea over several months. They often dive to significant immersion depths, which can exceed 500 m for elephant seals. They migrate to regions such as Antarctica, that are completely covered in ice in winter, or the continental shelves of Arctic or Antarctic. They also explore marine environments such as some fronts of the austral circumpolar current, which are particularly interesting because of their biogeochemical functioning. The instrumentation they carry to measure their surrounding environment allows us to obtain profiles of P, T, S, sometimes oxygen, illumination, or chlorophyll fluorescence. Other animals have also been instrumented. This is the case for whales, but also for large pelagic fish such as tuna or marine reptiles such as certain sea turtles, but their features make the collection of data and the retrieval of instruments riskier (Figure 2.11).

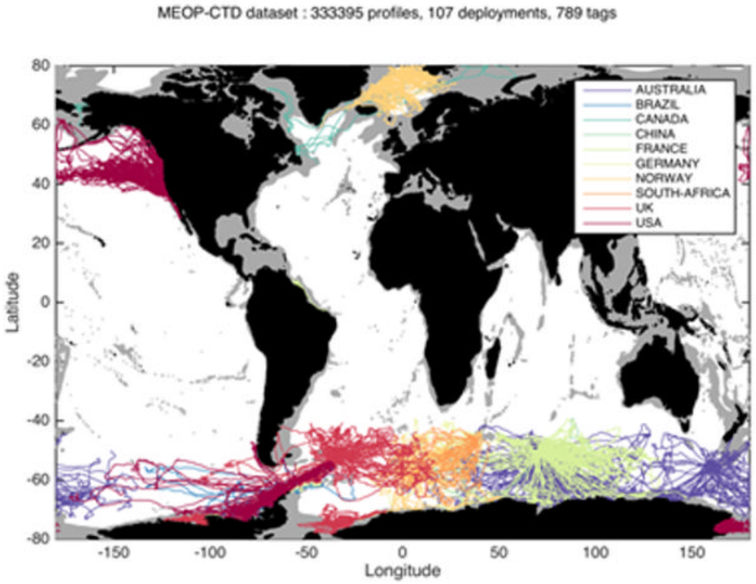

Figure 2.11. *Distribution of profile measurements taken by instrumented marine mammals in the circum-Antarctic area (source: meop.net). See color section*

We are currently testing other sensors for the measurement of dissolved nutrient salts or the partial pressure of CO_2 which could soon be attached to these Lagrangian vehicle[16].

2.5.1.2. *From floats to gliders*

In the 1990s, we saw the development of light vehicles that control their buoyancy in order to take vertical profiles and navigate thanks to compasses

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[16] We have also seen the development of acoustical measurements (to estimate remotely wind and rain) and, in the near future, we could see the appearance of new sensors for the measurement of turbulence through microstructure or for high-resolution imaging by means of video cameras. Let us point out that these new applications often involve significant vertical resolutions and the transmission of larger data streams. Since Argos cannot meet this requirement, other means of transmission, such as iridium, are being employed.

and by gliding when making profiles. In a way, this is the logical consequence of floats (Henri Stommel's prophetic vision at the beginning of the 1980s[17]), while also drawing from submarine machines. These instruments, called "gliders", communicate with satellites when they surface and calculate navigation by means of instructions received and precise measurements of their surface position. Since the end of the 1990s they have gradually become vehicles able to collect interesting data. They are not Lagrangian vehicles, even if they are strongly subjected to the effects of currents and their speed does not exceed 0.5 knots (Figures 2.12 and 2.13).

Figure 2.12. *The French SEAEXPLORER "glider" (source: AUVAC)*

Figure 2.13. *European Center of Submarine Technology "glider" fleet (source: Ifremer; picture: INSU®)*

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[17] Researcher at the Woods Hole Oceanographic Institute.

The experience acquired over the last decade has allowed us to develop some strategies to measure physical structures, such as certain mesoscale whirlpools, or even to cross the large western boundary currents using these instruments. Due to their economical locomotion and small size, they have a significant autonomy that ranges from 2 to 6 months, which allows them to gather a significant stream of profile measurements thanks to sensor batteries of the same kind as those used in the ARGO floats. They are easy to launch and to retrieve. They can generally dive down to 1000 m, which makes them interesting machines for missions leaving from coastal areas and destined to be repeated several times over the year (Figure 2.14). They have also become important aids in operations dealing with dynamic or biogeochemical oceanography. Their integration into the data gathering networks is harder to structure, since they are mainly used in regional or coastal observatories or during scientific missions, although uses on a larger scale are also under development (for example within the framework of the monitoring of thermohaline circulation in the Labrador and in the Irminger Sea).

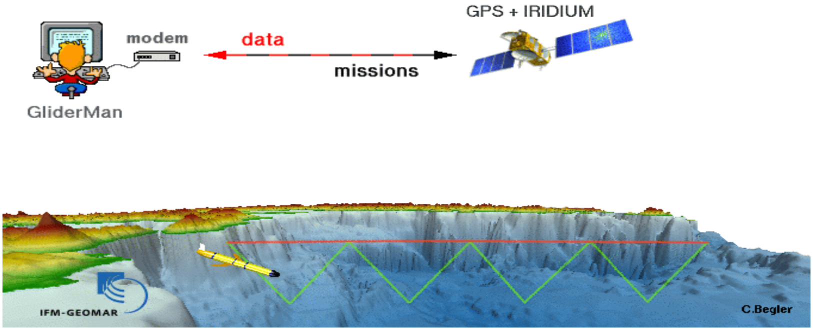

Figure 2.14. *Working principle of a "glider" (source: IFM-GEOMAR). The "glider" dives into deep waters (up to 1000 meters) and then resurfaces, all the while measuring physicochemical parameters. Upon reaching the surface, it sends the data obtained during the submersion to a satellite and recovers information from the control center, piloted by a "gliderman", for its next dive.*

"Wave-gliders", i.e. surface vehicles, have also recently been developed and can move by taking advantage of the vertical movements of waves and so they benefit from a significant energy source. These vehicles, which allow us to take measurements of the surface of the oceans down to the subjacent superficial layer, including surface meteorological parameters, have proved their remarkable ability to cross the oceans. Their role in oceanic observation remains yet to be defined.

2.5.1.3. *From manned to robot submarines*

In order to observe at depths beyond a few hundred meters, i.e. the boundary of the measurements taken by gliders, the tools available to oceanographers besides the ARGO profiler – currently limited to 2000 m, but soon to reach 4000 – consist of submarine robots, ROVs, AUVs, but also manned submarines, which can descend to 6000 m. The oldest and most legendary of them is the *Nautile*, a manned submarine able to carry two pilots and a scientist for 8–9 hours underwater. This vehicle makes it possible to take pictures and videos in immediate interaction with the scientist (Figure 2.15).

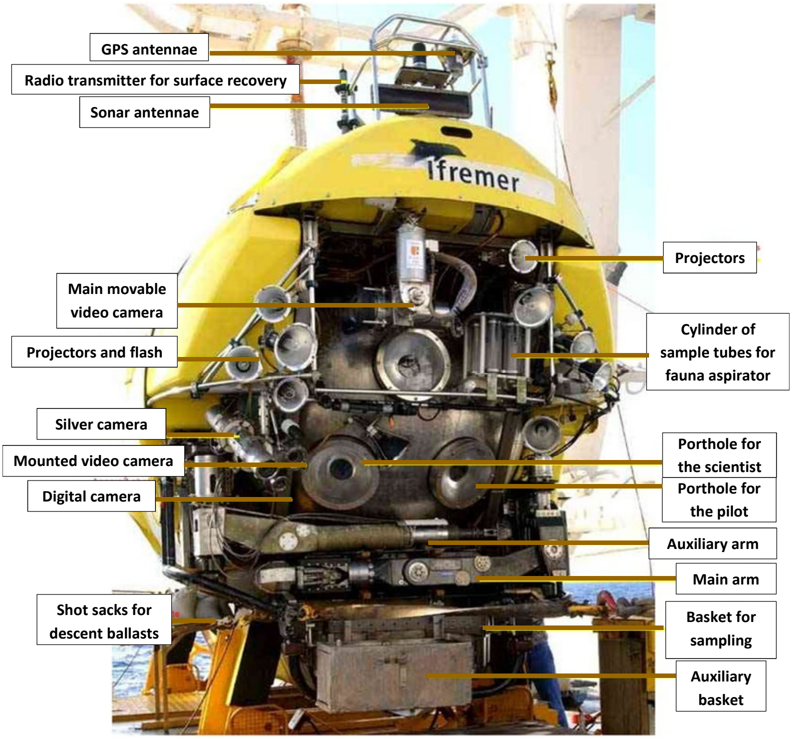

Figure 2.15. *Front view of the manned Nautile submarine (source: Ifremer – O. Dugornay)*

It also allows us to take samples of fauna, flora, cores, and to intervene on site as is the case for the interconnection of the ANTARES network of the IN2P3[18] off the coast of Toulon in the Mediterranean. The *Nautile* is set up by the research vessels *Pourquoi Pas*? or *Atalante*.

Thanks to ROVs like the ROV *Victor* (Figure 2.18), which dive down to 6000 m, and the AUVs *Aster*^{x} and *Idef*^{x}, which currently reach depths of 3000 m, we can sample water, sediments, fauna, flora, cores, but also include mapping and navigation systems (multibeam sounders, inertial measurement units, precise positioning [with a range of one to a few meters], physical and biological sensors, and high-quality video cameras and cameras. The *Victor 6000* is a remote-controlled vehicle guided by a surface ship. The AUV is unmanned: its mission and navigation are programed up front, before the vehicle is operated (Figure 2.16). It is difficult to interact with an AUV, whereas it is always possible to do so with a ROV. On the other hand, an AUV travels over much longer distances than a ROV. An AUV will be used more for scientific expeditions involved in regular monitoring, whereas a ROV will be more suitable for work in a fixed geographical location (Figure 2.17).

Figure 2.16. *View of the ROV Victor 6000 (source: Ifremer – O. Dugornay)*

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[18] IN2P3: Institut National de Physique Nucléaire et de Physique des Particules (National Institute of Nuclear and Particle Physics).

Figure 2.17. *View of the AUV Idefx (source: Ifremer – O. Dugornay)*

2.5.2. *Eulerian measurements*

2.5.2.1. *Ships*

Instrumented ships and, in particular, research vessels constitute one of the mainstays of oceanic observation. In this context, they allow to carry out precise observations in a diversity of thematic fields. These observations, once transmitted to global data centers, can be used as validation data for other measurements, whether *in situ* or by satellite. In certain fields, oceanographic research vessels remain the major source of observations: for example, in organic and nutrient chemistry, for biological or ecosystem-centered studies, in biodiversity, for ocean floor studies and in marine geophysics (bathymetric cartography, active seismic, core- and sample-taking, the launch of AUVs/ROVs). These researches allow us to deploy a significant part of the observation networks, whether fixed or drifting. They enable us to explore hard-to-access areas (the deep layers of the oceans, the slopes and certain continental shelves) and to carry out more precise monitoring in dynamically-active regions (in particular the currents along the slopes). Over their journeys, research vessels can collect significant observation and measurement interplays without interruption: the characteristics of surface waters (T, S, Chlorophyll A fluorescence, pCO_2, other chemical or biogeochemical types of monitoring), the measurement of currents with Doppler-effect acoustics, acoustical monitoring (for example to monitor zoo- and ichthyoplankton or small pelagic organisms), meteorological measurements, bathymetry through multi-trace echo-sounders, etc.). They can also tow profiling vehicles (moving vessel profiler, for instance) or take temperature sections with the disposable expendable bathy thermographs sounders (XBT).

Other instrumented ships are often merchant ships or ferryboats which travel on regular routes, but also sailing boats or cruise ships. With the exception of some measurements or means of exploration (seismic, ROV, AUV, bottles, core samples, etc.), in many cases the measurements taken on these platforms correspond to those collected during the journeys of research vessels. These ships are also often used to set up observation networks (deployment of buoys or floats) or to take temperature sections by means of XBT sounders. Some ships have been used for a long time (since the end of the 1930s) in the northern Atlantic for the filtration of large plankton out of surface seawater (used as a continuous plankton recorder), which are subsequently analyzed in a laboratory for studies on the distributions of zooplankton, biodiversity, or even chlorophyll pigments. More recently, other ships have been equipped with “Ferrybox” systems, i.e. standardized instrumentation that makes it possible to measure – besides physical data (T, C) – the chemical quantities of several constituent elements (carbon, nutrients, oxygen) but also of different contaminants, as well as other aspects of biological interest. More simply, some ships are fitted with temperature and conductivity probes (using the measurements taken from samples, as has been the case in France since the 1970s with the ORSTOM) or the instrumentation needed to measure the carbon dioxide dissolved in seawater (since the 1990s). These different systems are organized in thematic networks which structure observation on a global scale.

Some fishing vessels have recently been equipped so as to obtain certain parameters (temperature, sometimes salinity or turbidity) pertaining to the physical environment by instrumenting trawl nets. In France the effort put in for the RECOPESCA instrumentation and implementation, mainly in coastal areas for example. Data are not transmitted in real time, but upon returning to the port. The regulations governing fisheries will make the scientific instrumentation of fishing boats more common. The data gathered by fishing boats are therefore a major source of information on the distribution of fish, their size, their health, etc.

2.5.2.2. *Fixed platforms*

The fixed platforms of large observation networks include the moorings that were installed in a semi-permanent way in certain sites since the end of the 1970s. On continental shelves, these moorings were mostly surface moorings set up for the collection of meteorological or wave-related measurements, even though other parameters have since been measured. For example the Marel buoys were developed in France to be moored in a coastal or estuary environment, and measure a certain number of chemical or physical parameters. In the open-sea environment, the first networks consisted of tropical moorings set up for climate research, which measured atmospheric parameters and took temperature (and then salinity) profiles starting from discrete measurements on the vertical, sometimes associated with current measurements. These open-sea networks, i.e. TAO/TRITON, PIRATA, and RAMA, have been progressively set up over the past 30 years. These platforms can serve to support other measurements, for example those of pCO_2. At higher latitudes, fixed platforms, which are less numerous, have been conceived, as support for diverse and multi-parameter (physics, chemistry, atmosphere) instrumentation, even if only certain variables can be transmitted in real time. These different platforms, as well as specific moorings located in the strong currents of the slopes (sometimes combined with pressure inverted echo sounder acoustical measurements), are grouped within the OCEANSITES networks. Technologies are developing and it is becoming more and more common to have at our disposal on these moorings instruments that can take vertical profiles in the water column (on surface moorings this is by taking advantage of the movements induced by the swell and for subsurface moorings with instruments sliding along a cable and driven, for example, by changing their buoyancy). Let us also point out the presence of such moorings, in particular in Arctic regions, on the ice field or in areas seasonally covered in ice, which allow us to monitor the physical parameters of the upper layers of the ocean (T, S, oxygen, currents) and potentially some of the characteristics of the ice (thickness, temperature profiles). Some surface moorings have been placed above permanent observatories on the ocean floor in order to receive data transmitted acoustically and to relay it in real time via satellites. The data provided by observatories on the ocean floor can also be transmitted by cables, if these sites are not too far from the coast (for example, the “Antares” site off the Côte d’Azur, the “Neptune” network off the coast of British Columbia, or around the “Hots” station north-east of the Hawaii archipelago). Observations from these sites on the ocean floor can be of different kinds: physical or chemical measurements (currents, *T*, *S*, oxygen, but also nutrients, dissolved metallic elements, etc., and, in a coastal environment, the properties of sediments, the rate of sedimentation, etc.), but also ecosystemic (video cameras) and geophysical, most commonly by means of seismographs (either for tsunami warning systems or for instrumented sites such as MOMAR on the Lucky Strike region of the mid-Atlantic ridge), pressure gauges, or seafloor magnetometers.

2.5.2.3. *Tide gauges*

The tide gauge network started with the installation of sea level gauges in ports from the 18th century onwards. This network has progressively grown, covering numerous sites, mainly of tropical islands, especially in the 1970s and 1980s. The measurement systems have also often had pressure gauges. These tide gauges provide us with information about the measurements taken in relation to a substratum. In coastal areas, this substratum can present significant vertical speed, as a result of tectonic, seismic and eustatic (post-glacial rebound or subsidence) processes or, when its nature is sedimentary, because of the variations in the load of water or the transformation of sedimentary properties. It is therefore important to take absolute measurements of the altitudes of these instruments. This is currently being tried at most sites, at least in countries with an oceanographic tradition, which gives us significant information both about the use of these tide gauges in relation to sea-level rise and, in terms of geophysics, about the vertical movements of the instrumented sites. It is not always easy to link the coastal measurements of tide gauges with those taken by altimetric satellites, since their data are often less precise by the coast. On the other hand, comparisons have shown significant overlap between these two types of data, and the sea levels of tide gauges (corrected in relation to the vertical movements of the substratum) constitute a significant source of information to monitor the precision of altimetric measurements. Altimetric data also give us the opportunity to widen the statistical range of information on the sea levels provided by offshore tide gauges, which has been attempted over the past 60 years, in order to piece together the global variations in sea levels. A distinctly less dense network of pressure sensors at great depths also provides information on the variations in pressure associated with deep currents (in particular in the Austral Ocean or close to certain western boundary currents).

2.5.2.4. *Passive acoustics and seismic*

The data provided by passive acoustics is still being mainly gathered within the context of specific projects and not yet fully as part of a strategy of oceanic observation, apart from regional or "non-real time" projects, such as the monitoring of cetaceans and other marine mammals. This is not the case for seismic observations, owing to their application in tsunami warning systems. These observations are relayed to the surface either by cables directly onshore or by acoustics to surface buoys anchored close to the seafloor station (in this case the measurement is reduced in order to allow the transmission of the most relevant information). They are subsequently integrated in real time into surveillance and warning networks. Acoustic listening can also be used to measure the noise of waves associated with their breaking or the sound of the rain on the sea.

2.5.2.5. *Bathymetry and active seismic*

The surveys made are carried out less often with a view to long-term monitoring than out of the necessity to chart on the most appropriate scale certain marine structures as well as the whole of the seafloor. They are most often made by research vessels from the surface. However, in order to achieve bathymetric high resolution, we are using more and more instrumentation on ROVs or AUVs, which also allows us to make surveys on sites subjected to gravitational unpredictability. Data, at relatively low resolution, is pieced together in national, and then global, centers. Active seismic is used above all for geophysical purposes in order to have a better grasp of the geological structure underlying the ocean floor. More recently, this data has been used to better understand certain structures of the water column. Lastly, we can employ active acoustics, in addition to the monitoring and positioning of objects in the sea, to study the thermic properties or the currents of the oceans (by modulating the speed of sound through temperature or via the Doppler frequency-shift).

2.5.3. *Other significant parameters*

Several research questions, as well as operational oceanography, require so-called "complex" parameters. We will describe a few of them in this section.

2.5.3.1. *The measurement of the temporal gradient*

The variation speed of a parameter, in a given place, constitutes a dynamic vision of the evolution trend of the parameter which accounts for the observation. The deployment of an observation system and the acquisition frequency that characterizes it aim, in general, to monitor the variation of a parameter (simple or complex) under an environmental pressure, whether natural or anthropogenic. For example, the effects of global change on the temperature of an estuary (simple parameter) or on the reproductive abilities of a species living in this estuary (complex parameter) require constant, long-term, and low-frequency observation. In general, we make do with bimonthly measurements. On the other hand, effects involving rapid phenomena (storm, hurricane) can only be understood through high-frequency observation where data is obtained several times per day or even hourly. For example, a discharge of pluvial water to an estuary, deriving from a large city in a period of strong oxygen deficit (low flow combined with a tidal phase) can lead to severe anoxia, temporary but devastating for the whole ecosystem. Knowledge about the process and the speed at which it takes place can allow us to estimate with more precision the storage capacity of the purification network. In an operational mode, the observational monitoring of the system enables us therefore to postpone the discharge of pluvial waters to a more favorable moment.

2.5.3.2. *Biological and ecological parameters*

Fundamentally, the broad characteristics of living organisms (morphology, features, metabolism, reproductive and adaptable abilities, gene expression, behavior, etc.), the structure of populations and peopling dynamics (social or colonial organizations, food webs, etc.), and the links between living organisms and the physical and chemical environment (nutrients, contaminants, climates, habitats, etc.) are also particularly significant. Generally, it is not possible to measure them in real time, or even in non-real time at high frequency. For some of them, *in situ* measurements are not even possible and research is therefore endeavoring to develop experimental confined (to the laboratory, or close to the environment) systems from which some theoretical knowledge can be drawn and then reintegrated into models that can be applied to the understanding of natural or anthropogenic environments. In an ecosystemic context of research and monitoring of marine, coastal and littoral environments, one of the main issues concerns the definition of an observation strategy that can provide access to spatial resolution and the temporal gradients, while remaining significant on a biological and ecological level.

Several approaches are currently being developed. One pertains to the estimated measurement of primary production (phytoplankton or phytobenthos) which determines the nutritive condition for the development of heterotrophic populations[19]. This measurement is taken by means of an *in situ* quantitative analysis of chlorophyll or, more indirectly, through algorithms still to be improved, by spatial measurements of the water color and *in situ* marine optical measurements such as fluorescence. A second approach has to do with the observation of model organisms used as sentinels, sensitive to changes in the conditions of the environment. Once again, more thorough research is still necessary to identify these model organisms and to describe their profile as precisely as possible, even on a genomic and proteomic plan[20]. One of the challenges consists of finding biological features generic enough to make the "weight" of the individual lose its significance in relation to the species and to enable us to establish an univocal link between the variations observed and their causes. Lastly, a third approach consists of developing new sensors that can provide access to other characteristics of the living world, for example size structures in plankton by means of *in situ* high-frequency optical measurements, or the acoustical observation of certain biological activities.

2.5.3.3. *Chemical and ecotoxicological parameters*

Although we now have the technological abilities to measure *in situ* certain chemical parameters such as pH (acidity), the content of dissolved oxygen, major nutrients (dissolved inorganic carbon, nitrates, phosphates, silicates), or chlorophyll, this is not the case for the measurements of minor nutrients or trace elements, which are necessary mineral nutrients but, depending on their concentration and chemical state in water, may have a toxic potential. Lastly, several trace substances, most often of anthropogenic origin (heavy metals, pesticides, cosmetic or pharmaceutical products, etc.), are a source of widespread pollution which is very tricky to quantify and monitor *in situ*. However, certain technological developments are in the pipeline. They should enable us to make progress in this field. This is especially true for integrative chemical sensors, deployed in the environment, which provide an indication just as a cumulative dosimeter would do for radioactivity. However, these sensors do not assess fine temporal gradients. Only a measurement plan followed by laboratory

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[19] Heterotrophic populations: consisting of elements that do not synthesize their own organic matter, unlike autotrophic populations.

[20] Concerning the features of the proteins of a living organism.

analysis, on an evidently short timescale, can in this case deal with the research problem concerning the concentration dynamics and chemical state (adsorptions, complexes, etc.) of these contaminants and, consequently, the evolution of their potential ecotoxicity. Lastly, a major ecotoxicological issue concerns the “cocktail effects”, i.e. the increase in the toxicity of a contaminant for an organism living in precise physical and chemical conditions when exposed to other contaminants. The causal relationships of biochemical and cellular order behind these cocktail effects are still mostly unknown and several years of research in toxicology will be needed before we can make any predictions about this phenomenon. In the meantime, it would be best to deploy the necessary observation systems on the basis of empirical findings. However, this issue will be rather tricky, since it implies the simultaneous monitoring of some of the trace elements of the “toxic cocktail”. We have reason to think that integrative sensors and model organisms will be very useful aids in a very low-frequency approach (about a month).

2.5.3.4. *Sedimentological and coastal morphodynamic parameters*

At first glance, knowledge about the topography of the seafloor and the nature of the substratum has nothing to do with an observation strategy, in so far as these characteristics evolve only on the long term. In many areas, it is therefore enough to carry out bathymetric and lithological measurements to draw maps which are only updated every other decade or so. However, this is not the case for near-shore and coastal areas which, influenced by different factors (currents, tides, storms, rises, submarine avalanches, changes in the sedimentary flows transported by rivers, often together with the use and management of drainage basins), can be subjected to a rapid variation of their bathymetry, and even changes in the nature of their substrata (sand, mud, silt). This translates into erosions, accumulations, migrations of submarine dunes and bars, and evolutions of the coastline (beaches, cliffs). The observation of coastal morphodynamics is thus strictly necessary to understand these mechanisms and their causes, and to ensure monitoring and predictability. This knowledge is also the basis for the ability to expertly assess the suitability of coastal planning (urbanization, touristic or industrial establishments, protection works). Quite evidently, in this case an observation strategy is not limited to the acquisition of simple parameters (bathymetry, altimetry), but must also incorporate complex parameters such as the lithological composition of the sediments, the structure of benthic populations and the characteristics of their habitat, as well as the flows of solid matter transported by rivers (turbidity and nature of the particles). Such concerns are and must be dealt with by the main guidelines of EU management in terms of the environment, such as the WFD (Water Framework Directive) and the MSFD (Marine Strategy Framework Directive). Lastly, since it is a matter of understanding essentially morphodynamic mechanisms and their causes, it should be noted that observation, even of simple physical parameters (bathymetry, pressure, current flows), often constitutes a logistical challenge. For example, it is very difficult and dangerous to lead operations of physical and morphodynamic observation in the surf zone, especially during storms, when variation is most significant and rapid.

2.6. Observation strategies

2.6.1. *The "observatory" approach*

The observation of the oceans relies heavily, on the one hand, on the notion of observation networks, often structured in relation to the kind of measurement and spatially designed to cover a significant portion of the oceans. On the other hand, it also relies on the concept of observatories, structured more around multi-parameter instrumented sites or regularly manned stations, designed for multidisciplinary studies making use of the temporal series obtained. Observatories have allowed us to acquire long-term series. The variation speed of a parameter, in a given place, constitutes a dynamic vision of the evolution trend of the parameter, which drives the observation strategy[21]. The initial phase of observation can be modest and only deal with the simple parameters at sea surface, such as T and S, as was the case for the "Ellett Line". Since 1975, the information gathered has progressively expanded, mainly in connection with repeated operations on research vessels, which allowed us to obtain more diverse observations of a physical and chemical kind. Another of these old examples is the CALCOFI project off the coast of central and southern California, also centered on a strategy of observations made during seasonal researches on a pre-established set of sections. Since 1935 (the year when it started being operative), CALCOFI has had a multidisciplinary (physical chemistry, plankton, upper trophic levels, fish, etc.) purpose. Naturally, a part of these

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[21] Let us point out, among some old examples, some of the sites set up by meteorological observation ships in 1947-1948 and, in particular, the "OWS Mike" in the Norwegian Sea or the one that started the "Ellett Line" through the Rockall Basin.

monitoring operations have been completed, in recent years, by relying on other means of observation, such as moorings or instrumented gliders.

Instrumented sites have been implemented for over 30 years as moorings in the middle of the ocean. The most famous examples are HOTS (north-east of Hawaii) and BATS (south-east of Bermuda), which followed on from Hydro Station S (operative since 1954) as well as Boussole, located between Nice and Corsica. As required by some hydrographic research, these sites produce different kind of data (biogeochemical or physicochemical) with constant monitoring by means of instruments set on moorings and allowing us to observe a more reduced number of parameters (currently, these measurements are sometimes also taken by gliders). The measurements taken by these observatories give us a particularly interesting perspective on the long-term evolution of physicochemical properties and on the link between this evolution and the biological processes in action in biogeochemical cycles. Their significance lies in the fact that they offer an uninterrupted view of the oceans ranging from a rapid timescale to ten-year or even multi-decade evolution. They also give us the opportunity to carry out the testing of innovative instrumentation or to conduct experiments aimed at specific processes.

Ever since the 1980s, moorings networks have also given shape to observation systems “observatory-style” (multi-parameter). They are structured within the Oceansites program. Their large number, especially in tropical areas, allows us to categorize them as observation networks.

“Seafloor” networks have also been organized in permanently instrumented observatories for a decade. This is the case for the “Neptune Canada” network off the coast of British Columbia, centered on a network of sites linked by cable which ensure the high-speed transmission of information. A network of this kind, linking “seafloor” junctions, can integrate very diverse instrumentation of a physicochemical (T, S, dissolved gases, currents) as well as an ecological (video cameras, echosounders, acoustics), biological (samplers and incubators of microbes, zooplankton, etc., benthic chambers) and geophysical (seismometers, gravimeters, accelerometers, etc.) type. The instrumentation of these sites has often been driven at first by real-time monitoring operations of telluric accidents (originating tsunamis, for instance), and the aspect of real-time transmission is one of their very significant characteristics. They provide access, thanks to their array of very diverse instrumentation, to a wide field of multidisciplinary studies. The “Momar” observatory on the Lucky Strike segment of the mid-Atlantic ridge, south-east of the Azores, is another example of these “seafloor” observatories. On this site, real-time transmission is performed acoustically towards a surface mooring. Once again, the driving force behind this “real-time” transmission has to do with “hazard”, but it produces a cross-referencing of multidisciplinary information about an active volcanic site at the bottom of the ocean linked to hydrothermal sources.

Instrumented sites implemented in a coastal environment, often by a marine station, are also another kind of observatory. The starting point was often the implementation of hydrological stations, then completed by “seafloor” or mooring instrumentation. These easily accessible sites can gather observations overtime as well as conduct experiments on a shorter timescale. They can contextualize those monitoring operations that are carried out irregularly but cover a wider spatial network.

2.6.2. *Some examples of the complementariness of the measurements taken by networks*

It is interesting to note that the process of network structuring, implemented this way on an international level for logistical and methodological reasons or because of the organization of government agencies, is also in line, in a structured manner, with a global strategy of observation, modeling, or prediction of different quantities crucial either to scientific purposes or because of their application potential. As a “scientific” example particularly significant in the current context of climate change, the measurement of the ocean temperature relies on a wide array of *in situ* observation networks, whose complementariness is necessary to make sure of the spatiotemporal coverage obtained, in order to characterize accurately the variability of climate trends and the tendency to ocean warming (global assessment). Recently, this “climate” perspective stretched to include the measurement of the seawater salinity (to assess freshwater exchanges between oceans, continents and atmosphere). Integration is done on the basis of models that can be either statistical models, combining this information with the one provided by satellite altimetry (and other satellite measurements, such as surface temperature, sea ice, surface salinity) or, more directly, data-centric digital models of the ocean. It is important to point out that these systems simultaneously provide information on oceanic circulation, because of the “dynamic” interaction between this circulation, winds, and the density field (a function of T and S) of the ocean. In these different circumstances, let us point out that the interaction with satellite observations plays a very significant role, since it allows us to extrapolate spatially fairly localized oceanic observations, in a field often disrupted by oceanic eddies.

2.6.3. *What’s the point of modeling?*

It may seem odd to mention modeling in a chapter that deals with the observation strategies adopted in the marine environment. The kind of modeling we refer to can be qualified as operational and not as exploratory. It is designed to include quantitatively the main processes linked to the evolution of the marine environment observed and, potentially, to make predictions about its evolution (or at least to test its predictability). It is conceived on the basis of spatialized digital models and allows us to follow the evolution of the different parameters of the system, and, in the specific case of the physical aspect of the ocean, heat, water, or momentum exchanges. The complexity of these computer models can vary. They mainly have to do with the water column, but can sometimes be about the seafloor. They deal, on different levels, with the physical, chemical and biogeochemical aspects of the ocean, but sometimes also involve its ecological, ichthyologic, and even biological spheres.

These digital models, in which a significant portion of the community of researchers working in these fields are involved, have often achieved a degree of development that allows them to be used operationally. This is the case for certain models called physical models, which can be especially used to try to predict the drifting of objects on the sea surface or storm surges. They are important tools that can complement research/rescue operations, but they also come in handy in the case of extensive surface pollution (for example caused by hydrocarbons) or to estimate coastal hazards during intense storms. Within such a context, these models are combined with predictions about the atmosphere (provided, for instance, by medium-term [ten days] forecasts made by centers such as the ECMWF [European Center for Medium-Range Weather Forecasts] or, for the seas surrounding metropolitan France, Météo France) and integrate (through a process of so-called assimilation) the information provided by *in situ* (currents, temperature and salinity profiles, for instance) and satellite (observations of sea level as well as surface temperature, and soon of surface salinity, swell, and waves) observations. These models aptly describe these fields over the medium range and have proved their ability to predict evolution on these scales. Their application to the coastal environment also seems very promising, even if certain levels of the circulation or the interactions with the floor and the swell/waves are still not sufficiently taken into account, especially so in the case of shallow depths. The success of these models, at least off the coast, derives, apart from their optimized digital set-up and ability to be used in real time, from the *in situ* incorporation of the data provided by the observation networks that we have just described, as well as from the integration of satellite data.

Retrospectively, these models also offer fields that are dynamically stable over long periods of time which can exceed ten years, at least over the average and large scale of oceanic circulation, over a significant portion of the water column. Because of the predominant availability in the assimilation patterns of surface observations (satellite data) or profiles of the first 2000 meters of the water column, these models are well designed for the upper layers of the ocean (surface, thermocline, and intermediate layers), while they are less reliable for the deeper layers. However, even in the deep layers, they seem to reproduce some of the characteristics of ocean variability, which is essential to climate. This is the case, for instance, for thermohaline circulation, with the comparisons with RAPID or OVID, two observatories in the northern Atlantic whose data offers a thorough analysis of the variability of average circulation and especially of deep southbound currents. Models are a little less reliable and their development a little less advanced when it comes to the “green” ocean (i.e. the areas of the ocean where biology plays a significant role, especially because they are generally rich in nutrients) and those models that include at least one biogeochemical component. This happens partly because of the complexities of the interactions between physics, which can – among other things – supply the surface layers with nutrients thanks to vertical circulation, biogeochemistry, and the difficulties involved in quantifying the basic parameters crucial to the biological and biogeochemical functions of the ocean.

On a physical/dynamic level, data-assimilation models are interesting tools for the analysis of the past oceanic variability as well as for the definition of observation systems and their optimization. However, let us point out that these efficient simulations over a long timescale are used at relatively low spatial resolution, due to the digital costs involved, and therefore do not include the whole spectrum of scales and interactions between small and medium ranges, which play a central role in defining the dynamics, especially vertical, and the interactions between physics and marine biogeochemistry. Other simulations with data assimilation (limited to mesoscales by the observations) are, however, being developed with models with much higher horizontal and vertical resolution (closer grids), which should allow us to model the scale interactions taking place between these small horizontal scales (called sub-mesoscales) and larger scales. Targeted *in situ* observations made on these scales will ultimately allow us to validate the processes represented by the models on these scales.

2.7. What next?

The data provided by the *in situ* observation networks, by individual observatories, by satellite observations, and by the analysis of computer simulations are conceived more and more as complementing one another and are integrated through multivariate digital or statistical analysis, often by what we call the assimilation of data into the models. These approaches can assess the respective weight and impact of the different observation sources. They contribute to the detection of errors in the data, bias, drifts or inconsistencies deriving from our lack of understanding of the relationships between the different variables observed and consequently from a poor integration of the processes into the models. These approaches were first developed within a framework of physical and dynamic oceanography, but are being progressively extended to other fields, such as the assessment of biogeochemical fluxes in the oceans and of primary production or, at the other end of the food web, of fisheries resources. It goes without saying that such an approach requires significant interactions between data providers and modeling designers, as well as integrated access to observation. In France, this is what is being tried for certain well-observed parameters by the inter-agency organization Coriolis as well as by Mercator-Océan. Some of these systems have been mainly set up for operational purposes, which means they are designed to provide certain products to users, be they institutional, private or part of the community of researchers, within a pre-established deadline. Often, they can be predictions in support of decision-making, but they can also consist of analyses, whether in real or non-real time, targeted at understanding the variability of an area or ecosystem.

In the coastal field, it has become more and more necessary to get a better understanding of the phenomena that take place at the interfaces sea-coast, water-atmosphere, and water-sediments. In the fishing domain, adopting these small scales involves the ability to take into account the interactions between air and sea on these scales and to represent the “unmeasured” scales in oceanic circulation in order to assess the interactions between the dynamics and the biological or ecosystem activity. Since models have an increasingly higher resolution and can cover a wider and wider range of parameters, the need for “physical, biogeochemical” or ecosystemic *in situ* measurements to define sub-mesoscale phenomena or new parameters is becoming much stronger. This is due both to the need to better understand how the environment works and to calibrate these models through data assimilation. In terms of geophysical measurements, “seafloor” observatories create potential for scientific investigations as well as opportunities for monitoring in many ways. The issues at stake are significant and simultaneously involve operational, societal and research domains. In this context, coupling “operational” and “research” activities is highly desirable. In terms of observation, the whole chain, from the measurement to the product, will be affected. In order to work towards an optimization of the measurements, it will be necessary to rely on the existing means but also to be able to take advantage of opportunities. This requires the coordination of infrastructure networks, such as fixed buoys, profilers, gliders, Ferry boxes, autonomous measurement stations, HF coastal radars, satellites, etc., from the measurement all the way to the banking and diffusion of data and products.

The European and international approach has already given good results in the open-sea field and in terms of physical measurements. Thanks to new European projects, such as the setting up of the EOOS (European Ocean Observing System), this international coordination will be extended in the coastal field, where it had already started with the European projects JERICO[22] and JERICO-NEXT, but also in open ocean by taking more into account the biogeochemical, biological and ecosystemic parameters

We have to look for new opportunities to take measurements on commercial or fishing boats. The development of RECOPESCA[23]-like sondes represent some of these opportunities for fishing boats, which offers

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[22] http://www.jerico-fp7.eu.

[23] http://sih.ifremer.fr/Description-des-donnees/Les-donnees-collectees/RECOPESCA.

a wide range of uses, both in terms of the number of equipped vessels and in relation to the new parameters made possible by significant developments expected in terms of miniaturization (bio-sensors) and durability (reliability and reduction in electricity usage). Other ships of opportunity such as cargo boats, container ships, cruise liners, as well as oceanic racing sailboats, may be involved.

We are currently engaging in some types of experiments such as Sailing One's project Oceano Scientific or the experiments carried on Bernard Stamm's IMOCA sailing yacht during the 2012/2013 Vendée Globe. It is possible that these sailboats will provide *in situ* data in secluded, or rarely trodden, areas like the Antarctic Ocean.

In terms of deep-ocean vehicles, the next step consists of implementing a so-called hybrid ROV (Figure 2.18), ARIANE, which is lighter, more flexibly used, easier to set up on small ships, and combining the advantages of both ROVs and AUVs. The range of observations that can be made remotely from fixed stations or drifting platforms is getting wider and wider, and this will offer new opportunities for *in situ* monitoring in addition to satellite observations and digital modeling.

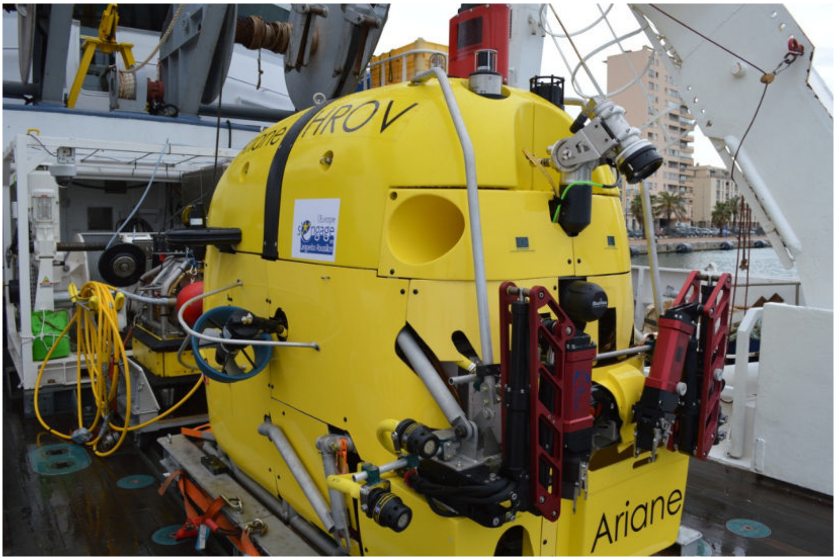

Figure 2.18. *The Hybrid ROV, able to reach depths of 3000 meters. (source: Ifremer – O. Dugornay)*

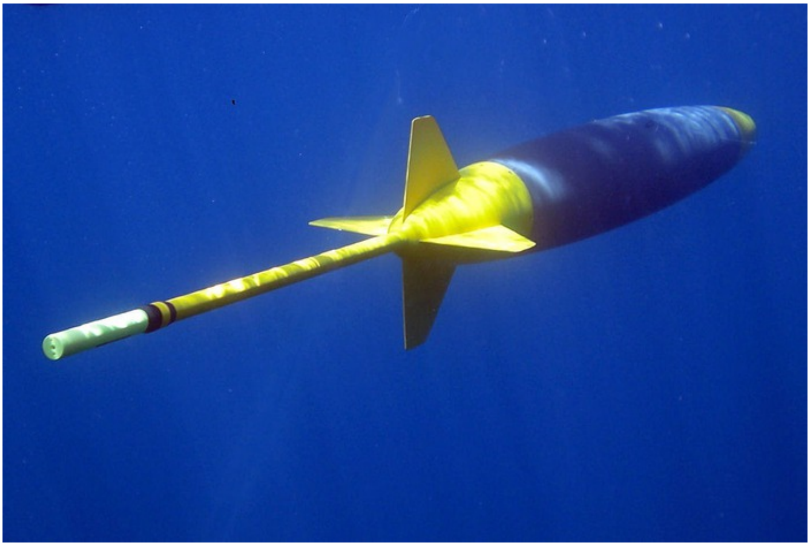

Figure 2.19. *The “Sea Explorer”, a French glider (source: AUVAC)*

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3

Fishing Technology for Fisheries Research

3.1. Introduction

The practice of fishing is a very ancient art which dates back to the Paleolithic, from catching fish with one's hands to using harpoons or fish-traps, and has not stopped evolving. Bone fish hooks dating back 42,000 years have been found in East Timor [IGN 11]. Much later, Pliny the Elder, a Latin historian (23–79 AD), mentions the existence of a "tragula", namely a fishing net dragged along the seabed [DES 04]. In Europe, the first drawings depicting modern trawling nets date back to the end of the 18th Century (Duhamel de Monceau, 1772). Fishing equipment did not stop being developed throughout the 19th and 20th Century (Figure 3.1).

In France, fishing technology started actually being regarded as a science at the end of 1918 with the creation of the Scientific and Technical Office for Maritime Fisheries. Since then, much work has been done to make the equipment better perform as well as selective, i.e. more targeted at the species and sizes wanted. If fishing technology contributed to "fishing more" until the mid-1980s, technology experts working at international institutions have since made an effort to favor the notion of "fishing better".

Chapter written by Pascal LARNAUD and Benoit VINCENT.

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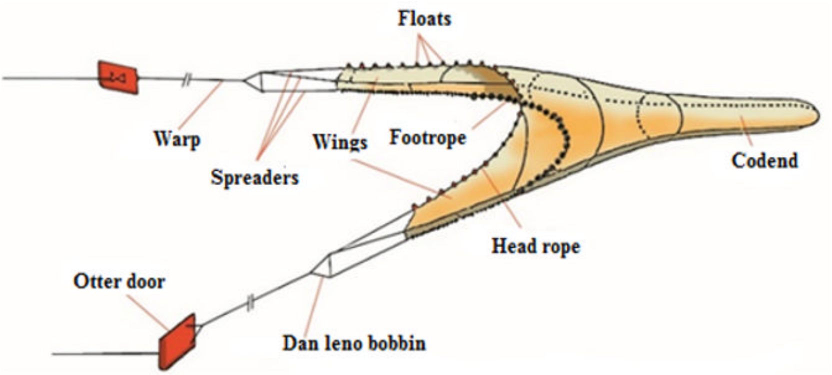

Figure 3.1. *An example of modern bottom trawl with its different parts (source: Ifremer [DES 03])*

This technology can contribute to sustainable fishing for a number of reasons, decreasing the ecological footprint while endeavoring to maintain the economic viability of the exploitation. The resulting research areas are all interrelated (Figure 3.2). For example, enhancing selectivity by increasing the mesh size will allow us to decrease the drag of a trawl in water and, consequently, decrease the towing force required, with a related drop in fuel consumption and CO_2 emissions. As a consequence of the limited traction, the downforce strength required at the front of the trawl is lower and the anterior parts of the trawl which are dragged along the floor must thus be made lighter (“footrope”, chains, etc.). This creates new opportunities for saving fuel and even limiting the impact on habitats. The increase in the mesh size and the weight reductions implemented can also have spillover effects on the quality of the catch and crew safety.

Another field of research consists of studying the potential change in fishing gear, most often through techniques said to be “alternative” to the towed gears. In this case, technology is one of the components of a global bio-techno-socio-economic approach.

Lastly, if fishing technology helps us deal with the key issues concerning professional fishing, it also guarantees support for research projects in halieutics as well as for the assessment of fish stocks.

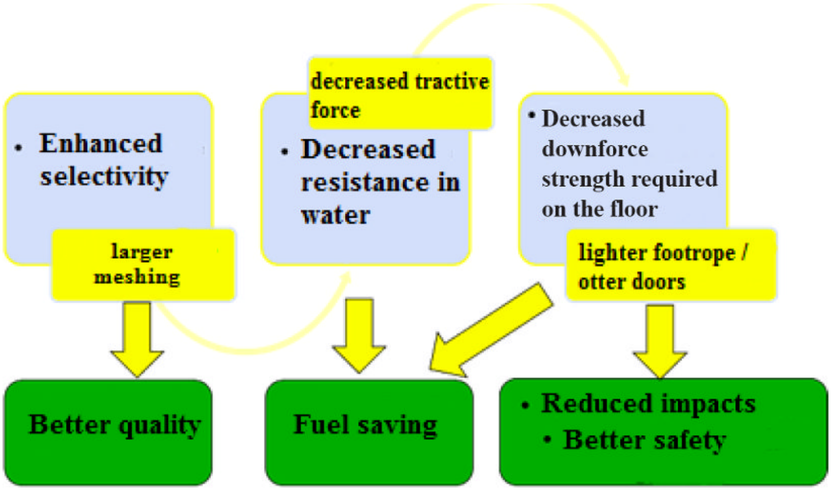

Figure 3.2. *"Everything is linked" (source: Ifremer – P. Larnaud)*

In order to bring all this work to fruition, fishing technology uses and develops specific tools, which constitute the subject matter of this chapter. We will deal with the methods employed to measure the selectivity of fishing gear, then the various tools used for physical measurement and for the physical or computer modeling of fishing gear. In the latter case, it is a matter of quantifying all the forces exerted, measuring all kinds of physical parameters, observing species and gears and using computer simulation to optimize said equipment.

3.2. The methods employed to measure selectivity

3.2.1. *What is selectivity?*

Selectivity is the selection of one species within a fishing community (interspecific selectivity) or of one size within a species (intraspecific selectivity) during fishing. This selectivity of the equipment can limit fishing mortality rates in small-size or commercially valueless fish.

Selective fishing can modify the exploitation diagram (the different sizes caught by a type of fishing gear) and will have a direct effect on the Maximum Sustainable Yield (MSY). The MSY is the largest catch that can be taken from a fishing stock long term and on average, in the present environment conditions (average), without significantly affecting the reproduction process[1] (FAO definition).

As fishermen say, “Better grading at the bottom than on deck”. A good level of selectivity of the fishing gear can decrease the volume of yield and the number of species caught, and also involves lesser mechanical stress. The grading and handling, as well as the time of exposure to ambient temperature, will be therefore reduced, which allows us to improve the quality.

Selective tools can be of a technological kind, with all the devices on trawls, but can also consist of the increasingly effective systems of acoustical detection, which can help the captain fisherman to get a better understanding of the nature (ideally the size and species) of the fish he is going to catch. In this case, especially with regard to pelagic trawls, it is a matter of being selective before the catch. Always in terms of technology, selectivity can also be enhanced by potentially changing the fishing gear within the context of a global bio-techno-socio-economic approach, which we have already mentioned, and case by case.

However, selectivity can also be tackled with a behavioral approach, whether statutory or voluntary. It is actually possible to enhance selectivity by closing down certain fishing areas for parts of the year (spatiotemporal closure), which can avoid exploiting areas where juvenile fish abound as well as, according to the case, breeding fish or scarce species. The captain fisherman or the producer organizations can also willingly decide, by “behaving selectively” either as individuals or together, to avoid this kind of area.

Meshing is certainly an important criterion affecting selectivity. However, it is not the only one. All the parameters that modify the shape, and especially the opening, of the mesh will be essential. We can also mention the role played by the material, the orientation of the mesh (Figure 3.3), the number of meshes on the circumference of the trawl (the more, the tighter), the kind of arrangement of the lateral selvageropes, which will determine how much the mesh will be stretched, and even the volume of catch; it goes without saying that trawl conditions (speed), currents and other elements also have an effect.

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[1] See Chapter 4, Volume 3, Ecosystem Sustainability and Global Change [MON 14].

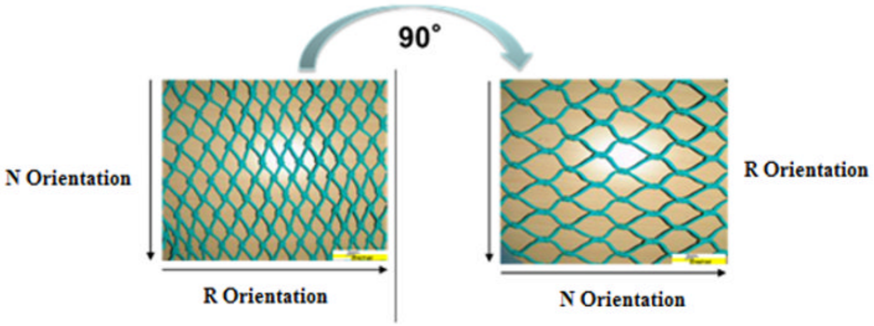

Figure 3.3. *The T90 is a kind of mesh rotated 90° in relation to the normal orientation N of the diamond mesh (on the left). The mesh T90 (on the right) will remain open even when it is stretched in water by the drag of the trawl. The diamond mesh with a normal orientation will tend to close when under traction (source: Ifremer [FIC 15, LAR 14])*

All the fishing gear can be more or less selective. Thus, a longline[2] will catch different species or sizes in relation to its position in the section of water, the kind of bait, or the size and shape of the hooks. The same can be said for creels or lobster pots, which rely on the meshing, the bait, or the form and size of the entry "gutters".

3.2.2. *The tools employed to measure meshes*

Being able to measure a mesh in an objective, comparative and repeatable fashion is certainly fundamental for the assessment of the selectivity potential of fishing gear made of net sections. The mesh gauge, which corresponds to the "mesh gap", is measured between knots, as shown in Figure 3.4. Fishery inspectors, for a long time, used either a triangular hand gauge, which was introduced in the mesh by hanging a 5 kg weight in it or a mechanical one called an "ICES gauge"[3].

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[2] Longline: a line of great length made of a main line on which several hooks are fixed through snoods of variable length and distance according to the target species and the type of longline.

[3] International Council for the Exploration of the Sea.

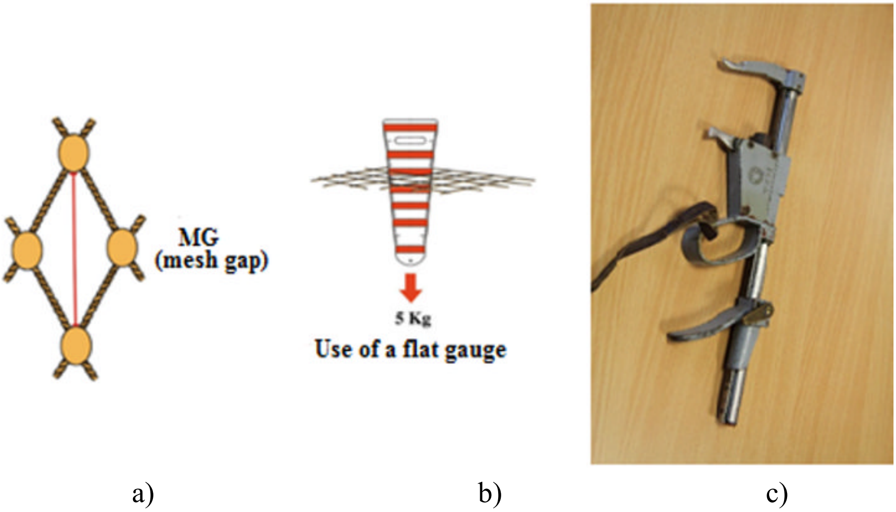

Figure 3.4. *Mesh gap and gauge measurement: a) the "mesh gap" measured by the gauge; b) triangular manual gauge; c) ICES mechanical gauge (P. Larnaud)(source: Ifremer [DES 04])*

In most cases, the triangular gauge was simply pushed manually into the mesh; similarly, the force exerted to separate the jaws of the "ICES" mechanical gauge depended on the user, which involved high measurement variability.

In 2002–2003, a new gauge, more objective and suitable for the survey of fisheries, halieutic research and professionals, was developed by several European partners financially supported by the European Union. This was the OMEGA gauge.

This tool can take measurements of the mesh width without the mistakes introduced by the operator. Implemented according to a standard protocol, it provides clear measurements agreed upon by the European Union (EU). The tool is characterized by its simplicity related to gathering and processing data; it has two measuring forces set at 40 and 100 Newton according to the mesh and it can measure meshes from 10 to 300 mm (Figure 3.5).

Figure 3.5. *The OMEGA gauge (source: Ifremer/G. Bavouzet – P. Larnaud)*

3.2.3. *The case of trawls*

3.2.3.1. *Measuring the selectivity of trawls*

The selectivity of a trawl is determined by the escape, through the mesh, of the fish (or Nephrops[4], for instance) which have gone through it. Two complementary approaches can measure the selectivity of trawls:

– catch comparison: we compare catch in terms of species, sizes, number or weight between a selective gear and a standard one in the fishing fleet;

– measurement of selectivity parameters: we estimate the number of individuals of each size penetrating the net either by lining the exterior of the cod end (see Figure 3.8) or another component of the gear of a net section with a finer mesh or by examining the composition, in terms of size, of the catch of nets with much smaller meshes used at the same time and in the same place [GUL 69] (Figure 3.7). This total catch of the individuals which have entered the reference trawl will have to be compared with the ones retained, in relation to their sizes, in the tested trawl. Regardless of which method is employed, the results can be expressed as proportions of individuals of each length captured within the net and retained during the fishing operation. These proportions, applied in relation to the length of the individuals, yield the selectivity curve of the tested trawl for the species considered (Figure 3.6). The calculations of the parameters that define this selectivity curve, resulting from the retention percentages of a fraction of the total catch, for each size category, can then be integrated into models assessing populations’ dynamics.

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[4] Dublin Bay prawns.

Evidently, from one tow to the other, fish can move and will not be present everywhere at the same level, sea conditions evolve, time passes, etc. Therefore, it will be necessary, regardless of the methodology adopted, to repeat a large number of tows to expect solid results.

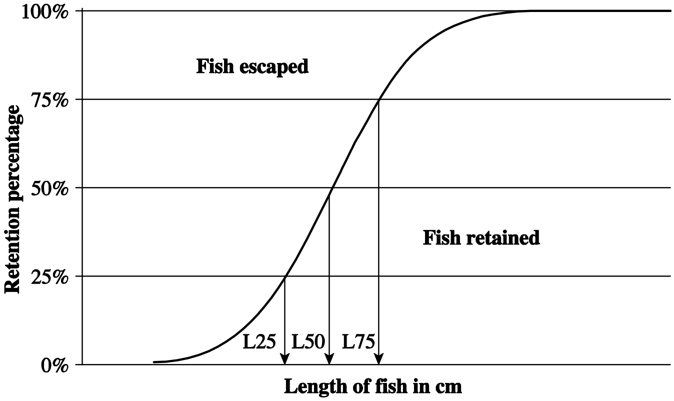

Figure 3.6. *Typical example of the selectivity curve of a trawl (source: Ifremer – [BRA 97])*

The size corresponding to 50% of the retention of a given species within the trawl tested is called the L50.

The steeper the curve, the greater the escape potential for small sizes below the L50 offered by the gear, while allowing a maximum of individuals above the L50 to remain.

3.2.3.2. *Trawling techniques used to assess the selectivity of a trawl [DES 03, WIL 96]*[5]

3.2.3.2.1. Alternated tows

In appearance, the easiest technique consists of performing alternated tows, first with the trawl whose selectivity we want to test and then with a control trawl. The latter can be fitted or not with a small-mesh (gauged at 20 mm) net commonly called a “sock” (Figure 3.7), depending on whether we want to compare the catch or obtain selectivity parameters. In the former case, for the comparison of catches, two tows will be necessary to compare the test and the standard gear of the fishing fleet. In the latter, i.e. when we

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[5] For more explanations see [DES 03, WIL 96].

want to obtain selectivity parameters, if we wish to compare the test and the standard gear, we will need three successive tows to measure the catch composition of the test, the standard, and the small-mesh control cod-end (in order to quantify all the individuals entering the trawl and their size). All these operations will have to be repeated enough times to obtain solid results.

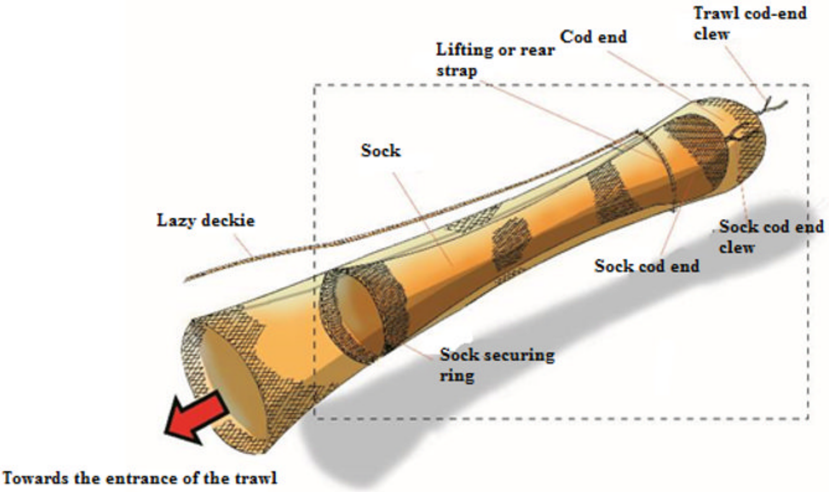

Figure 3.7. *Example of cod-end with a small-mesh "trawl blinder" (source: Ifremer [DES 03])*

A variant consists of conducting the experiment with two ships rather than alternating the trawls on a single boat. This enables us to carry out the fishing operations with the test and control trawl simultaneously, therefore, shortening the time gaps between the tests. In this case, we have to make sure that the tows are performed by the two ships by coordinating the beginning and end of the tows, following parallel and near routes, so that they can have a chance of working on populations of similar size and density composition. The main drawback of this two-ship technique is that their catch potential can, on the other hand, be different by design, because of radiated noises, traction forces, onboard measurement and regulation tools, etc. This is why, when handling such a situation, in most cases we will choose ships of identical or very similar design. In addition we will have to start by comparing the yield caught by the two ships, with the same control trawl, to make sure that the gaps between the two are very limited.

3.2.3.2.2. Trawls with hooped or kite cover

Another solution consists of working with a single trawl, whose cod end is lined with a small-mesh cover which will collect the totality of individuals escaped through the mesh of the rear end of the tested trawl. The proportion between the totality of individuals which have entered the rear end and those retained by it can then be calculated with a single fishing operation, which will then be repeated.

We have to make sure that the external cover does not touch the cod end of the test trawl and that it does not disrupt the individuals escaping through the mesh or the selective devices. To this end, we can use rigid hoops, which will maintain the gap, or kites that will open the cover with the current generated by traction (Figure 3.8). If all of this is not meticulously respected, we run the risk of creating significant bias in the results. We have to point out that this technique is complex to implement on professional fishing boats and in actual fishing conditions.

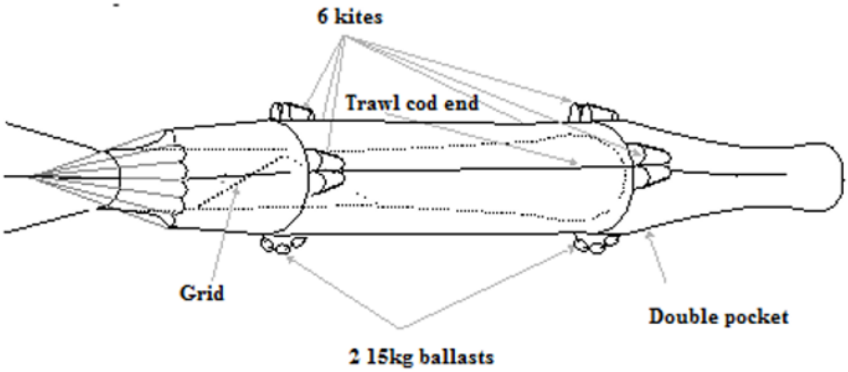

Figure 3.8. *Example of trawl cod end with small-mesh cover pocket. (source: Ifremer/ SAUPLIMOR project/S. Mortreux/Inspired by [MAD 01])*

3.2.3.2.3. Trawls with collection cover on a specific part

When the selective device only corresponds to a small specific part of a trawl, such as a square-mesh panel or a selective grid, these devices can be covered with a small-mesh cover to collect the escapees.

The main drawback of this technique, especially if the pocket is not big enough, can be that the dynamics of the fish escaping from the trawls can be perturbed for two reasons: either because the cover creates an obfuscation of the upper part, or because certain fish, which have already escaped and are trapped in the cover, perturb the escaping movements of the other individuals still in the trawl belonging to different species.

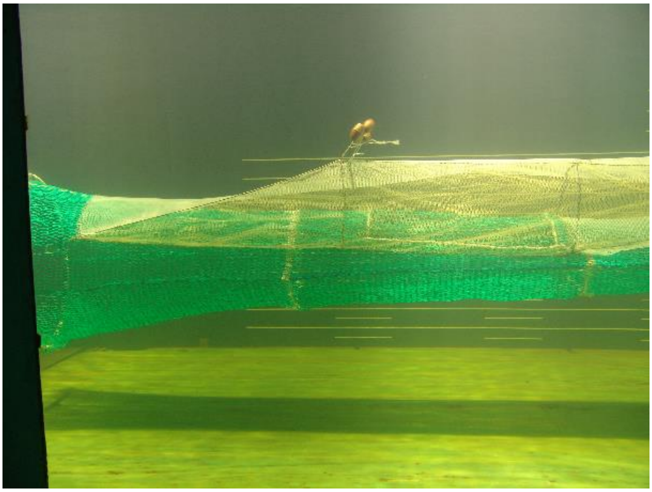

Figure 3.9. *Example of a small-mesh collection pocket above a square-mesh otter door (source: Ifremer/EU NECESSITY Project/P. Larnaud)*

3.2.3.2.4. "Siamese" or "trouser" trawls

Currently, we can only use one gear if we make use of a twin cod end trawl. Therefore, we talk about "Siamese" trawls or "trouser" cod ends. In this case, half of the trawl will integrate the selective device(s) and the other half will serve as the control trawl (with or without internal mesh, depending on whether we want to compare the catch or determine the parameters of the selectivity curve). The trawl will be separated throughout its central part by a vertical net (Figure 3.10). It must travel in a perfectly symmetrical way, according to precise rules, for the catch potential of both sides to be identical. If we leave aside the necessity linked to this imperative technical strictness, a school of fish – we have to take into account their gregarious behavior – could tend to gather more in one side than the other, without being separated into two equal parts.

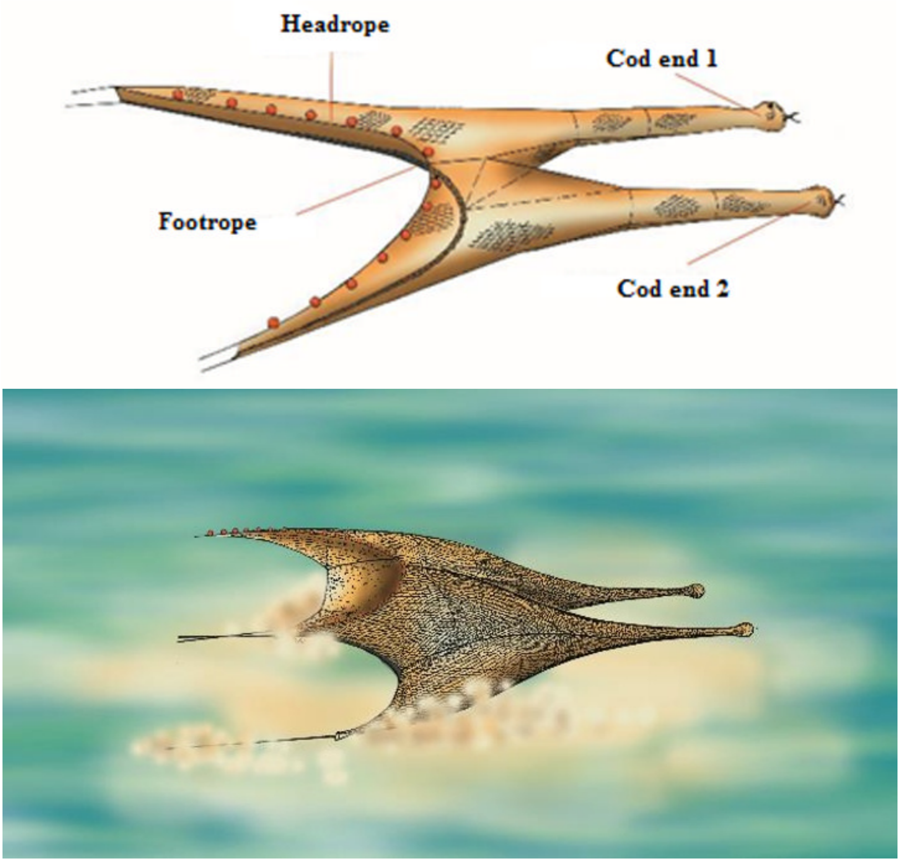

Figure 3.10. *An example of a Siamese trawl (source: Ifremer [DES 03])*

3.2.3.2.5. Twin trawls

Another solution consists of experimenting with “twin” trawls, namely with two trawls, one of them being the “test” trawl and the other the “control” trawl. This technique is easy to implement in fisheries that carry it out routinely, as is the case for langoustine or prawn fisheries. We have to make sure that the catch probability is the same for both trawls, hence the necessity of regularly alternating the test and control trawls on both the port and the starboard side (Figure 3.11).

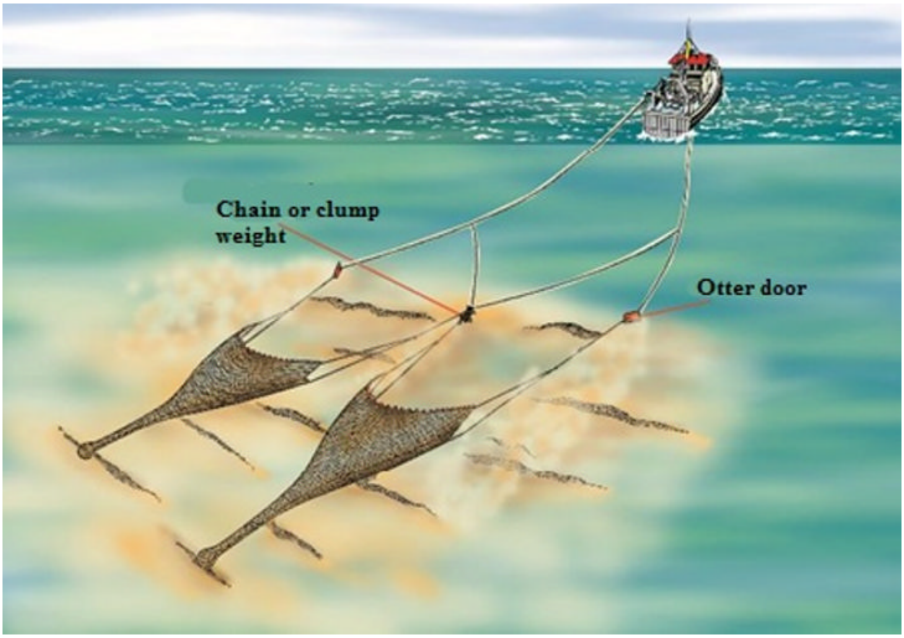

Figure 3.11. *An example of twin trawls (source: Ifremer [DES 03])*

3.2.3.3. *Specific trawls for sampling during scientific researches*

3.2.3.3.1. Beam trawls

During scientific research, it may be necessary to take samples, as far as possible, of all the species and individuals of all sizes located on or in proximity of the seafloor. To this end, we can use a kind of trawl which is regarded as being poorly selective, i.e. the beam trawl, fitted beforehand with a scraping chain called a “tickler chain” fixed on the head shoes, which helps in “peeling” animals off the seafloor. The net is lined with a small meshing that measures 20 mm at the gauge (Figure 3.12).

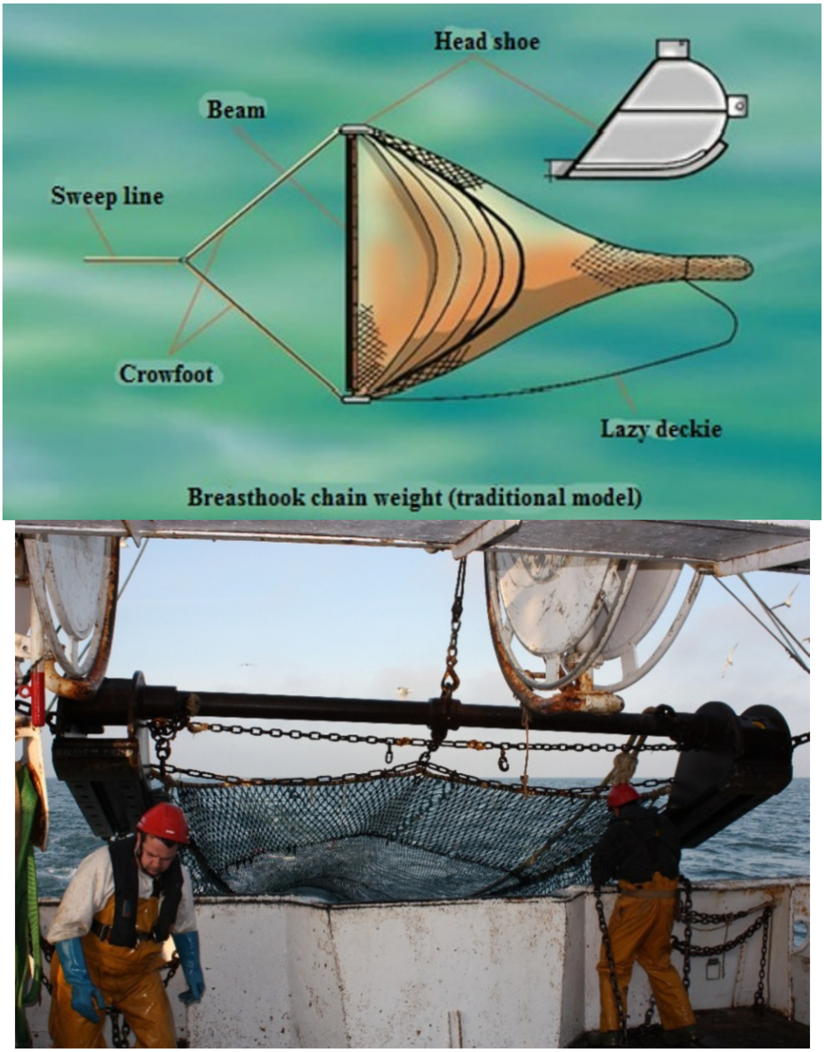

Figure 3.12. *An example of a sampling beam trawl (source: Ifremer – diagram [DES 03], picture G. Biais)*

3.2.3.3.2. Trawls for the sampling of larvae and juveniles

To take samples of pelagic larvae or juvenile species in a given area effectively, Ifremer set up a lightweight scientific "mesopelagos" trawl with small meshes [MEI 02] (Figure 3.13).

Figure 3.13. *A “mesopelagos” scientific trawl (source: Ifremer – M. Meillat)*

3.2.4. *Fishing nets and other gear*

3.2.4.1. *Measuring the selectivity of gillnets*

Gillnets catch fish by “enmeshing” on an opercular level (Figure 3.14).

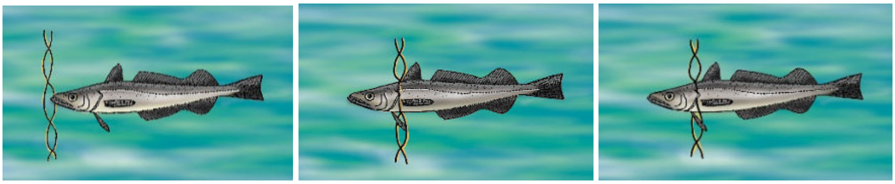

Figure 3.14. *The principle of gillnetting (source: Ifremer [DES 09])*

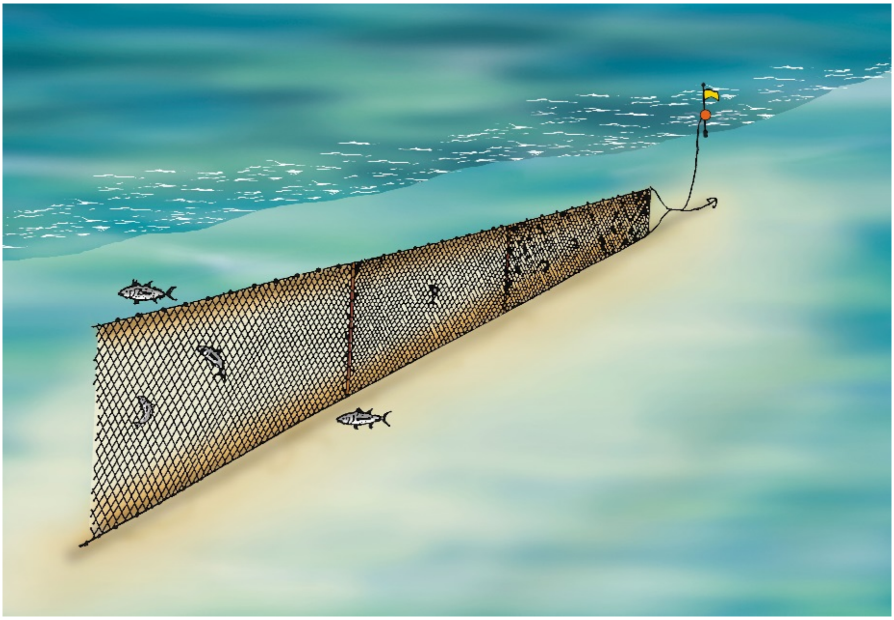

Figure 3.15. *Fish in a gillnet laid on the seafloor (source: Ifremer [DES 09])*

For gillnets, small fish pass through the mesh whereas bigger individuals cannot get through. Only the fish whose length is close to a size called optimum size, for which the effectiveness of the net is maximum, are trapped [BRA 97] (see Figure 3.16).

There is a constant relation, for a given species, between optimal length and mesh size, which is called the selectivity coefficient.

To establish the selectivity of a gillnet, we should know the distribution, in terms of size, of the species likely to be captured in the area exploited. To this end, we will carry out on-site fishing operations with non-selective equipment or tools with known selectivity. Therefore, a beam trawl fitted with small mesh can be used (see section 3.2.3.3.1). We can then estimate the selectivity curve of the gillnet (Figure 3.16) by comparing the distributions, in terms of size, of the fish on-site caught by a gillnet that needs testing and by the non-selective equipment.

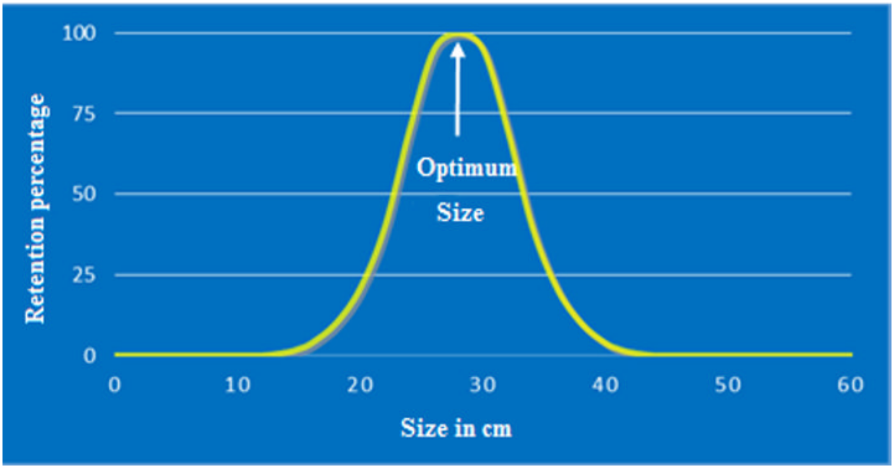

Figure 3.16. *Typical selectivity curve of a gillnet (source: Ifremer – P. Larnaud)*

When it is not possible to apply this trawling method, we will be able to estimate selectivity with gillnets which have different types of mesh, but identical dimensions and the same rigging. We will have to alternate between the areas with different mesh sizes (on a same net) and place the nets, during the experiment, in such a way that each net length of a given type of mesh can be exposed to the same probability of contact with the target species.

3.2.4.2. *Measuring the selectivity of trammel nets*

The methods applied to measure the selectivity of trammel nets correspond to those used for gillnets.

The principle of trammel nets is based on three sections of netting: two external sections (armored) with large mesh and inner netting (lint) with small mesh (regulatory) fitted quite loosely [DES 09]. Fish can get caught in the inner netting through "pursing", or getting enmeshed after crossing an external netting (Figure 3.17).

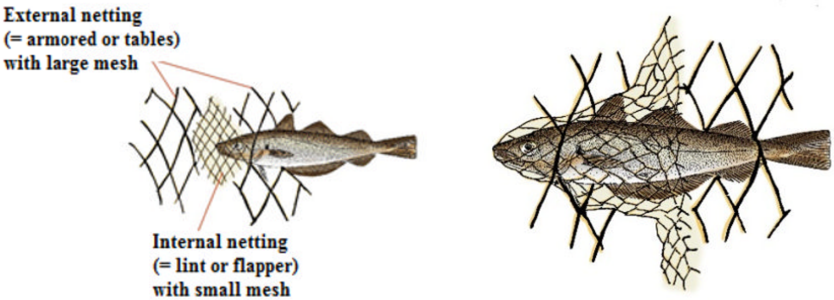

Figure 3.17. *Principle of trammel nets (source: Ifremer [DES 09])*

The general shape of the selectivity curve of a trammel net is represented in Figure 3.18.

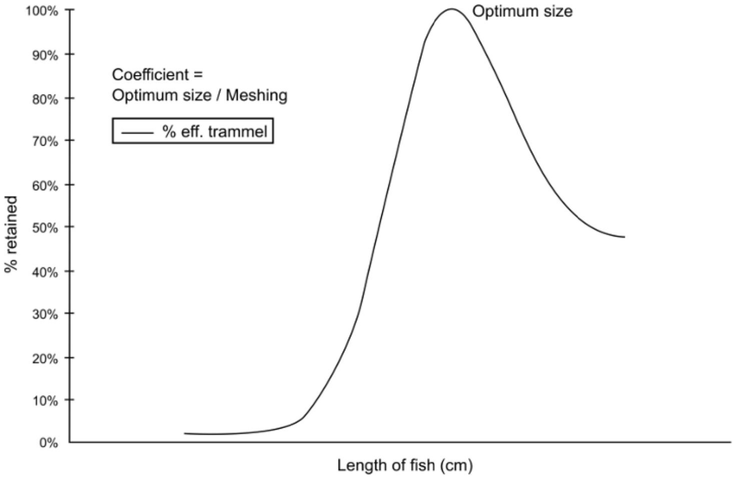

Figure 3.18. *Typical selectivity curve of a trammel net (source: Ifremer – [BRA 97])*

The peak of the curve corresponds to an "enmeshing" kind of catch, as is the case for gillnets [BRA 97]. On the other hand, the asymmetric part of the curve, typical of trammel nets, represents how fish whose sizes are bigger than the optimum size are also retained by tangling.

3.2.4.3. *Measuring the selectivity of longlines*

The methods applied to measure the selectivity of longlines are the same as those used for gillnets or trammel nets: we use a poorly selective piece of equipment to estimate, in the area exploited, the distribution by size of the target species. It is also possible to compare longline catches with different characteristics (in terms of hooks or baits for instance). If we test the size of the hooks, we can, for example, alternate each type of hook on the longline.

Figures 3.19 and 3.20 show two kinds of longlines, bottom and surface.

Figure 3.19. *Example of surface longline (source: Ifremer [DES 05])*

The kind of bait or the dimensions of the hooks contribute to the selection by species and size of longlines. Longlines attract fish at several hundred meters and since large fish feed and move over greater distances than small ones, their bait potential is greater for larger kinds of fish [COC 05].

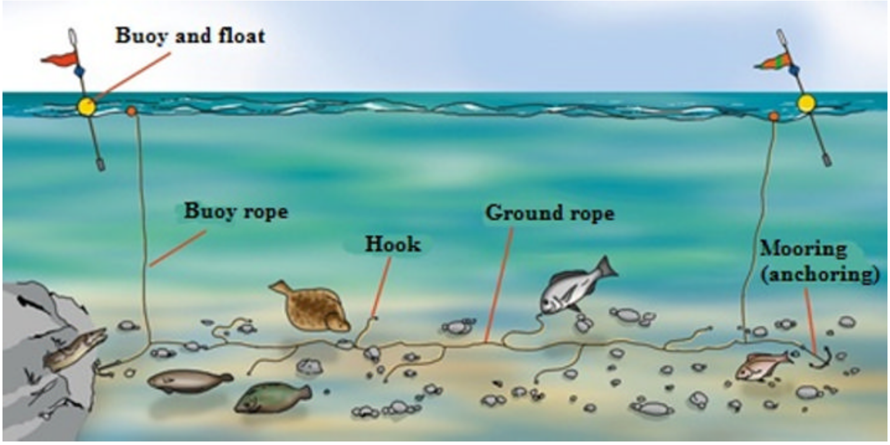

Figure 3.20. *Example of bottom longline (source: Ifremer [DES 05])*

3.3. The tools and observation methods of fishing gear

We can now state that the need to observe fishing gear in action was born exactly when these first pieces of equipment were submerged. This need was motivated by the desire to adapt the gear for catching purposes, to assess its shape when in operation, to understand its interactions with the seafloor environments and, more broadly, to enhance its effectiveness. The need for more effectively conceived fishing equipment grew with the appearance of the first engine-powered fishing vessels at the end of the 19th Century, when the propulsive forces available made it possible to tow distinctly larger equipment.

The 1950s saw the advent of acoustic tools, submarine instrumentation, and submarine photographing means which galvanized the works conducted in the field of fishing technology, the study of fish behavior [WAL 00], and the design of fishing equipment, showing how these domains could be regarded as sciences. Thus, in the 1960s the first scientific studies of trawls based on reduced-scale models in testing tanks were carried out at the ISTPM in Boulogne sur Mer.

Experiments, observation, then modeling and simulation constitute the bases on which fishing technology, which becomes a scientific discipline in its own right, is founded.

The tools developed and used to these ends can therefore reproduce under controlled conditions some trials on several pieces of fishing equipment on a reduced scale, namely in flume tanks, and are described in the following sections. The miniaturization of electronics and its greater energy efficiency provided access to performing video tools while reducing those restrictions linked to the hydrostatic pressure that decrease in relation to the dimensions of waterproof housings. This enables us to observe offshore fishing equipment in action and animal behaviors. At the same time, sensors can measure several physical quantities while perturbing the system observed as little as possible.

3.3.1. *Hydrodynamic tank test*

Hydrodynamic tank tests are experimental tools (where experience means control over laboratory conditions) which play a significant role in relation to hydrodynamic tests, be they studies conducted in ports, on the swell, on the features of ship hulls or several devices designed to be developed in the sea, or, more precisely, on fishing equipment and especially towed fishing gear. These tests conducted under laboratory conditions necessarily imply a good level of control over the experimental conditions and the means of observation and measurement, which are a lot trickier to be brought under control at sea. Reducing the size of the subject studied (mock-up) is often an essential step if we want to adjust to the dimensions of the test facilities.

Towing tanks, in which a movable bridge allows us to propel the object studied to a set speed as if it were the hull of a ship, are among the basins used for hydrodynamic tests. Gyration basins are based on the same principle, but in terms of rotation rather than translation.

The test basins more used in the field of fishing technology are flume tanks. Sometimes, it may happen that a calm-water basin is used to study non-towed fishing equipment, such as ocean purse seines, coastal purse seines (a kind of small seines), and some nets or fish pots. In these basins, water is made to circulate by one or several axial-flow pumps in a closed-loop system which ensures near-homogeneous velocity in the observation section, where subjects are tested. The current in the area studied is homogenized thanks to a pressure-drop device and/or a system of converging sections (the flow is accelerated by reducing the channel section, entailing a homogenization of the current). The largest vortices are broken by a honeycomb system. Thus, we obtain a relatively homogeneous flow with a speed that can be adjusted to any value in the range of 0/1 to 2 m/s for the most rapid flume tanks.

These basins have the advantage of offering constant availability in terms of experiment duration times, whereas towing basins have a definite physical length and, consequently, a set experiment time, besides having to be allowed to stand for several minutes to find a fluid in a state of near-rest before the following experiment.

The possibility of relating the observations made on a reduced scale in the test basins to the actual ones made at sea is centered on a similitude between hydrodynamic laws on different scales applied to the elements of the mock-ups studied, which shapes the way of conceiving these models.

We, therefore, have to respect this similitude if we want to make sure that the flows (mock-up and actual scale) will produce similar stresses in terms of viscosity, inertia and gravity force. This entails, for the two scales, constant Reynolds and Froude numbers, which are obtained by a "dimensional" analysis of the equations of viscous fluid dynamics. As it is not possible to keep this relationship, we have to make a compromise which generally leads us to keep Froude's number to be able to work at reasonable flow velocities, slower than the actual ones[6], in the flume tank.

We also have to respect the scaling ratios, imposed by the similitude, between the mock-up and the actual object in terms of friction and the effects of gravity by choosing wisely which elements will constitute the mock-up. More practically, the net of the mock-up and the floats often require us to make compromises in terms of the materials and elements available on the market.

Thus, we obtain geometric results on a small scale which generally correspond quite closely to actual-size observations or measurements.

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[6] Luckily, it turns out that the elements that make up the mock-ups of fishing equipment (the twines that create the mesh netting, which can be seen as cylinders, the floats, which we may regard as spheres, and the doors, which we can consider as plates) have relatively constant dimensionless resistance and lift (the famous Cx's) in the range of Reynolds numbers on the different scales. These observations justify the choice of Froude's similitude.

Scaling laws are based on the definition of Froude's number, which is kept at a constant whether we are dealing with scaled-down or actual-size models. It is defined by: $Fr = \frac{V}{\sqrt{gL}}$, where V is the incoming flow velocity, g the acceleration constant due to gravity and L a characteristic length of the system studied.

The length reduction ratio $\varepsilon = \frac{L2}{L1}$

where L1 is the actual characteristic length and L2 the characteristic length of the scaled-down model allows us to deduce the velocity ratios: $\frac{V2}{V1} = \sqrt{\frac{L2}{L1}} = \sqrt{\varepsilon}$

Reynold's similitude is not verified (actual Reynold's numbers and those of the test on the scaled-down model), but the system studied is essentially made up of cables, for which we can verify that the Cds (drag coefficient) are comparable between actual size and model. Similarly, the experiment shows that the divergent sections (actual size and model) have very similar hydrodynamic coefficients; see [NED 68].

As for the scaling down of surfaces, Froude's similitude leads us to a surface ratio of ε^2. For the scaling down of gravity stresses (weight or buoyance stresses), Froude's similitude yields a ratio of gravitational forces of ε^3. The different components of the mock-ups must then be chosen by abiding by these scaling rules.

Figure 3.21. *180-degree view of the basin of Boulogne sur Mer and mock-ups of trawl otter doors (source: Ifremer/B. Gaurier). On the right, view of the basin of Lorient (source: Ifremer/B. Vincent)*

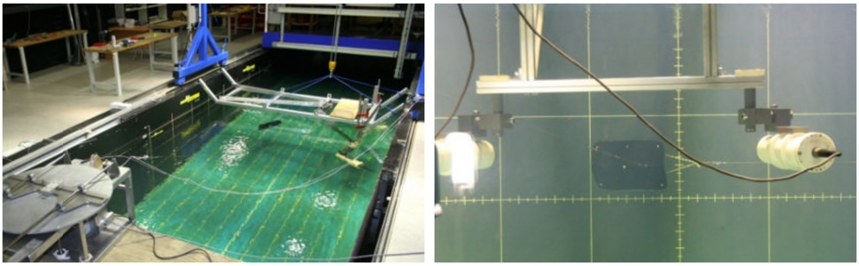

Figure 3.22. *Excitation and 3D trajectography system set up to study the dynamics of a trawl otter door in the basin of Lorient (source: Ifremer/T. Fabre, 2011)*

Box 3.1. *Scaling laws in the case of Froude's similitude*

The Ifremer flume tank in Lorient is currently the only basin in France dedicated to fishing technology. Overall, it is 24.5 meters long, 7.5 meters wide and 3.3 meters high. It is a freshwater circulation tank with closed-loop horizontal circulation. The test section is 12 m long, 2.6 m wide and 1.5 m deep. A 6.2 m moving belt simulates the seafloor. Water velocity ranges from 0.1 to 1 m/s and the moving belt moves in synchrony with it. The system of water homogenization is based on a simple convergent section and a pressure-loss system through screen plates. A surface raft can reduce the width of the wave produced by serving as overflow for the pressure loss.

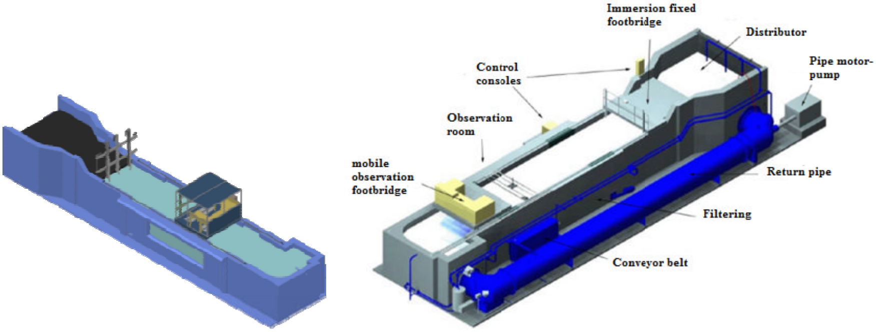

Figure 3.23. *View of a basin and of its main components (source: Ifremer)*

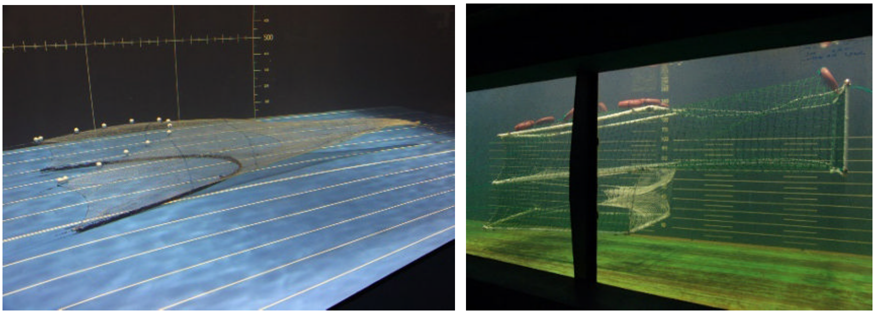

Figure 3.24. *Testing a mock-up trawl and an actual size fist pot in a basin (source: Ifremer/P. Larnaud)*

Box 3.2. *Characteristics of the Lorient basin*

We can see then that the size constraints of a basin require scaling down, which quickly necessitates the limitations of certain tests. For example, if we test in a basin on a reduced scale a trawl measuring 10 m in horizontal opening, towed by 100 m cables scaled down to 1/20, the cables will measure 5 m and will represent a limitation for the size of the basin. However, the same trawl used on a deeper seabed with 1, 500 m cables will have to be scaled down to 1/300. The mock-up trawl is then no longer representative because of its excessively small size: its level of detail is insufficient for an analysis of its geometry, for instance. This kind of dimensional constraint has led to the development of computer simulations of fishing equipment (see section 4.4).

3.3.2. *Submarine video recording*

Since the first submarine recordings [ANO 52], diving has been used by scientists to observe fishing equipment and fish behaviors first hand [DIC 67].

Submarine imaging (photos and videos) is used to study the performance of more complex material and systems, biodiversity, animal behavior and technical monitoring. These tools allow us to observe without taking samples and with a minimal perturbation of the subject observed. Artificial light is necessary in conditions of submarine darkness can disturb the animals observed.

These observation systems are made up of one (or several) optical sensors, a set of lenses and a lighting and monitoring system. Several approaches can be used to use the data: a) visual observation (with an operator) and manual analysis (possibly with computer-aided annotation); b) observation through software and more or less automated analysis, which often requires the presence of an operator due to the complexity of the images, which becomes very quickly a limiting factor for automated analysis.

The means employed by observation systems can be submarines (manned, piloted from the surface or towed) (see Box 3.3, "EROC"), buoys, submarine observatories or divers. They can be simply fixed near the target location, for example on the fishing equipment itself.

The EROC is a vehicle employed for real-time observation, towed by the trawler. It is fitted with a movable camera extremely sensitive to light. Movements in a direction perpendicular to its feed speed are controlled by forces produced by the rotation of cylinders (Magnus effect), namely quite constant stresses whose intensity is easily adjustable, which makes piloting the vehicle easier. By adjusting the length of the towing cable, and the altitude and horizontal axle offset of the vehicle, we can observe a trawl from every perspective. The following image (Figure 3.25) gives us an overview of the EROC located on deck of the Thalassa. This system was first developed in Scotland in the 1980s for fishing technology purposes and has afterwards been enhanced in several ways (fiber-optic transmission of video signal, support of fishing sounder [SIMRAD ER60 200 kHz] with the ability to correlate spatial distribution and density of demersal species on a small scale at very high resolution).

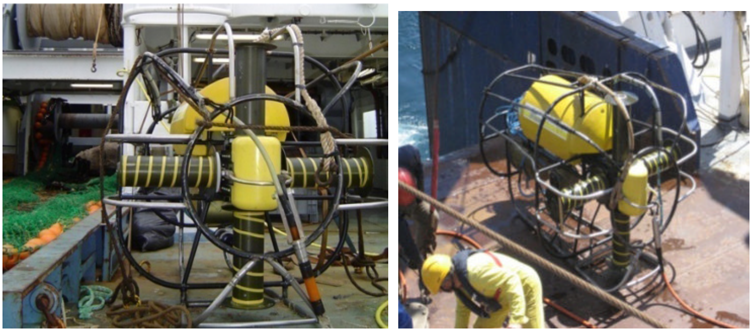

Figure 3.25. *EROC (Engin Remorqué pour l'Observation des Chaluts or Towed Vehicle for the Observation of Trawls) on deck of the Thalassa (source: Ifremer–[VIN 07])*

Figure 3.26 shows us some examples of the images captured by this device.

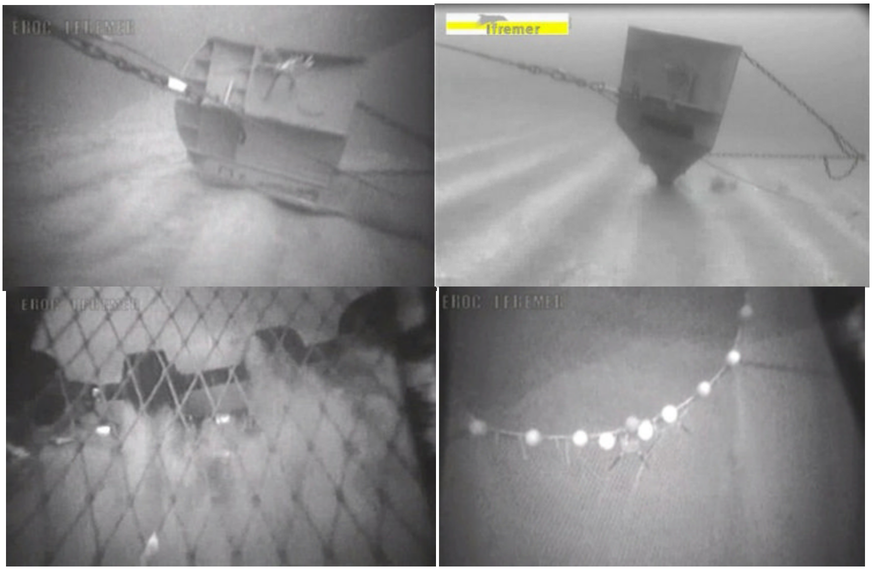

Figure 3.26. *EROC images, classic trawl otter door, Jumper otter door with low floor impact, footrope and headrope of a trawl, IFREMER images (source: Ifremer [VAC 10]*

Box 3.3. *The EROC*

Figure 3.27 shows us another example of an older observation system used by the Aberdeen Marine Laboratory [MAI 77] from the 1970s until the 1990s. It consists of a towed two-seat vehicle at ambient pressure used to observe trawls and animal behavior. Its buoyance is controlled by a ballast (above) and its position by hinged flaps.

In Figure 3.28, we can see fish escaping through the upper part of the trawl on the right-hand image, which was captured by the video system fixed by the selective device.

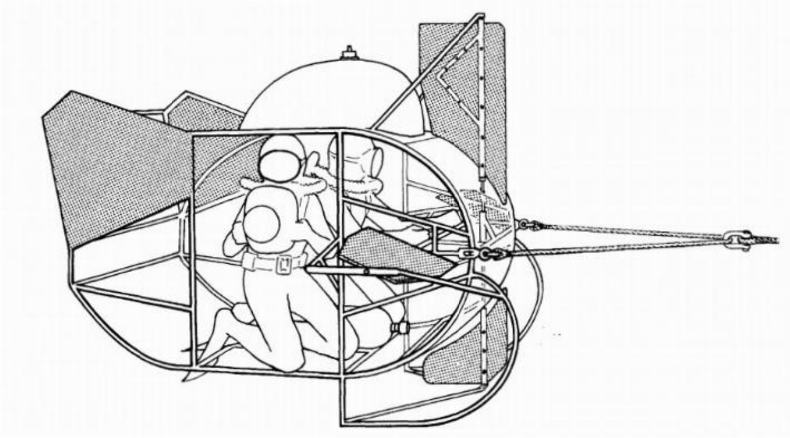

Figure 3.27. *Towed vehicle used by the "Aberdeen Marine Laboratory" [MAI 77]*

The decreased cost of observations systems and their miniaturization (which makes using them easier) are naturally leading to an increase in the volume of images and videos reaching the laboratory, where works about fishing are carried out. The operation time necessary for the analysis of these images and the human eye, which quickly reaches its limitations when it comes to counting dozens of fish escaping through a selective device in the same second, are leading to the development of methods of automated image analysis, which are nowadays rapidly expanding.

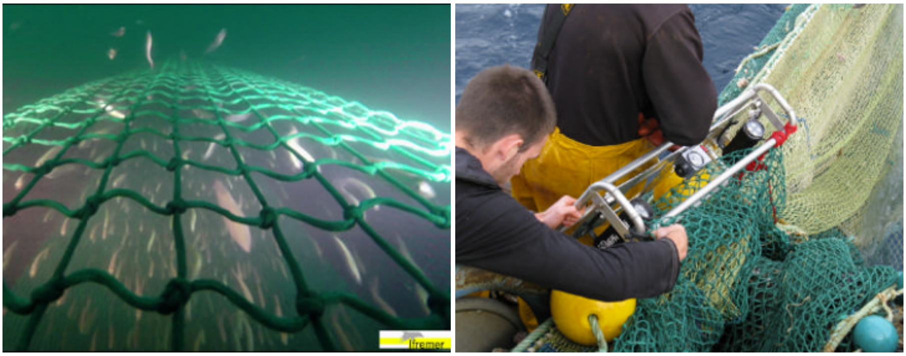

Figure 3.28. *Installation of a video system on a selective trawl device; a square-mesh panel (source: Ifremer – [VAC 15, SIM 15])*

3.3.3. *Measurement tools in the domain of fishing technology*

Generally, sensors can transform a physical quantity (length, force, velocity, etc.) into an electronic signal which is itself converted into a digital value directly displayed or stored in memory for further use.

They allow us to describe the system observed quantitatively, whereas the images mentioned beforehand provide mainly qualitative information, even if image analysis can provide quantitative data.

In terms of fishing technology, sensors address the need to define fishing equipment for optimization purposes: assessment of effectiveness, reduction of physical impacts on the seafloor, studies on crew safety. We can also find force, distance, speed, depth (actually manometers) sensors and many other kinds. Table 3.1 sums up the categories of the sensor used according to its kind of application.

These commercial sensors, some of them built according to particular specifications linked to the study, are being progressively supplemented by new automated sensors developed in laboratories thanks to the simplification and miniaturization of sensors and microcontroller-programmable systems: positioning and movement measurements (Figure 3.29).

Application		Sensor category
Understanding of the functioning, features, and optimization of the equipment	Fishing effectiveness Design operating state Positioning	Geometry measurement by means of acoustics Height measurement in the water column (acoustics or pressure) Angles
	Energy saving	Sensors of single-component forces Propeller or Doppler-effect speed sensors (ADCP)
	Assessing and reducing the impact on the seafloor	Multi-component force balances Turbidimeter (estimation of suspended particles), ADCP
Detection	Locating and identifying the resource	Single- and multibeam sounders, sonars Trawl “netsonde”

Table 3.1. *Different kinds of instruments used according to their applications*

Figure 3.29. *On the right: tensionsensors on the bracket of an experimental trawl, positioning system, system used to measure distance between the otter doors and their depth, otter door angle sensor (vertical cylinder). On the right: acoustic beacons working as master-slave to measure the horizontal opening of a pelagic trawl in relation to its rigging (source Ifremer – [VIN 08, VAC 04])*

The development of these measurement systems has allowed us to validate the virtual models of fishing equipment used to avoid carrying out, for all ships and all fishing equipment, measurement operations which were long, expensive and too dependent on the local conditions, which were not properly controlled.

Therefore, the generalization step, necessary to the scientific method, takes shape in the development of digital models of fishing gear, aiming to leave behind any means of measurement or observation. This step is somehow illusive, since the technical changes and the constraints that guide fishing practices evolve more rapidly than the simulation technologies used in this field.

3.4. Computer simulation tools

Like any technical system, a piece of fishing equipment combines different functions. Anticipating their interactions is an integral part of the engineer's skill. When the system depends on a significant number of parameters, it becomes difficult to predict everything. Simulation tools can assess the performance of the equipment globally designed even before its existence. This approach is typical to all sectors of the industry.

Therefore, we can build a virtual piece of fishing gear able to react in an equally virtual environment, according to the laws of physics: hydrodynamics, structure mechanics and soil mechanics. The resulting model thus constitutes an actual scalable prototype that can be manipulated, modified, assessed and eventually optimized.

The simulation systems employed for fishing equipment can be described schematically as shown in Figure 3.30.

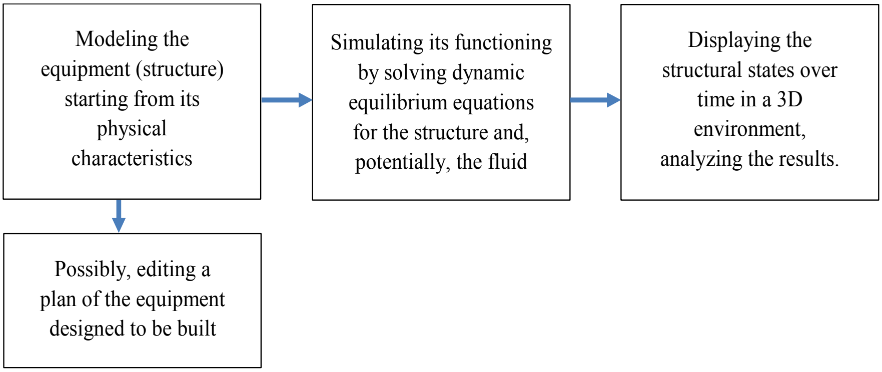

Figure 3.30. *Operating phases of a software simulation program: preparation of data, processing through computer algorithms, analysis of the results in the virtual environment*

The simulation phase is the one that takes the longest in terms of development, when it comes to establishing and testing the models.

The step of conceiving these calculation codes consists of describing the dynamic equilibrium between the smallest elements of the structure and, by means of spatial and temporal integration, predicting the performance of the whole structure.

These theories can be based on different methods for the structural part (nets, cables, accessories, etc.): the most commonly used are the models centered on mass-spring systems [BES 98, KIM 02, VIN 99] and finite element methods [PRI 99].

Simulating the fluid, the velocity of which is affected by the presence of the moving structure, is more complex. An approach, to be rigorous, requires us to solve averaged Navier-Stokes equations (mainly finite volume methods [MNA 11]).

During the operational phase, depending on the power of the machine used and the part manufacturers, the calculation times needed to solve these models are quite short, so that we can repeatedly build an optimized piece of equipment in a few hours (Figures 3.30 and 3.31).

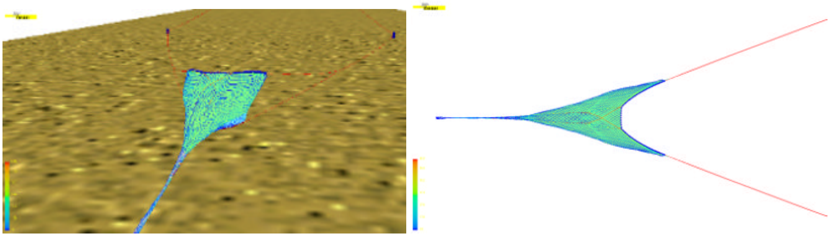

Figure 3.31. *Six-panel bottom trawl simulated by the Ifremer commercial software DynamiT, used by several authors for fishing research purposes [DAN 09, TRU 15]. The colors of the cables represent their internal tension. See color section*

Lastly, it seems natural to improve the simulation of the tools used for fishing by integrating simulations of the animals' behavior. The interaction between the two types of modeling should allow us to study selectivity and, more broadly, the catch process. An approach we could use to solve this type of modeling consists of observing the behavior of animals starting with video data and then in reproducing it in a model solved together the structural model (IBM model, Individual Based Agent [MAE 92]). Since 2005, simpler models have been able to predict the selectivity curves of certain species in highly specific conditions [HER 05].

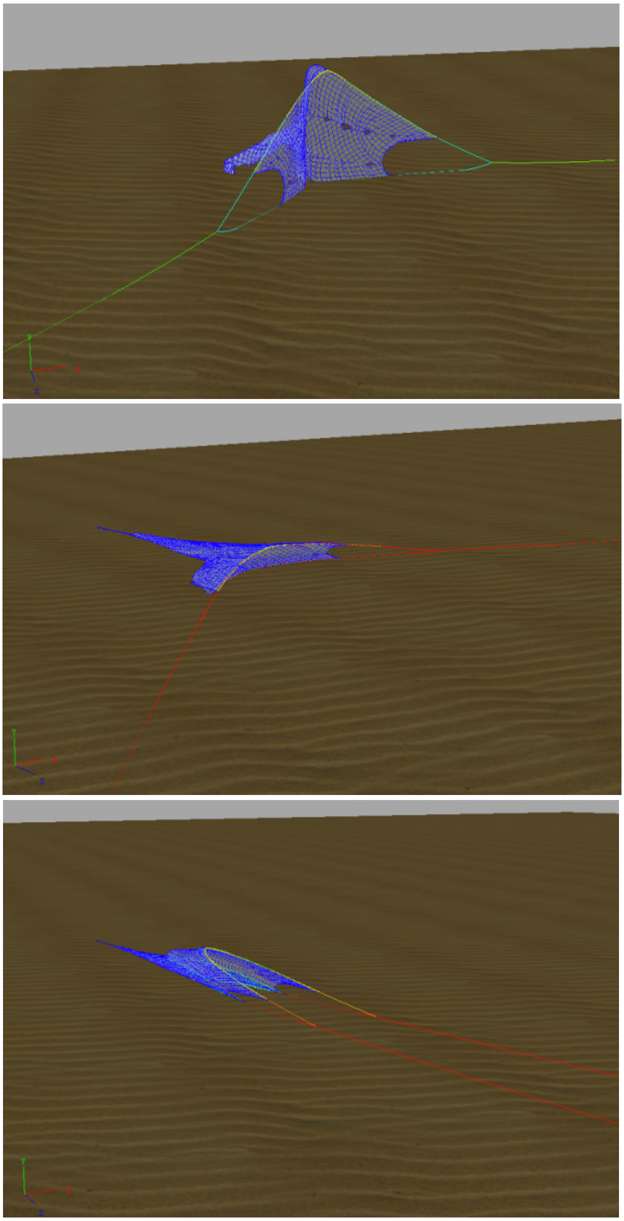

Figure 3.32. *The shape of a Danish seine changing during a turning maneuver (source: Ifremer – Lorient). See color section*

DynamiT (Ifremer, Lorient) was the first commercial software that could simulate the functioning of any kind of trawl (it became operational in 1999). It was followed in 2000 by a Korean software program called SimuTrawl, belonging to a society named MPSL, with the same goals but a lower definition of the simulated trawls. Lastly, the Uruguayan software TrawlVisionPRO focused more on a strong accuracy of the representation at the expense of the reliability of the simulation.

Several software programs designed for internal laboratory use have also been developed, such as FemNet (Ifremer, Brest) and RopeNetCalculator (University of Rostock). Other software programs are being developed in Japan, Norway and Denmark.

Box 3.4. *The development of commercial software*

3.5. Perspectives

The development of tools designed to observe and help us understand and conceive fishing equipment has undoubtedly allowed their optimization for fishing purposes (more effective equipment) and better conditions for the crews involved (reduced time spent at sea, less significant sorting operations, limited risks, etc.), even if the number of workers onboard has concurrently been decreased. However, these developments have also made it possible to reduce the environmental footprint (reduced CO_2 emissions, incidental catches and physical effects). It should be pointed out that these aspects of environmental progress are closely interrelated.

Miniaturization and the decreasing costs of the materials necessary for measurements and imaging are leading to an increase in the stream of data, as well as an improvement in their quality, especially because we are perturbing the systems studied to a lesser degree. We can, for example, instrument some fish with pressure/temperature sensors[7].

Semi-automated or entirely-automated image and data analysis in general will naturally improve in terms of helping process the increasing steam of measurements, photos and videos deriving from the systems studied. Moreover, the simultaneous use of optical and acoustic images contributes supplementary scales. Thus, optical images are limited by turbidity and become dark in the order of a few meters, whereas acoustic images (rotating and lateral sonars, sounders, acoustic cameras among others) have a wider

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[7] See Chapter 5 on Bio-logging.

range (from a few dozen meters to a few hundred, but with a lower resolution)[8].

The assessment of the selectivity of a fishing gear is currently mostly based on methods that compare a selective and a non-selective device with bias which will be decreased by new approaches that make use of imaging.

Part of this chapter presents the tools developed for computer simulations of fishing gears. The progress of optical and acoustic imaging, together with the developments of modeling, will allow us in the medium term to simulate the behavior of fish. The association between fishing gears simulation and the modeling of the behavior of these species, before or within these gear, will make it possible to gain a better understanding of the process of catching animals. This knowledge should ultimately lead to the development of catching techniques with a minimal ecological footprint, especially on the seafloor.

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4

Acoustics to Detect and Measure Underwater Organisms

4.1. Introduction

In the underwater environment, electromagnetic waves, including light, attenuate quickly. This reduces the ability of aquatic animals to perceive their environment visually and adapt their reactions. Similarly, visual observation tools used by scientists, such as video recording or radars, are limited in range. Acoustic waves attenuate significantly less than electromagnetic waves in water and can thus propagate further.

For this reason, aquatic animals such as marine mammals and fish use underwater acoustics rather than vision to position themselves, to communicate, to find their prey or to avoid predators. In ecology, ethology and fishery science, scientists also employ acoustics to study marine and freshwater fauna and flora. Acoustics offer the possibility to explore large volumes of water at large distances, in most cases with minimal disturbance to the environment given the frequencies and exposure times used.

4.1.1. *Physical principles of underwater acoustics*

Remote observations of the underwater environment rely on the transmission of sound waves, which are mechanical vibrations propagating through a medium. The conditions for sound propagation in water are very

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favorable: the velocity of propagation is more than four times faster than in air and sound waves are attenuated little compared to light waves.

Passive acoustic methods rely on the reception of a signal transmitted by an external source. The sources that can emit a signal are of very different natures. Cetaceans, fish, crustaceans and other living marine organisms generate sounds, in addition to anthropogenic activities (maritime traffic, underwater explorations, sonars) and the surrounding environment, due to thermic agitation and meteorological conditions. The acoustic signals of these sources, of natural or anthropogenic origin, differ quite substantially in terms of duration, intensity, and frequency. These sounds can propagate omnidirectionally or in a given direction only.

Active acoustics transmit a signal and register its scattering on a target. When an acoustic wave encounters the interface that separates two media with different acoustical impedance[1], part of the wave energy is transmitted to the other medium while the other part is reflected back. As is the case for the sound sources studied with passive acoustics, the transmitted signal is characterized mainly by its duration, frequency, intensity, and directivity. After transmission of the signal, the echosounder[2] or animal receives the echoes generated by its surroundings (seafloor and sea surface, fish, plankton layers, etc.). If the transmitted signal is directional, the portion of the environment generating echoes is limited to a certain angle and area. The resolution of the transmitter is thus defined by its angular opening and the wave length of the transmitted signal. At any given time, all targets located within the insonified volume will simultaneously send back echoes which will tend to overlap at the receiver (Figure 4.1).

Thus, we can distinguish two broad target types in acoustics:

– individual targets, which are smaller than the insonified volume so that they individually reflect back the echo of a single organism at a given time (individual fishes);

– volumetric targets, whose overall size is larger than the insonified volume and which fill it homogeneously (fish school, plankton layer).

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[1] Resistance of the environment to the acoustic wave.

[2] An electronic device transmitting and receiving sound waves.

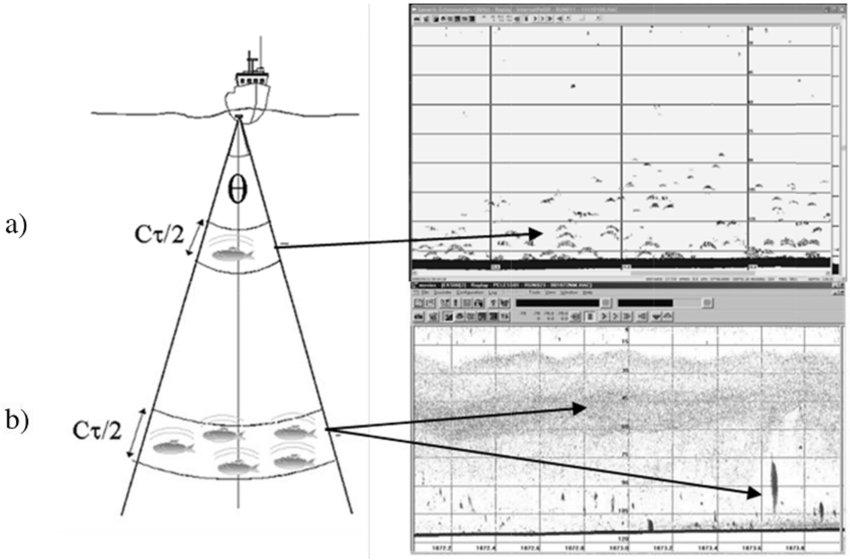

Figure 4.1. *The relation between the size of a target and the volume insonified by an echosounder placed on the hull of a ship (on the left) and an image of the echoes received by the same echosounder (on the right): a) single targets (individual fish) < insonified volume; b) multiple targets (fish school or plankton layer) > insonified volume. θ represents the opening angle of the echo-sounder. The thickness of the insonified volume depends on pulse duration τ and celerity C of the signal emitted by the echosounder (source: Ifremer)*

The echosounder or animal emitting an acoustic signal aims to detect, localize, identify and quantify biological targets. The direction of the backscattered echo as well as the time elapsed after transmission can determine in the case of an individual target its reflection index, called target strength and denoted TS. This measurement provides information about the species and its body size.

For a given species, the bigger the animal, the larger its TS. Similarly, for a given size, the TS depends on the type of target (gas bubble potentially approaching resonance, soft tissues not very reflective, presence of a reflective hard shell), on its shape, and on the incident angle of the acoustic wave if the target is large compared to the wavelength (the echo intensity of a target can vary according to its orientation in relation to the transmitter). Thus, the same target has a different TS and echo intensity for different frequencies. The change in TS with frequency allows us to characterize different groups of scatterers, as illustrated in Figure 4.2. The big difference between fish with and without a swim bladder derives from the fact that the swim bladder, used for lateral stabilization, is filled with gas (mainly oxygen), oil or fats, which contribute greatly to the reflection of acoustic waves. Most fish species have a swim bladder while mackerel, which is an abundant species, has none. As for plankton, the target strength varies between hard elastic shelled and fluid-like soft tissue organisms, and those containing gas bubbles. Euphausiids (krill) are part of the fluid-like plankton.

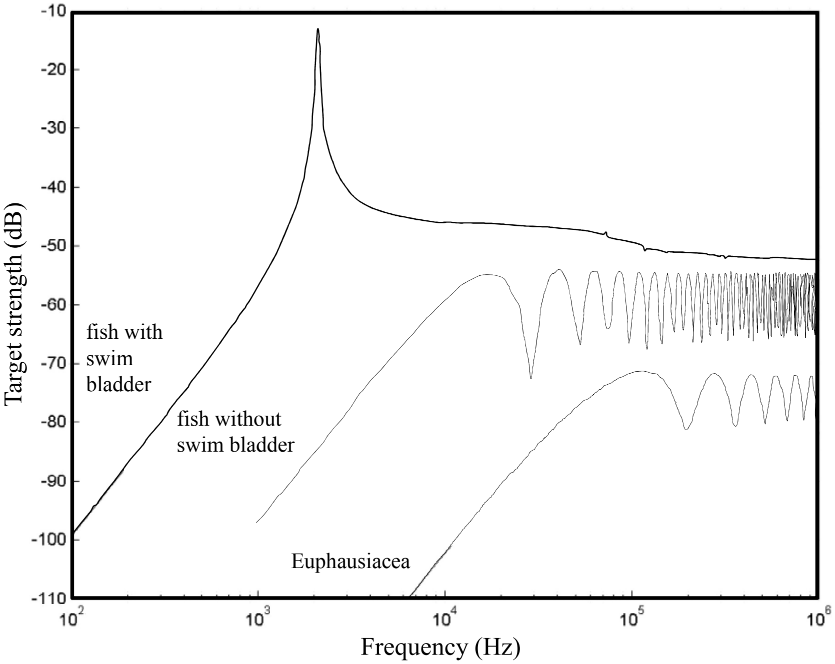

Figure 4.2. *Target strength as a function of the emission frequency for different marine organisms. This curve is called frequency response curve (redrawn from [STA 10] and modified)*

In the case of volumetric targets, the larger the number of individuals in the insonified volume, the higher the echo intensity. Assuming a certain TS for individual targets, we can estimate their density based on the received echo intensity and subsequently their number.

4.1.2. *Instruments*

The system that can detect and measure the TS of a target is called an echosounder or simply, a sounder. SONAR (Sound Navigation and Ranging) is used as a general term for all systems transmitting sounds in water. An echosounder consists of a transducer emitting acoustic signals and a transducer, potentially identical, receiving the signals reflected by the target(s). The transducer transforms electrical energy into mechanical or acoustic energy and vice versa. The received signals, attenuated by the propagation conditions in water, must be amplified and possibly combined among the different elementary transducers which together form an antenna (Figure 4.3) to position the target.

Figure 4.3. *A multibeam ME70 acoustic antenna (part of the Simrad echosounder) (source: Simrad)*

The choice of echosounder, especially its emission frequency, depends on the type of organism we wish to observe, the desired range (maximum distance from echosounder), the required resolution (the ability of the sounder to distinguish two targets), and the precision of quantitative estimates aimed for. The echosounders used by scientists span a wide range of characteristics, performances and costs.

The emission frequency is an important parameter, which heavily influences the features and capabilities of an echosounder.

As shown in Figure 4.2, the TS of different scatterers depends on the frequency used. This means the employed frequency range needs to correspond to the range for which the TS and the observed echo intensities are sufficiently high (e.g. high frequencies for Euphausiids). Note that the higher the frequency, the more directional the echo becomes which is similar to measurements become more dependent on the orientation of the target. This effect complicates quantitative estimation for observed individuals.

The range of an echosounder decreases as the frequency increases (Table 4.1). This is due to the fact that as the distance increases the absorption of acoustic waves in water increases, and the transmitted signal is increasingly attenuated.

	Ecosounder frequency (kHz)					
Parameter	18	38	70	120	200	333
Beam angle (°)	10	7	7	7	7	7
Transmitted power (W)	2000	2000	600	200	90	40
Impulse duration (ms)	1	1	1	1	1	1
Range (m)	4200	2300	780	410	220	120

Table 4.1. *Range of EK60 echosounders used for fisheries research on RV Thalassa (range for which the volume backscattering strength (Sv) caused by noise is -70 dB for a celerity of c = 1494 m/s)*

The echosounder frequency also affects the resolution, which is defined by the beam angle (angular resolution θ in Figure 4.1) and the pulse duration (radial resolution). The angular resolution increases with frequency since, as is the case for a target, the transducer is more directive if its size is large in relation to the emitted wavelength. The higher the frequency, the narrower the beams formed by an echosounder of a given size. On the other hand, the higher the frequency, the greater the ability of the echosounder to transmit signals of short duration. Thus, radial resolution increases with frequency.

Thus, the frequency range selected for an echosounder is a compromise between the desired range and resolution.

The design of an echosounder influences its performances rather significantly, in terms of resolution and the ability to make quantitative measurements. An echosounder can concentrate the acoustic energy transmitted or received in an angular sector, but it does not completely neutralize its impact in other directions. The directivity of an echosounder makes it possible to describe more thoroughly the angular distribution of the energy transmitted or received by the transducer. Figure 4.4 shows the directivity pattern of an echosounder with a beam angle of 7°, which has smaller side lobes in other directions. The side lobes have a great influence in situation where the transducer simultaneously insonifies targets whose TS differ by several orders of magnitude (seafloor or sea surface in comparison with fish or plankton). A target with high TS observed in the side lobe simultaneously with a target with low TS in the main lobe will be confounded within the acoustic signal of the later (Figure 4.5). This phenomenon is another source of signal pollution and imperatively needs to be limited, especially if we wish to make quantitative measurements of the target strength.

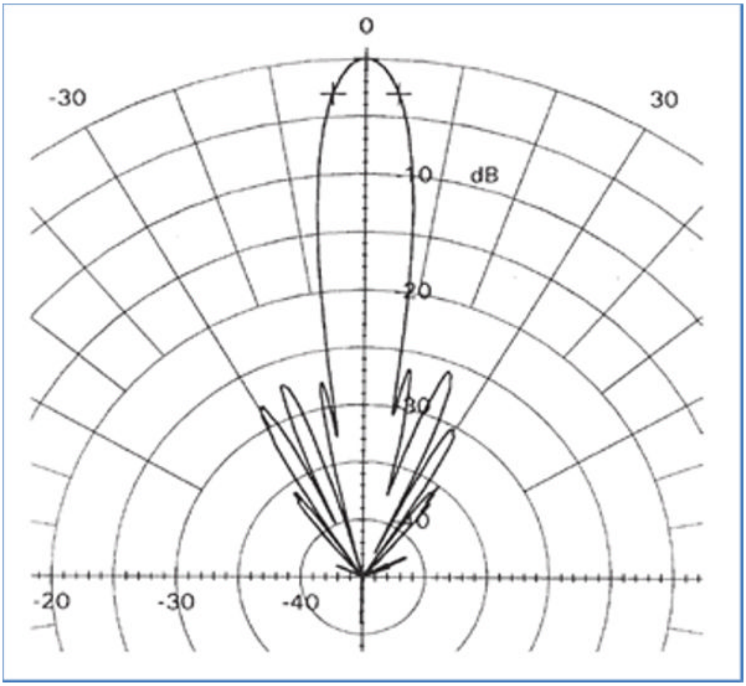

Figure 4.4. *Beam pattern of a Simrad ES -1207C transducer at 120 kHz in polar coordinates, the 7° angle at -3 dB is shown by the crosses on the main lobe (at the center, 0°), the side lobes (small side beams) have been optimized to less than -25 dB by the manufacturer (source: Simrad)*

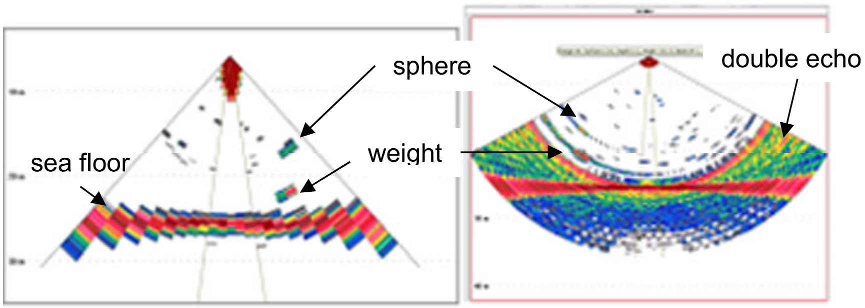

Figure 4.5. *Echogram of a tungsten sphere and its weight used to stabilize the sphere for a multibeam ME70 echosounder configuration with (left) and without (right) minimization of side lobes. In the latter case, the double echoes of the targets and the seafloor significantly complicate data analysis (source: Ifremer). See color section*

Lastly, to collect quantitative information, echosounders and sonars must be calibrated. The calibration is carried out with one or several spheres whose target strength at a certain distance is known in relation to the frequency of the sounder, the physical parameters of water and the material the sphere is made of. The targets commonly used are made of copper or tungsten carbide with a cobalt alloy. As the physical parameters of the environment affect the propagation and also the performances of the transducer, ideally the echosounder or sonar should be calibrated in the conditions in which it will be used, i.e. at sea in the same conditions of temperature, salinity and – if possible – depth where it will be employed.

4.2. How animals use acoustics

The aquatic environment represents a rich habitat in terms of plants and animals, and new species are being discovered every day. Like their counterparts on land, marine animals must be able to communicate, feed, avoid predators and reproduce in a continuously changing environment. Light dissipates very quickly in the aquatic environment and the photic zone (where light is available) is limited to the first 200 meters below the sea surface. Thus, most aquatic species rely greatly on acoustics to survive in the aquatic environment.

4.2.1. *Marine mammals*

Having completely abandoned the terrestrial environment, cetaceans (of the order Cetacea) such as dolphins, porpoises and whales have had to adapt to an aquatic environment rather unfavorable to visual or olfactory communication. The order Cetacea is divided into two Suborders: Odontoceti, i.e. toothed dolphins and whales which use echolocation, and Mysticeti or baleen whales that do not echolocate and lack teeth. Instead they filter their food using baleen plates. During their evolution and re-adaptation to the aquatic environment, these animals have completely altered their anatomy in order to make room for a dorsal blowhole, a melon and acoustic fats to channel and focus the sounds transmitted and received, as well as an ear structure very different from the one of their terrestrial counterparts.

Unlike land mammals, odontocetes do not produce sounds with their vocal chords. Instead they use a series of air sacks located below the blowhole, the equivalent to the nasal structures of mammals. The airflow between these phonic lips can create a multitude of sounds such as clicks (often used for echolocation) or whistles (Figure 4.6). Cranford [CRA 11] provides more details on the sound production of odontocetes.

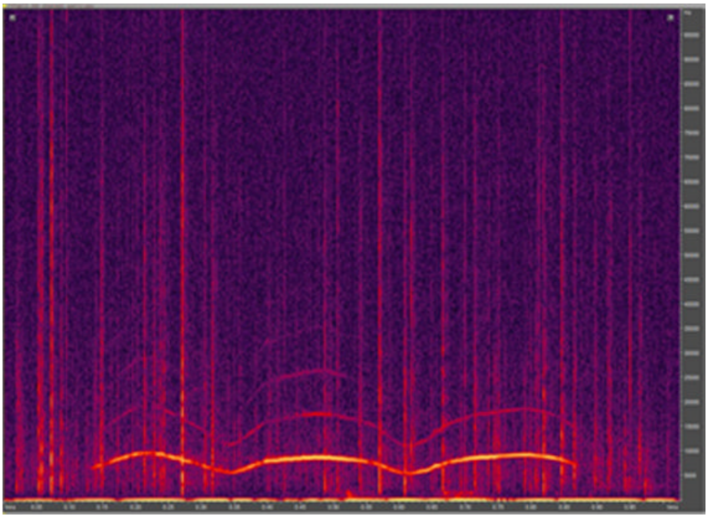

Figure 4.6. *Spectrogram of a whistle produced by an Indo-Pacific bottlenose dolphin (Tursiops aduncus) (source: Aude Pacini)*

How mysticetes produce sounds remains a mystery for scientists; recent studies have shown that these species may use their larynx to emit sounds.

To understand how cetaceans use and rely on acoustics, scientists have focused their efforts on hearing. Currently, there is no audiogram available (or hearing test) for mysticetes, but significant efforts have allowed scientists to better understand the hearing of odontocetes which can identify and distinguish objects with a precision distinctly higher than any man-made sonar. Hearing tests have revealed, among other things, that dolphins such as bottlenose dolphins (*Tursiops truncatus*) could hear sounds whose frequency was as high as 150 kHz (for comparison, human hearing plateaus out at around 20 kHz).

What are the main functions of these adaptations, so advanced in terms of sound production and hearing? Odontocetes can use acoustic information to locate and identify objects in their environment. This echolocation ability, similar to the one employed by sonars used on research vessels or fishing boats, allows animals to distinguish objects on a millimetric scale. In general, odontocetes produce clicks that are short in duration (in the order of milliseconds) and broadband. There exist, however, a few exceptions which include sperm whales, whose clicks have low frequencies, porpoises, with narrow band and high frequency clicks and beaked whales, which produce frequency-modulated upsweep clicks that are longer in duration.

Besides echolocation by odontectes, all cetaceans use and rely upon acoustics to communicate among each other and to coordinate their foraging strategy.

Cetaceans use the physical properties of the marine environment to communicate over long distances. It has been shown, for instance, that fin whales use the SOFAR (Sound Fixing and Ranging) channel to communicate over several thousand kilometers. This channel, generally located within 600 and 1,200 meters below the sea surface, is a layer where the speed at which sound propagates is at its lowest. Thus, sounds are trapped in this layer and can propagate over very long distances with minimal attenuation. Fin whales produce a sound within the 20 Hz frequency range which, before the industrial revolution, could probably propagate from one hemisphere to the other. Unfortunately, the increase in the level of sounds generated by human activities restricts the propagation of these sounds.

Even though we do not yet understand the meaning of the sounds produced by cetaceans, we know that the diversity between and among species varies tremendously from one region to another. Here are some examples illustrating how diverse this communication can be.

Killer whales (*Orcinus orca*) on the North-west coast of the United States have been described as being divided into two groups, transients and residents. Their acoustic repertoire varies mainly because of the prey they feed on. Transient killer whales prey on other marine mammals like dolphins or pinnipeds and are known to be silent predators and thus avoid detection by their prey. On the contrary, resident populations are organized into matriarchal groups and can be identified acoustically since they each have a repertoire unique to their group.

Humpback whales might be the most studied cetaceans, even though their songs are still the subject of many studies. Currently, we know that only males sing during the mating season, but the purpose of these songs still remains a mystery for scientists as singing males are often seen escorting a female and her whale calf (the female being thus unavailable for mating). Research has also shown that these songs are extremely complex and made of several units and levels of complexity and that all humpback whales sing more or less the same song, even if it changes over the course of the season.

Our last example is the social structure of sperm whales which are also organized into matriarchal groups. Similar to killer whales, each group of sperm whales uses a specific communication variation. They mainly produce clicks which are organized temporally in codas or communication units. These codas vary between groups and thus allow scientists to identify each group.

Like many mammalian species, cetaceans have a highly complex social structure, which is often reflected by the vocal repertoire and the complexity of their acoustic communication. There are several other examples of these adaptations, both elegant and fascinating, in aquatic life.

4.2.2. *Fish*

Most fish species produce sound for communication and reproduction, to defend their territory or food resources (competition) or as a response to a predator threat. Some fish can also hear the sounds emitted by their predators. Fish have a variety of mechanisms for sound production: friction between different parts of their body (teeth, spines, etc.), muscular movement of the swim bladder, of the peritoneum, of the tendons or of the whole body, tossing of sediment and swim bladder gas expulsion. The most common mechanism consists of vibrating the swim bladder. Most species have a specific acoustic repertoire, which includes certain types of distinct sounds used in specific situations. The dominant frequency is generally below 1 kHz. The message seems to be coded with a temporal, rather than frequency-related, modulation. The size of the fish, as well as ambient temperature, affect the dominant frequency, duration and frequency range of the sounds transmitted.

4.2.3. *Other marine animals*

Besides cetaceans, other marine mammals such as pinnipeds (sea otters, sea-lions, seals and walruses), polar bears and sea cows (dugongs and manatees) are also known to use acoustics to communicate. However, most of these species do not necessarily communicate solely underwater, preferring the air environment.

Lastly, marine birds are also known for their large acoustic repertoire and its importance for aerial communication.

4.3. How researchers use acoustics

Since the 1930s, underwater active acoustics has become increasingly important in the fields of biological oceanography, marine ecology and fisheries science. Sound waves or ultrasounds are used to study underwater life and to define the characteristics of seafloor or freshwater habitats. The use of passive acoustics has greatly developed since WW-II, led by military research focused on underwater detection.

4.3.1. *Widening the observation scope*

Active acoustics plays a special role among the observation methods available to researchers due to the size of the area they can cover (Figure 4.7). Active acoustics are the only method with which patterns ranging from one centimeter to 100 km can be observed simultaneously.

Within this range, the spatiotemporal coverage depends on the observation method. The sampling volume covered by passive acoustics is smaller than for active acoustics. This shortcoming can be overcome by using a large number of hydrophones spread in the study area.

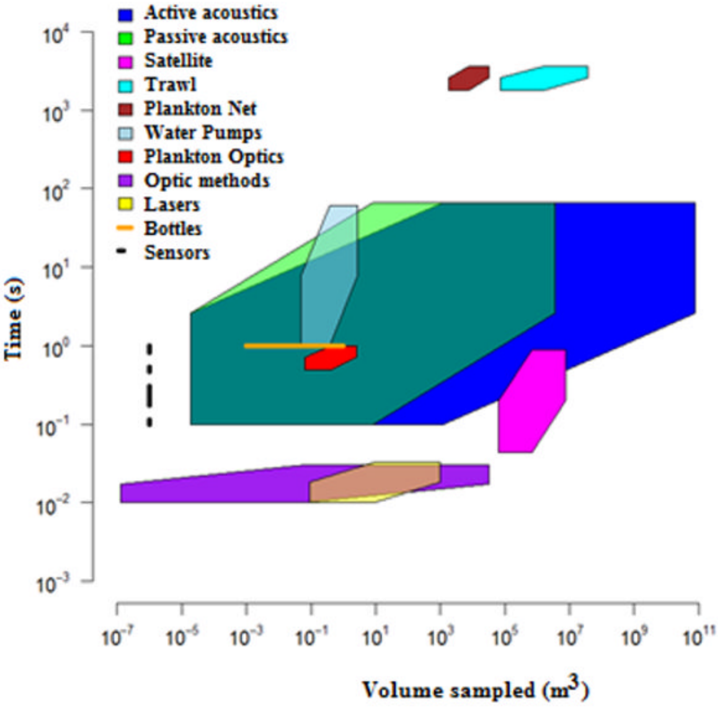

Figure 4.7. *Spatiotemporal scope of a single observation unit for different observation methods. The lower left-hand corner of each polygon shows the resolution and the upper right-hand corner the range. The dark green area indicates the overlap between the volumes sampled by passive and active acoustics to drawn from [TRE 11] and modified. See color section*

For a given instrument, the coverage of acoustic observations in time and space depends on the observation platform, whether fixed or mobile, and the sampling duration. Globally, a compromise has to be made between spatial and temporal coverage. Quasi-constant observation over months and even years is now possible thanks to moored stations. On mobile platforms, such as a research vessel, spatial coverage is often limited to regional seas, like the North Sea or the Bay of Biscay.

4.3.2. *Describing animal behavior*

Active and passive acoustic methods are used by researchers to study and describe animal behavior, interactions between individuals and their distribution and movement patterns. The sounds emitted by animals can be recorded by a series of listening stations or with a hydrophone installed on the animal as part of an archival tag. Archival tags including an active acoustic transmitter are mainly used to monitor the movement of individual animals, sometimes over several months. Active tracking has been used to study the behavior of tunas around fish aggregating devices (FAD), i.e. how much time they spent there and for studying their migrations. The 3D track of individual animals and its relationship with the physical and biological environment provides information about the use of space, the foraging strategy, and the relationships between animals.

At the population level, passive acoustics provide valuable information on reproduction and feeding areas, as well as migration patterns of marine mammals such as whales. This is possible because of the distinct sounds emitted by certain species in relation to the type of activity they are engaged in, as we have previously described. Thus, passive acoustics has shed light on the communication repertoire of different species which, in the case of Balaenidae, consists of three kinds of calls varying according to the area considered. This data can also be used to identify the species present in a certain area at a given time. Many species are actually identifiable through the characteristics of their sound repertoire. For example, fin whales are known to produce a very low-frequency sound (20 kHz). Beluga whales are often called the ‘canaries of the sea’ because of the richness of the whistles in their acoustic repertoire. Similarly, scientists can identify species such as beaked whale, Risso’s dolphin, or Pacific white-sided dolphin merely by analyzing the frequency components of their clicks. This type of research makes it possible to relate the presence of certain species to physical or oceanographic features, and also to get a better understanding of the role played by marine mammals in the food web. Some fish emit specific sounds during spawning, which allows identification of spawning areas.

At the group level, especially in schools of pelagic fish[3], active acoustics allow us to describe in detail their morphological features and spatial

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[3] Pelagic species live in the whole water column, unlike demersal and benthic species, which live near or on the seafloor.

organization. For example, it has been found that for small pelagic species (anchovies, sardines, mackerel, horse mackerel, etc.) the number of individuals fish per school increases with the overall abundance. The kinetic aspect of the formation and dispersion of the schools of certain species, as well as the diving of fish schools on approach of a ship, have been revealed by active acoustics (Figure 4.8).

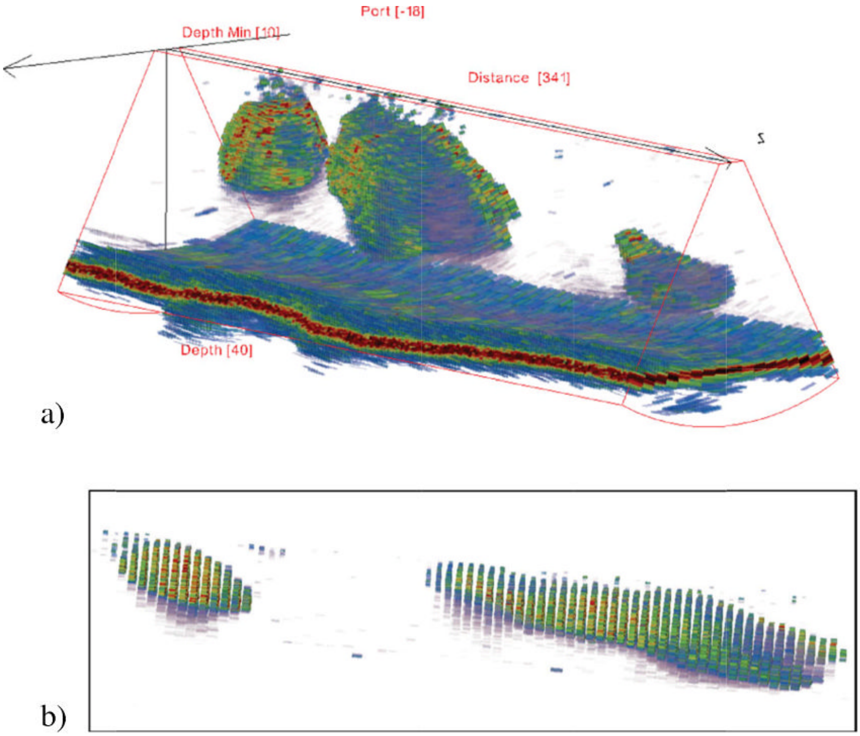

Figure 4.8. *A herring school diving on approach of the survey vessel. a) 3D view, b) 2D lateral view (source: Ifremer). See color section*

At the fish and plankton assemblage level, active acoustics have made it possible to describe variations in structure and spatial distribution (horizontal and vertical), from diel to seasonal and inter annual variations.

4.3.3. *Estimating fish abundance*

To estimate fish abundance, i.e. the size of exploited populations, two types of data are used by fisheries scientists: commercial catches and scientific survey data. For pelagic species, scientific data are collected using active acoustics. As it is impossible to count all fish in the sea, the population size is then estimated using this data. The estimate is generally called the abundance index. For this a model describing the relationship between acoustic observations and the actual (unobserved) population abundance is defined. This model includes a catchability factor describing the proportion of individuals of the population covered by the survey and the proportion of those present that was actually observed.

The acoustic sampling during scientific surveys estimating fish abundance of small pelagics is traditionally carried out using hull mounted echosounders (Figure 4.9). This permits sampling the whole water column, with the exception of a so called dead zone near the seafloor where benthic and demersal species live; and a blind area near the sea surface (Figure 4.10).

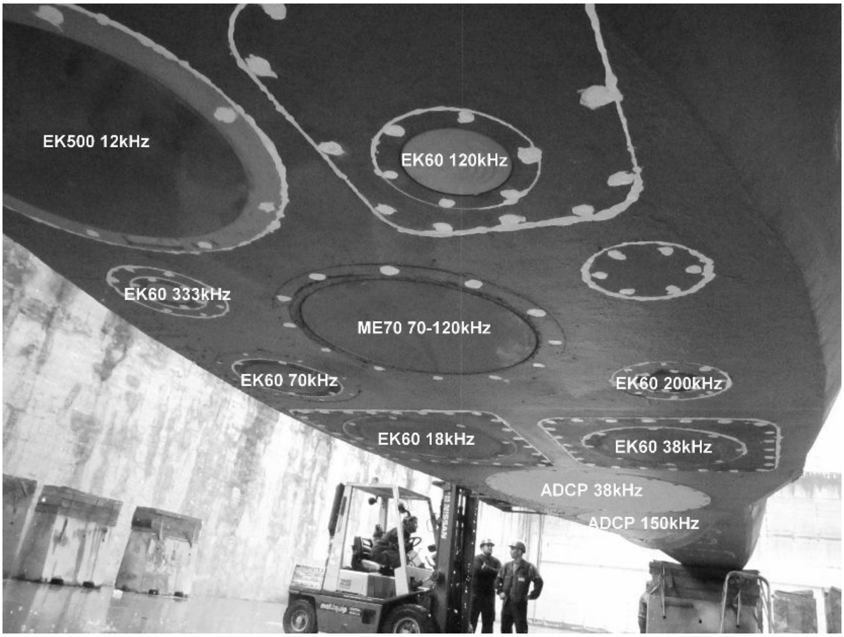

Figure 4.9. *Echosounders installed on the hull of RV Thalassa (source: Ifremer)*

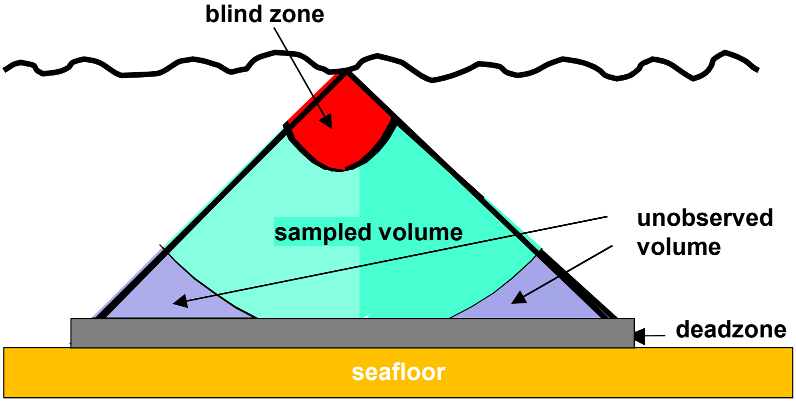

Figure 4.10. *Volume sampled by a vertical fisheries echosounder (source: Ifremer)*

The estimation of abundance indices by species in a given area, whether as numbers or biomass, is carried out by echointegration. Echo integration uses the fact that the intensity of the echo is proportional to the number of scatterers, that is the density of individuals in the fish school. The disadvantage of classic acoustics is that the species contributing to the echo cannot be determined with certainty. Therefore, we often have to work with mixed species groups and carry out pelagic trawling operations to estimate species composition. However, for favorable areas or situations (limited number of species with individuals spatially well separated), techniques involving acoustic species identification are starting to be implemented. These classification methods use morphological, spatial and energy-related features of the detections (reflecting species-specific behavior) and the difference in energy intensity at different echosounder frequencies used simultaneously. These classification methods constitute a significant step forward compared to the precision of estimates based on the energy reflected by fishes. Unlike trawling, these methods have the advantage of considering all targets and not only those located in the trawler path. Further, the way fish escape the trawler or are herded by it can lead to selective sampling by the trawler.

4.3.4. *Ecosystem indicators*

The development of ecosystem indicators using data from active acoustics to describe and monitor organisms in the water column is an active research field. In addition to biomass and abundance index estimates for some target species, these indicators are essential for the development of the ecosystem approach to the management of anthropogenic activities, especially fishing. Thus, using active acoustics we can obtain information on several ecological components and species groups of an ecosystem on different spatial and temporal scales (Table 4.2). The potential uses of these indicators are variable and often multiple.

Ecosystem component	Measurement or process	Spatial scale	Temporal scale	Usage
fish, krill	biomass/ abundance	stock	multiannual	stock estimate; data for ecosystem models
zooplankton, jellyfish, fish, species groups	density/abundance	ecosystem	multiannual or short-term	prey estimate; data for ecosystem models
fish	relationship between biomass/abundance and spatial density	stock	multiannual	monitoring catchability
fish-zooplankton, marine mammals-zooplankton	spatial relationships between predators and preys	local/ ecosystem	short-term	monitoring food webs; data for ecosystem models
fish, zooplankton	relationship between spatial distribution and habitat	ecosystem	short-term	data for ecosystem models; habitat mappings; climate change scenarios; spatial management

Table 4.2. *Summary of the measurements and processes active acoustics can provide information about and their usage for ecosystem-based management. The spatiotemporal scales are those of ecosystem-based management. Adapted from [TRE 11]*

4.3.5. *Seafloor and benthic habitat characterization*

Bathymetry and its small-scale variations are the first seafloor characteristic provided by active acoustics (Figure 4.11(a)). Sediment type is the second characteristic obtained using measurements of reflectivity (Figure 4.11(b)). Geosciences are mainly interested in these two characteristics. Ecologists interpret these features and combine them with other data like sediment samples and video images to define categories of benthic habitat. For example, some Scottish researchers have used this method to define the preferred habitat of sandeel, a fish that burrows itself into the sediment at certain times, and then used the map of habitat types to extrapolate local density estimates to an abundance estimate for the whole area.

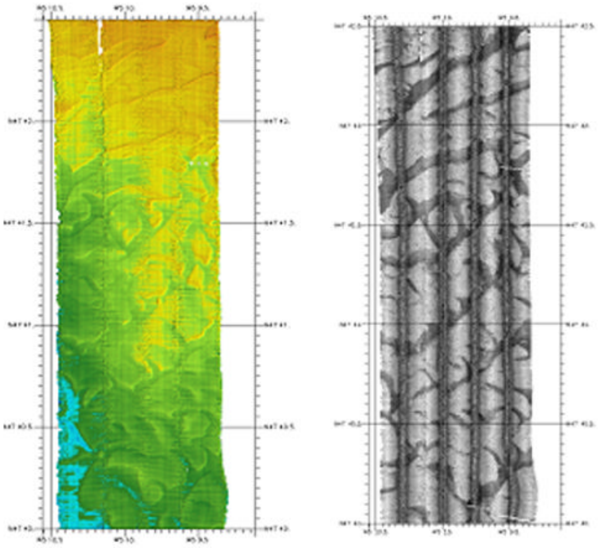

Figure 4.11. *Seafloor maps obtained with a Simrad ME70 multibeam echosounder; a) a bathymetric image; b) reflectivity image (source: Ifremer/Genavir)*

4.3.6. *Quantifying the impact of human activities on ecosystems*

Passive acoustics can be used as a tool for identifying and quantifying the impact of human activities on benthic ecosystems such as coral reefs (Figure 4.12). Additionally, acoustic recorders can nowadays obtain information on the presence of certain species as well as their seasonal variation and the potential stressors that could interfere with their behaviors. In many countries, manufacturers are required by law to quantify the impact of construction noises such as those made by pile driving or the machines used for the extraction of oil and gas.

Figure 4.12. *Environmental Acoustic Reader (EAR) in a coral reef (source: M. Lammers)*

4.4. Practical uses of acoustics

4.4.1. *Equipment*

A variety of acoustic equipments can be employed depending on the question to be studied (Table 4.3). In terms of echosounders and mono- or multibeam sonars there are portable and fixed versions. Fixed versions can only be used on the hull of large ships. The portable models can, on the other hand, be used on a manned or remote-controlled underwater vehicle, a moored station[4] or a small boat. Mounted on a trawler they can be singlebeam echosounders or omnidirectional sonars and be used to detect and study the behavior of fish when they enter the trawler. Some models send their data in real time to the carrier ship by acoustic communication, which can simplify their use.

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[4] A rigid structure anchored to the seafloor.

Equipment	Description	Applications	Main features
Singlebeam multi-frequency echosounder	Standard equipment for abundance estimation, it has different frequencies thanks to several transducers. The use of split beam transducers enables individual target strength measurements by interferometry. The recent advent of wideband echosounders makes it possible to cover the response spectrum of the target without interruption.	– Estimating abundance for fish/plankton – Classifying species based on their frequency response	– frequencies ranging from 12 kHz to 400 kHz – beam angle around 5° – range from 50 to 4,000 m depending on the frequency
Multibeam echosounder	Developed in the 1990s for seafloor mapping purposes, they can image the seafloor in several directions at once. Over the last few years, specific tools have been developed to measure the echoes in the water column.	– Estimating abundance – Studying behavior	– frequencies from 12 to 200 kHz – beam angle from 0.5 to 3° – range from 100 to 2,000 m
Lateral sonar	Single-beam echsounder towed close to the seafloor at shallow angle to image the fine-scale structures and shadows.	Fine-scale description of the seafloor topography to define benthic habitats	– frequencies from 100 to 500 kHz – asymmetric beam angle of 1° longitudinally 40° transversally
Omnidirectional sonar	Used by fishermen to search for fish, it provides adjustable panoramic horizontal monitoring (“umbrella-like” directionality).	Studying the behavior of schools of fish as a ship approaches and around it.	– frequencies from 30 to 100 kHz – beam aperture of about 10°, scanned – range of up to 2,000 m

Acoustic camera	High-frequency acoustic lens providing very high resolution.	Studying the behavior of individual fishes.	– frequency in the order of MHz – spatial resolution in the order of cm, temporal resolution of up to 10 Hz – range of about 10 m
Hydrophone	They constitute the elementary components of transducers.	Lab tool used to qualify transducers, it is used in passive acoustics to study sounds in the sea	– frequency from 1 to 200 kHz – general beam angle of 360° – Standard hydrophones are calibrated reciprocally

Table 4.3. *List of acoustic equipment together with their characteristics and application fields*

Over the last few years, our knowledge about the behavior of marine mammals has significantly improved with the introduction of acoustic recorders attached directly to the animals. For example, the DTAG (Digital Acoustic Recording Tag, [JOH 09], Figure 4.13) can record not only acoustic data in stereo (due to two hydrophones that can record frequencies of up to 96 kHz), but also other types of data such as the acceleration of the animal, its depth, as well as the pitch and roll axes of its movements. Scientists can, therefore, get a better understanding of the relationships between sound production and behavior, even at depths where direct observations are impossible.

Figure 4.13. *Digital Acoustic Recording Tag (DTAG) on an Atlantic bottlenose dolphin (Tursiops truncatus) (source: Aliza Milette – Winfree)*

4.4.2. *Carrying out a research cruise*

Planning acoustic data gathering in a given area and over a given period of time requires considering several aspects:

– choosing a platform and acoustic equipment;

– choosing the strategy for the acoustic observations, for example the route of the ship or the installation plan;

– choosing the parameters of the acoustic acquisition in relation to the instrument used (frequency of the transmission, signal strength, etc.);

– sampling strategy to gather supplementary data to identify species (trawling, video, etc.).

There are several types of observation strategies. For acoustic research on board a ship aiming to estimate biomass parallel transects arranged perpendicular to the coast are generally used (Figure 4.14). The goal is to cover the whole study area, for example the distribution area of a fish population. The inter-transect distance is determined by the spatial distribution of the studied species. The more heterogeneous the spatial distribution, for example an organization into some large schools, the narrower the radials must be so as not to bias biomass estimate by not observing enough schools. As for fixed observatories, a network of stations is often used (Figure 4.15). In this case it is not possible to extrapolate the local observations to a larger area.

The sampling strategy used to gather supplementary observations, such as trawl locations, are generally of two kinds: random sampling (random draw to decide which schools to sample) or targeted sampling, for example to take samples of fish schools of a certain shape and appearance. When combining this data with acoustic data to estimate biomass, the methods will vary in relation to the sampling strategy employed.

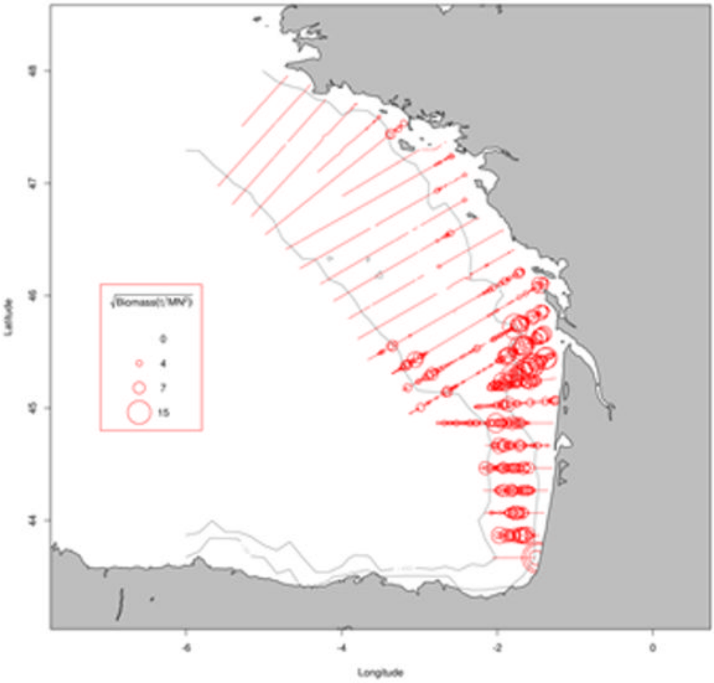

Figure 4.14. *Transect design of the acoustic survey carried out in the Bay of Biscay. The diameter of the circles is proportional to the biomass of acoustically detected anchovies (source: Ifremer)*

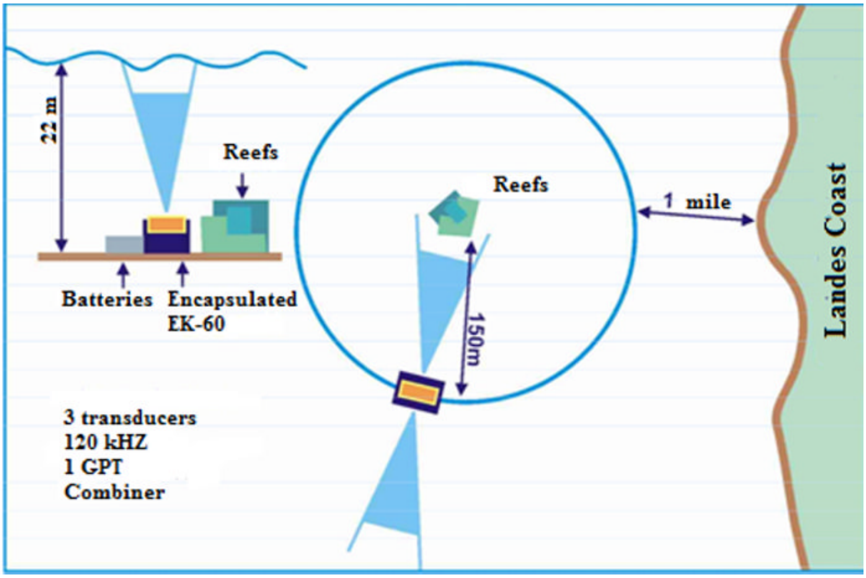

Figure 4.15. *Installation plan of a fixed station in the south of the Bay of Biscay designed to observe an artificial reef (source: Ifremer)*

4.4.3. *Data processing*

A common feature of all acoustic methods is the large quantity of data gathered. Automatic or semi-automatic data processing is crucial. Depending on the equipment used and the goals of the analysis, several data treatment softwares are available.

The data processing steps can vary, but there is always a data cleaning step to eliminate the interference noise created by other acoustic equipments, multiple seafloor or surface echoes, or signal attenuation caused by air bubbles in the water generated by the observation platform and/or the state of the sea. Next, it is necessary to detect the seafloor or other objects of interest. In addition to statistical analyses, visualizing the observations is important. Figure 4.16 shows an example of a processing chain as well as the software used to obtain biomass indices by species, size, age or geographical area. The 3D representation of fish schools is illustrated in Figure 4.17.

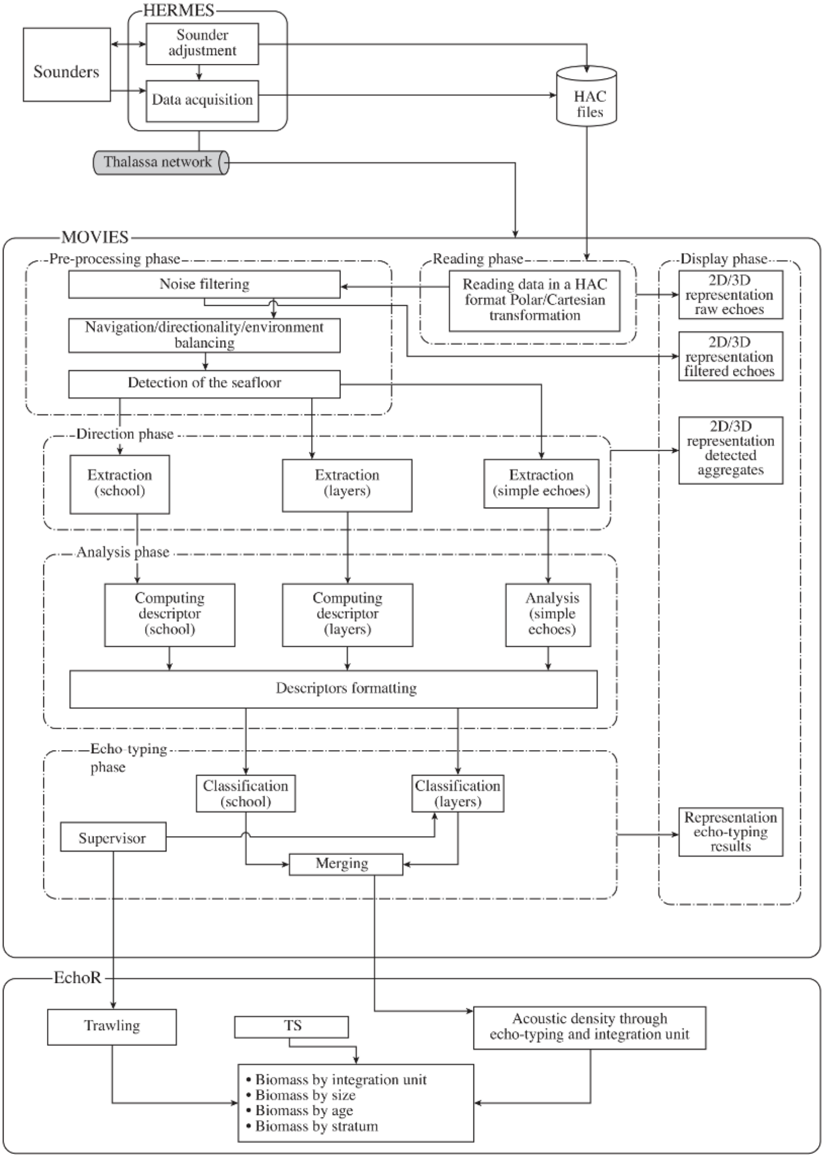

Figure 4.16. *Flow diagram of acoustic data acquisition and processing for biomass index estimation. The solid-lined boxes correspond to examples of specific software programs (source: Ifremer)*

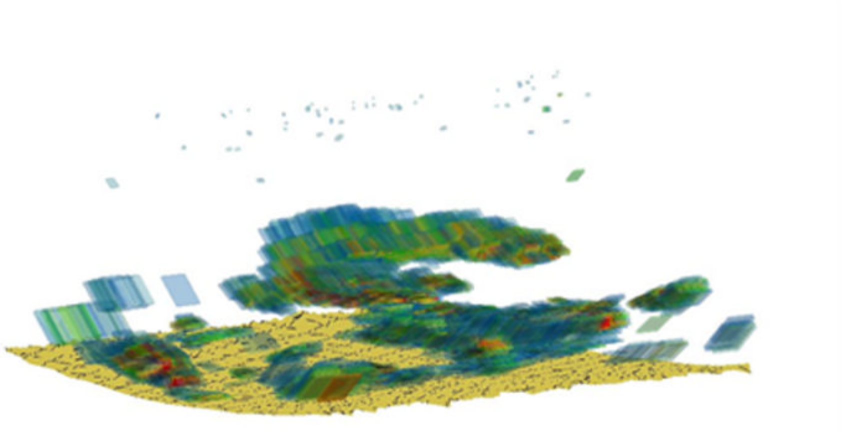

Figure 4.17. *3D representation of fish schools above the seafloor (source: Ifremer). See color section*

4.4.4. *Advantages and drawbacks of acoustics*

A great advantage of active and passive acoustic methods lies in their non-invasive nature. Nonetheless, sampling for species identification is required to estimate species-specific abundance indexes.

The drawbacks of active and passive acoustics are linked to the limited detection distance and the decrease in resolution with the increase in distance between the transmitter (echosounder or animal) and the target (see Table 4.1). However, active acoustics is the only method that can sample the whole water column continuously, allowing us to visualize the presence and density of organisms from zooplankton to large predators like tunas.

As for marine mammals, passive acoustics can only give us information about the presence of these animals at a given moment, but in no case allows us to estimate the number of individuals in a group, since silent animals cannot be detected. Thus, passive acoustics must be supplemented with visual observations at sea, to estimate group or population size.

The assessment of the impact linked to the use of active acoustics, especially the type implemented by the military or oil exploration groups, as well as the one used for seismic research, is currently an active research and debate topic. Several studies have shown that human activities and the use of active acoustics could cause significant damage. One of the effects on marine mammals is sound masking, whereby animals can no longer hear the sounds transmitted by other animals. Animals can change the frequency of their signals to avoid this masking, but their effort in terms of energy is yet to be studied. Globally, these mechanisms are still mostly unknown. More scientific studies are necessary and we can expect significant progress in the years to come. These problems do not arise in the case of fisheries echosounders, given the frequencies and energy levels employed.

4.5. Acknowledgments

We would like to thank Xavier Lurton, Anne Lebourges-Dhaussy and Naig Le Bouffant for their constructive comments. The EURO-BASIN project (no. 264933) of the 7th PCRD has provided financial support for the preparation of this chapter.

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5

"Bio-logging" as a Tool to Study and Monitor Marine Ecosystems, or How to Spy on Sea Creatures

5.1. Introduction

The term "bio-logging" was proposed in 2003 by Professor Naito during the first conference dedicated to this field of research [NAI 04]. Literally meaning the "recording of the living world", it refers to the use of electronic sensors directly attached to living organisms. Basically, the aim of the science of "bio-logging" is to record physical parameters using miniaturized electronic tools attached directly to free animals. A more operational definition has been proposed: "to understand certain parameters inside or outside a free organism, something which lies outside our direct comprehension" [BOY 04]. The process is based on three clear steps: sense – transmit – store. When we use a logger, these three steps are performed with the same instrument, transmission being reduced to the simple passage of information between the sensors towards an internal memory through the circuit board. The instrument must therefore be recovered to access the data. If we use a "transmitter", there may be no attached sensor or storage tool; the first step consists of the transmission of a radio signal, and the rest of the information is obtained remotely through a receiving antenna and possibly a related logger. This approach is known as "telemetry" (i.e. remote measurement) even if, strictly speaking, there is no measurement to speak of. This approach does not always entail the need to recover the instrument to

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access the data. Some instruments are more complex: they are fitted with one or several sensors associated with a recorder, in turn connected to a transmitter to allow information to be received remotely. The number of possible and actual combinations by which the three processes (sense-transmit-store) are associated has blurred the lines between "bio-logging" and "telemetry". Currently, the operation consisting of attaching electronic instruments to free animals is termed "bio-logging". There is a need for a distinction between "bio-logging" and "marking", the latter involving attaching a mark (such as a band for a bird) to an animal to identify it, as a tool for population biology studies (survival rates, population monitoring, etc.). Many combinations are possible, but in this chapter we will only focus on the most common ones. It is important to point out that all these instruments fitted with sensors measure physical parameters. When we talk about dive recorders, we refer to a recorder of hydrostatic pressure. When we mention a device recording the captured prey, we refer, depending on the technology used, to a temperature or magnetic field recorder. Similarly, we should point out that the information obtained through the same sensor varies according to its position: a temperature sensor situated inside the body of the animal will provide information of a physiological nature, whereas the same sensor attached to the outside of its body will provide information about the environment. For a given problem, the overall bio-logging technique consists of finding an ideal configuration between the kind of sensor, the position of the sensor(s) on the animal and the type of instrument (recorder or transmitter), in a device small enough not to interfere with the animal to an excessive degree. This chapter aims to give an overview of this field, and to understand its benefits as well as its issues and limitations.

5.2. The variety of sensors and measurements

5.2.1. *Position measurements*

The animals' position in terms of space and time is a measurement which is crucial to the study of the individuals' spatial distributions and behavioral strategies. Several techniques are currently available, each with their own advantages and drawbacks.

The triangulation of VHF signals is the oldest technique and is based on the reception of a VHF radio signal emitted by a transmitter attached to the animal. It does not work unless the transmitter and receiver are within a specific range of each other, typically about ten kilometers for marine applications. Simultaneous measurements of the reception angle from several listening stations are required to determine the position, which very quickly makes detecting a very large number of individual animals over short periods of time a complex task. Therefore, this technique is not suitable for the meticulous study of the animals’ movements or for those animals moving over distances which are too vast. However, a new project based on the idea of setting up antennae in space, is on the brink of revolutionizing animal monitoring through VHF transmitters, perhaps giving us the means to monitor dragonflies via satellite! [PEN 11, RIE 08, WIK 08].

Argos has long been a reference system for those animals that roam over vast distances for extended periods of time. The instrument carried by the animal is a transmitter, which emits radio waves at frequencies that can be picked up by satellites moving around the Earth in polar orbits. Satellites use the Doppler effect, i.e. they detect whether they get closer or farther from a transmitter along their orbits. Once again, the position measurement relies on the principle of triangulation. Satellites send their information to ground-based receiver centers which summarize this information and provide it to the user through computer servers. Several consecutive transmissions are required from the transmitter in order to calculate a position. The polar orbit of the satellites means that the transmitters will be more visible at high latitudes than they are at tropical ones. The diving behavior of certain animals means that the transmitter will not always be able to send a signal, since electromagnetic waves cannot propagate through water. The precision of the paths obtained with the aid of the Argos system can then vary quite substantially, and it is not possible to control the rates of tracking acquisition, with intervals typically ranging from several minutes to several hours [GEO 97, NIC 07, TRE 06]. In the best case, precision falls within a range of 100–300 meters, but many points could be several kilometers off. Therefore, this system is not suitable for animals moving over short distances or resurfacing infrequently. However, the position estimation system was perfected in 2011 and both the estimate of the positions and the related errors were improved. One of the greater advantages of the Argos system lies in its ability to receive tracking information nearly in real-time and send coded information besides obtaining the position. An Argos transmitter can thus be linked to other sensors, and transmit, for example, temperature, depth, and even GPS data!

More recently, global positioning system (GPS) recorders have emerged. Unlike the Argos system, a GPS recorder does not transmit anything and merely receives the transmissions sent by a group of more than thirty satellites orbiting around the Earth. Position tracking is once again performed through triangulation, by using the distance separating the recorder from the different satellites. This distance is estimated by measuring the time gap between the transmission and the reception of the signal. To calculate a position, we need to receive the signal of at least four satellites (only three if we know the altitude). This condition is sometimes crippling for recorders attached to diving animals. For these kinds of animals, the time ranges within which the recorder can receive satellite signals are quite narrow, which makes the receiving process complicated and uncertain. To overcome this problem, a new technology that allows us to perform no computing within the recorder has been developed. Only the information sent by satellites is stored, which can be performed in only ten milliseconds or so. The position tracking is then delayed until a future time and will be performed when the information has been downloaded from the recorder to a computer. The paths obtained via GPS are much more precise than those provided by other systems, making it possible to check the recording time interval. Thus, a path can have a spatial precision within the range of a few meters and a temporal resolution of only one second. GPS recorders are, on the other hand, limited by their battery capacity and memory size. They cannot provide information in real time, unless they are linked to a transmission system.

The geolocation by light sensing (GLS) system does not depend on satellites or the transmission of radio waves. A GLS logger records sunlight at pre-established and regular time intervals (for example, every five minutes). This system thus allows us to measure the day and night period, to estimate at what time the sun rises and sets, and the length of the day. Sunrise and sunset times depend on the longitude, whereas the length of the day varies according to latitude. The system can, therefore, calculate one position per day. Some enhancements make it possible to obtain up to two estimated positions a day. The precision of this kind of recorder is in the order of a few hundred kilometers [SHA 05]. On the other hand, these recorders use only a slight amount of energy and can be extremely miniaturized, and can function for several years. Some versions designed for marine animals such as tuna or sharks can correct the attenuation of light caused by depth and geo-locate individual animals that never resurface. The

GLS system is typically used to study migrations on large spatiotemporal scales.

Dead reckoning is another geolocation system. The principle is based on the knowledge of time, direction and speed in relation to a starting point. These parameters allow us to calculate a course, but this technique is subjected to errors mainly due to drifting, for example linked to marine currents. On the other hand, it has several advantages, especially its ability to work underwater. Linking this system with a GPS system (on the surface) can correct drifting and provide a 3D course [MIT 03, SHI 08, WIL 91].

5.2.2. *Physiological measurements*

Bio-logging has been met with a lot of interest in the physio-ecological community. Certain recorders measuring a number of parameters directly linked to broad physiological functions like thermoregulation, nutrition, oxygen and energy management [PON 07] have been developed.

If certain parameters can be measured with external recorders, this field has benefited significantly from the development of methods designed to surgically implant recorders in the animal's body. These techniques have allowed us to place temperature recorders in different positions inside the animal's body, so that we can find out how the body temperature of diving animals is regulated. Similarly, heart rate and even actual electrocardiogram sensors have been developed to answer questions on the physiological adaptation and energy management of diving animals [MEI 08, WOA 95]. Gastric pH recorders have been developed to study digestive processes [PET 97]. Finally, built-in recorders of the concentration of dissolved gases have been developed to study the dynamics regulating oxygen use and the adaptations associated with the optimization of the energy metabolism [MCD 13, STO 05].

5.2.3. *Behavioral measurements*

In the field dedicated to the study of animal behavior, "bio-logging" was a revolution. The development of pressure sensors linked to a time base has allowed us to record the diving behaviors of marine birds and mammals. Altimeters attached to birds have made it possible to understand their movement strategies [WEI 03, WEI 04, WEI 05]. The development of miniaturized accelerometers and magnetometers has allowed us to measure a number of parameters, like the 3D representation of behaviors, feed intake activities, as well as estimates of energy expenditure, establishing a link with energy physiology [LYO 13, NAR 09, OKU 09, WIL 06]. Other Hall effect sensors have been employed to determine feeding activities thanks to the measurement of mandibular opening [WIL 02]. Feed intake can also be measured thanks to temperature recorders situated in the stomach. When a cold-blooded prey (fish, squid, etc.) is ingested by a warm-blooded animal, the temperature decreases quickly before returning to its original state [KUH 09]. Certain very simple conductivity sensors attached to the feet of seabirds are used to determine if the bird in question is flying or resting on water [FER 00]. Lastly, some hydrophones can record the reaction of individual animals to their sound environment [JOH 03].

All of these sensors are based on the same principle, according to which a physical variable (pressure, acceleration, conductivity, etc.) is altered when a specific behavior takes place. Therefore, there are no behavior recorders. It is always necessary to establish a connection between a behavior and a physical variable. Sometimes this link is evident, like the fact that hydrostatic pressure increases when an animal swims down the water column. On the other hand, certain connections are less direct, like the recording of the changes in the magnetic field when the jaw opens and its relationship with the swallowing of prey. If the magnetic field does change with mandibular movements, it is trickier to associate this change with feed intake. The relationships between recordable physical variables and behaviors are sometimes subtle. A remarkable example comes from a study on southern elephant seals: the prey they ingest during their long migrations are turned into subcutaneous fat. This fat accumulation increases the animal's buoyancy. This change in buoyancy can be seen during diving behaviors, i.e. by analyzing the temporal series of hydrostatic pressure [BIU 03].

5.2.4. *Environmental measurements*

The possibility of attaching sensors to animals has made it possible to use animals as oceanographic platforms. For example, by combining location and temperature information, we obtain *in situ* measurements of water temperature in places that may be hard and/or expensive to reach [BIU 07, BOE 09, CHA 08, JAU 12, ROQ 09]. Different sensors have been developed to this end, such as salinity or chlorophyll sensors.

However, the environment is not limited to the ocean and physics. The animal’s surroundings are also a biological environment containing prey, fellow creatures, etc. In this context, we have developed acoustic recorders, built-in sonars or micro-cameras [JOH 03, KUD 07, MOL 07, RAS 13, TAK 04, THI 13, VOT 13, YOD 11] able to report on the biotic environment and, therefore, provide a better understanding of the interactions between animals and the environment itself [TRE 14] (Figure 5.1).

Figure 5.1. *An example of a picture taken by a micro-camera attached directly to a Cape gannet (Morus Capensis). The picture was taken as the animal fitted with it was diving (it is possible to see the bird’s back and wings in the foreground), and shows a fellow gannet about to capture a prey in the presence of a dolphin (Delphinus capensis) (source: Andrea Thiebault)*

5.2.5. *Presence measurements*

Even if we do not necessarily know all the behavioral details concerning individual animals, the simple fact of being aware of their presence at a specific point can be extremely informative.

For example, the presence or absence of a seabird in its nest allows us to measure the length of the sea journeys it carries out to feed its chick. This length is typically associated to certain environmental aspects (like the availability of prey) or phases of the reproductive cycle (such as egg hatching, the starting point of feeding journeys) [BER 01, FRA 02, TRE 05]. Recording the presence of an animal is also a means of monitoring it. Lastly, if the location where presence is recorded is part of a listening network, it is possible to measure the connectivity between different places, as well as migration patterns. Finally, if the listening points consist of the animals themselves, we can then shed light on social relationships and the frequency with which groups meet.

Presence measurements may rely on several principles: the aforementioned VHF technology consists of fitting an animal with a VHF transmitter which is picked up (presence) or not (absence) by a listening station. A system relying on the same principle but based on soundwaves is in place for submarine use, an environment where radio waves do not propagate (acoustic transmitters) [CLE 05]. Depending on the strength of the transmitters and the configuration of the listening station, presence can be detected several hundred meters away. On the other hand, these transmitters need energy and presence can thus only be detected during the battery lifetime. Another system can overcome this drawback: transponders or chips [CHI 99]. These transponders are used in the veterinary and agricultural fields to detect the identity of the individuals. The transponder is inert, has no batteries, and is very small. It can be implanted into the animal subcutaneously and theoretically remain there for life (rejection does occasionally occur). In this system, energy is produced by the listening system itself. A signal is transmitted and "reflected" by the transponder according to its number. The drawback of this system is that detection only works over a very short distance (often less than a meter) and requires a relatively significant and permanent supply for the listening system. A transmission/reception system has been developed to record contacts between individuals. This system is known as "business card tags" [HOL 09]. The transmitters also work as receivers, and they listen for, transmit and store information. When the animal is close to a receiving station, information is downloaded to the station. We then know which individuals were near the animal in question.

5.3. Attachment methods: limits and ethics

Attaching an instrument to an animal goes hand in hand with the need for irreproachable ethics and a lot of professionalism in order to ensure the animal's and the staff's safety. The animal must first be captured, then kept during the procedure time, before being released. The methods used to capture, restrain and fit instruments to the animal are very different and adjusted to each animal. As for birds, if no surgical implant is performed, the instruments can be attached to a band on its foot or with a harness (this method is no longer used in the marine field) or stuck or attached to its feathers with a kind of adhesive band resistant to seawater. This last approach is currently by far the most used since the bird's plumage remains intact after the removal of the instrument.

For marine mammals like sea lions or seals, the instruments are glued with epoxy. The glue film remains on the animal when the instruments are removed. It will detach naturally during the molting process, which generally takes place every year. This method is very safe and allows us to avoid cutting any hairs. Instruments are attached to marine mammals like whales by means of a suction cup while using a pole (for instruments which will remain attached for a short time) or are implanted and fixed in the layer of subcutaneous fat (or even in the muscle tissue) of the animals. As for fish, instruments are either surgically implanted in the abdominal cavity (the way instruments are recovered depends on fishing) or fastened to the exterior of the animal to cartilaginous areas. Instruments attached to the exterior parts of the animal can, in certain cases, detach themselves after an established period of time when the device is programmed, resurface and then transmit their information to the Argos system satellites.

Minimizing the discomfort of the animals is always an underlying concern. Therefore, it is necessary to miniaturize the instruments and minimize their impact to the best of our abilities, for example by optimizing their shapes, thus making them as hydrodynamic as possible, or by carefully studying their position on the animal.

On a technical level, the main limitation of "bio-logging" consists of the size of the instruments. It goes without saying that they have to be as inconspicuous as possible for the animal. Several studies have focused on the impact left by the instruments and have determined a certain number of rules. For certain gliding marine birds, instruments should not exceed 3% of the body mass of the individuals [PHI 03]. Other studies have focused on the shape of the instruments, the points where they should be attached, and their effects on the animal's hydrodynamics [CUL 94, HAZ 09]. The impact of the instruments remains a major concern and gives rise to many targeted studies [BAL 01, BOI 01, GUI 02, LUD 12a, MEY 98, PHI 03, QUI 12, VAN 12, SIM 02]. Miniaturization has not stopped its progress, which allows us to work on increasingly smaller species. However, an increasing number of new, more sophisticated recorders are being developed and, as a consequence, the problem of their size arises again for every new instrument.

Thus, the future of bio-logging will clearly revolve around miniaturization. Some types of instruments, such as small VHF transmitters or radar reflectors, can now be attached to insects [BOI 01, HED 02] but other kinds, like GPS recorders, cannot be used on animals weighing less than 200 grams. By the time this text is published, this limit may have already changed!

It is evident that the question of the size and mass of loggers is linked to the problem of autonomy. For the most part (chips or transponders are an exception), instruments need to be supplied with electricity and it often happens that batteries or solar panels take up more than half of the size/mass of the instrument. Therefore, miniaturization will involve improved storage in terms of energy production or consumption.

Generally speaking, energy-related constraints are much more significant than those concerning information storage. The memory embedded in loggers is often significant and more than sufficient in most cases. However, the increase in the number of sensors on recorders requires more and more memory. Certain sensors, like accelerometers or recorders of cardiac potential, are useless unless values are recorded at high frequencies (for example between 25 and 100 kHz). These sensors, sometimes in combination with others, generate significant streams of data. Technological progress makes it possible to integrate more and more sensors on the same instrument [WIL 08]. A recorder can currently measure temperature, pressure, light, speed, acceleration and the magnetic field on three axes. The increase in memory size is crucial for multi-sensor recorders. Finally, the cost of the instruments is often an obstacle for studies involving a large number of animals.

5.4. Current challenges

Most of the studies have focused on relatively large animals, generally predators. If we decrease the size of the devices, access to smaller species opens up interesting prospects in the field of ecology, with an increasing availability of prey species. However, if the dimensions of the devices remain an obstacle in many cases, other aspects represent as much of a barrier. Recorders generate significant streams of data which accumulate over time. Every year, thousands of devices gather an ever increasing mass of information. Data must be controlled qualitatively, which turns out to be crucial when this data is of an environmental kind. This quantity of information must finally be analyzed in order to be interpreted, which is where another challenge arises. Analysis protocols, programs and formats are not necessarily standardized. Each team develops their own analysis methods and tools, and it is rather complicated to follow the methodological developments linked to technological progress. In the past few years, we have seen the appearance of some initiatives focused on online data storage and management, aiming to make data more visible and accessible to a larger community of researchers and to favor digital data-mining. For example, internet domains like "Seaturtle.org", "Seabirdtracking.org" or "Movebank.org" host animals' pathways as well as some data processing tools.

5.5. Some examples of discoveries resulting from bio-logging

While it is easy to list technical developments linked to bio-logging, it is trickier to assess it scientifically because of the large quantity and variety of information. With the help of some specific examples, we will give an overview of a certain number of important discoveries in the next few sections. Our choice in terms of studies is neither exhaustive nor exclusive and, in a few cases, other studies may be used as examples.

5.5.1. *The marine field is huge, and yet…*

Monitoring marine animals in their environment has allowed us to shed light on the scale on which animals operate, which has resulted in quite a few surprises. For example, the wandering albatrosses *Diomedea exulans* of the Crozet Islands can travel about 15,000 kilometers during the incubation period [JOU 90]. The grey-headed albatross *Thalassarche chrysostoma* can travel around the Southern Ocean during winter [CRO 05]. White-chinned petrels *Procellaria aequinoctialis* can travel over 7,000 kilometers to feed their chicks once [CAT 00]. Sooty shearwaters *Puffinus griseus*, which reproduce in New Zealand, feed their chicks with Antarctic prey and winter in Japan, Alaska or California, before returning to the same nest the following year [SHA 06]. Arctic terns *Sterna paradisaea*, which weigh less than 125 grams, can migrate over 80,000 kilometers per year across the Atlantic Ocean [EGE 10]. An Atlantic bluefin tuna *Thunnus thynnus* located in the eastern part of the Northern Atlantic in January can be found in the Mediterranean a few months later [BLO 01]. After molting, male Northern elephant seals *Mirounga angustirostris* leave their colony in California to reach the continental shelf of the Aleutian Islands, whereas females go to the subtropical frontal zone in the middle of the Pacific Ocean [LEB 00]. Their cousins, the Southern elephant seals *Mirounga leonina*, travel a few thousand kilometers as far as the polar front or the Antarctic shelf [BAI 07, BOM 00, FIE 01, MCC 92]. Great white sharks *Charcarodon charcharias* link Australia to South Africa [BON 05] and salmon sharks *Lamna ditropis* connect Alaska’s arctic waters to the tropical waters of Hawaii [WEN 05]. Leatherback sea turtles *Dermochelys coriacea*, which reproduce on the beaches of Costa Rica, migrate in the gyres of the Southern Pacific, sometimes beyond Easter Island [SHI 08], whereas loggerhead sea turtles *Caretta caretta* can roam over nearly the entire Northern Pacific [PEC 11].

We often find these results extraordinary because of the challenge to common sense they represent. These studies show us how incapable we are of understanding processes on such large spatial scales, understandable as our lives are not lived on those kinds of scales. However, another remark is more worrying: we find it very difficult to organize, legislate and exert control over human activities when they involve large-scale processes. For example, the management of large-dispersal fish stocks and the conservation of migratory species are real administrative and legislative conundrums.

5.5.2. *To adjust, yes, but how?*

The study of marine predators by means of recorders has also allowed us to shed light on a certain number of processes of remarkable behavioral and physiological adaptation. If the marine field is vast, it is also dynamic and unpredictable; it imposes significant thermic constraints (water is about twenty times more dissipative than air and organisms function with more difficulty, or even stop functioning altogether, at low temperatures) and does not show any obvious discontinuity that could serve as spatial point of reference. How is it possible to live in such a universe?

A first answer comes from the use of wind and marine currents as a means of movement. Leatherback sea turtles *Dermochelys coriacea* use marine currents to move around, which allows them to save energy and remain within favorable areas more easily [GAS 06, LAM 08]. Wandering albatrosses (and probably most gliding seabirds flying long distances) sail into the wind like a sailboat [WEI 02] to make best use of the wind. Cory's shearwaters *Calonectris diomedea* do not travel from one point to another in a straight line, but use migration corridors which allow them to exploit the different wind conditions all over the world, such as equatorial trade winds [GON 07, GON 09]. Great white pelicans *Pelecanus onocrotalus* have shown us that flight formations or "V" formations make it possible to save energy by decreasing flutter frequency and heart rate [WEI 01]. Magnificent frigatebirds (*Fregata magnificens*) show us another system with energy-saving potential. They use upward air streams up to an altitude of 2,500 meters to glide over very large distances without having to flap their wings [WEI 03].

A second answer is provided by the studies on adaptations in terms of diving. Emperor penguins *Aptenodytes fosteri* can reach depths of 500 meters [ANC 92, KOO 82, KOO 95]; their Subantarctic counterparts, king penguins *Aptenodytes patagonicus*, can regularly dive down to 200 meters [CHA 99]. Both northern and southern elephant seals dive typically without interruption to depths within a range of 400 to 800 meters, with maximum depths of 900 meters and apneic spells reaching 48 minutes [LEB 88]. Thick-billed murres *Uria lomvia* (about 1 kg) have been recorded at depths of 210 meters [CRO 92], and the tiny common diving petrel *Pelecanoides urinatrix* (143 g) regularly dives down to 30 meters, but can reach 64 meters [BOC 00]. In the case of air-breathing homeotherm divers (birds and mammals), these diving feats can be the result of the convergence of two factors. On one hand, they store enormous amounts of oxygen in their tissues thanks to high concentrations of oxygen-binding proteins (hemoglobin in the blood, myoglobin in the muscles). On the other hand, they are extremely oxygen-efficient when they dive, thanks to a decrease in their body temperature and an interruption of the blood supply to all non-vital organs during the dive. It is, therefore, evident that most marine areas with high productivity (surface marine areas, euphotic areas or coastal upwelling areas) or concentrating marine organisms (deep scattering layer or benthos) are accessibly by marine homeotherms. Only the expanse of the seafloor seems inaccessible to them.

Finally, a third kind of answer is social. The recent progress made in the miniaturization of micro-cameras has allowed us, among other things, to observe for the first time the surroundings of an animal when it is at sea. Some seabirds like Cape gannets *Morus capensis* interact with one another and form networks within which information is circulated. When an animal detects a school of fish, the nearby individuals are warned and the recruitment of predators for the school is, therefore, expedited. This recruitment ends with the formation of a foraging group, which can increase the catching success rate [THI 14a, THI 14b]. Thanks to the use of micro-cameras, social interactions and group behaviors of other species are being discovered and described [THI 13, VOT 13, YOD 11]. Up to now, this has been one of the lesser-understood domains of the ecology of large marine predators.

5.5.3. *Animals as oceanographers*

The presence of sensors attached to animals has given us the idea of using these animals as oceanographic platforms. Temperature sensors can provide detailed thermal profiles of the water column crossed by diving animals [SIM 09], and certain CTD sensors have been specifically developed for oceanographic purposes [BOE 09]. They are recorders/transmitters able to measure conductivity, temperature and hydrostatic pressure with respect to time. They can also transmit information through the Argos system, which complements data with spatial location. In other words, these tools can obtain CTD profiles that allow us to describe bodies of water. These instruments can be used on elephant seals to make the most of their high-skill diving abilities. Therefore, it has been possible to obtain very precise information on the position of marine fronts and icefield areas where research vessels do not venture [CHA 08]. South of the Kerguelen Islands, “oceanographer” elephant seals have made it possible to remap marine currents and obtain a better understanding of the marine circulation between the Kerguelen and Antarctica [ROQ 09].

5.5.4. *The impact of oceanographic structures*

If animals can be used to measure oceanographic parameters, they also behave in different ways with respect to the body of water they cross. The ocean is not uniform and these irregularities form certain structures on different spatial scales. These structures, like some fronts or eddies, have an effect on the distribution of the living organisms that constitute the basis of the food chain. Following the dynamics of a ripple effect, these structures partially affect the predators' behaviors. The significance and the prevalence of a targeted use of these structures are clearly established for nearly all the groups studied and on several spatial scales [BOS 09]. Among these structures, the large thermal fronts that separate larger bodies of water give shape to the dispersal of several animals, such as Laysan albatrosses, which exploit the Subarctic frontal zone of the Northern Pacific [KAP 09], or king penguins, which exploit the polar front in the Indian Ocean and the Southern Atlantic [CHA 01, SHC 10]. Southern elephant seals exploit the edges of eddies in the Atlantic and Indian Ocean [BAI 10, CAM 06]. In the Mozambique Channel, Pacific great frigate birds *Fregata minor* follow Lagrangian coherent structures to look for their prey [TEW 09], as do northern fur seals *Callorhinus ursinus* in Alaska [NOR 13].

This study also shows how the horizontal stratification of the water column affects diving behaviors. Bio-logging research can then reveal association patterns and the mechanisms affecting the spatial distribution of animals in the marine environment.

5.5.5. *Interactions with fisheries, their management and conservation*

In several ecosystems, top predators like birds and mammals interact with fishing activities. These interactions can be of different kinds depending on the species and fishery considered, and include:

– accidental catch in fishing equipment;

– changes in the natural behavior of the animals, which may get used to feeding on the waste produced in the sea by fishing boats rather than their usual prey;

– a direct competition for access to prey fish when they are also the target of a fishing activity.

In the current paradigm of an ecosystemic approach to the management of fisheries [FAO 95], the quantitative assessment of these different types of interactions is crucial.

Bio-logging has given rise to significant progress in terms of understanding these interactions. A certain number of works have made it possible to better assess the risks of accidental trawl catches by fitting some albatrosses with GPS devices. Southern royal albatrosses *Diomoedea epomophora* in New Zealand tend to be attracted by the trawlers who fish hokis (or blue grenadiers, *Macruronus novaezelandiae*). They seem to be able to detect the presence of ships at work more than 25 kilometers away, either directly because of the noise and smell produced or by step-by-step attraction towards a group of birds which are already around the ship [WAU 05]. Buller's albatrosses (*Thassalarche bulleri*), however, do not necessarily react to the presence of trawlers in their foraging areas [TOR 13]. The small-scale analysis of the GPS flights of these birds shows that in 50% of cases of spatial co-occurrence of birds and ships, there is no direct interaction but only a simultaneous use of the same habitat. The mere overlapping in areas frequented by albatrosses and fishing boats is not a measurement precise enough to assess the risk of accidental catch.

Bio-logging also allows us to better assess the problem concerning the seabirds' reliance on fishing waste. Several species of gannets in the Celtic Sea (*Morus bassanus*) and in South Africa (*Morus capensis*) have changed their natural foraging behavior by leaving their natural prey, i.e. small pelagic fish, to feed on the trawlers' waste at sea. Two problems arise in this context. First of all, the trawlers' waste consists in most cases in species of demersal fish whose energy value is lower than that of the gannets' natural prey, i.e. particularly fatty members of the Clupaeide family. Therefore, there is a risk that this new feed source may be of mediocre quality and affect the reproductive success of the birds [GRE 08, MUL 09]. It is also possible that, by becoming accustomed to feeding on this new source, the populations of gannets may be eventually weakened, especially when an increasing number of fishing laws are considering prohibiting sea waste; several countries, such as Canada, Iceland, New Zealand and Norway, have already implemented total or partial bans on sea waste. The European Union is currently assessing the pertinence of such a step. In the Celtic Sea, GPS-monitored northern gannets (*Morus bassanus*) change their behaviors according to the position of fishing vessels [VOT 13]. However, there are differences between the behavioral reactions of the individuals. Males in particular seem more attracted by the presence of trawlers. In a similar vein, by analyzing the (GPS) movements of Cape gannets (*Morus capensis*), the distribution of fish (observed acoustically) and the distribution of ships, we can see that the birds' reliance on the waste produced by ships is reversible and only takes place in those years when their natural prey (anchovies and sardines) are scarce or not simultaneously accessible [TEW 13]. It seems that the feeding behavior of birds in relation to fishing waste is primarily opportunistic and motived by difficulties in finding natural prey. All these studies highlight how every step aiming to reduce or ban sea waste must be supplemented by the resolution to restore the natural prey reserves on which the birds feed.

Finally, bio-logging allows us to get a better grasp of the problems concerning the direct competition between fishing and natural predators for access to prey fish. For example, in South Africa populations of anchovies and sardines have seen a significant shift in their distribution since 1997; very abundant on the west coast before this date, these populations have since moved towards the southern coasts [ROY 07, VAN 05]. Because of its reliance on the location of factories set up for fish processing, seine fishing targeted at these species has not totally adapted to this resource distribution and continues to fish mainly on the west coast. The west coast is home to sites that play a major role in the reproduction of Cape gannets and African penguins (*Spheniscus demersus*). Given the scarcity of fish in this area, the competition between fishing and birds has become a concern. Several works on these species of birds based on the deployment of GPS devices have measured the degree of overlap between bird feeding areas and fishing spots. Thus, if only 13.5% of the surface used by gannets is also exploited by the fishing fleet and if only 3.6% of the total fishing catch is made there, these catches still represent 41.6% of the demand for prey fish of the gannet colonies studied [OKE 09]. Similarly, there is a significant overlap between fishing areas and the feed zones of a colony of African penguins during mating season when energy needs are at their highest [PIC 09].

Figure 5.2. *A Peruvian booby (Sula variegata) fitted with a miniaturized GPS recorder (which weighs 12 grams) (source: Y. Tremblay)*

COMMENTS ON FIGURE 5.2.– The recorder is attached to the base of the tail feathers, which can protect the device upon the violent impact created when these birds dive down on a shoal of fish. The device is attached to the feathers with a type of adhesive tape resistant to seawater, which prevents the bird from being "damaged" when the recorder has to be retrieved. Thus, the device is recovered by removing the adhesive tape.

These two studies converge on the proposition of restrictive measures for fishing activities, either through temporarily closing certain fishing areas around important colonies or by means of permanent protected marine zones. [PIC 09] also recommend that we take into account the bird populations' quantitative need for prey when fishing quotas are decided. In Peru, another ecosystem where small pelagic fish are preyed on by seabirds and a very active fishing industry, the problem concerning competition for resources arises in a slightly different way. Here, the risk of competition between birds and fishermen is not linked to the migration of stocks of small pelagic fish, but to the dimensions of the fishing spot (a fishing fleet facing overcapacity of about 300% [FRE 08]) and the intensity of its catch (a fishing season reduced to around fifty days, because of the overcapacity faced by the fishing fleet). In these conditions, Peruvian boobies (*Sula variegata*) tend, over time when industrial fishing is being carried out, to get farther from the fishing boats and to increase their efforts by traveling farther and for longer periods in order to find food [BER 12].

This change in the birds' behavior can be explained by the quantities of fish caught, which exceed by more than a hundred times the needs of the whole bird colony. This study pointed out the existence of possible local fish depletion, which can be particularly critical when taking place in breeding colonies that play an important role for populations of birds. This study can offer some management measures:

– restricting fishing around the colonies;

– keeping in place a policy of individual fishing quotas to curb the overcapacity of the fishing fleet. In Uruguay, [RIE 13] are studying the phenomenon of competition for resources between South American sea lions (*Otaria flavescens*) and two kinds of fisheries: artisanal and bottom trawling. By examining the movements of South American sea lions (fitted with GPS devices) and the distribution of fishing fleets, these authors show that there is a significant overlap between the sea lions' feed zones and the areas where fishing activities are carried out. However, the kind of overlap varies depending on which of the two kinds of fishery we consider, which makes us think that it would be relevant to take different management/conservation steps for the two types of fishing.

Seabirds and pelagic birds like Procellariiformes (albatrosses, whale birds, petrels, etc.) are the most endangered kinds of birds globally. This has led Birdlife International (birdlife.org), an international organization dedicated to bird preservation, to bring together some seabird pathways (seabirdtracking.org) to target with more precision the preservation steps that need to be taken. This is especially with respect to the reduction in the number of birds accidentally trapped in fishing equipment like longlines (long hook lines stretching for several kilometers) which raise serious problems in relation to preservation [BIR 04, DEL 09, JIM 12, LEW 03].

Understanding the movements of individual animals at sea also allows us to better assess conservation priorities. This is how the implementation of marine protected areas (MPA) can take into account information provided by bio-logging to define which significant areas need to be conserved [LAS 12, THA 12, WIL 09]. As for the MPAs already in place, this data provides us with information on the effectiveness of the steps taken [CHI 11, LUD 12b]. Similarly, knowledge about migration routes can help us to assess the impact of structures which are potentially dangerous for seabirds, like offshore wind farms [HUP 06] or oil fields [DEE 02].

5.6. Conclusion

The 1980s were a decade of bio-logging pioneers in the marine environment. Even if older works exist, the 1980s mark a turning point, especially with the appearance of the first diving recorders on the market together with their series of analysis software and programs. The 1990s were characterized by intense development and constant deployment of devices on species that had never previously been studied. It was also the decade that saw the formation of the first generation of specialized scientists in these techniques. During the 2000s, technological developments have followed one another, but it was the progress in terms of analysis methods that became considerably more significant, especially in trajectometry (i.e. movement analysis). It was also in the 2000s that the first conference dedicated to this domain was organized: the "bio-logging conference". It has been held every three years since 2003. The 2010s seem to be continuing this tendency of progress and analysis. It is striking to remark that among the review articles about bio-logging, many date back to the last few years [BOY 04, BRI 13, EVA 13, ROP 05, RUT 09, SCH 08, TRE 09, WAK 09, WOM 13], which indicates that we are currently thinking about what comes next and what our future priorities should be.

The market for electronic devices designed for bio-logging has enabled the emergence of businesses specialized in this activity, mainly in the United States, Canada, the United Kingdom, Australia and New Zealand. Continental Europe, in comparison, has few suppliers.

If it is clear that bio-logging science is no longer in its infancy, its constant growth shows that it is still far from reaching its prime. It is then an adolescent science, which has made progress in certain fields (such as the recording and analysis of diving behaviors) but continues to develop in others (oceanographic sensors, cameras, etc.). Technological progress, especially in relation to nanotechnology, gives us hope that future discoveries will be as fascinating as those that have already been made.

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6

Modeling Strategies for Ecosystems

6.1. Definition of mathematical modeling

"A common misconception about mathematical models is that it is characteristic of them to simplify the actuality being investigated very much. It is true that mathematical models simplify very much. But this is not characteristic of mathematical models, it is characteristic of any attempt to comprehend the world. For instance, even decades of intensive empirical study of an ecosystem leave us with a simplified view of the system. The real issue is: how much simplification and what kind of simplification is it sensible for us to make?" Yodzis [YOD 89].

6.1.1. *Introduction*

Mathematical modeling covers a wide range of applications and methods. A model can be described in general terms as any representation of a system. The kind of system studied, the problems raised, the protocol used for the representation of this system and its application constitute the core of modeling operations. A system can be defined in abstract terms as any set of interacting elements performing one or several functions, while these interactions ensure information, energy or matter exchanges [VOI 08]. Such a set is dynamic: its components vary over time and the nature and

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orientation of the interactions determine the direction of the exchanges[1]. A living organism is, therefore, a system made of cells, the interactions of which are defined by a very large number of chemical reactions resulting in its growth, energy needs, reproduction and survival. On a completely different scale, an ecosystem is made of biological compartments (in a given space) regulated by relationships, for example of the predator/prey sort. The set of these interactions ensures important functions which have recently led to a kind of typology of "ecosystem services". We also refer to the "Earth system" and its elements, which contribute to thermodynamic exchanges (oceans, plants, glaciers and icecaps, gas elements of different atmospheric layers, human activities causing greenhouse gases, etc.).

Modeling a system becomes meaningful only when it comes to answering a specific question, since this question affects the definition of the elements and interactions considered. A system cannot actually be represented in its entirety (the extreme case would consist of the identification of all the atoms that constitute this system and the assessment of all the chemical reactions representing elementary interactions). Modeling can then answer a number of questions which define its usefulness. As a representation, a model can lead us to summarize theoretical or practical knowledge on a subject, to conceptualize a problem, to identify shortcomings in our knowledge and to define the lines of research. As a tool, a model allows us to test, by means of calculations, certain hypotheses by comparing predictions/observations; it also enables us to predict the evolution of a system, compare evolutionary scenarios and organize the most important processes into a hierarchy.

Besides being the representation of a system, modeling is based on certain methodological choices which constitute the formalization of the system. Thus, we go from conceptualization to a more operational stage: the representation of interactions by means of mathematical functions, the definition of spatial and temporal scales, data gathering (literature, on-site work, experiments, etc.). These stages are a pre-requisite for the calculation phase, which involves significant work in terms of computer programming, parameter calibration and result assessment. As these models are being used in an increasing number of fields, especially in decision support, these kinds of procedures are systematically described in detail in summary works and methodological guides.

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[1] "Macroscopic system properties such as trophic structure, diversity-productivity relationships, and patterns of nutrient flux emerge from interactions among components, and may feed back to influence the subsequent development of those interactions", from Levin [LEV 98].

6.1.2. *The main currents of ecological modeling*

Population dynamics is based on Malthus' works dating back to the 18th century and has focused for a long time on a single homogeneous species. Taking into account trophic interactions when modeling animal populations allowed us to make the step forward that we made in 1926, when Alfred J. Lotka and Vito Volterra developed, independently from each other, a mathematical model able to reproduce the cyclic behavior of predator and prey abundance. Vito Volterra's motivation [VOL 26] was then quite similar to the one animating the modelers of the field of the ecosystem approach to fisheries nowadays: it was a matter of understanding how the state of equilibrium between animal species could account for the amounts of fish caught in three Italian ports observed from 1905 to 1923. Charles Elton [ELT 27] then put forward the idea that communities organize themselves in relation to their feeding relationships, either as "predators" or as "prey". Among the several concepts developed by Elton we can find the notion of the food web, even though Elton did not employ this term yet and instead referred to "multiple food cycles". He also developed the idea of abundance pyramid with respect to the position within food chains, linked to the increasing size of the animals. Elton's paradigm was then improved by Raymond Lindeman [LIN 42], who came up with the concept of trophic dynamics in the ecosystem based on trophic levels described, for the first time, from the perspective of thermodynamic principles in terms of energy transformation. Afterwards, works started taking into account the complexity that regulates the formation of communities. The rejection of linear vision of the food chain and the awareness of a network of complex interactions date back to MacArthur [MAC 55]. His thought was based on the notion of a positive relationship between the complexity of food webs and their stability. This observation, grounded in logic, refuted in 1973 by May [MAY 73], was to be afterwards picked up by a series of modelers. Their models show that stability decreases with complexity, thereby creating opportunities for several attempts to refute or experimentally validate these ideas.

Lastly, in Yodzis and Innes's words [YOD 92], population modeling has to rely on general laws that can allow us to reduce the number of parameters required in order to account for their dynamics (Yodzis tackles a problem he calls "the plague of parameters"). Yodzis proposes, therefore, to curb the parameters of population models by having recourse to allometric laws. This kind of approach had several consequences and led to the association between populations, the trophic structure of communities, and bioenergetics – see for example Brose *et al.* [BRO 08]. Levins [LEV 66] had already identified these associations while emphasizing their complementary nature[2]. Thus, ecological modeling, which started with works on the increase of a population and the interactions between two populations, tackles some questions on different organizational levels:

– the coexistence of species;

– the role of space in the distribution and maintenance of populations (notion of meta-community);

– structure, stability and change in the state of complex systems;

– biological performances (fitness on an individual scale, production and flow of matter on an ecosystemic scale);

– the evolution of populations and adaptive strategies.

6.2. Mathematical formalization

6.2.1. *State variables, process variables and the equation of state*

In the following sections, we will deal with a particular class of models within the framework of system dynamics based on the representation of a process as differential equations (when time is represented as continuous) or discrete evolution equations (for example by considering a year as the timeframe to simulate abundance in relation to the age groups of a population). We will start with the representation of the system as state variables, i.e. those quantities whose evolution we want to calculate over time. For example, the size or mass of an individual, the abundance of a population, or the biomass of a biological compartment (phytoplankton, zooplankton, etc.) are classic state variables that we find in many ecological models. In such systems, the question of modeling boils down to determining how these variables evolve over time on the basis of a certain number of biological processes which determine their response. This leads, therefore, to the identification of the variations linked to these processes. When we try to predict the growth of an organism over time, its mass

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[2] "The multiplicity of models is imposed by the contradictory demands of a complex, heterogeneous nature and a mind that can only cope with few variables at a time; by the need to understand and also to control; and even by opposing aesthetic standards which emphasize the stark simplicity and power of a general theorem as against the richness and the diversity of living nature" from Levin [LEV 66].

variations can be determined by taking into account, on one hand, the processes of catch and food assimilation and, on the other, those related to metabolic costs, which constitute an expense linked to the organism's functioning. Assimilation (A) and metabolism (M) are expressed as quantities (mass and energy) per time unit, and the variation of the individual's mass is formulated by the following differential equation:

$$\frac{dX}{dt} = A - M$$

To sum up, the state of the system studied is represented by a variable; we know the evolution equation, also called equation of state, of this variable, which determines its change rate (or instantaneous variation). The modeling problem consists of estimating the value of X over time and can be formulated as follows:

– what is the value of A and M, what do they depend on, which are the working hypotheses?

– how can we go from the equation of state to the evolution of X over time?

– what is the validity and the uncertainty of the results?

– how can we extrapolate the result to other topics of research?

Evidently, systems are more complex and, therefore, require several equations of state. This is the case for the dynamics of a population, if they involve the awareness of the interactions with other populations (prey and predator). Let us call N the size of the population whose temporal evolution we want to assess, P the size of its prey and Q the size of its predators. Such a system is thus represented by a set of differential equations of the type:

$$\frac{dN}{dt} = f(N,P,Q)$$

$$\frac{dP}{dt} = g(N,P,Q)$$

$$\frac{dQ}{dt} = h(N,P,Q)$$

where f, g and h are functions defining the interactions between the three populations.

Being based on a very classic kind of mathematical formalism notwithstanding, the evolution of the state variables can be calculated analytically only in very rare cases. There are some elementary cases, like the following equation of state:

$$\frac{dX}{dt} = k \cdot X$$

If k is a constant, the solution $X(t)$ is given by the formula $X(t) = X_0 \cdot e^{k \cdot t}$. This is the analytic solution of the modeling problem, in which X_0 is a parameter corresponding to the value of X for $t = 0$ (called the initial condition). In most cases, however, the solution of the differential equation can be obtained at the end of a calculation based on the numerical integration of a computer program that calculates the evolution pathway repeatedly. Such a program relies on an algorithm set by the repetition of a sequence of instructions that allow us to calculate a solution approximated over small time intervals (or no time). This stage of modeling is called computer simulation and involves the following elements:

– the definition of the initial conditions for all state variables;

– the use of a simulation program – see Voinov [VOI 09] for a non-exhaustive list of available software and programming languages;

– the definition of time units and the assessment of the approximation level of the simulated solution.

The results of a simulation are represented graphically by the evolution courses of the state variables. Thus, these pathways reveal certain changes that define the dynamics of the system and let us identify some of its properties. We will remember, for example, the existence of states of equilibrium, fluctuations that could reveal cyclic patterns, rapid changes in the evolution of certain variables or state changes.

6.2.2. *Functional responses*

At the basis of the modeling of dynamic systems, biological and physical processes are represented by mathematical functions expressing the interactions between variables. The functions used represent causal relationships between state variables, the evolution of which can be found in the two following sources of variation. Firstly, the way the system is forced externally by time-dependent functions drives the systeme changes. Biological systems are open systems: they are affected by external factors, called forcing variables, the most common of which is temperature, which acts on the set of biochemical and biological mechanisms. Secondly, the mathematical functions used to describe the internal interactions that give some inherent properties to the system. We will use as examples some commonly used functions, which took shape in the study of population dynamics and, more precisely, within the context of predator–prey interactions.

When the dynamics of two populations are linked, for example as interactions of the predator-prey sort, the most general form is given by the two-equation system:

$$\frac{dx}{dt} = f(x) - h(x,y)$$

$$\frac{dy}{dt} = g(y) + e \cdot h(x,y)$$

x being the number of prey, y the number of predators, $h(x, y)$ the interaction between the two populations and e the conversion rate of the number of prey into the number of predators.

The simplest interaction, which Lotka, concurrently with Volterra, explained as the dynamics of two populations, consists of the function $h(x,y) = c \cdot x \cdot y$, which these authors established on the principle of the Law of Mass Action that regulates chemical reactions. The function $f(x)$ simply corresponds to a boundless population increase, whereas $g(x)$ represents constant-rate mortality. Thus, the system of equations becomes:

$$\frac{dx}{dt} = a \cdot x - c \cdot x \cdot y$$

$$\frac{dy}{dt} = d \cdot x \cdot y - b \cdot y$$

The origin of this model dates back to a very practical problem faced by Volterra in 1926 concerning the effects of fishing on the change in the balance between prey and predators in the Adriatic (see Kingsland

[KIN 86] – we can also find some highly applied examples which combine experiments and trajectory calculations in Gause *et al.*, [GAU 36]). Auger *et al.*, [AUG 10] provide a mathematical analysis of this model. For this model, the result is that predators and prey follow regular cycles representing:

– the increase in prey for a low level of predators;

– an increase in predators curbing and then decreasing the level of prey;

– a decrease in predators in response to a low-level of prey.

A graphic representation of these properties is presented in Figure 6.1 as the direction of the velocity vectors in the plane of the variables x, y (phase plane).

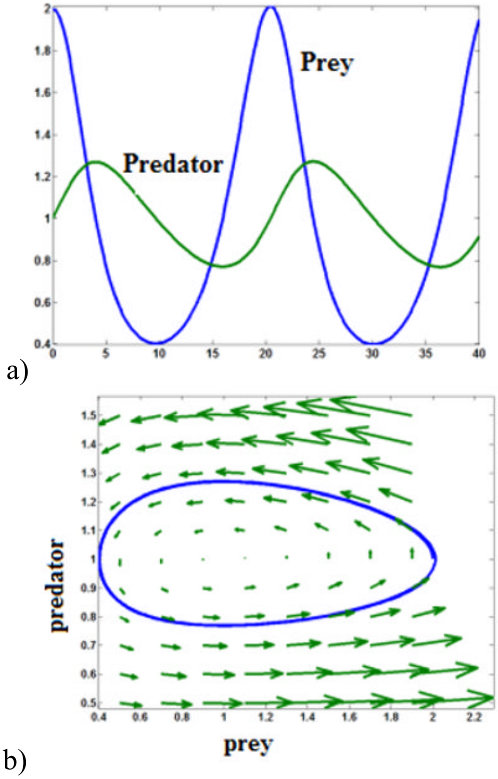


Figure 6.1. *The result of a simulation of a prey/predator system based on a Lotka-Volterra equation: a) evolution of the two variables over time; b) phase plan ad velocities. See color section*

The interaction is said to be of type I when it is proportional to x and y. Two changes can be made to this model: we can introduce a logistic equation restricting the number of births due to the limitation of resources available to this population, or a function, called Holling function, that curbs predation. Holling [HOL 59] established a predation functional response on the basis of the following remarks: the predator's consumption rate is an increasing function of the density of prey and the predators' density increases with that of the prey. His analysis is centered on the strategy of the predator, which is assumed to forage unpredictably. The predator's activity is divided into a certain amount of time spent looking for prey and the time employed to capture and ingest all the prey found, the latter being proportional to the number of prey caught. We define as:

– x the density of prey;

– a the surface explored per time units dedicated to foraging;

– Ts the time dedicated to looking for prey – $Ts.a.X$ represents, thus, the number of prey found during this exploration phase;

– Th the time necessary to catch and ingest prey that has been found – $Th.Ts.a.X$, therefore, represents the total capture and ingestion time;

– T the total time: $T = Ts + Th \cdot Ts \cdot a \cdot x$;

– $F = \dfrac{Ts \cdot a \cdot x}{T}$ the number of prey found per time unit, which is therefore, equal to: $F = \dfrac{Ts \cdot a \cdot x}{Ts + Th \cdot Ts \cdot a \cdot x} = \dfrac{a \cdot x}{1 + Ts \cdot a \cdot x}$

This function depends on the two parameters a and Ts, which are specific to the predator's ability to move and feed. The following form of this equation is the one most commonly used:

$$F(x) = \frac{b \cdot x}{x + x_k}$$

with $F(x) = \dfrac{b \cdot x}{x + x_k}$ and $x_k = \dfrac{1}{Ts \cdot a}$ determined empirically.

This function, called a Type-II Holling function, is used quite generally to express a form of non-linear reliance consisting in a reliance on the number of prey (in this case study) when they are scarce (what we call limiting conditions), and reaching a maximum value when there is enough prey (the limit is then set by the predator's ability to ingest the available prey).

This Holling function is an example of function used to describe a certain kind of interaction, on the basis of a certain number of hypotheses on the processes we wish to formalize. We find this function again for the description of the ingestion of prey given in some eco-physiological models (such an example is provided further on), but also for the representation of a process relying on a limiting factor. An equivalent formula consists of the Michaelis–Menten or Monod equation and was established to describe enzymatic reactions within the context of the Laws of Mass Action of a substrate (S) which, associated with a catalyst (E), produces a compound P [MUR 02, REA 77]. This process, and the resulting formulas, are described and used to model the dynamics of phytoplanktonic populations, which are limited by one or several nutrients (see, for example, Poggiale *et al.* [POG 10]).

A second mathematical formula consists of the logistic function:

$$\frac{dx}{dt} = r \cdot x \cdot \left(1 - {}^{x}\!/_{K}\right)$$

described by Verhulst in 1838, which has been compared with several experimental results (see, for example, Hutchinson [HUT 78]), to express the growth of a population in two phases. When the size of the population is small, growth is exponential – in the previous formula, the ratio x/K is negligible before 1 and the equation is reduced to:

$$\frac{dx}{dt} = r \cdot x$$

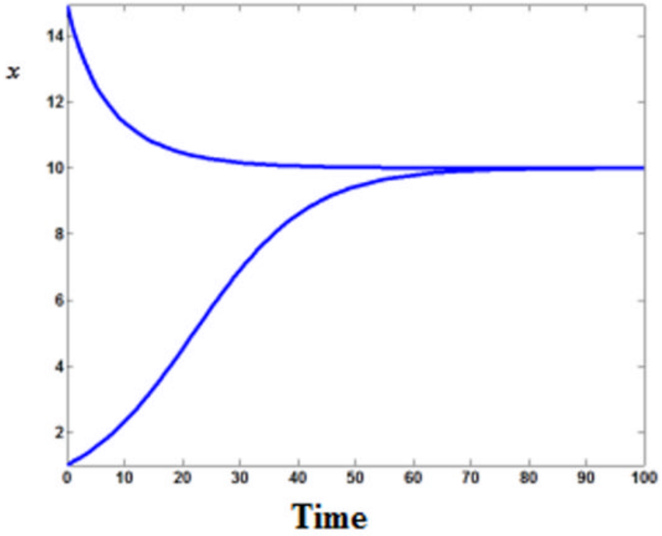


Figure 6.2. *The evolution of a variable x in relation to a Verhulst's equation for two different initial values*

When size increases, growth slows down and is affected by the decrease of the quantity ($1-x/K$) until it becomes close to 0 when x gets close to K. The evolution of x over time takes the shape of the sigmoid curve represented in Figure 6.2. The previous type of reasoning also holds true when the initial size is greater than K: in this case growth is negative and x gets closer again to the quantity K. K is called "trophic capacity" and corresponds to the value approached by the population, whatever the initial condition might be. The process of growth curbing by means of the term ($1-x/K$) summarizes the constraint related to environmental resources, while avoiding making them explicit as an equation of state. With two parameters, Verhulst's formula is therefore the simplest equation that can represent the dynamics of a population realistically.

The new system becomes:

$$\frac{dx}{dt} = a \cdot x \cdot \left(1 - {}^{x}\!/_{K}\right) - \frac{c \cdot x \cdot y}{x + k}$$

$$\frac{dy}{dt}=\frac{d\cdot x\cdot y}{x+k}-b\cdot y$$

The properties depend, therefore, on the value of the parameters: there can be fluctuations between predators and prey (unlike the initial model, the range of this fluctuation is unrelated to the initial conditions and there is a limit cycle), a point of stable equilibrium expressing a coexistence between the two populations with constant sizes, the extinction of the predators and the preservation of the prey at an insufficient constant value, in this case, to allow the predators' population to remain stable. This system of equations can be extrapolated to more than two populations. The behavior of a system of *n* equations cannot be analyzed mathematically and requires calculations by means of simulation – Berlow *et al.* [BER 09], therefore, use this kind of generic formalism to simulate a food web and assess its properties.

Choosing functional responses is, therefore, an important step in the modeling strategy. It is conditioned by the degree of knowledge of the processes brought into play. The development of these models in ecology over the past 100 years (if we take as initial reference Lotka [LOT 25] or Volterra's [VOL 26] work) has made it possible to formalize and test functional responses for different levels of biological complexity: individual, population, communities and ecosystem. There is a substantial amount of literature proposing equations and parameters for the biology of populations and the dynamics of ecosystems [JOR 01] (see section 6.5.2). On this basis, several extensions have been put forward to take into account the role of spatial heterogeneity, the conservation of matter (recycling, see the example in section 6.2.3.), the competition between several species for the same resources (exclusive competition [GUR 98]), the association with the notion of ecological niche [LEV 68], the role of non-trophic interactions in a predator/prey web [LEI 96], and the constraints linked to the equilibrium between the structural elements of living matter (stoichiometry [PAS 08]).

6.2.3. *Simplified food web*

The food web approach proposes a generalization of matter and/or energy exchanges in an ecosystem made of complex and interconnected food chains. We can find some concepts we have seen before: consumption and predation interactions, lifecycles of the species or groups of species making up the food web, which are supplemented by hypotheses on matter exchanges (conservation of mass and energy, the cycle of the building blocks of matter), the organization of species into a hierarchy through the notion of the trophic level (which distinguishes between primary, secondary producers etc.), the multiplicity of links described by a network structure and, very often, the need to combine species in groups with similar ecological functions (functional groups based on feeding strategies and modes – filter feeders, grazers and carnivores – or habitats [COV 01]).

To illustrate this approach, we will use an example drawn from Soetaert and Herman [SOE 09] called the NPZD model. It is a model made up of four functional groups which describe a simplified food web involving a process of primary production (nutrients/phytoplankton interaction), a grazing process (phytoplankton/zooplankton interaction), mortality and recycling processes (mineralization of detrital organic matter). The concept map is illustrated in Figure 6.3. There are then four state variables and six processes which are put into relation in the following equations:

$$\frac{dP}{dt} = f_1 - f_2$$

$$\frac{dZ}{dt} = f_2 - f_3 - f_4 - f_5$$

$$\frac{dD}{dt} = f_3 + f_5 - f_6$$

$$\frac{dN}{dt} = f_4 + f_6 - f_1$$

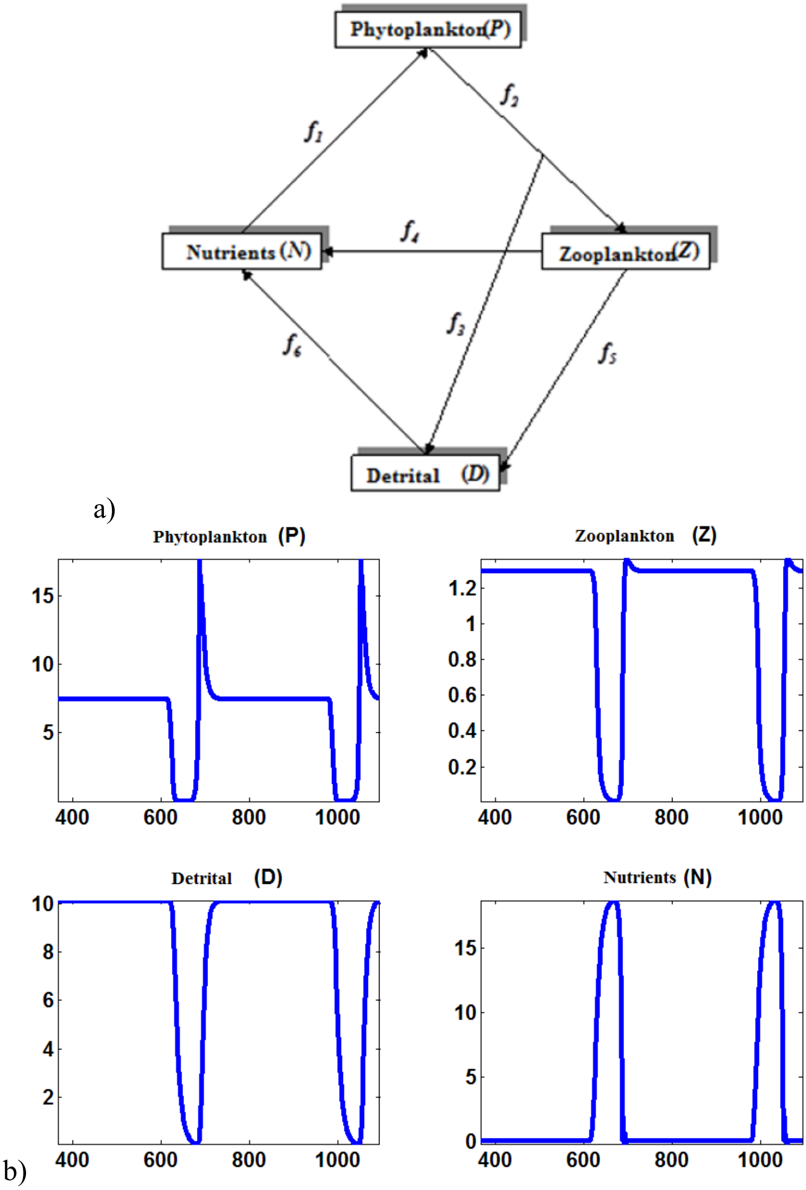
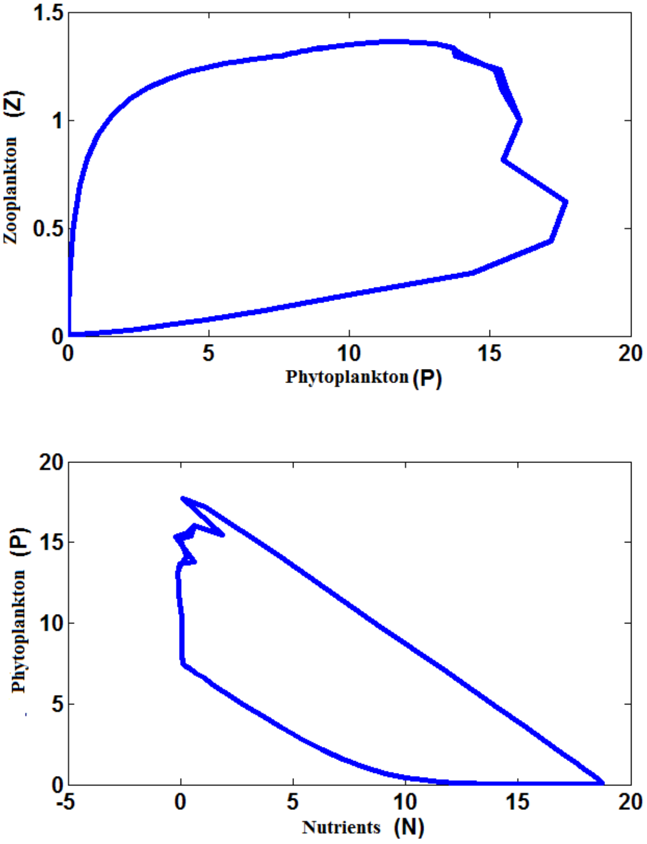


Figure 6.3*a–b*. *a) Diagram representing the bio-interactions between the state variables of Soetaert and Herman's NPZD model [SOE 09], b) the result of a simulation showing the variable dynamics over time*



c)

Figure 6.3*c*. *The representation of the same results in a phase plan*

The parameter equations and values are detailed in Table 6.1. This model represents the nitrogen budget in a nutrients-phytoplankton-zooplankton-detrital matter cycle. Its goal is to simulate in a simple way the phytoplankton dynamics in relation to a certain number of control factors. It is structured according to the following principles and hypotheses:

– the unity employed corresponds to concentration expressed in mole of nitrogen per volume unit. The variables P, N, Z and D therefore represent the nitrogen contents of the biological and biogeochemical compartments;

– the system is conservative globally or, in other words, there is neither loss nor creation of matter. Mathematically, the derivative of the quantity $N+P+Z+D$ is zero;

– the interactions between two compartments are expressed as a generic flow according to the origin (source) or final compartment (sink). The growth of phytoplankton, therefore, is proportional to its concentration, the term of proportionality being a rate expressing a change for each unity of the compartment. On the contrary, the phytoplankton grazed by zooplankton is proportional to the "active" compartment (zooplankton), whereas the concentration of phytoplankton is involved only in the formulation of the grazing limit;

– the "Phytoplankton" and "Zooplankton" variables represent functional groups. We assume that different species which belong to the phytoplankton and zooplankton communities have behaviors that represent the set of primary producers (for phytoplankton) and the set of herbivore plankton (for zooplankton);

– the set of equations represents a nitrogen cycle. Two nitrogen flows link phytoplankton and zooplankton as a source, and the detrital compartment as a sink. The former derives from the zooplankton's incomplete assimilation of phytoplankton (flow $f3$), the latter is the result of the zooplankton's mortality. Lastly, two new nitrogen flows close the system by taking into account the degradation of detrital matter (flow $f6$) – a key process for pelagic ecosystems – as well as the dissolved excretion associated with the metabolism of zooplankton (flow $f4$);

– the growth of phytoplankton is controlled by light and the concentration of dissolved organic nitrogen (N). These two influences are described by a Type-II Holling function (sometimes also called Monod's function), which we have already seen. It expresses the linear reliance of the assimilation process for low levels of nutrients (or light), whereas the influence of the nutrients wanes when they no longer constitute limiting factors. We also find a Type-II Holling function for the zooplankton's grazing of phytoplankton;

– there are several ways of expressing the combined effect of these two factors (nutrients and light) on the growth of phytoplankton. The choice is not insignificant, and quite an elaborated comparison is given in detail in an article written by Poggiale *et al.* [POG 10]. Without going into detail, the co-limitation of the two factors is here expressed by a threshold effect, but it could take a more mechanistic shape based on other hypotheses concerning the physiology of photosynthesis.

We have to realize that these equations are very classic but we can find abundant literature on the subject and a large number of variations. Such variations can be partially explained if we know the system – and a given model is not always transposable as such to another system. Thus, limitation by means of only one nutrient (in this case dissolved mineral nitrogen) is a significant simplification of the physiology of phytoplankton, which is known to depend on essential components such as phosphorus, silica and iron. Other variations respond to necessary choices between several mathematical formulations – as is the case here for the co-limitation of light and dissolved inorganic nitrogen. The biological foundations have been more or less well laid, but it could actually be enough to use an equation that expresses globally the expected functional response – for example the limitation of phytoplankton growth through dissolved inorganic nitrogen only in cases of low concentrations of the latter, when it is a limiting factor. In any case, the functions chosen and the values of the parameters reflect the hypotheses that must be put forward and discussed.

To determine the properties of this ecosystem, we carry out simulations for two configurations of the model: at first the environment, represented by light, is constant – this is what may result from an experiment in a controlled environment aiming, for example, to test the model (i.e. its mathematical structure and the values of the parameters involved in the equations). This simulation shows that the system becomes stable: each compartment reaches a value corresponding to a null variation over time and depends on the initial conditions defined by the concentrations at the beginning of the simulation. Another simulation is carried out in a variable environment, with a seasonal fluctuation in light levels, to assess the response of this simplified system to an environment fluctuation (Figure 6.3). Without any aspirations to realism, this simulation shows some of the typical patterns of the state variables that we find in most ecological models applied to concrete problems.

Description	Equation	Variable/Parameter (unit)
Combination of two Michaelis–Menten effects limiting photosynthesis (light and nutrients)	$g = \min\left(\frac{PAR}{PAR + K_{PAR}}, \frac{N}{N + K_N}\right)$	N = *concentration of nutrients* ($mmolN\ m^{-3}\ d^{-1}$) PAR = *irradiance* ($mEinst\ m^{-2}$)* K_{PAR} = 120 ($mEinst\ m^{-2}\ d^{-1}$) K_N = 0.5 ($mmolN\ m^{-3}\ d^{-1}$)
Growth of phytoplankton, linear function of P	$f_1 = \max Uptake \cdot g \cdot P$	P = *concentration of phytoplankton* ($mmolN\ m^{-3}\ d^{-1}$) $maxUptake$ = 1 (d^{-1})
Zooplankton's grazing of phytoplankton	$f_2 = \max Grazing \cdot \frac{P}{P + K_P} \cdot Z$	Z = *concentration of zooplankton* ($mmolN\ m^{-3}\ d^{-1}$) K_P = 1 ($mmolN\ m^{-3}\ d^{-1}$)
Faeces produced by zooplankton, a fraction of the grazing.	$f_3 = f_2 \cdot pFaeces$	$pFaeces$ = 0,3 (d^{-1})
Dissolved excretion of zooplankton	$f_4 = excretionRate \cdot Z$	$excretionRate$ = 0,1 (d^{-1})
Mortality of zooplankton	$f_5 = mortalityRate \cdot Z^2$	$mortalityRate$ = 0,4 ($mmolN^{-1}\ m^3\ d^{-1}$)
Mineralization of detrital matter	$f_6 = mineralizationRate \cdot D$	mineralizationRate = 0,1 (D^{-1}) D = *concentration of detrital matter* ($mmolN\ m^{-3}\ d^{-1}$)

Table 6.1. *List of parameters and functions used for Soetaert and Herman's NPZD model [SOE 09] (*Einstein: quantity of energy linked to the flux of photons within the range of wavelengths used)*

6.3. Metabolic foundations of population dynamics

6.3.1. *Metabolic laws*

Modeling population dynamics leads naturally to an association with the species' physiology and their biological features, such as growth, reproduction and survival. Von Bertalanffy [VON 68] was one of the pioneers in this domain, coming up with a general equation of the growth of an organism:

$$\frac{dw}{dt} = a \cdot w^c - b \cdot w^d$$

where w represents the mass of the organism, and the two terms on the right some processes of energy gain (anabolism) and expenditure (catabolism). The relationship between these two processes and the mass (or size) of the organism dates back to the empirical observations that led to the definition of allometry[3]. The determination of the coefficients of this equation, of the two exponents c and d, relies at once on theoretical considerations about the mechanisms of assimilation, ingestion, and respiration, and on the combination of experimental data. A very widespread version of this equation is based on the hypothesis that the anabolic term is proportional to a surface ($c = 2/3$), whereas the catabolic term is proportional to a volume ($d = 1$) [GUR 98]. The equation becomes:

$$\frac{dw}{dt} = a \cdot w^{2/3} - b \cdot w$$

and, if the parameters a and b are constant, its integration leads to the expression of w in relation to time as:

$$w = \left(w_\infty - w_0\right) \cdot \left(1 - e^{-K \cdot (t - t_0)}\right)^3$$

Schematically, this equation gave rise to two kinds of applications in the modeling field: the empirical modeling of the individuals' growth [PAU 80] and the analysis of the organisms' lifecycle [KOO 10]. The former essentially aims at combining data concerning individual growth to compare the populations' performances in different environments [CHA 12] or several species with one another. In the latter kind of application, the initial principle leads us to study physiological mechanisms and even attempt to define the general principles regulating the living world [BRO 04, BRO 08,

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[3] This term was defined by Huxley and Teissier [HUX 36] as follows: "To define a type of growth in which the dimensions of an organ vary more quickly than those of the rest of the body (or of a reference organ) […] we propose [the term] of allometry, in opposition to that of isometry, which is applicable to the case where the growth rate of the organ studied is the same as the reference organ's".

KOO 10]. We will only show the application of the model called the "Dynamic Energy Budget" (DEB) as an actual example, associating it with the dynamics of a population limited by a resource. More detailed descriptions can be found in Kooijman [KOO 10] and Sousa *et al.* [SOU 10, SOU 12].

In short, the DEB is based on the energy balance of a living organism, which is the result of the set of biochemical mechanisms applied to the living sphere including processes of nutrition, growth, reproduction and maintenance costs during the different stages of development (embryo, juvenile and grown individual). Several works endeavor to confront this theory with general empirical rules drawn from observations and experimental studies in the living sphere [SOU 12]. In the simplest version of the model, the organism is represented by three state variables called structure (V), reserve (E) and reproductive behavior (R). The first two variables do not correspond to physical compartments of the organism (for example organs), but they are justified by the distinction between two categories of biochemical compounds; the former is used to represent growth, while the latter corresponds to the set of compounds drawn on during energy transfers (reproduction, maintenance cost, growth). The rules and hypotheses are as follows (Figure 6.4 and Table 6.2):

– the flows represent energy processes and are expressed as Joule/day. The state variables E and R are energy quantities, expressed in Joule. The structure variable V represents the size of the organism, expressed in volume (cm^3);

– the reserve compartment is supplied directly by the energy gain linked to nutrition. This flow is proportional to the surface, represented here by the quantity $V^{2/3}$;

– the use of these reserves for growth and reproduction responds to a simple rule of distribution between these two flows, regardless of time, and the size or age of the organism (parameter *Kappa*);

– maintenance costs are proportional to the volume of the structure V. They are deduced from the two flows of growth and reproduction;

– all flows depend on temperature according to a Law called the Arrhenius Law;

– the availability of food is described by a Type-II Holling Law. When temperature and food availability are constant, the ratio E/V is also constant. This rule, called homeostasis, ensures the constancy of the energy content of the organism in stable environmental conditions;

– the equations are generic: they can be generally applied to any organism. Specific developments (also formulated in a general way) are implemented to summarize more complex features, such as the taking into account of several food sources, embryonic development, the simulation of elementary components (C, H, N and O), mortality, etc;

– the parameters are specific: they depend on the species considered and must be estimated experimentally (see, for example, Pouvreau *et al.* [POU 06]).

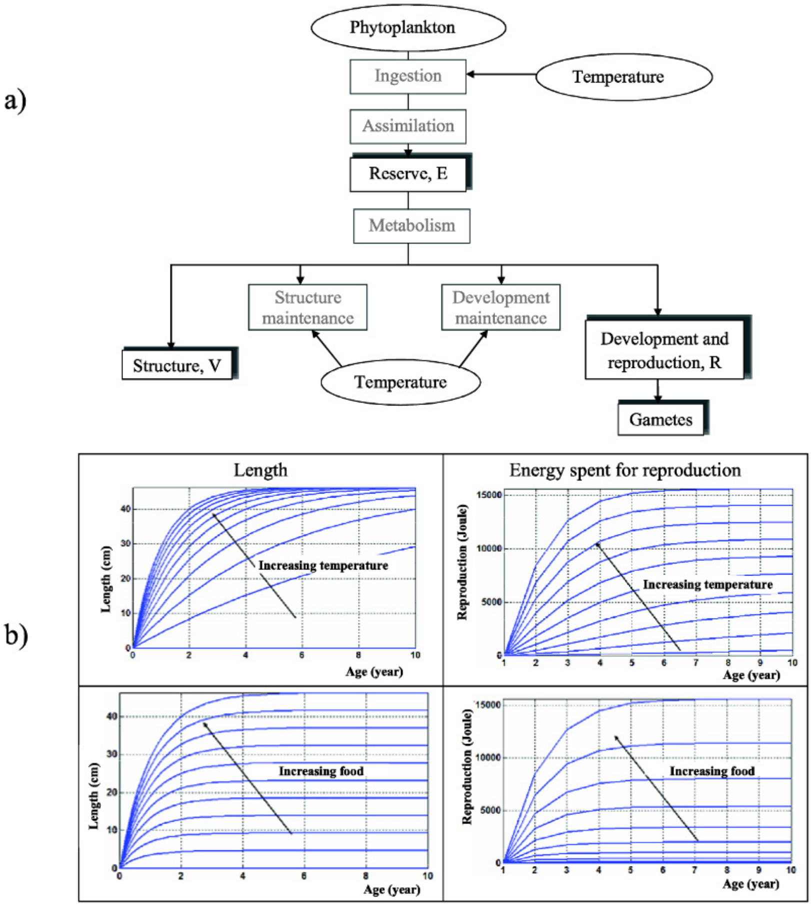


Figure 6.4. *a) Functional diagram of the processes and state variables of a Dynamic Energy Budget (DEB) model, b) an example of simulation of individual growth and reproduction for different temperature and food values (phytoplankton)*

Description	Equation	Variable/parameter (unity)
Temperature effect (Arrhenius law)	$limT = e^{\frac{T_A}{T_1} - \frac{T_A}{T}}$	TA = 5 800 (°K) – Arrhenius temperature $T1$ = 293 (°K) – reference temperature T = temperature (°K)
Limiting effect of food (type-II Holling functional response)	$\lim X = \frac{X}{X + X_K}$	X_K = 2,73 (μgchl l^{-1}) – semi-saturation constant
Assimilation	$A = limT \cdot limX \cdot A_m \cdot V^{\frac{2}{3}}$	A_m = 420 (J cm^{-2} d^{-1}) – maximum assimilation rate A = assimilation (J cm^{-2} d^{-1}) V = structure volume (cm^3) – state variable
Maintenance cost	$P_M = limT \cdot P_m \cdot V$	P_m = 24 (J cm^{-3} d^{-1}) – unitary maintenance cost P_M = maintenance cost (J d^{-1})
Catabolism	$P_C = limT \cdot \frac{E_g \cdot A_m / E_m \cdot V^{-\frac{1}{3}} + P_m}{\kappa / V + E_g / E}$	E_G = 1 900 (J cm^{-3}) – Unitary structural cost E_m = 2 295 (J cm^{-3}) – maximum value of storage energy density κ = 0,45 – fraction assigned to somatic growth E = storage energy (J) – state variable
Somatic growth	$P_G = \max(0, \kappa \cdot P_C - M)$ $\frac{dV}{dt} = \frac{P_G}{E_G}$	P_G = net flow of the growth of the structure (J d^{-1})
Maintenance cost for reproduction	$P_J = V \cdot \frac{(1-\kappa)}{\kappa} \cdot P_M$	P_J = maintenance cost linked to reproduction (J d^{-1})
Reproduction	$P_R = (1-\kappa) \cdot P_C - P_J \quad \frac{dR}{dt} = P_R$	P_R = net flow for reproduction (J d^{-1}) R = reproduction energy (J) – state variable
Net flow of the storage compartment	$P_E = P_A - P_C \quad \frac{dE}{dt} = P_E$	P_E = net flow of the storage compartment (J d^{-1})
Length	$L = \frac{V^{-\frac{1}{3}}}{\delta}$	δ = 0,175 – conversion coefficient L = individual length (cm)

Table 6.2. *Parameters and variables of a DEB model for the species Crassostrea gigas [POU 06]. J = Joule, chl = chlorophyll a (measurement of the biomass of plankton)*

An interesting property of this model is that it is equivalent to von Bertalanffy's model when environmental conditions (food sources and temperature) are constant. The two parameters of von Bertalanffy's equation, L_∞ and K, are then deduced analytically from the parameters of the DEB model and can be easily estimated for different species on a physiological basis. The result is that, for example, L_∞ depends only on the food limitation and not on the temperature considered (Figure 6.4).

6.3.2. *Population and communities*

The DEB theory, just like the metabolic theory developed by Brown *et al.* [BRO 04], relies on physical, chemical and biological principles to quantify the use of resources, a living organism's allocation of energy, and its biological features (growth, reproduction, survival). These theories also aim to deduce certain properties of populations and communities from these processes within an ecosystem approach. The stakes are at once theoretical and methodological, especially when it comes to moving from the history traits of the individual's life (growth, reproduction, state of energy reserves, etc.) to the dynamics of a population. Three modeling strategies are applied in turns – the choice depending mainly on the question considered and the complexity of the implementation on a mathematical and computational level.

The example described in Box 6.1 belongs to the category of individual-based models (IBM), in which a population is described through a series of individuals. The individuals can, thus, interact according to behavioral rules, but this kind of formalism is also recommended when relatively complex life history traits require the simulation of a variety of individuals (for example, a stochasticity problem, Martin *et al*. [MAR 13]). The choice also depends on the treatment of time: for a population whose dynamics depend on the stages of development of the individuals that make it up, the recommended solution consists in a matrix approach.

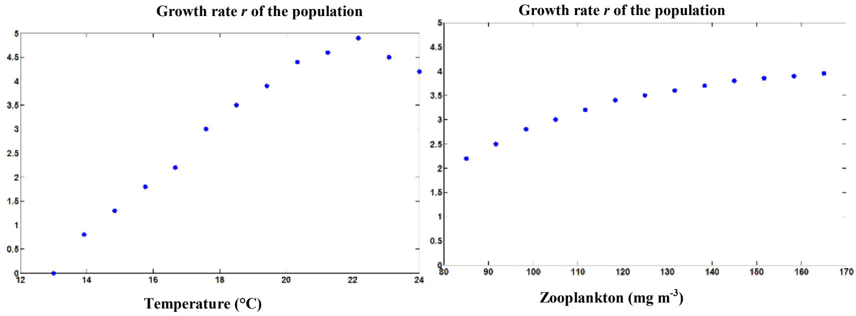
Thus, several actual examples combine formalized life history traits with a DEB model and a population approach such as the aforementioned one [BIL 07, KLA 06]. According to de Roos [DER 08], on the contrary, the treatment of a continuous kind of time and a population distributed according to age or size requires mathematical formalism. A proposition of this formalism can be found in Lotka's works [LOT 39] and de Roos applies it within the DEB framework.

The model aims to assess the effect of environmental changes on the biological features of anchovies *Engraulis encrasicolus* in the north-west of the Mediterranean. The authors have applied a DEB model (see text) that can simulate the effect of food (zooplankton) and temperature on individual growth and reproduction, from the larval stage to the fully grown organism. The population model consists of simulating some groups over the course of several years and in calculating the intrinsic growth rate r of the population, with no other effect on physiology apart from the environment (abundance of prey and temperature). This rate corresponds to the equation:

$$\frac{dN}{dt} = r.N$$

where N is the size of the population.

It goes without saying that the population is also affected by other factors (for example, natural or fishing-related predation). Besides, this growth rate represents how sensitive the population is to the environment and it is calculated by simulating different scenarios of temperature and food change. These simulations show that r can be reduced by 15% if the average temperature varies by about 0.8°C, food availability by 18% or egg mortality increases by 30%. The following figure represent some of these results.



Box 6.1. *An example of population dynamics model [PET 13]*

The relationships between individual size and the networks of interactions between populations within a community have been the object of empirical analysis for a long time (see Raffaelli [RAF 09] for a rapid review of this topic). With the development of theories on metabolism, and specifically, its relationship with the size of individuals, ecological modeling is following new paths to integration. We will only give two examples: the assessment of the properties of populations [SAV 04] and the analysis of energy flows in a food web linking physiological processes to predator-prey interactions [AND 10, BRO 08]. Andersen and Pedersen [AND 10] thus combine the allometric Laws regulating the ingestion and reproduction equations (which reproduce von Bertalannfy growth curves) with predation rules based on the sizes of a prey and predator respectively. As it is, this kind of model represents a community in relation to a size structure (called size spectrum) rather than through a list of species. It can assess how this structure reacts to environmental changes –represented by the stress caused by fishing in this example. On a population level, Savage *et al*. [SAV 04] link the two parameters involved in Verhulst's growth model (growth rate r of a population and trophic capacity K) to the size of the individuals and temperature by also using some of the general principles that regulate metabolism. If we test the results in relation to experimental data, they reveal that individual size and temperature account for most of the trait variation on a population level (growth and mortality).

6.4. Modeling complexity

"Perhaps the most fundamental property of life is its ability to use energy and materials to maintain and reproduce itself, providing energy and materials to support more life in turn. This generation and consumption of biomass enabled the evolution of biological diversity and concomitant trophic structure among ecosystems" [DUN 08].

6.4.1. *Introduction*

If NPZD models become increasingly complex when we take into account more and more compartments, they still remain one of the many methods used to approach the modeling of complexity. A possible definition of complexity is the "nature of that which is difficult to untangle or analyze because of the intricacy of its elements". This definition perfectly corresponds to how marine ecosystems work, and, in particular, to food webs, which constitute one of their possible representations. A food web is the representation of the set of matter flows within an ecosystem, especially on basis of predator-prey relationships. Modeling food webs is crucial to the understanding of the indirect effects of anthropogenic stresses. For example, the removal of fish caused by fishing is likely to reduce the stock of the species caught, but it can also have cascading positive effects on prey or competitor of this species. These repercussions thus propagate step by step through trophic links. Thus, we can wonder, for example, what the indirect consequences of the removals are, but we can also think about the emergence of invasive species, changes in communities linked to habitat alterations, or management measures like the preservation of certain species. The distinctive features of all these actions is that indirect actions will have repercussions on the whole of the ecosystem through trophic pathways. It is, therefore, important to adopt a holistic perspective when studying how marine ecosystems work, i.e. to take into account all the complexity of the ecosystem (see Box 6.2). This complexity is particularly important in the marine environment because of the spatial continuity interlocking spatial and temporal scales that range widely according to the species considered, from highly localized sessile species to very mobile species like marine mammals or birds.

Trophic cascade

A trophic cascade is an ecological phenomenon resulting from the addition or removal of a top predator which affects the populations of prey, then the prey of this prey, etc., cascading down the whole of the food web (drawn from Encyclopaedia Britannica, http://global.britannica.com/EBchecked/topic/1669736/trophic-cascade, and modified).

Community

The set of species interacting in a given ecosystem (drawn from Huxel and Polis [HUX 01]).

Connectance

The number of links made in a food web divided by the number of possible links. The more numerous the interconnections *via* flow relationships in a food web, the greater is the connectance.

Ecosystem

A system which consists of an environment (biotope) and the set of species (biocenosis) that inhabit it, feed in it and reproduce in it (*Larousse*).

Functional group

Group of species with similar roles in the ecosystem. Examples: suspension feeders, predators and decomposers (from Covitch [COV 01]).

Omnivory

Food behavior pattern based on several trophic levels.

Recycling

In ecology, the recycling of food webs corresponds to an operative aspect of the network consisting of a circular path which returns to its starting point (example of a short cycle: zooplankton produces waste and then feeds on it).

Energy-flow food web

A representation of the relationships within a community based on the quantities of energy (or organic matter) circulating *via* the links that connect functional groups (drawn from Huxel and Polis [HUX 01] and modified).

Size spectrum

A graph indicating the mass of organisms by size class, according to a double logarithmic scale. In marine ecosystems and large lakes, these size spectra are generally regular [GAE 95]. A steep negative slope in the spectrum indicates that the availability of prey plummets when the size increases [BLA 09].

Stability

There are several definitions of stability of an ecosystem, but most often we deem an ecosystem stable if there is low variability in terms of its average state (resistance) or if the ecosystem can go back to its starting state (resilience) after a perturbation (drawn from Cleland [CLE 12] and modified).

Trophodynamics

A concept developed by Lindeman [LIN 42] which aims to propose a unified principle of quantification of energy exchanges between the elements of a biotope (drawn from Lévèque [LEV 01]).

Box 6.2. *The complexity of ecosystems: some definitions*

Researchers, who have been for a long time hindered by computing times and are still always limited by time itself, have to choose where to focus while studying the high complexity of marine ecosystems. The variety of problems faced, in this context, is leading to the current use of a multitude of models of ecosystemic interactions in coastal ecosystems. Gaedke [GAE 95] proposes a classification the models dealing with the interactions within the ecosystem, starting with binary food web models (the processes studied consist in present or absent flows represented by 0 or 1), including quantified models (processes consist of flows associated with a unique numerical value which characterizes an instantaneous or average situation of the network of trophic interactions), and finishing with the dynamic models (processes are described with a mathematical equation, the variables of which represent the different pressures affecting the values of the flows) presented in the previous sections. In this classification, the first two methods are static approaches concerning the networks of interactions, whereas the last one differs due to its dynamic aspect. The significance of the last approach lies mainly in its ability to predict, whereas static methods are more used to describe how the ecosystem works in all its functional diversity. The precision with which processes are understood increases in relation to this classification but, on the other hand, the level of diversity considered decreases. Nowadays, thanks to improved computing power and the organization of researchers into networks of modelers, we are evolving towards dynamic models which are richer and richer in terms of functional diversity. This category of dynamic models, which include a large number of compartments, is called end-to-end, which goes to show the holistic nature of the way to account for the system. To date, the number of compartments represented is still lower than the one found in static models, and the enormous quantity of information required for their construction restricts them to the most studied coastal sites.

This holistic approach to the study of the functioning of ecosystems is significant in terms of both basic and applied research. Nowadays it aims, for example, to carry out research on the general rules regulating how pressures affect the way ecosystems work. Which operational properties of the whole of the food web (which we call emergent properties, since they emerge from the association between the several elements that make up a food web) are most sensitive to pressures? Among these properties, which ones determine whether an ecosystem reacts to a pressure in a resistant (by not changing) or resilient (by changing and going back to its original state) way? Which determine whether this results in a change in state? On a more applied level, modeling complexity allows us to assess some management policies and opens the door to ecosystem approaches: the ecosystem approach to fisheries as well as to any activity directly affecting the marine environment (for example pollution, dredge spoil sediments or the construction of wind farms and marine current turbines at sea).

6.4.2. *From NPZD to trophodynamic models*

The hypothesis of an interaction between the models mentioned in the previous paragraph and upper trophic levels, considered in all their diversity, derived mainly from the necessity of comparing the effect of fishing on the ecosystem and the prediction of the effects of climate change. A rapidly growing modeling method used to face this problem is the OSMOSE model [SHI 01].

It is an individual-based model (IBM) centered on schools of fish or cohorts [SHI 01]. These schools are generally established for ten to fifteen different species and are characterized by a given size (or age) class. The dynamics of each school are defined in relation to its location in a section of space and the probability of finding its prey there. Prey is established in relation to a possible range of values resulting from the predator individual size/prey individual size ratio. Thus, the dynamics of each school and their spatial movements can be defined.

Input parameters involve a series of rules on growth, reproduction, migrations, consumption of species of fish as well as the mapping of their spatial distribution. This model is supplied with quantitative information about the available plankton resulting from the NPZD models of lower trophic levels. At first, such a relationship, which can simulate the impact of climate changes, consisted of a mere forcing of the fish’s response with no feedback on plankton. A bilateral interaction is being developed, which will allow us to remove from the stock of planktonic compartments the prey consumed by fish. The difficulties faced when developing this kind of modeling are related to the very large quantity of information necessary for the parametrization of the models considered, which raises some problems in those areas where the species of fish have not been thoroughly studied or their diversity is considerable. In this sort of situation, dynamic approaches are, therefore, generally left aside in favor of a static method that can take into account the set of the ecosystem in all its functional diversity.

6.4.3. *Static holistic models*

Different numerical methods, at the interface between modeling and data analysis, will allow us to build food web diagrams, whether quantified or not. The analysis of the structure of these diagrams provides us with a description of the functional properties linked to the inter-association of these interactions. For example, the recycling process is characterized by a matter cycle, starting with prey and ending up back with it. Such a cycle can be illustrated by the example of an organic carbon atom which is produced by a heterotrophic bacterium, consumed by a bacterivore, then expelled as feces towards the detrital matter which is, in turn, transformed into dissolved organic carbon and used by heterotrophic bacteria for their growth. If the construction of binary models does not involve specific calculations but the demanding gathering of all the information available on the elements of the network of interactions, it is the other way around for quantitative models. We will provide some examples of these methods used to estimate the numeric values of trophic flows. In terms of binary and quantitative models, the numerical analysis of the result obtained is essential since the emergent properties of the association are then defined.

Non-quantified binary models of food webs, together with their topological analysis, are still very useful today despite being old, since they can take into account the totality of functional diversity in a global perspective encompassing the functioning of the ecosystem. Each species is represented by a compartment and so does each phase of its lifecycle if changes in its diet or predation occur during transition phases. The numerical indices used today derive from graph theory and topology, the origin of which dates back to Euler's works (the problem of the Seven Bridges of Königsberg, as seen in Gauzens [GAU 11]). A graph is a mathematical object made of vertices (species in a food web) and edges (predation relationships within a food web). In the context of food webs, these relationships have an orientation, since they link one vertex to another in a unique direction [GAU 11]. Topology is defined as "a set of Laws that give mathematical meaning to the notions of limit, continuity and neighborhood" (group Nicolas Bourbaki, 1966, in [GAU 11]). The different indices used to characterize the structure and functioning of binary food webs are based on these laws. For example, we can find connectance, which is the number of links made divided by the number of possible links, average length, which is the average distance (defined as the shortest path) between all the vertices of the graph or modularity, which assesses if the graph is made up of subsections or modules more strongly connected with each other than with the rest of the vertices.

These indices can be applied to food webs as well as to mutualist networks [THE 10], even if the latter have not been particularly studied in the marine environment yet. They can describe the structure of complex food webs or work towards the definition of the effects of climate change on the organization of these webs [TYL 08].

While maintaining a strong level of functional diversity, the food webs in which flows are quantified constitute a first stage of aggregation. Species are gathered in trophic groups which share most of their prey and predators. Several techniques are, therefore, used to calculate the numerical values of these flows. We will delve into two of these: the Ecopath model, presented as part of the program EwE (Ecopath with Ecosin) and linear inverse analysis, the most recent version of which is the LIM-MCMC (linear inverse modeling – Monte Carlo Markov chain). These two methods are steady-state models, i.e. they consider the biomass variation to be known (or null by default). We will now present the numerical indices that can define the structural and functional properties of the networks obtained, which give an instantaneous image of the quantified network of interactions.

The Ecopath model is mostly studied to determine the effects of fishing-related activities and their management on the whole of the food web and the functioning of the ecosystem. It requires us to assess, for each trophic compartment, its diet as well as three of the four following parameters: biomass, production/biomass, consumption/biomass and ecotrophic effectiveness (a fraction of the production consumed in the food web). Ecopath is based on two equations that characterize each trophic compartment.

The first equation describes the fate of the production of each compartment (the resulting matter):

Production = catches (by fishing) + predation + other kinds of mortality [6.1]

On the right hand of this equation, sometimes we can also find two supplementary terms: the accumulation of biomass and net migration. Predation defines therefore the link to upper trophic levels whereas the catches by fishing characterize the link with Man.

The second equation describes the fate of the consumption of each compartment (the input matter):

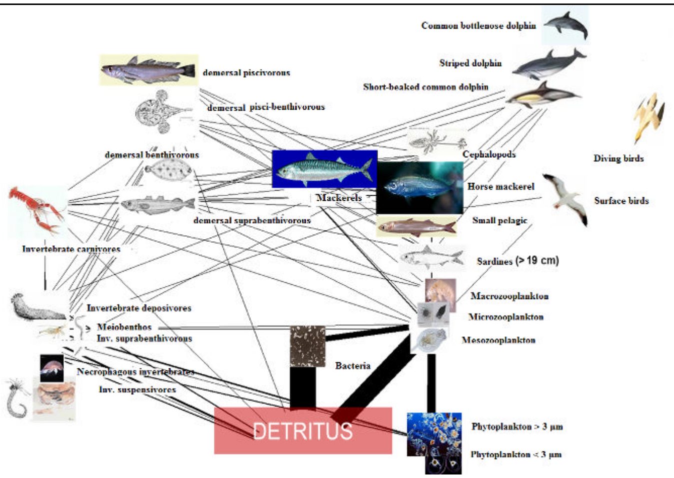
$$\text{Consumption} = \text{production} + \text{respiration} + \text{non-assimilated food} \quad [6.2]$$

Consumption defines the link to lower trophic levels. These equations are solved by assessing each flow of the food web with a numerical value. A trial-and-error approach is generally employed so as to ensure the coherence of the set of results and the plausibility of the parameter estimated. For example, ecotrophic effectiveness should not be estimated to be greater than 1 (see Box 6.3 for an applied example).

The LIM-MCMC method [KON 09] has the disadvantage of involving a more complex and therefore less widespread, implementation. However, it can offer the advantage of avoiding the trial and error phase in favor of the automatic research of an optimal solution. It can also directly integrate the notion of confidence interval of the input parameters and estimate a probability density rather than a unique value for each flow. This allows us to estimate the range of possible values for the flows as well as some indices defining the properties of the whole network, which we will deal with further on.

The current version derives from inverse analysis as it has been defined by Vézina and Platt [VEZ 88] and taken up by Leguerrier [LEG 05]. The flows between biological compartments are the unknowns of the system. Compartments are arranged in a vector the dimension of which corresponds to the number of flows identified for the system. Some field data can determine certain components of this vector and/or allow us to write linear equations linking them: for example, the production of a compartment will be equal to the sum of the flows on their way out towards the predators of this compartment or to the sum of input entering the compartment, excluding its respiration and elimination. The application of the principle of matter conservation and the hypothesis concerning the steady state of the system imply that the sum of the flows entering each compartment is the same as the sum of the output flows plus the biomass gain (negative in case of loss, null in the state of equilibrium). We obtain a set of linear equations written as matrices. If we call r the vector of the unknowns, which consists of the set of possible flows in a food web, we realize that:

$$A \cdot r = b \quad [6.3]$$



The ecosystem described corresponds to a coastal strip of the Bay of Biscay defined by a bathymetry within the range of 30 to 150 meters. An ecopath model with 32 compartments was built, ranging from primary producers to top predators and including the benthos and the pelagos. The compartments correspond to the groups of species that share the same features on a trophic level (prey, mode of predation). A large proportion of the energy flows circulating within the ecosystem derives from detrital matter and, therefore, from the recycling of organic matter. Moreover, some phenomena of control of the prey over their predators (bottom-up) have been shown to strongly affect the dynamics of higher trophic levels and the global structure of the ecosystem. A strong benthos-pelagos interaction is observed. Zooplankton appears to be a key compartment for the functioning of this food web and acts as a regulator of the abundance of small pelagic fish. In an attempt to validate the model, the trophic level of several shelf species has been calculated on the basis of the outputs of the model and compared to the estimate based on isotopic analysis. The values obtained are close. A multi-model approach is being developed to assess the uncertainty associated with the flows estimated by applying the LIM-MCMC.

Box 6.3. *An example of application: the Ecopath model of the Bay of Biscay [LAS 11, LAS 13, LAS 14, CHA 15].The thickness of the line is proportional to the significance of the flow. The classification from bottom to top corresponds to the one by trophic levels (image made by Jeremy Lobry and Géraldine Lassalle)*

We have to add to this system a set of limiting factors which curb the research area for the flows and take the shape of a set of linear inequalities, also presented as one matrix inequality:

$$G \cdot r \geq h \tag{6.4}$$

The statistical method used by inverse analysis, called LIM-MCMC, enables us to sample the whole of the polyhedron that characterizes the space of possible solutions and, therefore, to obtain some output vectors for the values of the flows. We can thus deduce a probability density for each flow and a related confidence interval.

A third approach, called "direct approach", consists of assessing directly the set of flows on the basis of estimates of each flow and the simple application of mass balances to deduce an unknown flow per compartment. This method is mostly only used in those ecosystems where the food web is very well known in terms of both present biomasses and flows concerning the various (primary production, respiration, production, consumption, etc.). An example of this approach consists of the interconnected benthos-pelagos food web in the bay of Sylt-Rømø, which has gained more than thirty years of observation and experiments on the set of trophic compartments [BAI 04, BAI 07, BAI 12].

The functional properties of the food web, the flows of which have been estimated by means of these three methods, can then be characterized by the indices of the ecological network analysis (ENA). Indices, as well as analyses conducted from the perspective of ecological functioning, are quite numerous. They draw from topology (the organization of flows), input-output analysis (based on the model of econometric analysis drawn from Leontief's works [LEO 51]) and the analysis of cyclic pathways or food chains [ULA 86, ULA 97, ULA 09]. The last category includes Lindeman's chain [ULA 97], which consists of associating each trophic compartment with a whole trophic level by breaking it down into several onesaccording to its feeding regime. Level 1 includes detrital matter and primary producers. A compartment which is one-third herbivores and two-third consumers of herbivores will be linked to level 2 for one-third and to level 3 for two-third. The flows entering and coming out of this compartment are then associated in the same fashion (one-third to level 2 and two-third to level 3). This representation allows us to characterize the transfer efficiency from one level to the following. Some properties concerning the analysis of networks, such as recycling, omnivory or the redundancy between flows, are then examined from the perspective of the evolution of ecosystems under anthropogenic pressure [BON 06] or with respect to to their stability [LOB 08]. Nowadays, some of these indices are being analyzed in the attempt to describe the state of health of marine ecosystems from the point of view of their global operational properties.

6.5. Conclusion

6.5.1. *The ideal of end-to-end models*

Ecological modeling is evolving in several directions. A first tendency has to do with the enhancement of physiological processes. We have seen the growing significance of metabolic Laws in relation to an organism; other developments also aim to take into account the balance and command of the structural elements of the living world (stoichiometry) or of some specific processes that can modify physiological processes (ecotoxicology). Research carried out on the adaptive strategies of populations can be also considered as part of this trend.

Another tendency, linked in many ways to the effects of human activities on ecosystems, involves the awareness of the globality of the ecosystem while also requiring us to be able to simulate future scenarios. This is the case for the studies on the consequences of climate change on fishing [FUL 10, TRA 07]. This problem is at the basis of the definition of end-to-end models, presented as an ideal we try to work towards. The goal consists of representing the whole of the ecosystem, together with the human components, integrating physical and biological processes on different scales and authorizing a complete interaction (two-way) between the different fishing components [FUL 10, TRA 07]. As an example of two-way interaction, we can mention the fact that the quantity of prey must affect a predator's consumption and, conversely, a predator's consumption must also modify the prey's biomass dynamics. One of the most significant end-to-end modeling platforms focusing on these two-way interactions is the Atlantis platform [FUL 05]. It involves physics and the set of trophic levels as well as the human sphere from the perspective of various forms of action: industry, monitoring, management, etc. The difficulties linked to such an application are related to calibration, due to the large number of parameters and the need for data set covering the maximum amount of trophic compartments and information on the role played by man from a dynamic long-term perspective (see Table 6.3).

Name of the model	Category	Organization level	Concepts implemented	Example of application	Reference
OSMOSE	Model based on fish	NPZD + cohortsof fish/ species	Based on the NPZD model with the addition of fish. Opportunistic predation defined by size	Definition of the effects of the interactions between climate change and fishing	[SHI 04] [TRA 07]
Ecopath with *Ecosim*	Model structured into compartments	Trophic compartment often defined by a dominant species	Mass balance for *Ecopath* but not for Ecosim. Constant ratio production/biomass	Assessment of the effects of fish management methods on ecosystems	[PAU 98] [HEY 11]
LIM-MCMC	Statistical model structured into compartments	Trophic compartment, smaller number	Mass balance but possibility of accumulation or losses	Assessment of the role of wading birds in the food web of intertidal flats	[SAI 13]
Atlantis	*End-to-end*	Trophic compartment often defined by a dominant species and size classes	Trophic relationships based on prey availability, predator size/prey size relationship, and refuge effects	Comparison between the effects of fishing and those of climate change on the life history traits of fish	[AUD 14]

Table 6.3. *Summary of some models that take into account the complexity of ecosystems and have been used as examples throughout the chapter. The categories used are modified with respect to those used by Travers et al. [TRA 07]*

6.5.2. *To find out more*

Several works delve into the different domains of modeling that we have just touched on. We provide here some examples that we have chosen for their educational value and interrelatedness to other kinds of modeling we have not dealt with in this chapter (complete references are listed with the rest of the bibliography at the end of the chapter):

– [AUG 10]: a mathematical analysis of several classic examples in population dynamics. Examples and exercises also implement calculation programs developed with the software Matlab® and Netlogo®. This book is published in French;

– [FEN 04]: an introduction to modeling in the marine environment, with actual examples drawn from real cases. Some programs in Matlab® can simulate the simplest models;

– [GRI 05]: a work entirely dedicated to individual-based models (IBM) and their applications in ecology. It is useful to get an idea about this modeling approach and is illustrated by some examples drawn from the literature;

– [HAN 97] and [HAN 01]: two didactic works based on several examples of simulation developed with the modeling software Stella®;

– [JOR 01]: within the context of a didactic approach, it presents several kinds of actual models and applications in aquatic ecosystems – for example, Ecopath, NPZ, ecotoxicology, pollution, biogeochemistry, population and chemical processes;

– [ODU 00]: an introduction to the modeling of simple systems in biology and economics, with different simple support tools – Extend®, Excel® and Stella®;

– [PAS 08]: a very progressive approach to population dynamics models and to simple Matlab® programs for the analysis of their stability properties;

– [PLA 07]: a list and comparison of several models implemented in fishery science with the potential to be used as a methodological guide;

– [SOE 09]: some examples of modeling used in biology, including some interactions between physics and biology, with free programming software (R);

– [ULA 97]: a presentation of a theory about the evolution of food webs in relation to the indices drawn from information theory (Shannon);

– [LEV 01]: a collection of the definitions of diversity in ecosystems from all perspectives, ranging from biogeography to ecosystem services and conservation issues;

– [VOI 08]: a practical guide to modeling within the context of the “system” approach. It is useful for the modeling of man/ecosystem interactions. It includes a useful chapter on simulation tools.

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7

The Ecosystem Approach to Fisheries: Reconciling Conservation and Exploitation

7.1. The ecosystem approach to fisheries: a shared view on the management of marine resources

7.1.1. *The challenges of the ecosystem approach*

Marine fisheries have a direct impact on the resources they exploit but also indirectly affect other species, habitats and the way ecosystems work [JAC 01]. Marine resources have for a long time been managed species by species, regardless of the complexity of the interactions as well as spatial dynamics. Thus, we have managed populations of sardines, herring, cod or hake without taking into account the environmental effects and without worrying about the repercussions of the exploitation on the structure and functioning of other species of the ecosystem. An outlook that could take into account the complexity of these interactions in the marine world was necessary.

As Robert Costanza [COS 00], an American researcher, underlines: “the most critical task facing humanity today is the creation of a shared vision of a sustainable and desirable society, one that can provide permanent prosperity within the biophysical constraints of the real world in a way that is fair and equitable to all of humanity, to other species and to future generations” and he adds that “Vision can change the world. In fact, it is one of the few things that really can”. This outlook is often utopic, but it leads us to take a fresh look at our incoherences and can shed light on what we

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consider as long-term sustainable development. Thus, a global vision of the management of ecosystems has recently established itself with the ecosystem approach to fisheries (EAF) and it offers a long-term vision for the management of marine biodiversity: sustainable exploitation of resources while respecting marine ecosystems. Not only does the EAF have to ensure the renewal of the multiple living organisms exploited, but it also promises us reconciliation between the exploitation and the preservation of the set of species. This actual challenge has only just started, but it is changing our relationships with nature at the core [CUR 08, CUR 13].

The ecosystem approach to fisheries, as well as the one to renewable resources, contributes thus to this crucial challenge that consists in keeping ecosystems productive and in good health, while proposing a new way of considering marine exploitation (www.fao.org/fishery/eaf-net). There are several definitions that consolidate the balance between the preservation of the features of marine biodiversity and the sustainability of its exploitation and that highlight the necessity of widening the field of research and increasing the awareness of new factors in the management of resources.

According to the FAO (Food and Agriculture Organization of the United Nations), the ecosystem approach to fisheries strives "to balance diverse societal objectives, by taking account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries". The definition given by the national marine fisheries service, USA (NMFS), if close to the one provided by the FAO, focuses on the spatial integral aspects of the EAF: "A geographically defined and adaptive process assesses the several exogenous factors and strives to reconcile different societal objectives". More pragmatically, [PIK 04] emphasizes how this approach must keep ecosystems in good health and support the sustainability of fisheries by taking into account the following objectives:

– to avoid the degradation of ecosystems, such as it is measured by the quality indicators of the environment and of the state of ecosystems;

– to reduce as much as possible the risk of irreversible changes in the natural grouping of species and in the ecosystem processes;

– to obtain and keep socio-economic benefits long-term without jeopardizing the future of ecosystems;

– to produce enough knowledge about ecosystem processes to understand the likely consequences of human actions;

– to implement a solid and cautious type of fishing management to favor the ecosystem when scientific knowledge is insufficient.

Thus, ecosystems are now known to represent the right scale within which we can integrate scientific knowledge and the management of renewable resources. This approach has been, for several years, the reaction to international expectations and commitment, which have been established under the aegis of the UN.

7.1.2. *Three bodies of the United Nations structure the ecosystem approach to global fisheries*

For more than half a century, the modern principles of the governance of the world's oceans have been established under the aegis of the UN. The institutional framework (principles, rules, conditions, agreements, processes, mechanisms and organizations) for the development and management of the usage of the marine ecosystems' goods and services – especially the exploitation of fishery resources – is based on three pillars: the United Nations Convention on the Law of the Sea (UNCLOS), the process of the United Nations conference on Environment and Development (UNCED) and the FAO. We will focus here on their key role in the conceptualization and implementation of the ecosystem approach to fisheries (EAF).

Since the 1950s, national representations have elaborated several concepts and instruments – either legally binding (hard law) or voluntary (soft law) – which additionally ensure consistency between the UNCLOS, the UNCED and the FAO. The result is a coherent and relatively complex set of rules pertaining to:

– the conservation of marine fish stocks, their habitats and more generally biodiversity;

– the management of natural resources (especially the integrated approach for their sustainable use and fair exploitation) as well as its tools and principles (medium- and long-term planning, transparency);

– the applications of the results of scientific and technological research (observation networks, indicators, impact assessments and biodiversity conservation targets);

– capacity building: education, information and involvement of stakeholders.

Figure 7.1 specifically highlights the main landmarks of the progress towards EAF at the global scale.

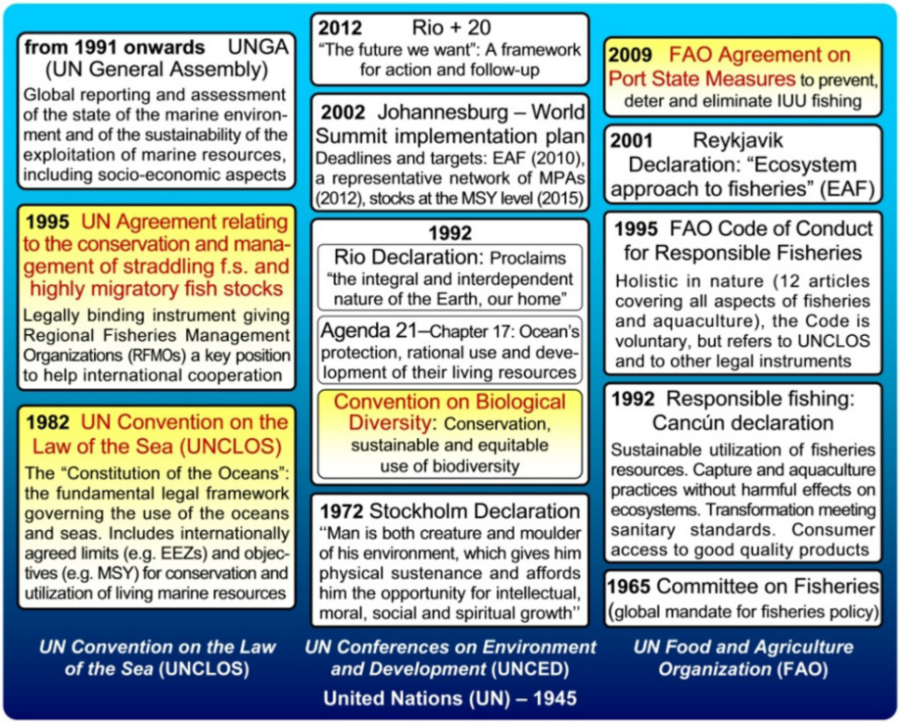

Figure 7.1. *Major institutional steps of the advancement in the construction of ecosystem approach to fisheries*

COMMENTS ON FIGURE 7.1.– Cross-linked contributions of three UN bodies (UNCLOS, UNCED and FAO) to the development and implementation of the main founding concepts and instruments for a sustainable and fair exploitation of marine fishery resources. Binding instruments are highlighted: The 1982 Convention on the Law of the Sea, the Convention on Biological Diversity, the 1995 UN Fish Stocks Agreement and the FAO Port State Measures Agreement.

7.1.2.1. *From Stockholm to Rio: the main founding principles*

It is at the end of UN conferences on the environment and on development that policymakers (heads of state, government leaders, ministers, etc.) engage with the strategy they have chosen to face global challenges, particularly the reduction of poverty, the protection of the environment and the sustainable exploitation of natural resources. The declaration that finalizes each conference is the result of globally coordinated talks between the representatives of the scientific and administrative spheres, political power and civil society.

The core of the ecosystem approach to the management of fisheries[1] took shape within the context of this process. The seminal concepts of the EAF were recorded in 1972 in the Stockholm Declaration[2] (UN Conference on the Human Environment), the preamble of which states that "man is both creature and moulder of his environment [and] has acquired the power to transform his environment in countless ways and on an unprecedented scale". Among the 26 principles of the Stockholm Declaration, which gave rise to a vision that would be consolidated over the following conferences, we can find those that promote the integrated management of the environment and its resources, based on the best available scientific knowledge to support decentralized and transparent decision-making procedures involving all interested parties[3]. Moreover, it is widely recognized that industrialized countries differ from developing ones in relation to both the causes of their environmental issues and their remediation[4].

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[1] A fishery is a relatively homogeneous fleet of fishing vessels operating in a given marine ecoregion, where they deploy fishing gears of similar type and catch species inhabiting habitats of similar characteristics. The huge diversity of world fisheries results from the combination of differences between vessels, between their fishing gears and fishing areas, their target species and several other criteria [GAR 10].

[2] www.unep.org/Documents.Multilingual/Default.asp?documentid=97&articleid=1503.

[3] For example, man "bears a solemn responsibility to protect and improve the environment for present and future generations" (Principle 1). "[R]epresentative samples of natural ecosystems must be safeguarded for the benefit of present and future generations" (Principle 2). "Nature conservation […] must […] receive importance in planning for economic development" (Principle 4), "[…] economic factors as well as ecological processes must be taken into account" (Principle 10).

[4] "Without prejudice […] to standards which will have to be determined nationally, it will be essential in all cases to consider the systems of values prevailing in each country, and the extent of the applicability of standards which are valid for the most advanced countries but which may be inappropriate and of unwarranted social cost for the developing countries" (Principle 23).

Following the Stockholm Declaration, industrialized nations have set about making its principles most a reality. On the other hand, in the rest of the world their implementation has been hindered by underdevelopment and poverty. Furthermore, these principles were not interpreted in the same way by different countries. To reach the goal of sustainable development, the United Nations general assembly (UNGA) decided in 1987 to hold a conference on the environment and development. This conference took place in Rio de Janeiro in 1992 after several preliminary negotiations, which also led to the drafting of Agenda 21[5]. In conjunction with the Rio Declaration and Agenda 21, ratified at the "Earth Summit" in June 1992, two other conventions were held in the same year within a different context: the Convention on Biological Diversity[6] (CBD, legally binding) and the United Nations framework convention on climate change[7] (UNFCCC).

The preamble to the Rio Declaration[8], a short text including 27 principles, reaffirms what the Stockholm Declaration[9] stated and sets the objective of a "new and fair" cooperation between States, in the common interest of a form of human development that respects the Earth's environment ("recognizing the integral and interdependent nature of the Earth, our home"). Several principles of the Rio Declaration provide the basis for the EAF, among which the precautionary approach (principle 15: the absence of scientific

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[5] http://sustainabledevelopment.un.org/content/documents/Agenda21.pdf. The programme areas in Agenda 21 are described in terms of the basis for action, objectives, activities and means of implementation aiming at sustainable development in the 21st century. Agenda 21, divided into four sections and 40 Chapters, contains 2,500 wide-ranging recommendations for action. Chapter 17, called "Protection of the oceans, all kinds of seas, […] rational use and development of their living resources" is central to marine fisheries and aquaculture and deals with several management and development strategies globally and locally relevant, including the precautionary approach.

[6] https://www.cbd.int/convention/text/default.shtml. The CDB, dealing with conservation, the sustainable use of biodiversity, and the sharing of profits (especially "the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, including by appropriate access to genetic resources and by appropriate transfer of relevant technologies, taking into account all rights over those resources and to technologies and by appropriate funding", see the "Nagoya Protocol on Access and Benefits-sharing", an international agreement which entered into force on 12 October 2014). The CBD is relevant for the EAF, even if the convention does not explicitly mention fisheries. The importance given to marine biodiversity was pointed out in 1995 with a decision of the second conference of the parties which established the "Jakarta Mandate".

[7] http://unfccc.int/essential_background/items/6031.php.

[8] http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm.

[9] Principles 4, 5, 6, 9, 11 and 13 formulated in Rio echo their counterparts in the Stockholm Declaration (principles 8, 9, 11, 12, 20, 23 and 7 respectively).

knowledge should not be an excuse to defer the decision), the “polluter pays” notion (principle 16), and the cooperation of the stakeholders (principle 10, “each individual shall have appropriate access to information concerning the environment that is held by public authorities […] and he opportunity to participate in decision-making processes”).

7.1.2.2. *A universal right-based regulation to peaceful use of the maritime space*

Adopted on December 1982 at the end of a 10-year-long council, the Convention on the Law of the sea[10] – the “constitution of the oceans”– strikes a subtle balance between hard law (delineation of maritime frontiers) and soft law (environmental issues, among which the ecological viability of marine fisheries). It is the access to resources, at the time essentially fish stocks, that motivated the creation of exclusive economic zones (EEZs), areas where the exploitation of the natural resources of the water column, the bottom and the subsoil is subjected to the sovereign rights of the coastal state. Stretching from the coastline up to 200 nautical miles (370.4 kilometers), the EEZ includes the territorial sea (area of sovereignty from the baseline[11] up to 12 miles at sea) set up by the Geneva Convention in 1958. Beyond the EEZ, Law is defined by exclusion: what does not fall under the jurisdiction of either the territorial sea or the EEZ belongs to the “high seas” (64% of the area covered by the oceans) – it is the area where the Law of flag state rules[12]. At the high seas limit of the EEZ also begins the “Area” (the bottom and subsoil of the high seas), where exploration and concessions for the exploitation of mineral resources – which are world heritage resources – are managed by the International Seabed Authority.

The Convention on the Law of the sea came into force in November 1994 and was ratified by 167 countries in 2015[13]. Regarded as the “mother Law” underlying the exploitation of marine resources, the 1982 UN Convention

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[10] www.un.org/deps/los/convention_agreements/convention_overview_convention.htm.

[11] The “baseline” is normally drawn from the low-water mark on the nautical charts of the coastal State.

[12] Boats on the high seas are best regarded as mobile pockets of sovereignty, governed by the rules and regulations of the State whose flag they fly. The UNCLOS makes the principle of exclusive flag state jurisdiction subject to a number of extremely narrowly defined situations of extraordinary jurisdiction, such as piracy, slavery, illicit traffic in narcotics and unauthorised broadcasting from the high seas [HIG 06].

[13] The USA has not ratified the Convention yet. It seems likely that they will do it within the next few years, especially to reinforce legally their diplomacy in the negotiations pertaining to several critical regions (Arctic Ocean, South China Sea, etc.).

stipulates that fishery management must ensure the conservation of stocks, their restoration if needed and maintain populations of harvested species at levels which can produce maximum sustainable yield (MSY, see Chapter 4 of [MON 14]; see also [TRA 14]). Let us point out that biodiversity is not mentioned and that ecosystems and habitats are brought up only in a few very rare cases. On the other hand, these notions are recorded in the below-mentioned 1995 agreement.

The majority of fish and other organisms (crustaceans and mollusks) targeted by fishing fleets cross the limits of the Law of the Sea. Thus "straddling stocks" (for species such as cod, which may travel over the EEZs when migrating) and "stocks of highly migratory fish" (such as tunas, capable of transoceanic migrations) were defined. To fulfull the requirement for concerted international cooperation, a legally binding instrument of the UNCLOS – the agreement on straddling and highly migratory fish stocks[14] – was adopted in 1995 and came into force in 2001. Developed partly in reaction to the management failure of high-seas fish stocks, the agreement's primary goal is to achieve their long-term conservation. Beyond prescribing a detailed framework for the management of the highly migratory and straddling fish stocks[15], the agreement further includes broader objectives (avoidance of negative impacts on the marine environment, preservation of marine diversity and maintenance of the integrity of marine ecosystems) whose implementation requires a holistic ecosystem approach.

The 1995 UN fish stocks agreement provides for the establishment of about 20 regional fisheries management organizations (RFMOs) and places them as a keystone for its implementation[16]. The agreement indeed sets out

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[14] This agreement was ratified by 83 countries on February 11, 2016 (half the number of countries that have ratified the UNCLOS). Its exact designation is: "The United Nations Agreement for the implementation of the provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the conservation and management of straddling fish stocks and highly migratory fish stocks".

[15] In terms of management goals, we should also point out article 7 of appendix II: "The fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points"; in other words, MSY is a limit that should not be surpassed for underexploited stocks and can serve as a rebuilding target for overexploited stocks.

[16] Among the around forty Regional Fishery Bodies (RFBs) – groups of States or organizations that are parties to an international fishery arrangement – RFMOs have a fishery management mandate including the competence to establish legally binding conservation and management measures with their contracting parties.

comprehensive marine areas – together covering almost all the oceans – in which such a RFMO will have competence encompassing scientific research, stock assessment, monitoring, surveillance, control and enforcement[17]. RFMOs facilitate international cooperation for the conservation and management of fish stocks throughout their range of distribution, while taking account of the need for compatible management tools in areas within and beyond national jurisdiction (regarding transboundary, straddling, highly- or high seas migratory stocks).

Several obstacles hinder the functioning of the RFMOs, such as decisions by consensus – applied late – in a context of primacy of national interests (where crisis management plays a major role) or contracting parties reluctant to finance research supporting expert assessments [CUL 10]. In the specific case of the international commission for the conservation of Atlantic tunas (ICCAT), more than a decade of mismanagement of the east Atlantic and Mediterranean stock of the Atlantic bluefin tuna (ABFTE) led to a critical overexploitation, as formally stated in 1996 by the scientific body of ICCAT[18]. Despite having gradually implemented (from 1998 onwards) total allowable catch (TAC), size limit regulations and time/area closures, ICCAT did not follow the advice of its own scientific body and always adopted TACs exceeding the scientific recommendations[19]. Especially under pressure from several NGOs, ICCAT began to implement a rebuilding plan in 2007 (more restrictive management regulations) which was reinforced in 2008 (control strengthening and reduction of fishing capacity). In 2009, ICCAT endorsed for the first time the TAC recommendation of its scientific body (a low TAC for the three following years). Now, given the impact of numerous uncertainties on the mid-term projection outputs of ABFTE population size, the best way to increase the likelihood of stock rebuilding is to keep such a low TAC during the forthcoming years [FRO 14].

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17 Concerning the high seas exploitation of the living resources of the water column, RFMOs palliate the lack of an *ad hoc* body such as the International Seabed Authority, established by the UNCLOS to manage all mineral-related activities in the area.

18 “The available information indicates that the 2003-2004 fishing mortality rates [of the ABFTE stock] give rise to a high risk of fishery and stock collapse”.

19 High bluefin tuna prices, ineffective management regulations, compliance deficiency and lack of control paved the way for considerable illegal, unreported and uregulated (IUU) catches. The total catch of ABFTE was thus estimated at or above 50,000 tonnes per year during the 1998-2007 decade, while ICCAT scientific body recommended a TAC between 15,000 and 25,000 tonnes in the same period.

The fact remains that assessing almost all of the main world fish stocks requires the creation of new RFMOs, besides the performance examination many of the existing ones carried out (for example, the NEAFC in 2006 or the ICCAT and the IOTC in 2008[20]), given the issues related to their effectiveness [ROC 15].

7.1.2.3. *The determining impetus of the FAO initiatives*

Several of its achievements exemplify the essential role the FAO has played in the advancement of EAF:

– the creation of the COFI (Committee on Fisheries) in 1965. It is the only intergovernmental forum that has gathered, since 1966, delegations of fishing nations, representatives of the UN, RFMOs, international organizations and NGOs to deal with global and regional issues concerning fisheries and aquaculture. The goal would involve states, the FAO, intergovernmental bodies and civil society putting forward joint policy recommendations. Since the 1990s, the FAO's biennial report on the state of world fisheries and aquaculture (SOFIA[21]) has been presented to the COFI before the sessions's formal opening. Moreover, the elaboration of an agreement to harmonize port controls to counteract illegal, unreported and unregulated (IUU) caught fish from entering international markets through ports provides a convincing example to highlight the time it takes for the changes that the COFI strives for to become a reality. These works started in 1999 (23rd session) and drew to a close in 2009 (28th session): the COFI members thus contributed to the finalization of the project of legally binding measures under the jurisdiction of the Port State and the global record of fishing vessels, before the FAO Conference approved in November 2009 the "agreement on port states measures to prevent, deter, and eliminate illegal, unreported and unregulated fishing" [DOU 12, FAO 10][22].

– the definition of the concept of "responsible fishing" (Cancún Declaration[23], 1992), which encompasses within a framework of international cooperation (i) the sustainable use of fisheries and aquaculture

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[20] NEAFC, North-East Atlantic Fisheries Commission; IOTC, Indian Ocean Tuna Commission.

[21] The State of World Fisheries and Aquaculture (www.fao.org/fishery/sofia/en).

[22] The Agreement will enter into force after the deposit of the 25th instrument of adherence (the EU became a Party on behalf of its 28 Member States, and counts as only one party). 19 States had ratified and acceded to the Agreement in the first days of 2016.

[23] www.fao.org/docrep/003/V5321e/V5321e11.htm.

resources and the protection of the environment, (ii) capture and aquaculture methods with no harmful effects on ecosystems, resources or their quality, (iii) wealth creation through product transformation processes conform to sanitary standards and (iv) trade practices that guarantee access to quality products to the consumers.

– the publication, in 1995, and dissemination of an overarching guide that has become a global reference, i.e. the code of conduct for responsible fisheries [FAO 95][24]. Holistic and integrated in its approach, this voluntary[25] tool integrates the whole scope of the fisheries and aquaculture systems to promote structural changes, rational and sustainable use, stakeholder involvement, greater responsibility and higher standards of behavior, and taking account of the special requirements of developing countries. Keeping with the Law of the Sea[26], the Code defines principles and norms for the preservation of resources and the development of the management of the fisheries and aquaculture sector, and recognizes the nutritional, economic, social, environmental and cultural significance of fishing. From a scientific standpoint, the appropriation of the interdisciplinary nature of the EAF-related research questions should be highlighted: "states should ensure that appropriate research is conducted into all aspects of fisheries including biology, ecology, technology, environmental science, economics, social science, aquaculture and nutritional science" (Article 12.1). Assessing advance in implementation of the Code is part of the tasks that the COFI has to carry out over time due to how slowly several countries are adopting it [PIT 09].

– the organization of the "Conference on Responsible Fisheries in the Marine Ecosystem", which aimed to come up with specific recommendations ("Reykjavik Declaration"[27]) for the promotion of the EAF in the action plan of the World Summit on sustainable development (WSSD) held in Johannesburg in 2002 (see below).

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[24] http://www.fao.org/docrep/005/v9878e/v9878e00.htm.

[25] The principles and requirements contained in the 1992 Rio declaration and Agenda 21, together with the provisions of the UNCLOS have provided the basis for the development of the Code of Conduct for Responsible Fisheries. The Code includes thus several measures which are legally binding in other legal instruments.

[26] By way of example, the Article 7.6.2 of the Code: "States should adopt measures to ensure that no vessel be allowed to fish unless so authorized, in a manner consistent with international law for the high seas or in conformity with national legislation within areas of national jurisdiction".

[27] www.fao.org/docrep/meeting/004/Y2211e.htm.

We should also add to these initiatives the effort of the FAO to implement the EAF effectively [GAR 03], backed by the diffusion of a series of technical guidelines[28] started in 1996.

7.1.2.4. *The multilateral implementation of the EAF: goals and reality*

Ten years after the "Agenda 21" program adopted at the Rio conference, the "plan of implementation of the World Summit on sustainable development"[29] was ratified in Johannesburg. Rather than proposing new concepts, this plan aims at making these engagements a reality and to reinforce existing tools, especially the measures concerning the EAF mentioned in the fourth of its eleven parts ("protecting and managing the natural resource base of economic and social development"), such as the implementation of the Code and its international plans of action (section 31c, d)[30] or the elimination of subsidies contributing to IUU fishing and overcapacity (section 31f). First of all, the plan sets deadlines for several ambitious objectives (Figure 7.1):

– 2010: application of the ecosystem approach (section 30d); a significant reduction in the current rate of loss of biological diversity (section 44);

– 2012: a "representative network" of marine protected areas is established (section 32c);

– 2015: stocks maintained or restored to levels that can produce the MSY (section 31a).

Nowadays, the backlog faced by these commitments emphasizes the globally worrying character of the overview of worldwide fisheries; the assessment of the state of world fish stocks in 2011 has revealed that 60% of them are exploited at nearly MSY and that the number of overexploited stocks has reached 30% (against 10% in 1974) [FAO 14]. In addition to overexploitation, the chronic, and costly, overcapacity faced by the global fleet of decked fishing vessels has caused a drop in its productivity: catch per capacity unit in 2006 was a sixth of what it had been in 1970 [WOR 09]. The great variety of fisheries and their management create contrasts in this global report [COS 16], the most remarkable of which consists of the divergent courses taken by the fisheries of industrialized countries and those of several

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[28] www.fao.org/fishery/publications/technical-guidelines/en.

[29] www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImp.pdf.

[30] In particular the IPOA (international plan of action) for the management of fishing capacity and the IPOA to prevent, deter and eliminate IUU fishing.

developing countries, the latter often lacking the capacities necessary to the management of and control over the exploitation of their EEZ resources [WOR 12][31]. Gaps in performance also appear between industrialized countries. For instance, North American stocks are on average in a better state than those of the European Union [RIC 12].

We have to add to this heterogeneity the time necessary to carry out a project involving new management measures: from the beginning of its conception to its actual implementation we will have to wait at least a decade. Besides, this is the rate at which the common fisheries policy (CFP) of the European Union is revised. For example, it was only in 2013 that the MSY goal was introduced in the CFP reform, whereas the European Union had approved the plan of the Johannesburg summit in 2002 and reformed the CFP in the same year by adopting "the gradual implementation of a fishing management approach based on the ecosystems" underpinned by "principles of good governance". Broadly speaking, the obstacles that hinder the progress towards the EAF result from a combination of several causes, which vary in relation to the countries considered [COC 05]:

– the priority given to short-term socio-economic expectations, to the detriment of strategic long-term sustainability goals;

– the failures in fisheries governance (ill-defined goals, weak – even absent – regulation of access to resources, stakeholders unaware of their responsibilities, lack of administrative, monitoring and control capacities);

– the numerous sources (ecological, economic, etc.) of uncertainty that undermine scientific advice and their impact on the communication of recommendations designed to policy support.

7.1.3. *The complex matter of scientific issues supporting governance*

The goal of the EAF consists of transforming strategic concepts and perspectives into operational tools for management and organization. The challenge faced by research is to identify which management tools can lead fisheries steadily along an ecologically and socio-economically sustainable

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[31] Current status of fisheries is highly heterogeneous. The "median fishery" is in poor health, although one-third of fisheries is in good biological, not necessarily economic, condition. Recovering depleted fisheries would eventually increase fish catch, profit and fish biomass, depending upon distinctions across recovery policies. In the best cases, the median time to recovery would be about a decade [COS 16].

path. To this end, we have to elucidate the functioning and dynamics of the “fisheries system”, a complex object comparable to a socio-ecosystem [COS 07]. Figure 7.2 sums up qualitatively the main drivers of the ecological and socio-economical components of the system, acting at several scales. According to the DSPIR[32] logic, it is a matter of:

– human population growth and global development of human societies;

– the resulting pressures (food requirements, overexploitation of resources, climate change, and other anthropogenic pressures);

– the state of fisheries (altered biodiversity, degradation of exploited ecosystems, sub-optimal performances of fishing fleets);

– related impacts (growing scarcity and/or instability of resources, contaminants and health hazards, economic losses);

– societal reaction, especially in relation to governance and progress towards the EAF.

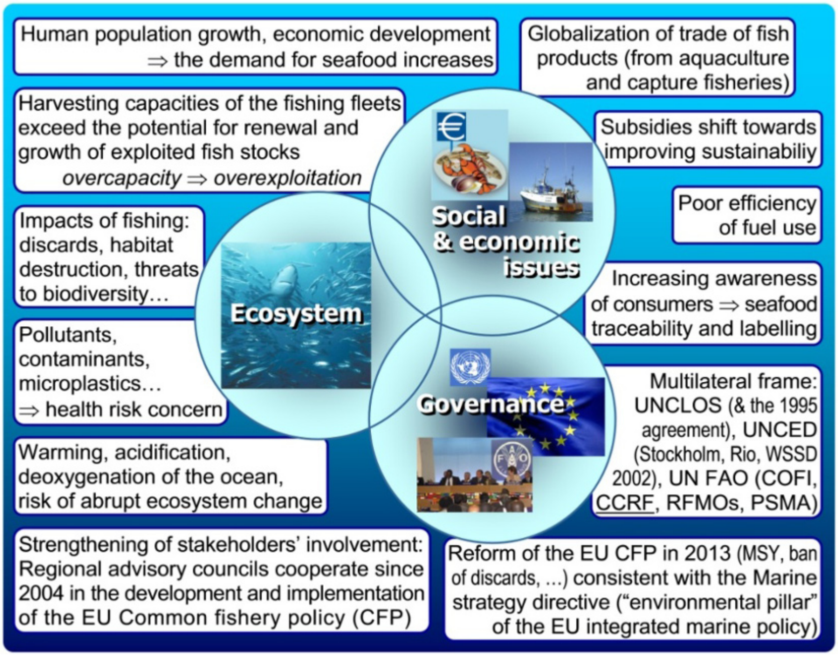

Figure 7.2. *Diagram of the main ecological and socio-economical inner workings of the “fishery system”*

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[32] DSPIR: Driver, Pressure, State, Impact and Response (causal progression).

COMMENTS ON FIGURE 7.2.– Demographic growth, coupled with the related increase in the demand for food, is the principal driver of the evolution of fisheries in an ocean transformed by the effects of climate change, to which we have to combine the footprint of various anthropogenic pressures on marine ecosystem services. Here, the common fisheries policy (CFP) of the European Union illustrates how multilateral instruments are implemented at the regional scale–notwithstanding the complex interactions between the Commission, the Member States regional groups, the Regional Advisory Councils and Regional Sea Conventions, which postpone the execution of EAF [RAM 16].

The expected outcome is the staging of plausible future scenarios for fisheries in relation to socio-economic development strategies, such as the one described by the United Nations development program [UNE 12]. The results published in 2013–2014 by the IPCC[33] relates future changes in the concentration of greenhouse gases (RCPs: representative concentration pathways) with trajectories of development (demography, GDP, energy consumption, land use; see [VUU 11]). Climate models then provide RCP-based projections of trends in future climate over this century and afterwards. These results are combined with other models (ecological and inter alia) to forecast planetary environmental changes.

Next comes the characterization of the impacts on biodiversity and ecosystem services. To shed light on the resulting effect on fisheries, a thorough understanding of the non-linear relationships between stability, productivity of ecosystems and biodiversity is needed [CAR 12]. Regarding fishery resources, knowledge gaps are related to the oceanographic, biogeochemical, biological, etc. multiscale dynamics driving the variations of the marine biological productivity (primary production, transfers in food webs) which will shape the state, structure, and renewal of exploited populations, lead to changes in their habitats and cause the potential accentuation of zonal biogeographical contrasts (high versus medium and low latitudes) between marine biomes. Substantial progress is also needed in life sciences (physiology, population biology, evolutionary ecology supported by the new generations of sequencing, ethology, etc.) as well as in social sciences (multi-criteria analysis of mitigation and adaptation policies, assessment of management and conservation measures, etc.) and will depend crucially on a variety of observation and information systems [GOU 14].

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[33] Intragovernmental Panel on Climate Change, www.ipcc.ch/.

Another challenge consists of strengthening the links between the progress of knowledge and political decisions by relying on “interlocked” scientific assessments (from the progress of the EAF to the creation of scenarios linking together socio-economic dynamics with biodiversity dynamics in the context of global change). These challenges have motivated the creation in 2012 of a dedicated science–policy interface focused on global assessment, the intergovernmental science–policy platform on biodiversity and ecosystem services (IPBES). Due to the multiscale nature of biodiversity and the greater gaps in knowledge and capacity to address its loss, governments have given IPBES a broader mandate than the IPCC, with special emphasis on important goals for tackling the loss of biodiversity (increasing the knowledge base, building capacity, and policy support) [BRO 14]. Managing uncertainties will play a decisive role both at the beginning of the process – for example in modeling [FRO 14, LEH 13], and in the end when it comes to communicating information to policymakers and, more generally, to civil society. As for the last point, we can refer to the experience of the IPCC, which manages consistently the treatment of uncertainties by gauging its main scientific results with qualitative and probabilistic metrics [MAS 11].

By preserving the integrity of the different components and the health status of marine ecosystems, the EAF is a major aspect not only for the exploitation of marine resources but also for the conservation of species, all the while enabling the renewal and enhancement of the scientific topics introduced by marine ecology. We should thus get a better grasp of the kinds of controls at work in marine ecosystems. Understanding the way ecosystems work and how they are structured ultimately allows us to “fine-tuning” in the management of fishery resources.

7.2. The way marine ecosystems work

7.2.1. *Bottom-up, top-down and wasp-wait controls*

An ecosystem is classically defined as the set formed by an association or community of living beings (or biocenosis) and their biological, geological, edaphic, hydrological, climatic environment, etc. (called biotope). Ecosystems are characterized by complex and variable dynamic interactions, in which man's action through the exploitation of resources often ends up playing a dominant role. A marine ecosystem includes water, nutrients, detrital matter, several types of different organisms of various sizes and different life history traits ranging from bacteria, phytoplankton, zooplankton and fish to mammals and birds, as well as fishers. All these components are linked in several food webs through evolving interactions, which makes ecological systems astonishingly complex. Species interactions include predation, competition, the transmission of diseases and parasites, parasitism and mutualism. It seems difficult to untangle "natural" processes and impacts, especially those induced by the environment in response to anthropogenic activities [PLA 10]. The processes involved in the multiple interactions between species can be studied thanks to ecosystem models [CUR 08a] which are useful for the identification of the effects of certain variables on the global dynamics of a community or ecosystem. However, it seems that certain patterns, which are emerging steadily and globally, allow us to get a better grasp of the controls at work within the ecosystems.

7.2.1.1. *Bottom-up control or control through the environment*

Ecosystems are naturally controlled by their physical and biogeochemical environment. Using an analogy with agriculture, where the yield can be predicted on the basis of the input, [SME 99] has advanced the hypothesis that the supply of planktonic production regulates the stocks of grown fish, which results in a global production of phytoplankton and/or zooplankton that allows us to predict fishing yields [CHA 10, VER 98]. Plants dominate land ecosystems, but the ocean contains less than 1% of the global vegetal biomass (terrestrial and aquatic)[34] [SME 99]. Consequently, it is recognized that nutrient limitation is much more severe in the oceans than it is on dry land generally [POL 99]. These observations have given rise to the notion of ecosystems with bottom-up controls. In other words, the components of the food web are regulated either by primary producers or by limited nutrient supply [PAC 99] (Figure 7.3).

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[34] Accounting for less than 1% of the global photosynthetic biomass, phytoplankton produces half of the oxygen contained in its atmosphere. This is mainly due to the gap of more than three orders of magnitude between the average renewal time of oceanic (two to six days) and continental vegetal organic matter (19 years), without forgetting the effect of the stretch of the hydrosphere.

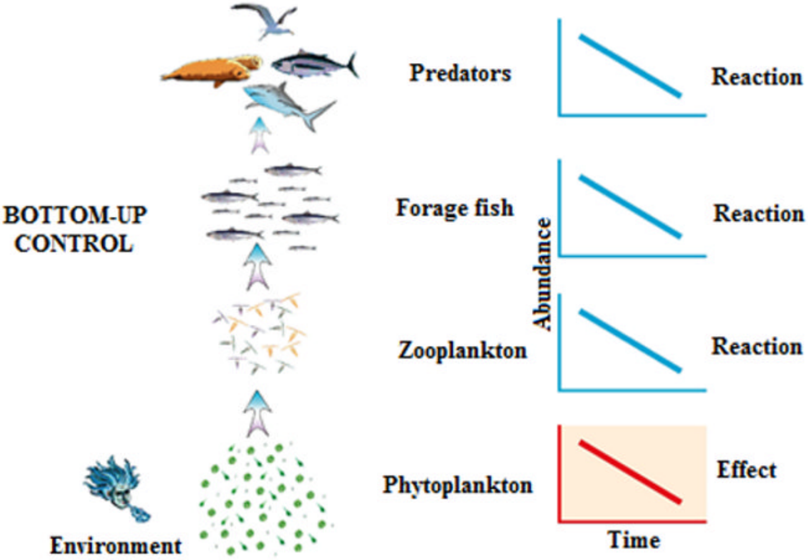


Figure 7.3. *Bottom-up control or control through primary production in a simplified four-level food chain in a marine ecosystem*

COMMENTS ON FIGURE 7.3.– Bottom-up control or control through primary production, in a simplified four-level food chain in a marine ecosystem can be summed up schematically: when, for example, the physical environment becomes less favorable, it controls the decrease in the abundance of phytoplankton, which, in turns, affects the abundance of zooplankton negatively. The decrease in the abundance of zooplankton controls the reduction in the abundance of prey fish, which in turns leads to a decline in the abundance of top predators (the control factor is represented by the solid line, while reactions are illustrated by the dotted lines) [CUR 03].

Several ecological observations can confirm this diagram representing the productivity of the ecosystems. The archives of the scale deposits of sardines and anchovies deriving from anaerobic sediments show that very large population fluctuations occur even when no fishing activity is practiced [BAU 92] and that they are linked to environmental changes. The impact of the environment on population dynamics has been highlighted in particular by studies on fish recruitment [CHA 09, HJO 14, NEE 02]. Feed availability as defined by the physical processes of production, retention and concentration [BAK 96] significantly affects the survival of fish larvae and determines the abundance of fish [CUR 89]. Even though the role of the environment on a global level is thought to affect set of the ecosystem dynamics, mesoscale events significantly structure the marine ecosystem and its productivity [CUR 08], for example through the trophic interactions between top predators and primary production [TEW 09].

The structure and functioning of marine ecosystems can react to long-term climate variations over time. This has been established for the California Current, the Gulf of Alaska [MCG 98], the northern Atlantic [AEB 90] and the section of ocean off the coast of Chile [HAY 97]. Long-term parallel trends on four marine trophic levels, ranging from phytoplankton, zooplanktons and herrings to marine birds, have been associated with environmental changes in the North Sea, consolidating the model of bottom-up regulation [AEB 90]. We can also mention the shifts in the climate patterns of the Northern Pacific in the mid-1970s and by the end of the 1980s, the changes in the Korean ecosystem [ZHA 00] or in the upwelling system [CHA 09]. These large scale changes structured by the environment are also observed between species that fluctuate in conjunction with the global level. Thus, the fluctuations in the size of the populations of sardines in the Currents of Japan and California, as well as in the Current of Humboldt, take place simultaneously and are influenced by environmental changes on a global scale [KAW 91].

It seems that the alternation between stable states is observed with respect to fish assemblages, sometimes over the course of decades. For example, upwelling systems tend to be dominated by a species of sardines and a species of anchovies but, at a given time, in most of the cases only one of them is dominant. Phenomena of alternation between the species of small pelagic fish have been observed in most upwelling ecosystems for the past few decades. The mechanisms we generally mention include the environmental effects that will favor one species or the other. The analysis of the changes in the abundance of pelagic species reveals that dominant species react to environmental factors whereas subordinate species react to the abundance of the former [SKU 82].

Thus, from an ecosystem perspective, climate-related factors are thought to affect the fluctuations of the abundance of a species whereas its absolute density is more determined by intra-specific competition [SER 98, SKU 82]. It has been recently shown that competition between species can be amplified by the behavior of fish within shoals made of mixed species

[BAK 99]. Thus, the “school trap” hypothesis constitutes a possible mechanism of interspecific competition where the subordinate species can be curbed to low-abundance levels over long periods of time. These long-lasting alternating patterns play a significant role in long-term management, since exploitation reduces the biomass of the dominant species, which are generally the target species and sometimes speeds up their demise.

The spatial distribution of species can be modified in a context of global change. Marine fish and invertebrates react to ocean warming by changes in distribution, with some species likely to migrate to higher latitudes or deeper waters. Climate change might entail a large scale redistribution of the global catch potential, with an average increase of 30–70% below high latitudes and a drop of up to 40% in tropical regions [CHE 10, CHE 13]. Moreover, the maximum catch potential would considerably decrease in the southern margins of semi-enclosed seas, whereas it would increase in the northern margins of the continental shelf. Such changes are taking place in the Pacific Ocean. Among the twenty most important regions of the exclusive economic zone (EEZ) in terms of landing, the EEZs that would see the sharpest increase in the catch potential from here to 2055 would be those belonging to Norway, Greenland, the USA (Alaska) and Russia (Siberia). On the contrary, the EEZs that would face the greatest loss of maximum catch potential include, among others, Indonesia, the USA (apart from Alaska and Hawaii), Chile and China. Nowadays, these migrations are important for the assessment of fishing management options in a context of resource redistribution under the action of climate change.

These changes in distribution have started to have an effect on global catches [CHE 13]. As a consequence, fisheries are affected by the “tropicalization” of catches (the increase in warm-water species caught). Warmer oceans have already had an impact on global fisheries over the last four decades, underlining the necessity of elaborating management plans to minimize the effects of such a phenomenon on the economy and food security of coastal communities, especially in tropic regions.

7.2.1.2. *Top-down control or control through predation*

Trophic aspects play a significant role in the structuring of the ecosystem. Predation mortality is considered the main source of mortality for the marine species exploited [BAX 91]. In six marine ecosystems (the Benguela Current, Georges Bank, Balsfjord, the East of the Bering Sea, the North Sea and the Barents Sea), predation – which is performed on all the development stages of the prey species – is estimated to be twice to 35 times higher than fishing-related mortality [BAX 91]. Consequently, we believe that the regulation of the components of the ecosystem at low trophic levels by means of species belonging to higher trophic levels (called top-down control) can be critical to the functioning of the marine ecosystem.

[URS 73] points out that “fish stomach contents are a simple function of local prey availability and suitability, this latter often simply being a function of size” or of the ratio prey size/predator mouth size. This is the case for marine food webs, where feeding can be most often considered as opportunistic and less dependent on prey taxonomy than on prey size. Since water is 800 times denser than air, a streamlined morphology allows fish to move efficiently in the aquatic environment. Appendages used to handle and capture large sized preys are not common among fish. Consequently, in aquatic communities, predation is determined by size [LUN 99, SHE 77]. Unlike land predators, such as lions, predator fish can only forage for those prey that are small enough to be swallowed whole. Thus, since the size of the jaw is related to fish size, it is generally believed that the size ratio between predator and prey determines whether predation is possible or not. Fish tend to take on varied species and to have a whole range of predators. At the larval stage, fish feed on the lower part of the food chain, but grown individuals belong to trophic levels that increase with their sizes [RIC 95]. During the process of ontogenesis, a fish, while developing, moves from one trophic level to another and the relationship between the trophic level and the logarithm of body length is linear, with a steeper curve for top predator species [PAU 01]. The eggs and larvae of teleostean fish constitute the basis of the piscivore food chain. Moreover, teleostean eggs are mostly uniformly sized, their diameter measuring about 1 millimeter [CUR 00b]. Thus, “community predation” [SIS 84, VER 08] can take place because each fish species is potentially in competition with all other fish species. Cannibalism often occurs in aquatic systems and can cause significant levels of juvenile mortality. For example, in the stock of Eastern Baltic cod (*Gadus morhua*), cannibalism can cause the death of 31% to 44% of the individuals within their first two years [NEU 00]. Unlike what happens on dry land, two aquatic species can be the predator or the prey of each other, with respect to their sizes. For example, North Sea cod forage for herring, but grown herring can also feed on cod larvae [STO 92]. This "inversion of the predator–prey roles" [BAR 88, VER 08, WAL 01] can account for the low success rate met by the attempts to recover certain stocks of predator fish after episodes of collapse (such as Newfoundland cod, the stock of which has not been recovered since 1992, i.e. the date of its collapse) [HUT 00].

The effects of predation can provoke major changes in the structure and functioning of the ecosystem by cascading down towards the lower levels of marine food webs. These trophic cascades occur when the abundance, biomass or productivity of a population or trophic level is altered at more than one link of the food chain, due to mutual predation effects [PAC 99].

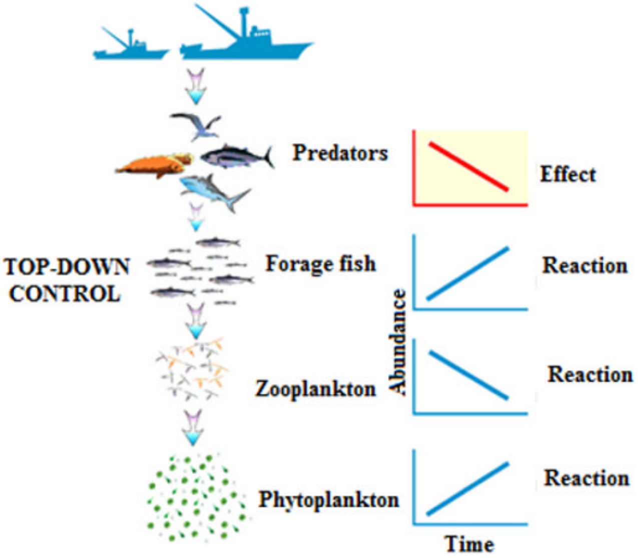


Figure 7.4. *Top-down control or trophic cascade in the food chain for four trophic levels in a marine ecosystem*

COMMENTS ON FIGURE 7.4.– The decline in the populations of top predators entails a reduction in predation, which produces an increase in the abundance of forage fish. The increase in the forage fish predation of zooplankton leads to a decrease in the populations of zooplankton. The reduced abundance of zooplankton in turns decreases the grazing pressure exerted on phytoplankton, which becomes then more abundant (the factor control is shown by the solid line, while reactions are illustrated by the dotted lines) [CUR 03].

Strong [STR 92] has discussed the evidence that trophic cascades have mainly been observed in aquatic systems containing few species. A key predator species can be involved in a trophic cascade [PAI 80], while the elimination of a species with top-down effects provokes the propagation of major perturbations through a food chain. Sea otters are thought to be key species in the Alaskan ecosystem and, when they are abundant, the pressure of their predation on sea urchins reduces the grazing of the latter on kelps, thus stabilizing kelp forests. When sea otters are scarce, sea urchins proliferate, strongly graze on kelps and reduce their productivity.

These examples of trophic cascades, observed in lakes (see [CAR 93] for a review) and intertidal areas [EST 95, PAI 80], were the first to be documented. Nowadays, several examples of trophic cascades are being observed in littoral or coastal marine environments. One of them has been described in the subarctic area of the northern Pacific, where pink salmon (*Oncorhynchus gorbuscha*) feed on macrozooplankton and phytoplankton, thus controlling the biomass of these planktonic groups during the summers. We have measured inverse relationships between the biomass of the plankivoros pink salmon and the one of zooplankton, and between the biomass of zooplankton and the one of phytoplankton [SHI 97]. Another example has to do with trophic cascades in marine pelagic ecosystems, where the effects caused by changes in the abundance of predators can cascade down towards the lower part of the food chain, sometimes as far as phytoplankton [MIC 99]. Thus, in the Black Sea, the exploitation of large pelagic fish has caused an increase in the number of small pelagic fish and brought about changes affecting primary production [DAS 02, DAS 07]. The chronology of piscivoros and planktivoros fish, zooplankton, phytoplankton and the phosphate content in the surface waters of the Black Sea were examined between the 1950s and the 1990s. Contrary tendencies in the various consecutive trophic levels have also been found. This cascade effect is attributed to the overexploitation of large predators such as dolphins, mackerel, skipjacks and bluefish. When piscivores were becoming scarcer, the biomass of planktivoros fish was increasing considerably at the beginning of the 1970s and zooplankton consumption became larger. The biomass of jellyfish also increased significantly during the 1980s, affecting the abundance of zooplankton. The increase in the biomass of phytoplankton has apparently led to the draining of nutrients in the surface layer since 1975.

A meta-analysis performed in the northern Atlantic reveals that the abundance of northern prawns (*Pandalus borealis*) is inversely proportional to the abundance of cod (*Gadus morhua*) [WOR 03]. The changes in the ecosystems of the north-west Atlantic have been drastic over the past three decades. The biomass of cod has dropped from 2.5 to 0.05 million tonnes due to overexploitation [BUN 01]. A trophic cascade occurred in the 1990s, a period during which the abundance of herrings, capelins, and other pelagic fish, freed from the strong pressure exerted by their predators, saw an increase. The abundance of zooplankton diminished, whereas the abundance of primary producers increased [FRA 05]. Several ecosystems thus illustrate that the overexploitation of top predators leads to a significant increase in the number of their preys or of short-lived species (for example, squid, octopuses, prawns, sardines, herring, anchovies, etc.) [BAU 09, DAS 07, FRA 05].

The inspection of global fisheries has suggested that the average trophic level of landed catch has decreased due to the exploitation of top predators, which caused the exploitation to involve species situated lower and lower down the food webs, a mechanisms known as “fishing down marine food webs” [PAU 98, PAU 00]. By eliminating large predators straight away, i.e. shortening the food chain, the pressure exerted by predators on small forage fish (such as sardines and anchovies) is relieved. This may lead to an increase in the biomass of small forage fish. Upon analyzing global fish catches, it seems that pelagic fish species reached a plateau in the mid-1980s, ten years after the stabilization of demersal fish catches, which suggests a possible increase in the abundance of forage fish species as a result of the intense exploitation of their predators in the 1970s and 1980s [CUR 00b]. Another explanation, which does not exclude the previous one, is that the drop in average trophic levels implies increased fishing at low trophic levels (fishing through marine food webs). By analyzing the tendencies of fishing landings in 48 ecosystems all across the world, [ESS 06] notice that fishing targeted preferentially at low trophic levels of the food chain is widespread among thirty of the ecosystems studied, and that this mechanism of selective exploitation has been one of the causes of the drop in the average trophic level of the landings.

7.2.1.3. *Wasp-waist control or control through dominant species*

The role of dominant pelagic fish in marine ecosystems has been recently highlighted, since these fish could control the structuring of energy flows, a phenomenon defined as wasp-waist control (Figure 8.5). In upwelling systems, few pelagic fish species occupy the intermediate trophic level, feeding mainly on phytoplankton and/or zooplankton. These species can present high levels of abundance, which vary with respect to the significance of the recruitment linked to the environment. It is thought that these features impose some constraints on lower and upper trophic levels. Planktivoroas fish could reduce herbivorous zooplankton, which would lead to an increase in the density of phytoplankton [HAI 93]. This idea has been further developed by using data on lakes (for example [CAR 93]) and the topic has drawn the attention of both terrestrial [SCH 89] and aquatic ecologists [PER 91]. The effectiveness of the consumption of herbivores on primary producers is much higher in freshwater pelagic communities (32%) than in dryland communities (3%) [HAI 93]. In comparison, the subject has only recently been focused on in the context of marine ecosystems. From 1988 to 1991, 8% of global aquatic primary production was necessary to maintain global fish catches (94.3 million tonnes) and refuse (27 million tonnes) [PAU 95]. This number is higher if we only take into account upwelling systems. On average, 25% (confidence interval ranging from 17.8 to 47, 9%) of primary production in upwelling systems is necessary to maintain catches and refuse, suggesting that there are close links between the trophic levels [PAU 95]. The inter-annual fluctuations of the biomass of mesozooplankton are negatively correlated with those of zooplanktivorous fish, which indicates that fish predation can potentially control the biomass of mesozooplankton [MIC 99]. By means of a meta-analysis, top-down control of zooplankton through sardines, Sardinella species, herring or anchovies has also been proved to take place off the shores of South Africa, Ghana, Japan, in the Black Sea [CUR 00a] and in the northern Baltic Sea [ARR 97]. In the central area of the Baltic Sea, the biomass of sprats has been shown to affect the production of water fleas in summer [KOR 01]. On the other hand, bottom-up control of predator fish through small pelagic fish has been noticed in the Benguela and Humboldt Current, and in Guinea, since several (although not all) predator fish suffer when their prey stock collapses [CUR 00a]. When the stocks of pelagic fish recover, predators can recover rapidly or be delayed from a few years to a few decades, highlighting the complex reaction of the ecosystem to change. A high level of adaptability in terms of life-cycle characteristics notwithstanding, several populations of birds are unable to counteract the effects of long-term fluctuations of prey resources [CRA 99b, CUR 11b].

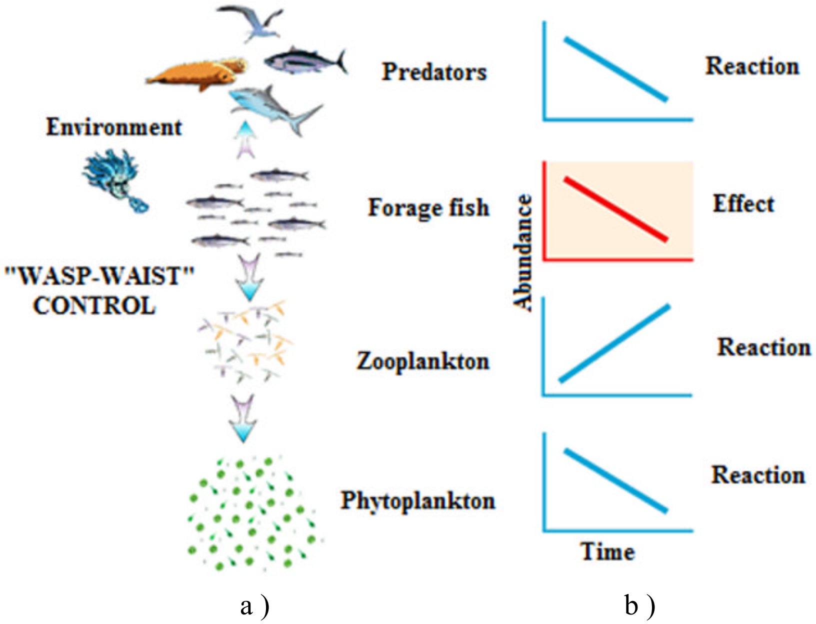


Figure 7.5. *a) Wasp-waist control in a simplified four-level food chain in a marine ecosystem. b) The abundance of prey fish (small pelagic fish), which depends on the environment, controls at once the abundance of predators and primary producers*

COMMENTS ON FIGURE 7.5.– A decreased abundance of prey fish negatively affects the abundance of predators and reduces predation on zooplankton, which becomes more abundant. A greater population of zooplankton increases grazing pressure and decreases the abundance of phytoplankton (the control factor is represented by the solid line whereas reactions are illustrated by the dotted lines). The environment is thought to have a direct physical effect on the recruitment of pelagic fish but no effect on the whole of the food chain [CUR 03].

These few examples illustrate a wasp-waist control, where small pelagic fish simultaneously exert bottom-up control on large predators and, more surprisingly, top-down control on zooplankton. Wasp-waist control has been studied in several ecosystems, like the North Sea [FAU 11] or the open-sea pelagic ecosystems of the Pacific [GRI 13]. However, some studies show that trophic patterns sometimes seem more complex, especially in upwelling areas [FRE 09, MAD 12].

Sometimes the overexploitation of one of the intermediate components, like forage fish, provokes systemic changes that affect deeply, and in the long term, the way ecosystems work and their productivity. In the northern part of the Benguela Current off the shores of Namibia, anchovy stocks (*Engraulis encrasicolus*), which are high-energy prey species, collapsed in the 1970s from about ten million tonnes (MT) to nearly zero due to the combined effects of overfishing and the evolution of the environmental conditions [ROU 13]. After this collapse, bearded gobies (*Sofflogobius bibarbatus*), which are low-calorie fish, increased rapidly and now constitute the main forage species for predators within this system. In addition, other prey like jellyfish (negligible before the beginning of the 1970s) reached a biomass estimated at more than 40 MT in the 1980s and at 12.2 MT in the 2000s. As a consequence of the replacement of high-energy sardines and anchovies with low-energy gobies and jellyfish, African penguins (*Spheniscus demersus*) and Cape gannets (*Morus capensis*) have decreased by 77% and 94% respectively. Shallow- (*Merluccius capensis*) and deep-water (*Merluccius paradoxus*) Cape hake catches have decreased from more than 7,25,000 MT in 1972 to less than 1,10,000 MT after 1990, and the production of brown fur seals (*Arctocephalus pusillus*) has fluctuated wildly. The overexploitation of forage fish increases pelagic-benthic interactions, leading to the anoxia of the system (below acceptable levels for many species apart from bearded gobies), which is another potentially irreversible state of the ecosystem. We are dealing here with a radical systemic change in an ecosystem in which one of the components has been overexploited, with little room for reversibility.

The question of the relative contributions of top-down control and bottom-up control in the structuring of ecosystems is certainly not new. It has been widely debated in terrestrial ecology, but no consensus has been reached yet [MAT 92, POW 92]. It is believed that top-down and bottom-up forces act simultaneously on populations and communities and that the understanding of the relative contributions is an important step for future ecosystem approaches to the management of ecosystems [CUR 03]. Hunter and Price [HUN 92] put forward a convincing argument in favor of the primacy of bottom-up forces in food webs: "… the removal of higher trophic levels leaves lower levels intact (if perhaps greatly modified) whereas the removal of primary producers leaves no system at all". However, we have to admit that this claim almost completely dodges the tricky question that consists of knowing which factors can modify the effectiveness of consumption. The debate is no longer about the kind of control produced, but focuses instead on what controls the force and on the relative significance of the different forces in variable conditions [MAT 92].

In the following sections, we will deal with ecological factors, such as trophic relationships and their measurements that can affect controls and talk about how spatial and temporal resolution can help us understand the contributions of different controls.

7.2.2. *Trophic relationships in marine ecosystems*

7.2.2.1. *The notions of trophic level and food web*

The different organisms belonging to a marine ecosystem (bacteria, animal and vegetal plankton, macro-invertebrates, fish, etc.) are interconnected through their trophic relationships. These trophic interactions play a key role in the functioning and dynamics of marine ecosystems, since the abundance of each population depends to a great extent on these links that connect predators and their preys. A food chain consists of a series of organisms in which each of them feeds on those that come before it in the chain before being consumed by those that follow it. A food web is a set of food chains which describe the trophic interactions between all the consumers and their resources within an ecosystem. Thus, marine ecosystems can be described as a collection of different trophic levels grouping those organisms that share the same feeding mode. At the bottom of the ecosystem, photosynthetic organisms belong in the first level and constitute the primary producers. The consumers of primary producers (phytophages) belong to the second level, secondary consumers in the third, etc. This notion of trophic level as it was introduced by Lindeman [LIN 42] seems simplistic. On one hand, the feeding habits of marine organisms are quite variable while on the other the feeding of a given species varies quite often in relation to its life stage (age and/or size) and immediate surroundings. Moreover, omnivores, which feed on several trophic levels, make this kind of approach more complex. The trophic level of an organism can vary in relation to intrinsic (biological and/or physiological) and extrinsic (environmental) constraints. It seems more like a property that derives from the feeding practices of an organism on a well-defined spatiotemporal level and within the given ecosystem. This conceptual approach, however, remains useful if we want to describe the relationships that link all the components of a given system and the way it functions on a trophic level (see the section on trophic tracers). The analysis of the different compartments of a food web allows us to understand more thoroughly the organization modes and dynamics of marine communities and, consequently, to study the reactions of marine ecosystems to the threats and perturbations they have to face.

7.2.2.2. *Predator–prey relationships*

Surviving, feeding to live, the feeding quest is one of the main goals of all living species. The trophic ecology of a fish is based on a body of knowledge about its diet, its ways of foraging, and where and when it feeds. None of these questions, “Why? How? Where? When?”, when taken one by one, can give us a global understanding of the trophic ecology of a fish. Thus, we define the feed niche of an organism as the part of the ecological niche referring to all aspects concerning the use of feed resources. The trophic component concerns the feeding regime (diet in terms of prey species and/or sizes), the spatial and temporal one focuses on foraging areas and periods, whereas the behavioral aspect deals with the techniques used to capture prey. There is a large number of behavioral tactics used by fish to find feed [GER 94]. However, nearly all fish use their sight to find feed (especially plankton eaters and predators) and ingest their prey through suction. For example, bathypelagic or deep sea, fish have adapted to the low levels of available light by increasing the size of their eyes, reducing the number of cones and developing more rods. The description of feed niches is widely used to understand the role played by species in the way ecosystems work. They allow us to study how different predators share or compete for resources, and their range also gives us information about the degree of feeding flexibility of a species. Specialist species include those organisms that feed on a limited number of food types. They generally meet when there is plenty of feed (narrow niche). This is the case for several species of reef fish. On the contrary, generalist species feed on a wide range of feeds. We can find them in those environments where feed is scarce (wide niche). Moreover, we call those predator fish whose feeding mainly reflects the availability of lower trophic levels in their environment opportunistic feeders.

7.2.2.3. *The predation cycle*

A predator fish is a free organism foraging for feed consisting of other mainly living organisms (its prey). It is physiological stimuli such as appetite (hunger and satiety) and the condition of the predator (linked to energy reserves) that trigger foraging. However, feeding success relies on the co-occurrence of the predator and its prey. This probability of encounter is influenced by a set of factors specific to the organisms, in conjunction with environmental variables (visual tracking, vertical distribution, etc.). A functional and mechanistic approach to predation, which breaks down the predation cycle into five consecutive stages, has been proposed by [JES 02]. Its phases are forage, encounter, detection, attack and consumption of the prey when the attack is successful. These authors model a predator's probability of effectively foraging for prey, the encounter rate between foraging predator and its prey, the predator's probability of detecting prey encountered, its probability of attacking the prey detected and finally the probability of success of the attack. Thus, the predator's appetite influences the probability of foraging for new prey. The relation between the predation rate (the amount of prey consumed by a predator per time unit) and the density of prey is also a significant feature of a predator–prey system. It is the functional reaction of the individual-predator to the variation in the density of prey. The amount of prey increases with the availability of preys but only up to a certain threshold. The specific forms chosen for this function contain a significant amount of biological information determined by the dynamics of the predator–prey system studied [GEN 03, JES 02]. Other approaches propose to model the prey's dynamics in the stomach content of a predator: foraging time, meal size (considered as one prey or a set of small preys captured over a small time interval) and decrease in the size of the stomach content on the basis of a stomach-emptying model. Approaches like these allow us to model the temporal evolution (i.e. the dynamics) of the stomach content of a predator and to estimate daily intakes [BEY 98, RIC 04]. The daily intake corresponds to the quantity of feed consumed by an organism over the course of one day. Related or unrelated to the weight of the organism, intake is a significant parameter of ecosystem models since it allows to quantify the distribution of energy flows among the compartments of a food web.

7.2.2.4. *The analysis of stomach contents*

A feeding regime (or diet) can be described in several ways. We can define it in relation to the zoological type of prey targeted: ichthyophages are fish consumers, teuthophages consume cephalopods, planktonophages feed on zooplankton, etc. A herbivorous, carnivorous or detritivorous diet will mainly consist in vegetal organisms, animal organisms or organic detritus. However, the nature of the predation relationship is often described taxonomically while making sure to precisely identify the preys. Despite involving some bias, the analysis of stomach contents constitutes the basis for studies focusing on feeding regimes [CHI 07]. When conducted rigorously, it allows for identifying prey with precision by creating reference collections. On the basis of the hard structure that has been ingested, like the otoliths of fish or the beaks of cephalopods, it is also possible to deduce the weight of preys at the time of ingestion. These hard parts allow identifying species and establishing allometric relationships between their size and the weight of the fresh prey. The prey contained in the stomachs can also be counted and measured either directly, if the digestion conditions allow it or indirectly on the basis of the hard parts. This information allows us to estimate some total rates calculated on the basis of the occurrence, total number, weight and size of the prey: similarity rate, overlap or selectivity rate, size ratios, etc. On the other hand, the stomach contents of top predators like large pelagic fish (tunas, green swordtails, sharks, etc.) also allow us to document the biological and ecological aspect and the diversity of the forage fauna that constitutes the preys of top predators (small fish, crustaceans and cephalopods ranging from a few to ten centimeters). These opportunistic predators are used as samplers of the intermediate levels of the open sea food web, which we know basically.

However, the study of trophic interactions in terms of species is limited by the variability of feeding regimes (among the individuals of the same population but also over the course of the lifecycle) and by instances of omnivory and cannibalism. Many recent studies show that trophic relationships can be modeled on the basis of the structure of organisms in terms of size. The size of the prey is a significant selection factor. A fish can start its life as the prey of a group of species and then become a formidable predator of the same group of species. As fish generally feed through suction, the size of the mouth determines the size range of the prey that can be captured.

7.2.2.5. *Feeding strategy*

It is a matter of optimizing the feeding success of a species to satisfy its survival needs and maximize its reproductive capacity. However, foraging and catching preys cost in terms of energy. The individual must then optimize the energy gain between the cost involved in implementing the strategy and feed intake. The pressures exerted by the environment, natural selection and the coevolution of species have shaped the morphological, physiological and social adaptations of marine organisms so as to optimize their foraging and the way they capture their preys. The “Optimal Foraging Theory” tries to explain how a fish “chooses” between different food sources by assessing the benefits and capture-related costs of one type of prey rather than another. This theory puts forward some models maximizing the energy gain, defined as the difference between the net gain and the energy spent to harvest for feed. Several works are also based on the energy content of prey. In fact, the satisfaction of the energy and nutritional needs of a predator can be compromised by a decrease in the general quality of preys available. The quality of the preys ingested becomes a fully-fledged feature of feeding, with possible effects on the population dynamics of the predator [OST 08].

7.2.2.6. *Trophic markers*

The perfect trophic marker is a unique compound that can be easily identified: it is inert and presents no danger for the organisms, it is not selectively transformed during the ingestion or incorporation and it is stable metabolically. It is transferred from one trophic level to the next at once qualitatively and quantitatively. Such a marker would give us an excellent overview of the ecosystem dynamics by revealing essential information on how energy flows within food webs. This information is crucial to the elaboration of ecosystem models [DAL 03]. However, “perfect” markers are unfortunately rare or inexistent and we have to deal with less ideal compounds.

7.2.2.6.1. The stable isotopes of carbon and nitrogen

Over the past thirty years, the carbon and nitrogen stable isotopes have become widespread study tools in marine ecology for the study of trophic locations, movements (migration, connectivity, etc.) or the contaminants bioaccumulation. The quantitative analyses of stable isotope compositions performed on individuals or on some of their tissues can confirm the results obtained through classic study tools, such as the analysis of stomach contents or let us grasp some ecological aspects that were previously inaccessible [DUF 01].

Isotopes are chemical elements with the same atomic number, namely with the same number of protons but a different number of neutrons. Stable isotopes have a stable nuclear structure which undergoes no changes over time in the absence of external energy inputs. On the contrary, radioactive isotopes have an unstable nucleus that spontaneously changes into another nucleus by emitting radiation or a particle. The energy stability of an element is affected by its number of neutrons. Thus, the isotopes of carbon ^{12}C (six protons, six neutrons) and ^{13}C (six protons, seven neutrons) are stable, whereas ^{14}C (six protons, eight neutrons) is radioactive. The difference in neutrons gives a different mass to the isotopes. Thus, isotopes with a supplementary neutron (^{13}C, ^{15}N) are called heavy, whereas all other isotopes (^{12}C, ^{14}N) are said to be light.

7.2.2.6.2. Isotope ratio measurements and notation

The abundance of stable isotopes on Earth dates back to their synthesis in the universe. As for hydrogen, carbon, nitrogen, oxygen and sulfur, the "light" isotope is much more abundant (Table 7.1).

Relative abundance (%)					Relative mass difference
	"Light" isotope		*"Heavy" isotope*		
Hydrogen	^{1}H	99.98	^{2}H	0.02	2.00
Carbon	^{12}C	98.89	^{13}C	1.11	1.08
Nitrogen	^{14}N	99.64	^{15}N	0.36	1.07
Oxygen	^{16}O	99.79	^{18}O	0.20	1.13
Sulfur	^{32}S	95.02	^{34}S	4.21	1.06

Table 7.1. *Abundance and relative mass difference of the stable isotopes of hydrogen, carbon, nitrogen, oxygen and sulfur*

Isotope ratios are measured through gas source mass spectrometry. The sample must be turned into its gaseous form: CO_2 for carbon and oxygen, N_2 for nitrogen and SO_2 for sulfur. An elementary scanner performs the combustion of the samples and the gaseous products of this combustion are separated by means of gas chromatography before passing on to mass spectrometry. Upon entering the mass spectrometer, molecules are vaporized and ionized. Afterwards, they are accelerated and then diverted into an electromagnetic field in relation to their mass before being finally detected.

The variations in the natural abundance of isotopes are low and rarely exceed a few thousandths. To quantify their presence, we use measurements of values in relation to a universal standard. Isotope compositions are expressed by the "delta" notation, which compares the isotope content of the sample to an international reference content (expressed in per mil):

$$\delta X = \left(\frac{R\text{sample}}{R\text{standard}} - 1\right) \times 1000$$

where X is the element considered and R the ratio heavy isotope/light isotope.

	Molecule	Ratio	R = H/L	Heavy (%)	Light (%)
PeeDee Belemnite (PDB)	$CaCO_3$	$^{13}C/^{12}C$	0.011237	1.10	98.89
Air (AIR)	N_2	$^{15}N/^{14}N$	0.003676	0.37	99.63
Vienna-Canyon Diablo troilite (VCDT)	FeS	$^{34}S/^{32}S$	0.044162	4.20	95.04

Table 7.2. *Isotope compositions of universal standards. R represents the ratio of heavy isotope/light isotope*

In trophic ecology, carbon and nitrogen are the two main elements being measured out, whereas the use of sulfur is more restricted and will not be dealt with here.

7.2.2.6.3. Isotopic labeling

Biological, physical and chemical processes lead to a differential distribution of light and heavy elements. The way isotopes are divided up into two compounds or two phases of the same compounds is called isotopic fractionation. This fractionation is basically due to mass difference between the isotopes. In kinetic reactions, light isotopes usually react more rapidly. This differential reactivity gives rise to isotopic differentiation.

The use of the stable isotopes of carbon and nitrogen for the analysis of trophic relationships is based on two hypotheses:

– there is a close relationship between the isotopic composition of a consumer and the one of its feed. The isotopic signature of feed is slightly altered by trophic transfers. However, these transfers occur with a trophic fractionation that can vary according to the isotopes, generally ranging from 0 to 1% for carbon and from 3 to 4% for nitrogen [DEN 78, DEN 81, POS 02]. This fractionation leads to a heavy-isotope enrichment for the predator in relation to its feed;

– primary producers possess different isotopic compositions (especially in relation to $\delta^{13}C$) mainly as a result of both the isotopic composition of the inorganic materials assimilated for the synthesis of their organic matter and the isotopic fractionation associated to different kinds of biochemical cycles (for example, for the photosynthesis of C3 or C4 plants).

Thus, the stable isotopes of carbon and nitrogen can help to determine the sources of organic matter and their future in the ecosystems, which leads to the definition of the food web structure.

Nonetheless, we have to take some precautions when using these trophic markers. Several sources of variability must be taken into account:

– the fractionation factor. A key element for the use of stable isotopes as trophic markers, the fractionation factor can vary in relation to several parameters, such as tissues, feeding regimes and their quality, sizes, ages, lipid extractions, etc. [CAU 09];

– the speed at which a predator acquires the isotopic signature of feed. This rate also affects the understanding of trophic processes. It depends on the turn over time, which maintains the metabolism in good conditions by replacing tissues and ensures the growth of the individuals. It is also tissue-specific [GUE 07];

– migrations. Several marine species migrate during their lifetime. If the nursery habitats they exploit have distinct isotopic signatures (coast vs offshore or pelagic versus benthic, for instance), we should take this aspect into account when analyzing the results.

7.2.2.6.4. Compatibility between stomach content and stable isotope analysis

The analysis of stomach contents and that of stable isotopes are methods used to determine complementary trophic relationships. The content of a stomach consists of the last (or last few) meals ingested whereas the isotopic composition measured in the organisms’ tissues reflects the feed assimilated over periods ranging from a week, for juveniles, to several months for older and more fully grown individuals. Taxonomic determination, sometimes in terms the specific prey contained in a stomach, allows us to claim unambiguously that they have been ingested. Isotopic compositions represent the trophic level and origin of the feed source, but they do not determine which species have been consumed. On the contrary, they can reveal unequivocally whether a nutrient has been used or not.

7.3. EAF and research on marine ecosystems

7.3.1. *Quantifying ecological interactions*

Birds are some of the most visible and widely distributed organisms and their interactions with other components of the ecosystem are the most easily studied. Birds belong in the trophic niches of top piscivore predators, as well as in those of planktonophages or scavengers. Their interactions with human activities at sea, especially fishing, can take several shapes, both direct and indirect [BOY 06, WAG 11].

Direct interactions consist, first of all, of fishing equipment accidentally catching birds. Birds can, for example, be trapped by baited hooks (example: long line fisheries), get caught in nets (example: diving birds) or get trapped in the sweep lines of a tacking trawl [WAG 11]. In the past, before being banned, drift nets deployed in the open sea caused significant levels of mortality for birds in the northern Pacific. Fixed gillnets have also affected the populations of marine birds in the south-west of Greenland and east of Canada considerably, among other places. Currently, one of the main problems in terms of accidental captures concerns albatrosses and petrels in the long line fisheries of the northern Pacific and the Southern Ocean [TAS 00]. Birds can also use the presence of ships as an indicator of areas characterized by a strong abundance of fish (local enhancement [BUC 97]). This interaction, which favors birds *a priori* since it facilitates their foraging for schools of fish, can become negative when birds, by dint of following fishing vessels, are led outside their optimal foraging area finally [BAR 10, VOT 10]. This attraction becomes particularly problematic during breeding season, when grown individuals have to return to their nest often. Moreover, birds can feed on the waste lying at sea which derives from the bycatch of fishing vessels. This interaction can be positive when this refuse makes available a large quantity of fish, which would normally be beyond the reach of these birds. It can be negative when the birds' opportunistic feeding on ship waste consists of fish with lower energy levels than their usual prey (junk food hypothesis [GRE 08, MUL 09b, OST 08]).

Interactions between fisheries and birds can also be indirect and take place through changes in the structure of marine communities as a result of fishing catches. Fishing can increase the abundance of prey fish through the exploitation of large predator fish, which could be competing with birds [WAG 11], or alternatively it can reduce the abundance of certain species of forage fish on which birds feed directly. When fishing and birds are in open competition for the access to forage fish, the latter can be penalized not so much in terms of the survival of grown individuals as in relation to their reproductive success, for instance [CAI 87, CRA 07, DUF 83], which constitutes a threat to the health of their future populations. For example, in Peru, Furness and Monaghan [FUR 87] mention that the quantities of anchovies caught through fishing activities remove the feed reserves on which populations of birds rely to recover after the frequent collapses of anchovy stocks during periods of intense climate perturbations such as the phenomena caused by El Niño.

There are several approaches used to quantify the competition between fishing and birds for forage fish, for example those put forward by [CRO 98, CUR 11a, OKE 09, PIC 09]. On a large scale, we can quantify a competition potential by estimating, for example, the respective needs of birds and fisheries in terms of global quantity of fish. To assess the birds' needs, we can make use of the knowledge on the physiology and energetics of an individual, which we then extrapolate to the population, as [CRO 98] and [OKE 09] do. These bioenergy estimates, however, are not enough to measure the quantities of prey that have to be left in the sea correctly, since such a calculation relies on the simplifying hypothesis that predators can find every single fish and that prey and predators have the exact same spatial distribution [FUR 06]. In practice, fish need the presence of a quantity of prey at sea much greater than the one they actually consume, since a minimum density of prey is essential for effective foraging. By examining seven ecosystems in the Atlantic, the Pacific and the southern seas, together with fourteen species of marine birds, [CUR 11a] believe that there is a threshold level of abundance of forage fish below which birds see a significant drop in their reproductive success. This abundance threshold, estimated to be a third of the maximum biomass of forage fish observed over time, constitutes a global reference value that the managers of fisheries in charge of the proposal of fishing quotas should not go beyond. On a medium scale, we can quantify competition potential by assessing the spatial overlap between fishing areas and the birds' feeding zones, as [OKE 09] does. In South Africa, 30% and 14.2% of the catches of a fishery are caught within the feeding zones of gannets and penguins respectively [PIC 09].

Finally, on a small scale, we can describe the precise mechanisms of interaction between birds and fishing. Birds can develop compensatory strategies for a certain range of prey availability. For example – [KIT 00] –

in case of low prey availability, grown individuals can reduce to a certain degree the damage done to their reproductive success by increasing their feed intake effort [PIA 07]. The key point of an ecosystem approach to fisheries consists, therefore, of identifying up to what limit birds can compensate low prey availability. Birds in breeding season have particularly high energy needs, especially to feed chicks, while facing limitations in terms of the area they can explore to forage, since the two parents must constantly take turns at the nest. Prey availability must therefore be ensured locally, around the colonies. Local decreases in fish availability caused by fishing, despite a reasonable global quota, can jeopardize the reproductive success of certain colonies. The small-scale patterns of the interactions between birds and fishing are also quite significant. Bertrand *et al.* [BER 12] are studying these mechanisms in the coastal Peruvian ecosystem, where bird populations are in competition with industrial anchovy fishing. The study is based on GPS marking of various gannets belonging to a significant colony quite close to one of the main anchovy fishing ports. The fishery, the movements of which are automatically observed by a satellite monitoring system vessel monitoring system (VMS), became operative when experiments concerning bird marking started being carried out, providing the opportunity to examine the daily effects of the deployment of an intense fishing activity on the birds' predation behavior. The study highlights how birds considerably increase their effort (maximum distance from the colony and total distance covered) over time and shows that this is due to catches made locally through fishing. In the area and period considered (about 220 × 330 kilometers, around 10 days), it is estimated that daily fishing catches (about 50,000 $t.j^{-1}$) represent quantities more than 100 times greater than the daily energy needs of the bird colony (about 200 $t.j^{-1}$). The study comes to the conclusion that birds have increased their foraging effort to compensate for the effects of local anchovy depletion caused by the extremely intense fishing activity. The threshold beyond which reproductive success would be jeopardized does not seem to have been crossed during the period studied, when anchovies were abundant, but it clearly appears that had the availability of anchovies been lower, competition with fishing could have significantly affected the reproductive success of this colony.

7.3.2. *Understanding spatial dynamics*

Marine ecosystems are fundamentally structured in space and time. Organisms are distributed as patches (hyper-aggregation) across a wide continuum of spatiotemporal scales. Patches are regions where abundance is greater than what can be expected in the case of random distribution. This structuring depends mostly on physical processes and it has a significant impact on how ecosystems work. The way space is occupied and the organisms' movements play an important role in the structure of the ecosystems and the dynamics of the populations by determining spatial co-occurrence between organisms [MAR 79]. They influence functional relationships (for example, predation, competition and reproduction) and consequently precede changes in the abundance of populations. Taking them into account is, therefore, crucial to the understanding of the way ecosystems work and to the implementation of an ecosystem approach to fisheries. In marine pelagic ecosystems, we observe generally a hierarchical [ALL 82] and fractal [FRO 87] structure in all the compartments of the ecosystem from the body of water to predators, including planktonic populations and forage species (Figure 8.6). Two pivotal processes are mentioned here to explain how this structure is created and maintained (Figure 7.6).

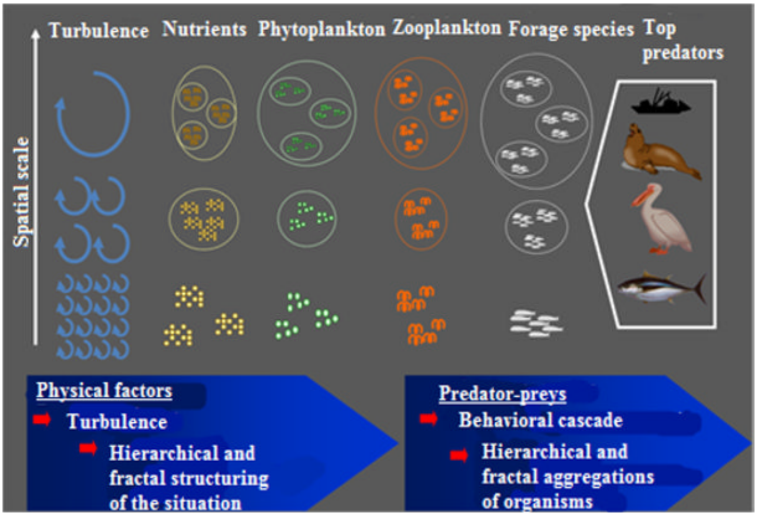


Figure 7.6. *A diagram of the concept of bottom-up transfer of spatial structuring (source: [BER 08b])*

COMMENTS ON FIGURE 7.6.– Physical forcing structures the environment by introducing turbulence. The dissipation of turbulence is fractal by nature and generates a hierarchical structure of the bodies of water. Inert particles (for example nutrients) and plankton passively structure themselves in this case.

Afterwards, biological interactions such as predator–prey relationships pass this spatial structure on to the top predators.

At first, large-scale physical forcing, such as currents and winds, by introducing energy into the system as turbulence, causes the appearance of gradients and structures in patches. This turbulent energy, dissipating continuously and in fractal patterns into smaller whirlpools up to the viscosity scale, is one of the driving forces of the spatial structuring of the body of water and passive particles (nutrients and plankton). In addition to the great oceanic currents, smaller-scale processes structure the ocean. Particularly intense mesoscale (about 10–200 kilometers, such as cyclonic or anticyclonic eddies) and submesoscale (about 1–10 kilometers, such as upwelling plumes or small eddies) activity significantly structures the system (Figure 7.7). Planktonic organisms are passively distributed in the ocean and concentrate in aggregative physical structures. This leads to the formation of patches, the dimensions of which depend mainly on the oceanic "landscape" created by physical processes. Then the necessity of the predators of encountering their preys along the different trophic levels generates a behavioral cascade [BER 08b, FRO 87], i.e. the propagation of this hierarchical and fractal structuring phenomenon through the ecosystem.

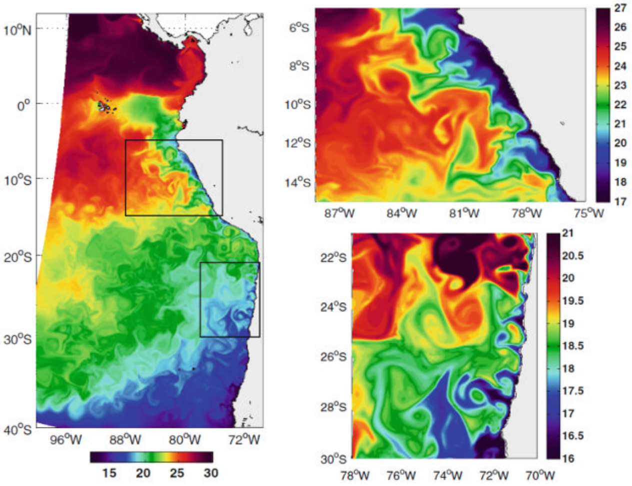


Figure 7.7. *An example of sea-surface temperature fields (in °C) simulated thanks to the Regional Ocean Modeling System model in the south-western Pacific (on the left) and in two specific regions illustrated by the black frames in the left-hand graph. We can see the presence of a large number of eddies and fronts that structure very significantly the oceanic landscape (source: [COL 12]). See color section*

For example, the distribution of small pelagic fish typically consists of different levels of aggregate structures (school, concentration of schools or cluster, population, etc.), interlocked on a whole range of scales [FRE 99] the size of which depends on the physical landscape [BER 08a] (Figure 7.8). However, pelagic fish are not passive particles, they can swim against the tide and their behavior, especially their schooling behavior, plays a very significant role in their dynamics. Thus, they have the ability to free themselves from turbulence and their distribution could be relatively unrelated to the phenomenon of physical structuring. The importance of physical forcing and of the behavior of fish varies according to the scales considered. In terms of individuals (ten or so centimeters) or schools (ten or so meters), social behavior (for example, the necessity of forming a school) is the main driving force of spatial organization. On scales greater than the shoal, environmental forcing becomes the dominant factor. On a sub-mesoscale, physical forcing (for example, fronts, small eddies) gathers plankton into aggregates (patches) and determines the spatial distribution of the anchovies (in cluster) that feed on it. On a mesoscale (ten or so kilometers), rich areas such as upwelling cells will concentrate the clusters of anchovies. Finally, on scales exceeding 100 kilometers, the distribution of a population is limited by large-scale physical processes (for example, favorable bodies of water).

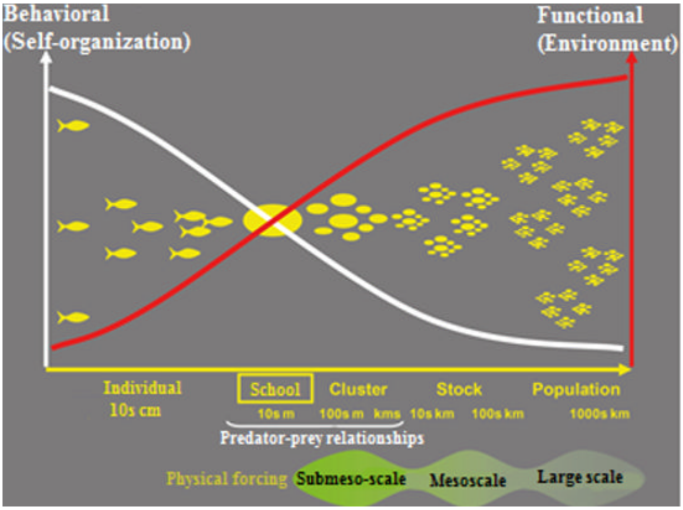


Figure 7.8. *A conceptual model which describes the relative importance of self-organization and environmental constraints in relation to the spatial organization of gregarious fish depending on the scale considered. The diagram is plotted around two axes, one based on self-organization (on the left) and the other on environmental forcing (source: [BER 08a]). See color section*

Thus, meso- or sub-mesoscale eddies can create actual oases which can favor or concentrate primary production and the organisms belonging to several trophic levels [BER 08a, BER 13, GOD 12]. Top predators like large fish, birds and mammals, can identify these structures and gather within them or on their edges in order to feed [COT 11, TEW 09].

7.3.3. *Modeling as a tool to integrate knowledge*

Implementing the ecosystem approach to fisheries involves a process of integration of spatial and temporal knowledge about the structure and functioning of marine ecosystems. Ever since the 1990s, the numerous developments of ecosystem models have been the direct consequence of this necessity and of the shifting paradigm, leading fisheries research from a purely monospecific approach to fishery management to the simultaneous awareness of different species and their interactions among each other and with their environment. Marine ecosystem modeling aims to further the knowledge on the way ecosystems work under the combined effects of exploitation and climate change. It proposes coherent theoretical representations of the ecosystems that allow us to conduct virtual experiments. It also enables us to establish a relationship between the scientific and the operational sphere by increasing the ability to produce a quantitative assessment of the effects of fishing on marine ecosystem, to predict the effects and measure the effectiveness of fishing management approaches and to propose plausible scenarios of the long-term impacts of global change on marine ecosystems. On a scientific level, the most significant changes have led to the development of ecosystem models concerning the awareness of the trophic interactions between species and the way food webs work, the effect of the physical and biogeochemical environment on larval survival, the physiology and spatial distribution of species, as well as the representation of multiple and combined human footprints.

Currently, few models elucidate the dynamics of the ecosystem as a whole, from climate forcing to the exploitation of marine resources. The integration of the processes concerning the impact of global change on marine ecosystems requires us to incorporate multidisciplinary knowledge and models, so as to build integrated models called end-to-end, i.e. models which (i) represent the whole of the food web and the related abiotic environment, (ii) require the integration of biological and physical processes on different levels, (iii) implement feedback between different components of the ecosystem, (iv) illustrate climate and anthropogenic forcing on the various trophic levels of the ecosystem explicitly [ROS 10, TRA 07]. These end-to-end models can obviously quickly become complex, since they require the interaction of oceanic hydrodynamic models, of the biogeochemical models that describe the cycle of nutrients and planktonic compartments, and of models representing higher trophic levels (macrozooplankton, fish, large predators). These multidisciplinary models are potentially quite heterogeneous, both in terms of the formalism they employ (Lagrangian, Eulerian, compartmental) and with respect to their structure and resolution.

Here we will deal with two conceptual difficulties faced when building end-to-end models [SHI 10]:

– the vertical integration of trophic levels or, in other words, the way in which models of different trophic levels can be linked. To represent predation, the key coupling function is the functional response (FR) which associates predation rate with the density of prey. Moreover, the way the FR is formulated and configured is crucial. However, when empirical quantification is lacking, the FR is often chosen arbitrarily, reducing the choice to a problem of parameterization;

– horizontal integration within a trophic level or, in other words, the way the species that need to be represented, key components of biodiversity, can be selected so as to reproduce and predict the ecosystem changes taking place under climate and anthropogenic pressures.

7.3.3.1. *Vertical integration: choosing the functional response for the interaction of plankton and fish models*

In the models illustrating carbon and macronutrients cycles (biogeochemical models), plankton is represented according to the Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD model), which appears in several structural variants: representation of the compartments of nitrate, ammonium and dissolved oxygen in the model proposed by Fasham *et al.* [FAS 90], size structure of the plankton community [KIS 04, MOL 91], modeling of limiting elements such as iron, phosphate and silicon [AUM 06], increase in the number of planktonic functional groups [LEQ 05]. Moreover, a model representing the emergence of the biogeography of pelagic microbial communities and their microbial communities has been developed [FOL 07]. The goals and applications of these models vary but their structure is generally easily comparable. Nowadays, these models are in most cases associated with tridimensional hydrodynamic models which represent the forcing physical variables (currents and temperature) in a Eulerian formalism and allow realistic spatialized simulations in a wide range of scales. The effect of transport in biogeochemical models is illustrated by the terms "diffusion" and "advection", in keeping with the Eulerian formalism of physical models [DIP 06].

On the other hand, the models representing high trophic levels developed in fisheries research are very heterogeneous, both in terms of their theoretical bases and in relation to their formalisms (continuous or discrete models, Eulerian or Lagrangian, employing differential equations, individual-based or multi-agent, etc.), their structures and the processes they represent (reproduction, growth, mortality, predation, migration, etc.). According to the approach considered, the processes are formulated with respect to individuals, species or communities. For example, the structure and processes of the Ecopath-with-Ecosim [CHR 04, CHR 08] or Atlantis [FUL 04] models are essentially based on biomass flows between species or functional groups (although recent versions can make size and age classes explicit [WAL 08, WAL 10]), whereas the Apescom [MAU 10, MAU 13] and Osmose [SHI 04] models are structured with respect to size, but also take into account specific life traits and multispecies interactions.

The main process linking plankton models to the models representing higher trophic levels is predation, which affects the growth rate of predators and leads to the mortality of planktonic preys. Modeling predation requires us to choose which processes should be represented and to speculate to specify the functional response (FR), feeding regimes (fixed or variable and opportunistic) or feeding preferences in terms of species or size. Choosing the FR is especially important and has given rise to several scientific debates which are still ongoing [ABR 00, ARD 89, BER 92, YOD 94]. Numerous FRs have been proposed as alternatives to the linear formulation of the pioneer model advanced by Lotka–Volterra. According to Holling [HOL 66], the FR depends on two terms: the time it takes to capture a prey (generally considered to be constant) and the attack rate, which is a function of the density of prey and/or predators. The attack rate also varies with respect to different biotic (for example, the morphology of prey and predators), behavioral (such as the formation of schools [CUR 05]) or abiotic factors, such as the optical properties of water [HUS 10].

Formalism	MODEL (reference)	Functional response *Predation hypothesis*	Parametrization
System of differential equations: Deterministic functional response	NEMURO.FISH [MEG 07] ATLANTIS [FUL 04]	Type-II Holling *No interferences, predators, preferential preys*	– vulnerability coefficient – half-saturation constant (clearance), calibrated – maximum ingestion rate
	APECOSM [MAU 07, MAU 10]	Type-II Holling *No interferences, predators, size-based predation, no preferential preys; effect of light on reaction distance*	– half-saturation constant (clearance), calibrated – maximum ingestion rate – selectivity function based on prey size
	ECOSIM and ECOSPACE [CHR 04, CHR 08, WAL 97, WAL 10]	*"Foraging arena" Natural shelter for preys, preferential preys*	– vulnerability coefficient – effective foraging rate Most parameter values derive from the calibration of a static Ecopath model
Individual-based model: Emergent functional response	High-resolution behavioral IBM [HUS 10]	*Significance of predation behavior on a small scale, effects of light on the predator/preys encounter ratio, preferential preys*	– capture time – half-saturation depends on the size of the preys, the predator's behavior (swimming speed, visual field), and environmental conditions (light emission, optical properties of water)
	OSMOSE [SHI 04, TRA 09]	*Opportunistic predation based on size, no preferential preys*	– maximum ingestion rate – minimum and maximum predator size/prey size ratios

Table 7.3. *Functional responses used in models of marine ecosystems [SHI 10]*

We distinguish two categories of FRs with respect to how we consider the interference between predators in the predation process [SKA 01, YOD 94]. According to classic Type-I,II and III Holling FRs, the per capita attack rate depends only on the density of prey. On the other hand, the second category of FRs believes that there is interference between predators or, in other words that the rate of attacks on prey per predator decreases when the density of predators increases [ABR 00]. The problem is that these theoretical debates are sustained by only very few observations in marine ecosystems. As a consequence, FRs used change very little and come from choices of pragmatic parametrization. The most frequent choice, since it requires few parameters while taking into account a phenomenon of saturation, consists of a Type-II Holling FR, which is functionally equivalent to a Michaelis-Menten equation [REA 77]. This FR is used in the Atlantis [FUL 04, Apecosm [MAU 10] and Nemuro-Fish [MEG 07] models which represent higher trophic levels, using the half-saturation constant as a calibration parameter. The specific FR formulation in Ecosim has been developed [WAL 07] by speculating on the presence of shelter areas for preys (Foraging arena theory), which implies that the predator can only feed on the compartment of available prey for which the functional response is linear (Lotka-Volterra). The resulting FR on the whole of the population of preys allows saturation with respect to the density of prey and predators.

In the lack of observations, it is useful for models to be subjected to susceptibility tests to the choices and parametrization of the FRs [FUL 03, KOE 05, PIA 06]. Another approach consists of elucidating processes, which are easier to measure, on an individual level and in bringing out the FR on a population one (Table 7.3). Huse and Fiksen's [HUS 10] individual-based model proposes an explicit representation of the predation compartment of fish (swimming speed, reaction distance and vision field) in relation to environmental conditions (irradiance and water turbidity). In the Osmose individual-based model, predation is curbed by minimum and maximum ratios between the sizes of the predator and those of the prey, by a maximum ingestion threshold and by the spatial co-occurrence of predators and their preys [SHI 04]. The FRs resulting from these simple rules on an individual level can vary (Type-II and Type-III Holling or ratio-dependent) and depend on the conditions of primary production and the dominance of predators within multispecies assemblages.

Other processes concerning the interaction between plankton and fish models can be represented. As it explained in the models representing higher trophic levels, fish excretion and egestion can supply the ammonium and nitrate compartments of biogeochemical models and the mortality of the various organisms constitutes a matter flow towards the detrital compartment [MAU 10, MEG 07]. The loss of biomass due to natural fish mortality (not including predation) can be associated with bacterial loop dynamics. The spatial distribution of lower trophic levels can also partly determine the spatial distribution of fish [LEH 03, MAU 10] and vice versa prey can adjust their distribution by escaping from their predators [HUS 10].

Models allow us to integrate biological and ecological knowledge, by representing a limited set of processes through mathematical functions, the parameters of which are estimated thanks to field observations. However, this combination can only be partial, to limit the complexity of the models and effectively direct their use to precise goals. The diversity of ecosystem models reflects the variety of ecological questions, hypotheses and resource management problems concerning an ecosystem approach to fisheries.

7.3.3.2. *Horizontal integration: choosing specific components for the simplified representation of biodiversity*

Horizontal integration, along an axis representing species diversity and on each trophic level, must allow us to account for functional biodiversity [DUF 07] without unnecessarily increasing the complexity of the models by multiplying the number of species represented. It is essential to limit the number of species and/or functional groups represented to be able to reproduce some of the patterns observed in marine ecosystems and employ the models for predictions: choosing the structure of ecosystem models does play a very significant role and will determine their degree of realism.

Scientists often face fundamental challenges to their approach when counterintuitive reactions of populations and ecosystems are observed [PIN 09]. These events, which we may describe as “ecological surprises”, are often the result of unexpected population booms or collapses frequently associated with notions of regime shifts, given the drastic and ostensibly long-term features of these changes in the species composition. It is in this context that the structure of end-to-end models becomes especially significant. Most of the dynamics observed in marine ecosystems cannot be understood if the ecosystems are only represented by a simple food web. Most pelagic species are generalist and omnivorous, which increases considerably the number of interactions among species and the complexity of marine food webs. In practice, however, the awareness of the multiplicity of trophic links and the diversity of species represented in the models is strongly limited by the goals of modeling, under the threat of creating an inextricable complexity. Food webs clearly need to be made simpler; taking into account functional biodiversity does not necessarily involve exhaustiveness.

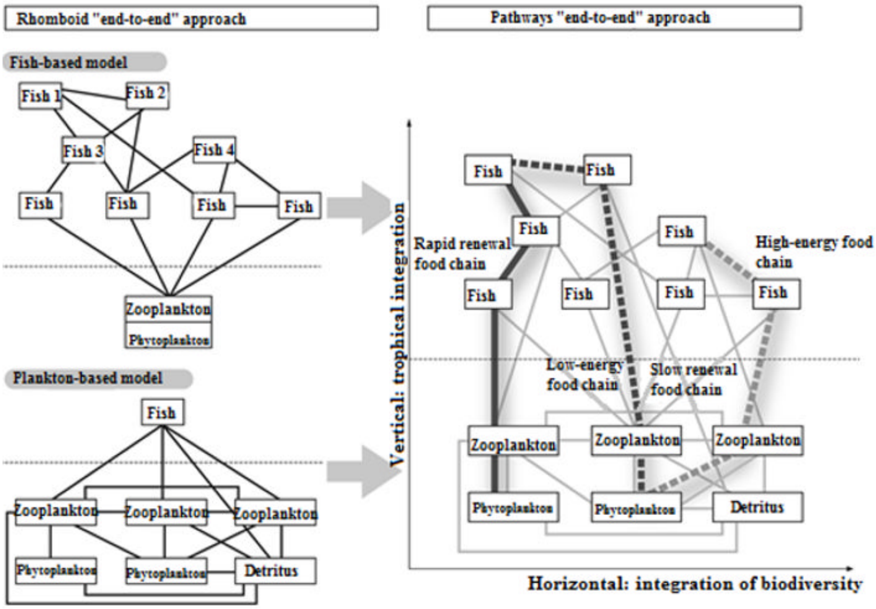


Figure 7.9. *Vertical and horizontal integration of end-to-end models*

COMMENTS ON FIGURE 7.9.– The compartments represent species or groups of species, whereas the lines illustrate trophic interactions. The "rhomboid" approach [DEY 04] consists of examining a target trophic level, such as fish communities, as [SHI 04, WAL 97] do, or plankton communities, as [HER 01, MEG 07] do, which results in the simplification, sometimes extreme, of certain trophic compartments. The pathways approach recognizes the role of biodiversity in the emergence of alternative trophic chains. According to the different kinds of climate and fishing forcing, dominant food chains can alternate, such as low-energy with high-energy food chains (light gray) or slow renewal rate chains with rapid renewal rate ones (dark grey) (drawn from [SHI 10]).

Pragmatically, De Young *et al.* [DEY 04] recommend a "rhomboid" modeling approach, which requires us to examine the processes concerning one or some target species belonging to a given trophic level and to simplify when we get farther from the trophic level considered (Figure 7.9). In the context of this “rhomboid” approach, the goals of fishery management should result in the use of end-to-end models examining the resources exploited, belonging to higher trophic levels. There are other pragmatic choices. For example, it is common practice to simplify the structure of ecosystem models by only considering the most abundant species and dominant trophic interactions. However, this method becomes inadequate when the dynamics of marine populations vary quite significantly. We then run the risk of obtaining snapshots which do not necessarily reflect the way the ecosystem works and will not be able to be used to make predictions in the context of a global change when environmental conditions have changed.

In addition to the previous pragmatic criterion, it is possible to consider food webs as a set of alternative food chains. There are a certain number of observations, such as those concerning regime shifts or the alternations between population growth and collapse, which could result from alternated food webs. For example, Parsons and Lalli [PAR 02] suggest that the demographic booms of jellyfish result from differential forcing on competing food chains, one dominated by commercially important fish and the other by jellyfish (Figure 7.10(a)). Similar analyses are being conducted in upwelling systems to explain the alternations between sardines and anchovies [VAN 06, VER 98], (Figure 7.10(b)) or in Antarctica with respect to the abundance or scarcity of krill (Figure 7.10(c)).

Several recent works in ecology focus on the same idea, according to which the way ecosystems function is linked to the existence of alternative food chains. Wanless *et al*. [WAN 05] believe that the major reproductive failure of birds in the North Sea in the 1990s was caused by a change in the dominant alternative chain which forced the birds to feed on sprats rather than sand eels, the latter constituting higher-energy feed. Food chains can also be characterized by their renewal rate. Thus, slow food chains can coexist or alternate with rapid food chains in the ecosystems. Rooney *et al.* [ROO 06] show that rapid chains are on average characterized by strong interactions whereas slow chains by weak ones, and that their coexistence allows the ecosystem to offer a certain degree of resistance and resilience to phenomena of perturbation.

Climate bottom-up forcing and nutrient intake can lead to the emergence of some dominant food chains within the ecosystem. However, top-down control can also play a key part. Opportunistic predation links the pressure of passive predation to the relative abundance of prey. It allows the coexistence of distinct food chains which differ, for example, in terms of productivity and length. By removing large-sized predator species, fishing would shorten food webs and consequently reduce the resilience of the ecosystems exploited [HUT 00].

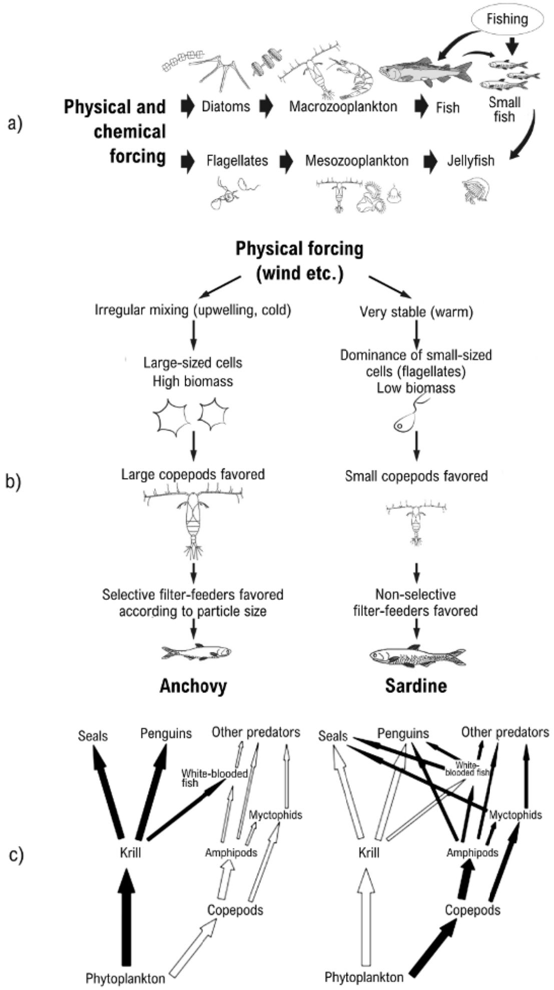


Figure 7.10. *An example of alternative food chains: a) drawn from [PAR 02], b) drawn from [VAN 06], and c) drawn from [MUR 07]*

Our suggestion is to rely on the size of the organisms to structure end-to-end models into a set of alternative food webs. Since size-structured predation is one of the basic features of pelagic ecosystems [JEN 02, POP 94], the links of food chains could be characterized by specific size ranges. The size of organisms is also a gauge that allows us to define the properties of different food chains. It is, for example, a good indicator of productivity. Size can also reflect the quantity and quality of the energy content [KAI 04], which could be determining factors for the demography of fish and top predators [LIT 06, WAN 05]. For example, it has been shown that large demersal species contain less essential fatty acids than small pelagic species [IVE 02, LIT 06], that large copepods are richer in lipids than their smaller counterparts [HOO 06], that large-size phytoplankton species such as diatoms are rich in EPA Omega-3 fatty acid (icosapentaenoic acid), and that small phytoplankton, such as dinoflagellates and coccolithophores, are rich in DHA (docosahexaenoic acid) [DAL 03]. The structure of end-to-end models should represent a wide range of sizes of organisms, with enough discretization to allow the emergence of distinct food chains. Models representing lower trophic levels, such as NPZD models, should at least include two sizes of phytoplankton and zooplankton, whereas the species of higher trophic levels should cover a representative range of sizes.

However, the role and operative aspect of certain species or compartments cannot be reduced to their sizes, particularly when their predation behavior is specialized (for example, selection of high-energy preys, lower energy cost of predation, morphological constraints unrelated to size, etc. [COL 13b]). This is the case, for example, for many benthic – and, to a lesser extent, demersal – species. Integrating size with other life traits becomes necessary when these specialist species are chosen to be explicitly represented in a model due to the key part they play in the functioning of the ecosystem or because of their dominance in terms of biomass.

7.4. Ecological indicators Marine Strategy Framework Directive (MSFD)

Marine and coastal areas house several human activities such as maritime transport, the production of renewable forms of energy, the extraction of raw materials, fishing and aquaculture, yachting, but also tourism. These activities lead to both a steady increase in use conflicts between the actors of the marine environment and a growing pressure on ecosystems. The European Union, after noticing the limitations of the sectorial policies applied to the marine environment in recent years, has committed to implementing a maritime policy that combines economic, ecological and social constraints in an attempt to exploit resources in a sustainable way. The framework of this ambitious policy has been decided by a blue book adopted by the European Council on 14 December 2007. It should strengthen the coherence of the different policies and favor the integration of environmental concerns. The marine strategy framework directive (MSFD) constitutes the environmental pillar of this new integrated maritime policy (IMP) of the European Union. The objective of each Member State is to implement a management plan that allows us to reach or maintain the good ecological state (GES) of the marine environment over the whole of the exclusive economic zone by 2020. Transposed into French Law on 12 July 2010 with the Grenelle 2 Law, it has been incorporated into the Environment Code through articles L 291–9 to L 219–18 and R 219–2 to R 219–17. The enforcement tool used to reach this goal is the "Marine Environment Action Plan" (*Plan d'Action pour Milieu Marin*, or PAMM), common on a national level and then adjusted in relation to the marine sub-region. It was established by a decree (no. 2011-492) on 5 May 2011. The scientific and technical coordination of the PAAM is ensured nationally by Ifremer and the *Agence des aires marines protégées* (AAMP), under the authority of the *Direction de l'eau et de la biodiversité* (DEB, or Water and Biodiversity Management) of the French Ministry of Ecology, Sustainable Development, and Energy (*Ministère de l'Environnement, du Développement durable et de l'Energie*, MEDDE).

The Marine Environment Action Plan (PAMM) describes a series of repetitive steps that create a six-year cycle. The first cycle started in 2012 and it follows the following progress steps:

– the initial assessment of the state of marine waters consists of the analysis of ecological features and conditions, the study of the pressures and impacts on the marine environment and an economic and social analysis of the use of marine waters and the cost of environmental degradation, based on current knowledge and data;

– the definition of good ecological state, which is the goal to be reached at the end of the cycle;

– setting environmental goals on the basis of the initial assessment and with a view to choosing the steps that need to be taken to reach the good ecological state thus defined;

– the elaboration of a monitoring program, which allows us to survey the effectiveness of the steps taken and to assess whether the good ecological state has been reached or not;

– the elaboration of a program of management measures in accordance with the environmental goals already established, to reach or maintain the good ecological state.

7.4.1. *Three current levels of organization: international, national and regional*

The MSFD covers the whole of the exclusive economic zone (EEZ) of European countries. In metropolitan France, the area covered by the MSFD is divided into four marine sub-regions: Channel/North Sea, Celtic Seas, Bay of Biscay and Mediterranean (Figure 7.11). These four zones can stretch out up to 200 miles off the coast and still be part of wider ecological regions that can integrate the EEZ of several countries. The collaboration of the countries belonging to the same ecological region is, therefore, vital, especially to assess the species or habitats that are geographically distributed over large areas and, more pragmatically, to achieve economies of scale in the implementation of the directive (in particular the one of the monitoring program). This collaboration takes place through regional seas conventions: the OSPAR convention for countries facing the north-eastern Atlantic, the HELCOM convention for Baltic countries and the Barcelona convention for Mediterranean countries. We still have to strike a balance between collaboration, networking of scientific expertise and data useful on a national level, and a cooperative approach between the Member States, through these conventions, to optimize the homogenization of the protocols used to monitor and assess the state of marine ecosystems on a European scale.

If the implementation of this methodology, the framework of these objectives and the scientific and technical expertise are firmly managed on a national level, the territorialization of the PAMMs requires a greater involvement of devolved state services. On a regional level, the PAMM will be implemented through port maritime councils, under the responsibility of maritime prefects, after consulting the local actors of the marine environment. This step should ensure coordination between the plans concerning Natura 2000 sites at sea for the elaboration of management objectives and the projects of each marine sub-region concerning the elaboration of PAMMs.

7.4.2. *The ecosystem approach of the MSFD*

Like the water framework directive (WFD), the MSFD proposes an ecosystem approach for the assessment of the marine environment. This approach is multidisciplinary by definition and allows us to assess the state of a species, habitat or community of species on an ecologically relevant scale. The implementation of this directive requires us to define the GES of eleven qualitative descriptors proposed by the European Commission (see MSFD 2008/56/CE of 17 June 2008, Appendix I). These eleven descriptors are represented in Figure 7.12 according to whether they define an input, an output matter, energy pressure or a state of the system (structure, functioning and dynamics). The decision taken by the European Community on 1 September 2010 about criteria and methodological standards defines a list of 29 criteria and 56 indicators to be used for the assessment of marine ecosystems. It also supplies some guidelines about the general approach that should be employed to apply these criteria and indicators. These guidelines are derived from recommendations made by groups of experts gathered under the coordination of the JRC and the CIEM to propose criteria and methods used to assess whether the good ecological state, defined for each descriptor, has been reached or not. Practically, the nine pressure descriptors and the two environmental state descriptors should group the most relevant elements that can define the state of marine ecosystems or the pressure they are subjected to.

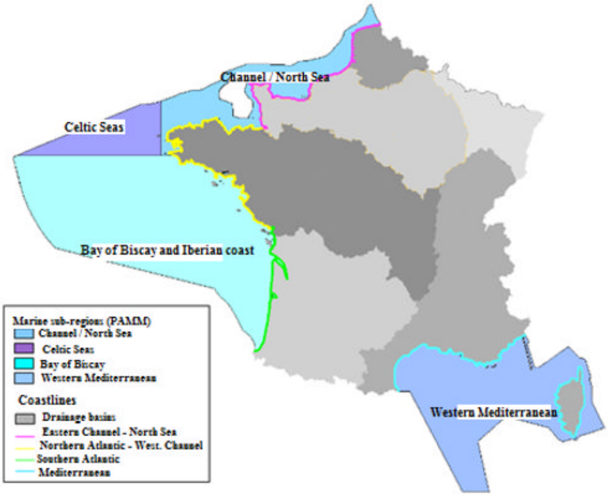
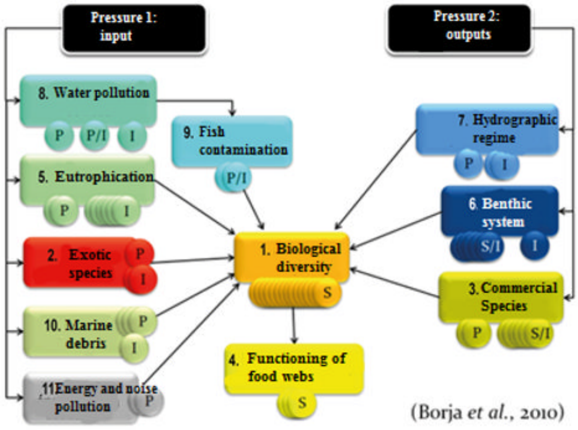


Figure 7.11. *The perimeter of the four French marine sub-regions of the MSFD (drawn from DRIEE Ile de France and modified). See color section*



(Borja *et al.*, 2010)

Figure 7.12. *A presentation of the eleven MSFD descriptors and their indicators of state (s), pressure (p), and impact (i) (from [BOR 10])*

We have selected 56 indicators that can tell us whether the good ecological state goal has been reached with respect to each descriptor. These indicators can describe a state of the system, a pressure or an impact within the system. They are calculated on the basis of the analysis of data available or derived from modeling, and can be either original or drawn from other European policies. For example, the descriptor "species exploited" proposes to assess fishing mortality, reproductive capacity and structure in terms of age and size. These stock-based analysis indicators are derived from the common fisheries policy (CFP), which employs data provided by the data collection framework. Choosing the appropriate indicator is, therefore, a crucial step at the basis of the assessment of ecosystems and, as a process, it must be regularly challenged by experts with respect to the progress of scientific knowledge.

7.4.3. *The assessment of food webs*

The assessment of food webs (descriptor 4) is not required by any other directive. It is, however, a significant parameter for the management of the conservation of the environment. It allows us to assess the relationships between organisms (structures) and the dynamic prey–predator interactions (flows). The simultaneous processing of the biological diversity of the trophic compartments of food web dynamics is key in understanding their complexity and assessing their state. Nonetheless, the high functional diversity of marine ecosystems requires us to describe food webs with respect to their functional groups and to propose community indicators. Community indicators are complex and are derived from modeling. It is also difficult to link their evolution to a specific pressure source. However, they are more integrative and allow us to assess some of the additional components of a system, such as its functioning, resistance or resilience in the face or wake of a pressure. They are presented in Table 7.4.

Criterion	Indicators	Aspect
4.1. Productivity of trophic species or groups	4.1.1. Performances of key predator species on the basis of their productivity per biomass unit (productivity)	Flow
4.2. Share of species selected at the top of the food web	4.2.1. Large-size fish (in weight)	Structure
4.3. Abundance/distribution of trophic groups/key species	4.3.1. Tendencies of significant species/groups on a function level in terms of abundance	Structure

Table 7.4. *A presentation of the criteria and indicators of the MSFD descriptor "food web"*

The operational limitations of the three indicators of the "food web" descriptor chosen on a European level have been criticized [ROM 13]. The indicator "performances of key predator species, on the basis of their production per biomass unit" is the only one that allows us to assess the way ecosystems function. It is based on the principle that productivity of predator species reflects food intake that derives from the consumption of prey. It can, therefore, be considered an indirect measurement of the energy flow between trophic levels. The first criticism directed at this indicator is that it focuses on one part of the food webs (predator species). Thus, it only partially addresses the objective of the descriptor. Besides, it relies on the hypothesis that prey availability is the major parameter that affects the performance of key predator species (marine birds, mammals and large pelagic fish). Actually, other factors can affect the reproductive success, such as accidental catches, epidemics and predation. The choice of indicator species requires us then to pre-establish an effective link between the predator's reproductive success and prey availability and to combine the use of performance assessment proxies (production of young, size of colonies, etc.) with other indicators like the state of nutritional stress or the availability of preys in terms of abundance and distribution in the environment. It is also important to widen the assessment of the operative state of ecosystems to the whole of the food web, particularly for lower trophic levels.

The indicator “large-size fish” (LFI) has been validated in the North Sea and is currently applied from the perspective of fishing stock management on the basis of the data of bottom-trawl fishing activities. Its adjustment as an indicator of the state of the food web is justified by the fact that the size of the fish is correlated with their trophic level (large-sized individuals belong to higher trophic levels). Thus, monitoring the size of the individuals will provide us with information on the evolution of the trophic level of demersal fish. As was the case for the first indicator, the first criticism is that the LFI can only be applied to a part of the food web. Moreover, each species will present a specific evolution in terms of its feeding regime. An approach based on the unique size to distinguish the fish belonging to higher trophic levels is not relevant within a community. One way of enhancing the indicator would be to define a size threshold per species, which would represent the ontogenetic changes in feeding regimes more precisely than a unique size for the whole community. Besides, other indicators relying on the data provided by scientific research can complete the assessment of this indicator: in particular indicator 3.3.2 (average maximum size for the set of species or fish) and the marine trophic index (MTI) defined as the average trophic level of the species captured, weighted by their respective biomass.

The indicator “tendencies of the species/groups chosen, significant on a functional level, with respect to abundance” takes into account the temporal evolution of the abundance of key biological compartments, but disregards the trophic links at the basis of the functioning and general dynamics of food webs. This indicator has the advantage of being suitable for the set of food webs, unlike the first two indicators, and allows us, among others, to monitor the lower and intermediate levels of food webs (plankton, benthos, etc.). It could become an indicator of the state of benthic or pelagic communities by monitoring the biomass of several trophic levels (biomass trophic spectrum) or the abundance of organisms by size classes simultaneously (size spectrum).

To summarize, the lack of knowledge about food webs and the slow development of specific indicators have restricted the abilities of descriptors to assess the few functional groups, which seems unsatisfying with respect to the initial ambitions of the directive. Thus, the definition of GES objectives specific to this descriptor remains qualitative. Some broad concepts have been proposed:

– key compartments (functional groups, species and habitats) must be kept in such proportions so as to allow the permanence of the general structure of food webs over time;

– abundance fluctuations, analyzed on sufficiently significant temporal scales, must remain in acceptable conditions with respect to the system. This implies that the fertility and genetic diversity of populations must remain the same;

– the main trophic links must be preserved so as to guarantee that energy is effectively and correctly transferred from lower to higher trophic levels.

7.5. Implementing the EAF: the Benguela and Humboldt examples

7.5.1. *The Benguela*

Since the beginning of the 1980s, the Benguela Ecology Program has developed an ecosystem approach to marine sciences in Southern Africa which has linked the disciplines of physics, mathematics, marine ecology, biology and economics in different institutes and universities in South Africa [MOL 04]. This approach has been used ever since, and one of its recent examples is the interdisciplinary project marine research in the Benguela and Agulhas systems for supporting interdisciplinary climate-change science (Ma-Re BASICS) started in May 2010, which provides us with a research framework for the collection of marine data and their integration into oceanic and ecosystem models. Data on social systems is also gathered to study the way coastal communities adapt to climate changes to enhance the social and economic planning of these communities. The BASICS project focuses particularly on the indicators of fishing management in an ecosystem context. Two of the major challenges faced by South-African fisheries when implementing the EAF consist of balancing sometimes conflicting management goals, given the wide range of parties involved and resource users and integrating information about the ecosystem into the existing fisheries management frameworks, which have been developed to manage stocks on a monospecific basis [SHA 10]. Implementing the EAF requires solid scientific foundations – a toolbox that enables us to conceive management steps [SHA 10]. However, making scientific information accessible in a relevant format that can be used by fisheries managers and facilitating the dissemination of this information through existing management frameworks remain challenging aspects.

On a regional and national level, several management steps have been taken, like the management of species captured as bycatch by fisheries (mainly in South Africa and Namibia) and the reduction in bird bycatch in long line and trawl fisheries. South Africa has developed a national plan of action (NPAO) concerning marine birds which is being effectively applied. It involves the implemention of regulations on bycatches in demersal fisheries, curbing shark and sea turtle captures, the management of beach seines in littoral fisheries and the enforced use of exclusion systems in prawn fisheries so as to reduce by catches and refuse (Angola and South Africa).

The EAF has been implemented [AUG 14] in the following way:

– ecological risk assessment (ERA): this is a way of validating the implementation of the EAF and identifying the main objectives (its methodology can be found at www.fao.org/fishery/eaf-net). A series of ERA workshops have been set up yearly to test the feasibility of the implementation of the ecosystem approach for each kind of exploitation (trawling, fishing of forage fish, etc.);

– each ERA gives us an overview of the current state of a fishery with respect to the importance of the ecosystem objectives;

– to follow and boost the implementation of the EAF, a monitoring tool that allows to quantify the progress made has been developed [PAT 10].

The Benguela ecosystem models have been used as a means of assessing the structural and functional changes in the ecosystems with respect to fishing and environmental change patterns [WAT 08]. An updated trophic model of the South Benguela for the period 2004–2008 has allowed us to compare a set of indicators derived from models representing several periods. Decision trees aiming to determine whether pelagic and demersal food webs, together with their ecosystem, had deteriorated, remained stable or improved over time, have been elaborated. An expert system has enabled us to communicate the results of trophic modeling in a general format, which is useful for fisheries managers. Recently, trophic models have been used with the aim of providing information for the management of fisheries of low trophic levels (sardines, anchovies, etc.), the species of which are crucial to South African fisheries and to the feeding regime of marine predators [SMI 11]. This study has highlighted that fishing of low trophic level species at MSY levels can significantly affect the other components of the ecosystem. The results of the model suggested that the adoption of an exploitation rate which is half the MSY levels calculated in a monospecific context would ensure significantly lower impacts on the other components of the ecosystem, while allowing catches to remain at around 80% of MSY. The marine stewardship council (MSC) has employed this work on the basis of these revised recommendations to certify forage fish fisheries, use the target biomass of 75% of unexploited abundance levels and decrease fishing mortality by 50%.

Ecosystem indicators are diversified and correspond to actual problems raised by the exploitation of local marine resources. The changes in the physical environment of the southern Benguela plateau and coastal regions have been associated to biological indicators of west coast crayfish and cormorants, which feed on crayfish, to set up an early warning system. This system can provide information about the migrations of crustaceans following anoxia periods [BLA 12]. A similar work is being carried out to identify physical and biological indicators that can be useful to understand the processes underlying the changes in the relative distribution of small pelagic fish stocks off the coast of South Africa. A range of ecosystem indicators have also been used to measure changes in the structure and composition of demersal fish assemblages in the Benguela, which reflect the direct or indirect effects of hake bottom trawling. Series of environmental data have been able to show that these effects, caused by fishing, have been exacerbated by poor environmental conditions [KIR 13].

In addition, an ecosystem model has been developed to assess the relative importance of the different pressures exerted on various breeding colonies of African penguins, a species in danger of extinction (*Spheniscus demersus*). The model aims to provide managers with a tool for the elaboration of the most strategic approach that could stop the severe decline of the population of African penguins, while recognizing the different pressures exerted on the penguins breeding in different locations along the coast. The first prototype of the model has been developed for the colony of African penguins on Robben Island, close to Cape Town. This modeling approach is unique in that it involves competences in terms of knowledge and guidance from the very beginning and throughout the modeling process. In addition to modeling and data analysis, a large-scale experiment is being conducted to study the possibility of shutting down forage fish fisheries around the penguins' breeding colonies, with the aim of relieving the pressure exerted on African penguins, which are in danger of extinction. The study started in 2008 and has employed a program that alternates between periods in which fishing is banned around four islands off the coast of South Africa. At first, seine fishing was prohibited within 20 kilometers seaward around Dassen Island from 1 January 2008 to 31 December 2009 [FAI 08], whereas fishing was allowed around the neighboring Robben Island, which also shelters a large colony of penguins. Afterwards, the alternation between closed fishing areas was adopted with a view to making the most of their potential to favor penguins by restricting fishing activities around their breeding colonies. Thus, between 2011 and 2013 it was decided that seine fishing would be banned in the feeding zone around Robben Island, a prohibition that was extended to the area around Dassen Island in 2014. Similarly, in Algoa Bay along the coast of South Africa, seine fishing was prohibited in the area within 20 kilometers of the seaward side of St Croix Island from 1 January 2009 to 31 December 2010 [FAI 08]; the prohibition was extended until December 2011. Furthermore, in recognition of the significance of Riy Bank for the feeding of penguins breeding on St Croix Island, when the St Croix region prohibited small pelagic fishing, the area within a 5 km radius of Riy Bank banned seine fishing as well. An area around Bird Island prohibited fishing in 2012–2014. On the four islands, as well as on Dyer Island and along the coast of South Africa, extensive monitoring of penguin breeding and population parameters is being carried out to facilitate the comparison between the colonies surrounded by open and closed fishing areas. However, results are not conclusive yet and data keeps being analyzed while the study enters its sixth and seventh year. This example shows that sometimes it is necessary to try out laborious strategy, on a large scale to find an adaptive implementation of the ecosystem approach and to quantify the repercussions on fisheries and preservation.

The compliance and support of the parties involved are necessary for the progress of the EAF in the Benguela and to bridge the gap between classic monospecific approaches and larger ecosystem approaches which require respectful collaboration between and within disciplines. The comments and participation of those involved have been encouraged in the context of the development of an ecosystem approach to fisheries in South Africa by adopting a method of ecologic risk assessment (ERA). In a recent summary of experiments concerning EAF in South Africa, Namibia and Angola [AUG 14], a certain number of difficulties and recommendations involved in an effective implementation were pointed out:

– the participation of the fishing industry is a significant aspect for the implementation of an EAF. In South Africa, a Responsible Fisheries Alliance (RFA) between the WWF and four large fishing companies in collaboration with other NGOs and the government has been a successful initiative;

– as for the ability to set up the EAF, fishers, fisheries officers and the other parties involved must possess the right competences to understand and implement tools such as those used to manage bycatch and protect marine habitats or vulnerable species. This is crucial for the transformation of management policies into effective and concrete action;

– the EAF increases management complexity by taking into account numerous components of the ecosystem, as well as social and economic questions. It is important to make sure that the regulation framework is supported by voluntary motivations and certification procedures. On a local level, three initiatives have motivated implementation, namely the Marine Stewardship Council's (MSC) certification of hake trawling South-African fisheries, the WWF southern African sustainable seafood initiative (WWF-SASSI) and the development of the RFA.

A successful implementation depends on several aspects linked to governance [AUG]:

– the participation of all parties involved is crucial to the successful implementation of an EAF;

– a structured approach provides a platform to express opinions, broaden perspectives and enhance the understanding of the issues;

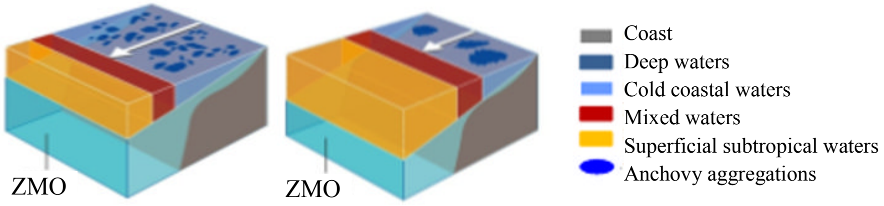
– all points of view must be represented and no group or individual should come first;

– the advantage of a generic approach is that it allows comparisons, questionings and reporting on all levels. Managers can follow the progress of the management steps in an interactive and transparent way to develop a work plan;

– NGOs such as the WWF have played a significant role in helping the implementation of the EAF and environmental initiatives.

7.5.2. *The Humboldt*

The marine ecosystem lining the coasts of Peru, also called the Humboldt Current ecosystem, is remarkable from many perspectives. It is one of the most important coastal upwelling systems [CHA 09], it is subject to some of the most intense forms of climate variability [CHA 08], it presents a very strong oxygen minimum zone and it constitutes the most productive fish system in the world (about 10% of the global catch is captured over less than 0.1% of the surface of the world's oceanic waters). Paleo-oceanographic studies show that the current period of strong productivity is relatively recent and only began at the end of the 19th Century [GUT]. The anchovy stock has been fluctuating for the past few decades between 5 and 20 million tons and falls prey to a fishing fleet (around 1, 500 vessels), significant populations of birds producing guano (about 4 million individuals, mainly made up of different kinds of gannets, Guanary cormorants, and Peruvian pelicans) and pinnipeds (South American fur seals and sea lions). The spatial structure of this pelagic ecosystem determines prey accessibility for predators and depends on warm or cold environmental scenarios (Figure 7.13).



Cold scenario Warm scenario

Figure 7.13. *A diagram of the environmental scenarios in the Humboldt Current ecosystem (from [BER 11]). See color section*

COMMENTARY OF FIGURE 7.13.– Large-scale oceanic forces generates cold or warm anomalies in the coastal environment, as shown by [BER 08b]. A cold anomaly results in a large expansion of the horizontal habitat of anchovies (upwelling coastal waters) and a weak expansion of their vertical one (waters above the oxycline marking the minimum oxygen zone which anchovies cannot reach). On the contrary, a warm anomaly reduces the horizontal area of the anchovies' habitat, but it increases its depth.

Currently, anchovy fisheries are managed by means of:

– an adaptive global quota, aiming to maintain at sea a minimum spawning biomass of 5 million tons;

– individual quotas since 2009;

– a 12 cm capture size limit;

– the prohibition for industrial fisheries to operate within 5 nautical miles of the coastline;

– adaptive seasonal closures when anchovies are spawning;

– local and temporary closures when catches contain more than 10% of juveniles.

There is still no specific measure aimed at the protection of the populations of natural predators if we disregard a theoretical exclusion of all fishing activity within two nautical miles of bird colonies. As we lack the means of controlling and fining, this step has not been actually implemented.

The adoption of an ecosystem approach to fisheries in Peru must face a certain number of challenges, which includes:

– streamlining the fishery from an economic point of view by insourcing the environmental costs linked to its activity (for example, the general pollution generated by the factories producing fishmeal) and management (for example, the costs of scientific research at sea necessary to establish global quotas and monitor the reproductive status of anchovies);

– reconciling the exploitation of anchovies and the guano produced by birds with preservation goals;

– developing adaptive management techniques as spatially and temporally precise as possible to optimize their effectiveness while making them more accessible to fishers;

– predicting the effects of environmental variability and climate change. These four challenges require more knowledge about the way the ecosystem works on different temporal and spatial scales, which constitutes the goal of a program of scientific cooperation between the French *Institut de recherche pour le développement* (IRD) and the Peruvian Sea Institute (IMARPE).

This program of scientific cooperation has specifically made it possible to gather detailed information on the behavior of top predators like birds, due to the development of electronic marking operations (GPS and diving recorders), carried out in conjunction with scientific research which gathers data through multi-frequency acoustics about the abundance and distribution of anchovies as well as the fine-scale structure of their habitat, for example [BAL 11, BER 08a, BER 10, BER 11, GRA 12], (see Figure 7.14).

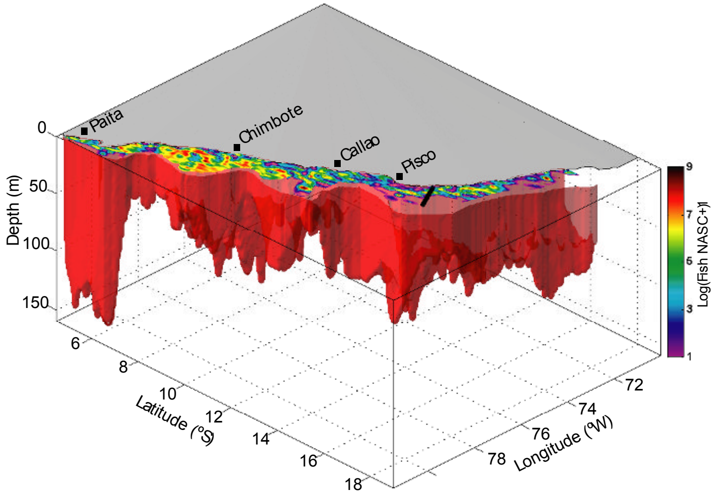


Figure 7.14. *A 3D structure of the habitat of anchovies, defined by the area of cold coastal waters and the depth of the oxycline. This 3D habitat is estimated on the basis of scientific research at sea employing multi-frequency acoustics. The image shown was taken during scientific research conducted in winter 2005 (austral) and the volume of the anchovy habitat is estimated at 9138 km^3 (from [BER 10]). See color section*

GPS wildlife tracking has, among other things, shown that three quarters of the sea journeys of gannets and cormorants during breeding season are carried out within a radius of less than 25 kilometers from the colony. These experiments have also been able to show that different species of marine birds (different kinds of gannets and Guanay cormorants), despite exploiting the same prey – anchovies – have different behavioral niches. Gannets, which are gliding birds, can deal with high levels of spatial dispersion of their prey, but can do nothing if their prey dives deeper (more than 10 meters); cormorants, which are diving birds, can easily exploit schools of anchovies up to 60 meters below the surface, but deal less well with the wide horizontal dispersion of shoals. These specific characteristics imply that the definition of "adverse conditions" vary quite a lot for these species: gannets will be more sensitive to the scarcity of anchovies in warm conditions, whereas cormorants will be more affected by the scarcity of prey in cold conditions.

Statistical models (for example, random decision forests) can then show how birds adjust their foraging effort at sea to compensate for the effects of environmental variability, the fluctuation of the abundance and distribution of anchovies and the competition with fishing activities. We can see in particular that fishing affects the behavior of birds at sea at least as much as the variability of the environmental conditions. It is also possible to see that when fishing activities are intense (i.e. many catches over very short periods of time, "the race for fish" as it happened in Peru before the implementation of individual quotas), they can create actual "holes" in the distribution of anchovies. When this happens around a breeding bird colony, consequences can be dire for birds especially [BER 12]. To conceive an ecosystem approach to fishery management in this ecosystem that can guarantee satisfactory feeding conditions for birds, it is necessary to adjust the pressure exerted by fishing activities with respect to the hostility of the environmental conditions unfavorable to birds and to limit the impacts of the "race for the fish" as observed in those fisheries where free access leads, in general, to an excessive number of vessels and an increasingly shorter fishing season.

On a larger scale, the modeling of demographical data about these same species gives us information on the sensitivity of their reproductive success to different parameters. We can see, for example, that cormorants use more sites to breed than gannets and pelicans, gannets and cormorants prefer islands to peninsulas and pelicans tend to choose large sites far from the coast (Figure 8.15). We can also see how birds breed mainly during the austral spring-summer, which allows juveniles, upon leaving the nest, to find the highest levels of abundance of and accessibility to anchovies at sea.

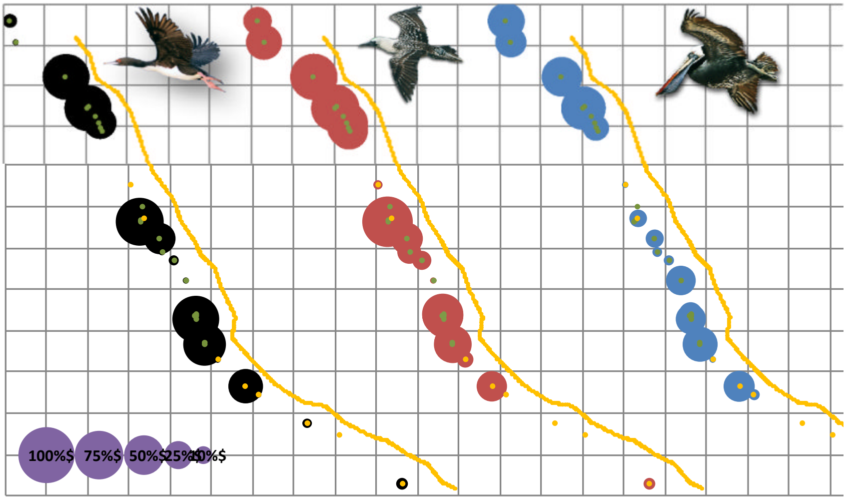


Figure 7.15. *Probability of encountering breeding birds of three different species according to the sites considered. The size of the circles represents the breeding probability of each species (in %, Guanay cormorants in black, gannets in red, pelicans in blue). Islands are shown in green and peninsulas in red. For ease of reference, the coastline is shifted longitudinally and is shown in yellow. See color section*

In this coastal upwelling system, where oceanographic and ecosystem conditions are dynamic and can vary from week to week, it is difficult to monitor in real time the ecosystem dynamics and logistically impossible to conceive permanent scientific research at sea. It is, therefore, interesting to complete the numerous scientific researches conducted (two to four per year) with real-time indicators of the dynamics of the system. Fishers are permanently at sea and, since the onset of the 2000s, their movements have been documented by a satellite monitoring system (Vessel Monitoring System, or VMS) entirely. A series of studies [BER 05, BER 08b, JOO 14, JOO 15] have focused on the variability of the spatial strategies adopted by fishers with respect to the changeability of oceanographic and ecosystem conditions. In particular, these studies show that the spatial distribution of fish and fishers reflects quite directly the changes in oceanographic conditions [JOO 15]. On the other hand, coastal oceanographic conditions are for the most part determined by oceanic waves originating in the middle of the Pacific Ocean and propagating along the equator before breaking on the coasts of South America. The journey of these waves lasts several months and, consequently, by observing their formation in the middle of the

Pacific, we can predict the dynamics of the Peruvian coastal ecosystem two to six months in advance (Figure 7.16, [BER 08b]).

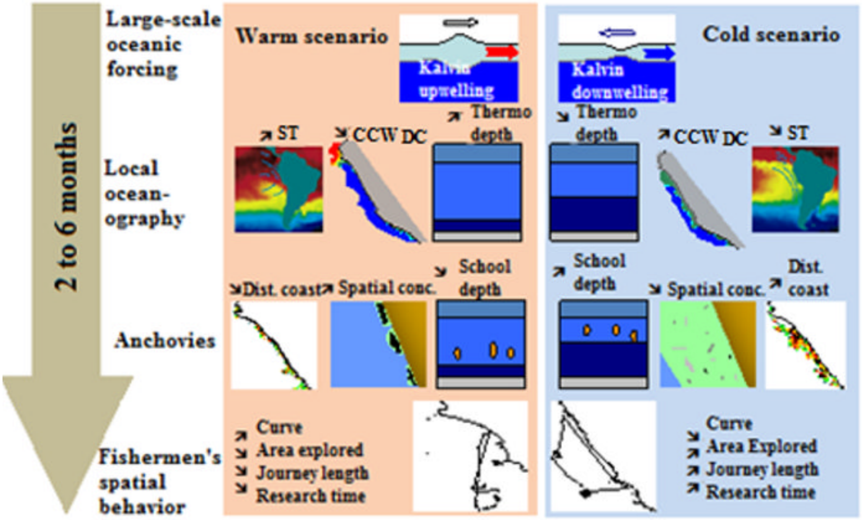


Figure 7.16. *Warm and cold ecological scenarios triggered by oceanic Kelvin wave forcing on the Humboldt Current coastal system. ST: surface temperature, CCW DC: average distance of cold coastal waters from the coast, Dist. coast: average distance of anchovies from the coast, Spatial conc.: spatial concentration index for the biomass of anchovies, School depth: average depth of the schools of anchovies (from [BER 08b]). See color section*

To summarize, the program of scientific cooperation between France and Peru has allowed us to highlight a certain number of key processes that need to be taken into account if we want to implement an ecosystem approach to fisheries through managing institutions:

– paleo-oceanography shows that with or without fishing activities, the strong productivity of the system is not a permanent property of this ecosystem;

– scientific research by means of acoustics is crucial to the assessment of the biomass of anchovies and the definition of the characteristics of their habitat in three dimensions;

– birds can compensate, to a certain extent, for low levels of abundance of and/or accessibility to anchovies, all the more so when the pressure exerted by fishing is relieved at that time;

– the definition of what constitutes adverse conditions for birds varies according to the species;

– areas where fishing is closed around significant colonies of birds can be an interesting option to curb the effects of local depletion. They must stretch at least up to about 25 kilometers from the colony;

– individual quotas reduce the risk of local depletion caused by fisheries by eliminating the effects of the race for fish;

– fishing closures aiming to protect anchovy breeding favor bird breeding as well;

– the analysis of the fishers movements is a good complement to the real-time survey of the dynamics of the system, since it allows us to identify the stretching/contraction of the distribution of anchovies and to deduce their accessibility to birds;

– environmental scenarios can be predicted a few months ahead by observing the dynamics of oceanic Kelvin waves. This information is crucial to an adaptive and real-time type of management of fishing activities.

7.6. Dynamic approaches to the ecosystem management of fisheries

Over the past decade, the EAF has significantly transformed our way of conceiving the management of marine resources and modified in many respects the objectives of scientific research conducted on the marine environment. Nowadays, the EAF is recognized internationally and its concrete goals for fisheries have been established in this new context on a UN level. By now there are several scientific conceptual frameworks that can conceive an effective implementation of the EAF which will lead us to achieve a good ecological standard for the oceans and their resources. However, it seems that a natural evolution which will allow us to integrate a dynamic vision of the EAF in a global context is about to take place. More and more evidence shows that anthropogenic pressure heavily affects the physical and biological systems of the world’s oceans [PAR 03]. Even though marine ecosystems fluctuate by nature, the breadth and frequency of these variations seem to be getting greater on a global level [ROS 08]. As a consequence, the ecosystem services provided by the oceans in quality of regulator (for example, control of the climate regime and carbon pump) or provider (for example, food, medicine and tourism) will be affected in the future [BRA 09].

In this context, the scientific community (for example, the Intergovernmental Panel on Climate Change, or IPCC) has provided us with a range of predictions so as to quantify the environmental changes that may take place in the next century (www.ipcc.ch). Thus, scenarios based on logical and likely behaviors and the choices made by society (for example, in terms of technology, economy, way of life, demography, etc.) have been developed. Like the IPCC, the newly set up intergovernmental science-policy platform on biodiversity and ecosystem services (IPBES, www.ipbes.net) intends to stimulate the scientific community with the goal of elaborating scenarios about the evolution of biodiversity (www.milleniumassessment.org, www.unep.org/geo). The IPBES platform will be the basis for the decisions taken by politicians and managers, while also strengthening the structuring of research carried out on marine ecosystems. In a global context and in face of a growing demand, the scientific community must make an effort to explore the future of marine ecosystems as well as the possible pathways leading to desirable goals in relation to different environmental, economic and social scenarios. From this perspective, the scientific community needs to set up a long-term scientific strategy in order to enhance its ability to provide suitable competences for the ecosystem approach to marine resources (www.eur-oceans.eu, www.ueromarineconsortium.eu). This results in innovative, integrated and multidisciplinary research, the ambitions of which are consolidated by the management and understanding of the state of marine ecosystems as well as by the implementation of the EAF.

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8

Modeling in Contemporary Sciences: Efficiency and Limits Examples from Oceanography

8.1. Introduction

Modeling has become a common and efficient methodology shared by an increasing number of scientific disciplines. For a long time, it has been developed mainly to solve problems in physical sciences. To represent relationships between quantities and to study their variations, mathematics was the principal formalism used and we observed a kind of co-evolution between these disciplines. It is largely still the case. However, progressively this methodology percolates through almost all other scientific domains.

During the second part of the 20th century, the advent of computers led to a terrific amplification of numerical calculation, then data acquisition, storage, handling and analysis. Formal computing is less known, but is an important tool for mathematicians and modelers (Macsyma, Reduce and Mathematica©). Moreover, the emergence of specific languages and innovative programming methods led to new modeling possibilities (Multi-Agent Models, individual based models, logical models, etc.) enabling modeling and simulation of the behavior of natural, technological, economic and social entities. Simultaneously, mathematics registered a wide spectrum of new results, particularly in the theory of dynamic systems. On the other hand, system analysis is devoted to representations of objects of

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varying complexity such as ecosystems. With these representations it is sometimes possible to associate mathematical models to study dynamics, for instance fluxes of matter between sub-structures, variations of biological populations, inside systems themselves and exchanges with their surrounding environments.

The efficiency of this approach is acheiving a huge set of goals has been widely demonstrated, for instance to solve practical problems, to assume possible existence of objects or properties not still observed, to forecast changes, to aid in management of natural or artificial systems, and to assess results of policies.

In other chapters of this book the use of models and some general points are presented and debated. It is not our purpose to recapitulate or to discuss them, our objective is not promote to the "method of models", but to underline some important aspects and also to discuss limitations sometimes forgotten. For instance, that a deterministic model may not be a good predictive tool (determinism doesn't imply predictability) or that a model is not a 1:1 map of reality, simplifications are needed to make it efficient. Mathematical rewriting is often used for technical reasons, but sometimes leads to new interpretations, revealing some kinship between models, etc. We also insist on the coupling between models originating from different domains, for example models of the dynamics of the environment and that of biological populations, on the necessity of having good data for an efficient modeling or, at least, to verify that model properties and simulation are not in contradiction with reality. Modeling facilitates dialog between disciplines (models appears as kinds of hyphen between them [SCH 02]) and it is a methodology embedded in systemic approaches.

8.2. A language to describe reality

The first interest of a model may be to have a synthetic representation due to a formal language, at least more synthetic than natural languages. Most often the model is a mathematical equation and terms of this equation can be interpreted in the application field: the size of a population, a rate of growth, an interaction between populations (e.g. competition, predation, etc.). So values are not only constrained by mathematical properties, but also by their meaning: the size of a population is measured by a number of individuals or a biomass, therefore, the associated variables are positive. This is obvious, but sometimes in more complicated cases, we have to be careful, for instance when formal transformations are accumulated, to avoid the loss of meaning or conversely to enhance it. Let us consider the classical logistic model to illustrate where elementary transformations can lead. In ecological literature it is written (Chapter 7):

$$\frac{dx}{dt} = r\,x\left(1 - \frac{x}{K}\right) \qquad [8.1]$$

Where x represents the size of a population, r the growth rate of this population and K a parameter characterizing the carrying capacity of the environment (i.e. resources) to ensure the growth of the population. It can be transformed in a differential system by explicitly introducing a variable $s(t) = 1 - \frac{x(t)}{K}$ representing the proportion of resources remaining in the environment at time t:

$$\begin{cases} \dfrac{dx}{dt} = r\,x\,s \\ \dfrac{ds}{dt} = -\,r\,x\,s \end{cases} \qquad [8.2]$$

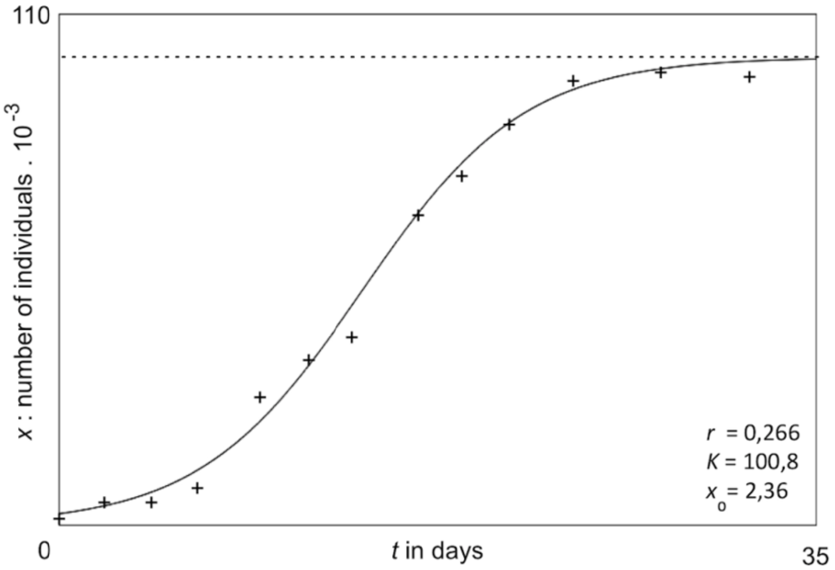
In fact, s is a first integral of this differential system: $s = s_0 - (x - x_0) = s_0 + x_0 - x$ and $K = s_0 + x_0$. Although it is trivial, this transformation is very rich in consequences, for example, this model has a huge field of applications. Moreover, from this expression other classical models of population dynamics can be rewritten and new ones can be proposed (a homogenization of theory) [PAV 93].

8.3. Relationships between models and reality

There are a lot of works about these problems. One of the first traps is to imagine that a model is an exact picture of reality and that mathematical developments lead to the truth. It is true in mathmatics, if demonstrations are valid, but not necessarily in reality. Trying to make the reality conform to a model is hazardous. Although in technological domains it is desirable, it is a risk in sciences where experimental data are difficult or even impossible to obtain and the objects under study are complex. However, models can be efficient aids. The case of the economy is well known and misuses might be dramatic. Concerning the economy, Henri Poincaré highlighted this difficulty in a letter sent to Léon Walras in 1901. Poincaré's criticisms seem to be not well understood by Walras. This exchange of letters and also the introductory note written by C.H. Bousquet to the article published in 1960 in Metroeconomica is surprising. In this note Walras is designed as "Le Maître" (The Master) and one of his former students as a "disciple". This kind of worship is unusual in science. Poincaré, one of the most important mathematicians, who was very concerned by implications of mathematical results in reality and in other disciplines, particularly physics, in the history of these disciplines, is curiously not well considered in these texts [BOU 60].

If the idea of generalized equilibrium, proposed by Walras, was a real progress in theoretical economy at this time, as it was in mechanics and thermodynamics, this notion has now been completely revisited. It is an ideal situation to facilitate reasoning but not validated in reality, what is interesting and pertinent is precisely the difference between the idealistic concept and the observed dynamics. Poincaré was specifically working on what we call today the theory of dynamical systems and he established the fundamentals of the mathematics of this theory. His work was not understood by many scientists for a long time, particularly by economists but also by ecologists. It is always surprising to hear journalists who are specialists of financial markets saying a thing like that "the stock prices are near equilibrium" while they are constantly fluctuating. The same can be said when in ecology we speak of an ecosystem at its equilibrium, however this approximation is better than in economy because most of time fluctuations are relatively slow, for example in forests, but it is perhaps not the case for many marine populations and ecosystems. But before we discuss that, let us examine other important points, which are often neglected.

The first relates to parameter values. Where direct measurement of these values is not possible, biometricians and control scientists have developed methods to estimate numerical values of these parameters from a specific set of data, for linear and nonlinear models relative to these parameters. For example, the values of r and K, or the initial value of the logistic model corresponding to a particular set of data (see Box 8.1). Moreover, we can also evaluate the precision of these estimations. Eventually, if necessary, statistical tests can be proposed to measure how models fit to reality.



Example of estimations of parameters obtained by a nonlinear regression. This methodology is based on a model of variability of experimental data. Practically, the modeling approaches associate different models and algorithms: model of the system itself, model of variability, algorithms for numerical computing, etc. Data concerns the dynamics of a microscopic fungi (*Fusarium solanii*) population present in soils. They have been obtained in a research laboratory (INRA, National institute for agronomic research, Dijon) [PAV 12]:

This simple work was at the origin of a more important study concerning the competition between different strains of *Fusarium* which contributed to biological control of pathogenic species [ZEG 87].

Box 8.1. *Logistic model, differential equation and explicit expression after symbolic integration:*

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right), x(0) = x_0 \rightarrow x(t) = \frac{1}{1 + \frac{K - x_0}{x_0} e^{-rt}}$$

The second concerns predictive properties. It is often implicitly assumed that a deterministic model, that is to say a model without probabilistic terms, is completely known at a time t_0 (i.e., its formal expression and values of state variables and parameters at this time) and that it is possible to compute these values at any time $t > t_0$ and possibly precisions of these guesses. It is also assumed that values computed for small variations of variables and parameters at time t_0 will be located in the neighbourhood of the computation using previous values. But Poincaré discovered a property for some nonlinear deterministic models called "initial condition sensitivity", that is to say the possibility of having values far from the neighbourhood of previous computation. As it is impossible to have exact values at t_0 (i.e., values with an infinite precision), these kinds of models cannot give reliable predictions (see Box 8.2). Furthermore, these models exhibit very irregular dynamics, for example chaotic ones, and more generally they are sensitive to small perturbations. Therefore, predictability is not a consequence of determinism, and determinism doesn't imply predictability.

For a long time, Poincaré's legacy has been mainly developed both by Soviet and American schools of mathematics[1]. Lorenz, an American meteorologist, was in a good context when he identified the chaotic behavior of his simplified model of meteorological system and spoke of the "butterfly wing" effect. More generally, deterministic models and systems which generate unpredictable results are more and more studied. This is a bridge between theory of dynamical systems and theory of probabilities. In the introduction of his book devoted to probabilities, Poincaré pinpoints: "*It may happen that small differences in the initial conditions produce very great ones in the final phenomena; a small error on the first produce a huge error on the last. Prediction becomes impossible and we have the fortuitous phenomenon*" Poincaré [POI 87][2].

Engineering sciences are very concerned with these kinds of problems. Engineers have to conceive devices to achieve a particular goal, for example

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[1] There are a lot of famous American mathematicians who worked in this field and more recently French researchers developed an original approach of PDE (Partial Differential Equations) and ODE (Ordinary Differential Equations). These mathematicians are often interested by applications, mainly in engineering.

[2] The introduction of this book is very detailed and very accessible to any reader. Poincaré wonder from where practically comes chance. To do this, he raises the problem: if I start a router on a shelf, I can write the equation of its motion, but I cannot predict where it will stop and the position of its axis when stop. We can also find other references in the book by Philippe Picard [PIC 07].

a chemical industrial process to synthetize a specified compound, or more basically a streaming machine to convert thermic energy into mechanical energy. For comprehensive reasons, such technological systems must be predictable. For this purpose, modeling is a key methodology, but has to be coupled with experiments to test it. During experiments, models can be changed to adapt them according to experimental results. Finally, we have both a technical device and a model of it, and if we wish to modify the device before functioning we can test it thanks to the model. We have also to note the necessity of regulations to maintain the system in a proper state (e.g., to avoid explosions!). Regulations are taken into account in the model. Predictability is most often strongly requested, but in some case it is unpredictability. For example, a manager of a casino may wish to have roulette devices which insure the unpredictability of the game. So the work of the engineer is the conception of an unpredictable device. In fact, he has to predict unpredictability! Recently mechanical games of chance have been modeled, mainly for fundamental reasons, which are to understand why such devices can generate stochastic behaviors [STR 08, STR 09][3].

Now we may ask the question: why talk about such stories which are far from our concern? Obviously they are interesting for themselves, but we have to now focus on the importance of *stochasticity* in biological and ecological systems, and more generally in natural systems and their evolution. To imagine how it is generated in simpler systems is a first milestone in paving the way in decripting its origins in complex systems where analogous mechanisms can be at least assumed and associated nonlinear models can be imagined. This kind of approach is also an illustration of interdisciplinary work and of the role of models in such approaches, from mathematics and mechanics to life sciences. “Chance” is a concept shared by many disciplines and at the heart of theory of probabilities, but nothing is said about its origin apart the Poincaré’s remark and rare works of some other authors (e.g. Kolmogorov and his student Iakov Sinaï, who received the Abel Prize in 2014). The generation of chance within biological and ecological systems has been underlined recently by some authors (Radman see [CHI 01, KUP 11, PAV 07]). The study of mechanical systems generating chance and their modeling is a good example for us. Common properties are nonlinearity of models and sensitivity to initial conditions and the possibility of erratic (e.g. chaotic) behaviors.

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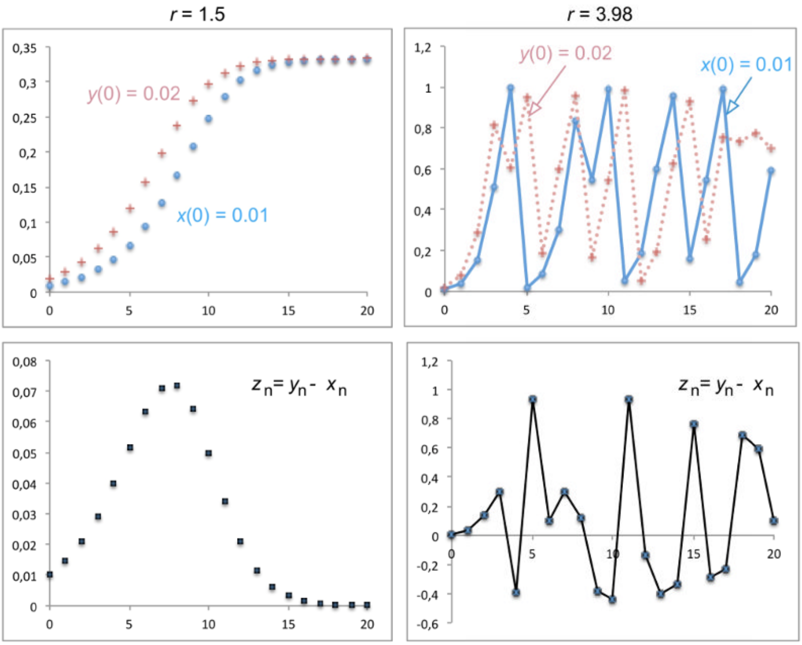
[3] One of the reasons for unpredictability is the complexity of the phase space of the dynamical system, model of the real one (See Box 8.3, sensitivity to initial conditions: Jurassik Park’s way).

Contrary to a widely shared idea of chaotic dynamics, stochasticity of living systems are often not negative but also positive, even necessary, for their working, survival, development and, at the end, to their evolution. For example:

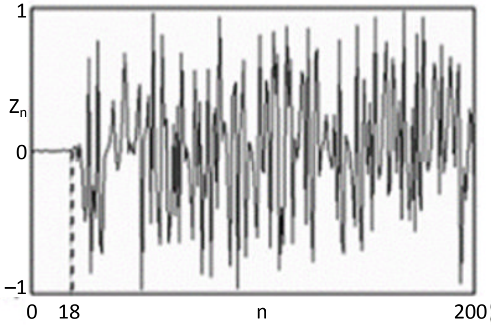
– Allen *et al.* have shown the advantage of chaotic dynamics in some metapopulations. The effect is to decorrelate demographic trajectories and then to avoid the extinctions of smallest populations [ALL 93];

– the disorder in natural forests facilitates their resilience and the maintaining of their biodiversity [WOR 93, PAV 07a];

– chance is an essential factor for biological evolution, first to generate biodiversity, through genetic drift and/or natural selection. Chance may be the result of internal or external processes [PAV 10, GAR 15] . In the last case, the generation of chance and of its effects are, possibly, regulated by internal processes, which are both results and drivers of biological evolution [RAD 76, CHI 01]. In this case we can envisage controlling them, to increase and decrease the note of evolution, for example, to prevent the emergence of resistance in populations of pathogenic organisms [PAV 07b].



(1) (2)



(3)

EXPLANATION.–

Let us consider the discrete time logistic model $x_n = r\, x_n(1 - x_n)$. For $1 < r < 3$ the values of x increase regularly from the initial condition to an equilibrium (or fixed point) $x^* = 1 - 1/r$. When $3.55 < r < 4$ the dynamics becomes more and more chaotic when r increases. Figures above show simulations of the models:

$x_n = r\, x_n(1 - x_n)$,

$y_n = r\, y_n(1 - y_n)$

and $z_n = x_n - y_n$

1) $r = 1.5$, $x_0 = 0.01$, $y_0 = 0.02$: the series are “regular” the difference z_n between these series varies regularly, smoothly and converge towards 0.

2) $r = 3.98$, $x_0 = 0.01$, $y_0 = 0.02$: the series are “irregular” (chaotic) the difference z_n between these series varies irregularly , widely and doesn’t converge.

3) $r = 3,98$, $x_0 = 0.5000$, $y_0 = 0.5001$: if the difference between initial conditions is very small, series diverge after a more or less short time.

(1) shows a case of low sensitivity, (2) and (3) exhibits high sensitivity to initial conditions.

This model was proposed by Robert May in 1976: [MAY 76].

Box 8.2. *Sensitivity to initial conditions and explanation*

The sensitivity of chaotic systems to initial conditions, then to low perturbations, can be used to control such a system in a non-expensive way or to stabilize erratic trajectories [SHI 93]. NASA and ESA specialists have applied this technique to pilot a spacecraft (ISEE 3/ICE) exploring the solar system and to fly in the neighbourhood of the Lagrange point L1 (which is unstable) and above comets [GIA 85, HAL 86, LET 09]. In these conditions, variations of the gravitational field lead to chaotic trajectories. If we have an efficient model, which is possible from Newtonian mechanics, it is possible to calculate the effect of a small perturbation in a limited interval of time, for example by activation of micro propellants and then to pilot with parsimony the spacecraft thanks to an adaptive control.

This example enhances the interest of such controls, step by step, of complex systems for which models, basically imperfect, cannot give reliable prediction beyond a limited time. This is the case in populations, communities and ecosystems. When dynamics a medium are turbulent, the movement of an object in such a medium, for example a liquid, is another practical example of difficulties.

For ecological systems, on the one hand we cannot expect to make predictions as precise as those for physical systems, and on the other hand, we have to do this and to develop good theories and methodology to assess what is possible. Let us cite two recent articles which, at our opinion, pave the way for such approaches: [NOR 15, MOU 15].

More generally, we can illustrate the role of the complexity of the phase space in the uncertainty of a result, although it comes from a dynamical deterministic system by using displacements in a geographic landscape (see Box 8.4).

On the left, an image from the movie “Jurassic Park”: Ian Malcolm, the “chaotician” explains to the palaeobotanist, Ellie Stattler, why a “complex system” such as the Park can drift. To this end, he asks which way the water drop, on Ellie’s hand will flow. She cannot answer because it varies depending on the starting point. The water will flow unpredictably on the back of her hand.

On the right, in this rugged landscape, from very neighbouring places, the paths of two balls can be very different. These trajectories are geodesics. Additionally, real systems are not isolated, for example, a "gale" can sweep the mountainous landscape and change the ball trajectory placing it on another geodesic. This "gale" is the result of another dynamical system, that of an "atmosphere".

Box 8.3. *Sensitivity to initial conditions: Jurassic Park way*

8.4. What about marine ecological systems and their management?

A great part of ecology has been developed on terrestrial ecosystems studies (for example, natural or artificial forests). Experiments have been designed to respond to simple questions (e.g., Gause's famous works on predation and competition)[4]. Today there is a lot of experimental work at different scales on specific field devices coordinated by devoted programs. We have common concerns about all kinds of systems under studies. Therefore, we can look at the science of automatic control.

Observability is the property which ensures that the measurement of some state variables, and of combinations of them appearing in the model can lead to the knowledge of all values of variables in the model. Two other notions are also useful: identifiability and controllability. Indentifiability ensures that all parameters of the model, not directly measurable can be estimated from a proper set of data. Controllability is the property that must be verified if we wish to control the system thanks to a model of it (if the model includes control variables). In the case of linear models, a strong theory and methodology has been established (e.g., Kalman's well-known work [KAL 60 KAL 63]), and for some nonlinear model also. If we are interested in natural systems, in our case ecosystems, generally they cannot be applied literally, but the ideas are interesting and may be conclusive to reflections on practices. For example, populations of fish are difficult to observe, one reason being the cost of statistically correct sampling. Fisheries sciences often use results from commercial fishing activities, however these data are biased because the primary goal of fishermen (or women) is the profitability of his work. Therefore, it is desirable to use these data with caution [GAU 97]. In the following short presentations of simple models we have to remember that.

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[4] The book [SCU 78] is devoted to the translation of articles published in France during the 1930's, under the initiative of Georges Teissier, and particularly, the Gause's work [GAU 35].

Practically, observability has to first be considered in a modeling framework and more generally in research on natural or artificial systems. We have just discussed that in marine systems observations and measurements are difficult. Moreover, dynamics of the environment have often have to be taken into account (e.g. oceanic currents and fluxes), as well as displacements of populations (e.g. fish), and finally spatial dimensions must be considered (from 1D to 3D) in modeling. Seas are important at many levels, from the global scale in relation to the climate, to the local one concerning the change of seashore and exploited resources (mainly fish and other sea-foods). We will present two examples that lead with this last problem, one about the definition of EEZ (Economic Exclusive Zone), and second a simple model combining economy and biology of living resources.

We know that the regulation of fisheries is a recurrent, sensitive and highly mediatized problem. The main reason is the persistent fear of over-exploiting living resources. A model referenced by Ludwig [LUD 76] was used as the basis for defining exclusive economic zones (EEZ) of 200 miles from the coasts of state territories which are under the responsibilities of the concerned Countries. Within their EEZ, countries can define rules for exploitation. Here we simply cover the principle of models used to define such rules. The basic mathematical expression is:

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial x^2} + ru(1-u) \qquad [8.3]$$

Where u is a function of the time and of a spatial dimension x (i.e. $u = f(x, t)$). This represents the density of a sea population u at a point x at a time t following a dynamic defined by the logistic term $r\,u\,(1-u)$. Moreover, individuals move along the x axis. This movement is assumed to be represented by a diffusion term $\frac{\partial^2 u}{\partial x^2}$. The expression above is therefore a reaction-diffusion equation.

The boundary conditions are defined by a distribution of fishing resources in the protected zone $u\ (0, x)$. Obviously, there is not such resources on the terrestrial part of the seashore: $u\ (t, 0)\ \forall t > 0,$ and by considering that beyond the limit L uncontrolled fishing leads to a total exhaustion of resources: $u\ (t, x)\ \forall t > 0, \forall x \geq L.$ The model, which enabled the definition of the zone of 200 nautical miles, was constructed on this basis according to [WAN 89]. As mentioned by the author, we can pinpoint the difficulty of mathematical study of this kind of model, yet numerical simulations remain possible. Similar and often more complex models can be proposed to represent dynamics of spatially referenced populations, which can also move in a moving medium.

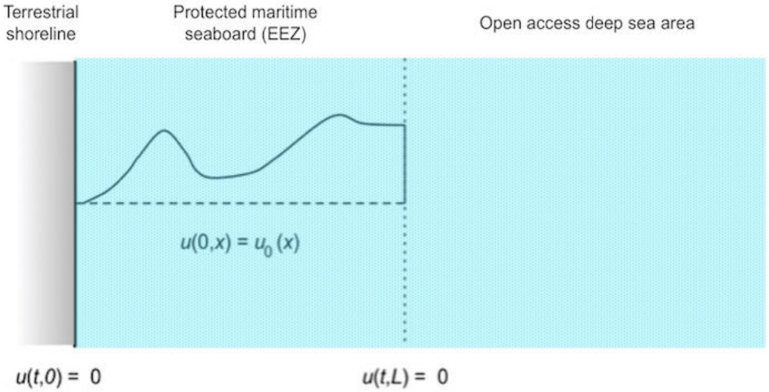

Figure 8.1. *Diagram of the spatialized dynamics of fishing resources showing the boundary conditions from which solutions of the model may be studied*

Previously, the so-called models of “bio-economy” were proposed. They combine the dynamics of biological resources and the economy linked to this kind of good. They come mainly from the study of marine fisheries and in particular from an analysis proposed by a Canadian economist, H.S. Gordon. This work was done at the request of Canadian government to try to explain the low income of marine fisheries and, therefore, of fishermen. He then offered an explanation in economic and biological terms of “overfishing” [GOR 54]. Later Colin Clark published books, which remain important references [CLA 85, CLA 90].

Once again, the logistic model is the basic one chosen by modelers to represent the dynamics of the resource. One of the first models coupling resource dynamics and harvesting effort (i.e. fishing) has been proposed by [SMI 69][5]:

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[5] This article is cited by Clark (1985, see above). A general presentation of optimal control models of fisheries can be found at: http://www.fao.org/docrep/003/w6914e/W6914E08.htm.

$$\begin{cases} \dfrac{dX}{dt} = rX\left(1-\dfrac{X}{K}\right) - qEX \\ \dfrac{dE}{dt} = k\left(pq\,X - c\right)E \end{cases} \qquad [8.4]$$

The state variable x measures the size of the exploited population, following a logistic model: $rX\left(1-\frac{X}{K}\right)$. E is a "fishing effort" (measured, for example, in number of ships within a fishing fleet). An increasing fishing effort harvests an increasing biomass, also proportional to this biomass ($-q\,E\,X$). This term corresponds to an additional mortality in the first equation. This effort is itself proportional to the resource ($pq\,X$) in the second equation, but will be limited by the cost of mobilization of a fishing unit ($-c$). It can be shown that there is a stable equilibrium (E^* and X^*) at the intersection of the lines, dX/dt =0 and dE/dt = 0 that preserves the resource. Adjustment of fishing effort can be made on economic criteria, for example, by choosing the "classical one" as per Clark:

$$Q = \int_0^\infty e^{-\delta t}\left(pqX(t) - c\right)E(t)\,dt$$

we then have to define a strategy $E(t)$ maximizing this criterion and avoiding exhausting the resource (equal to or below which is called MSY: Maximum Sustainable Yield).

The logistic part of the first equation of the differential system [8.4]:

$y = rX\left(1-\frac{X}{K}\right)$ represents the autonomous dynamics of resource (then assumed to be logistic). We have: $y_{\max} = y\left(\frac{K}{2}\right) = r\frac{K}{4}$. This quantity is the theoretical MSY. If the harvesting ($H = qXE$) is below this quantity (i.e. $qXE < rX\left(1-\frac{X}{K}\right), \forall t > 0$), then the derivative is positive and the resource can grow, if it is equal then the stock of fishes remains constant and the resource is preserved, but if it is greater, then the resource decreases and can disappear.

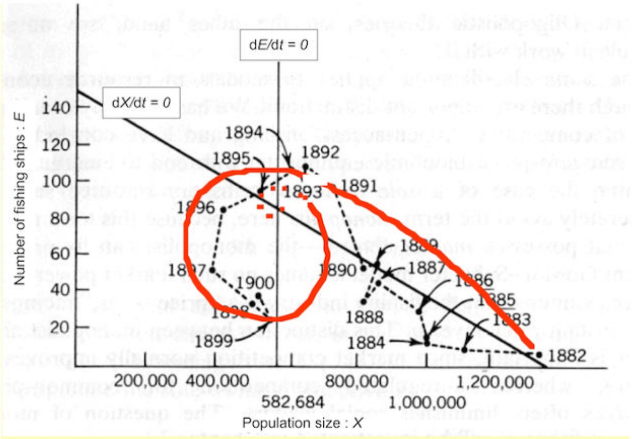

Figure 8.2. *Smith's model compared to historical data on whaling (Clark, op. Cit.). The fishing effort E is assumed to be equal to the number of ships. This model provides for certain parameter values a fixed point, which is a stable focus. Data coming from logbooks of ships do not contradict this result*

Choosing the exact value ($H = y_{\max}$) is hazardous because natural variability and model imperfection may lead to practical overfishing (i.e., the practical MSY quantity must be fixed to a value below the theoretical value given by the model to ensure sustainability, and then an harvesting value can be determined and if necessary modified over time). Many articles and books have been devoted to this problem and discussions about it.

We can remark that the model of natural dynamics of resource may be much more complicated, even if it can be considered autonomous (see Figure 8.3). This example shows the intermittent dynamics of a Californian population of the "Sardine of Pacific". This kind of data is not common in the literature and has been obtained thanks to a sedimentary process and of the resistance of sardine scales which are deposited at the bottom of the ocean. A specific drilling method has sampled a column of sediment, and the density of scales along that column has been estimated. This density is assumed to be proportional to the size of the local population of sardines at the time obtained by isotopic dating along the column. These kind of results require care in interpreting disappearances of species: is it transitory and dependent natural dynamics or is it the consequence of human actions (e.g., direct overfishing or anthropogenic perturbation of the marine ecosystem)?

As suggested in Chapters 6 and 7, trends are used precisely to envisage more general modeling of the concerned ecosystems and/or to adapt management of resources. The interest of the model [8.4] is not in its predictive capabilities, which is weak, but to try to combine natural and human dynamics.

However, mathematical modeling is limited when describing human behavior, environmental, ecological and economical dynamics. Therefore other simulations such as multi-agents ones can be used. One of the first examples is the modeling and simulation of fishing activity in the "Inner Niger Delta", which brings together a wide spectrum of scientific disciplines [BOU 93]. The drawback to this approach is the lack of generality; while mathematical reasoning can lead to general results (e.g., theorems), it is generally not possible with multi-agent simulation systems. Some of us have therefore proposed integrating them into a modeling approach: using observed data obtained from the system under study, multi-agent modeling and simulation ("virtual reality" and "virtual data"), and mathematical models representing a part of the system using both real and virtual data.

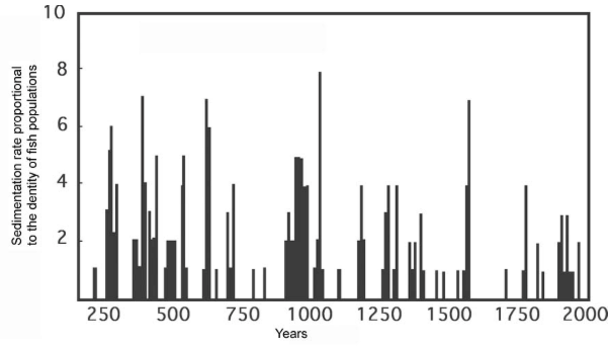

Figure 8.3. *Intermittencies in population dynamics: the example of sardines in the Pacific Ocean estimated from sedimentary marine deposits off of the coast of California (see Ferrière and Cazelles [FER 99]). Years are before present (2000)*

When considering living marines resources, we have to stress that they are increasingly produced by fish farming, and more generally by aquaculture. Once again, modeling is a precious tool to control such processes. The methodology is analogous to that developed by engineers for industrial applications.

8.5. Interdisciplinarity, transdisciplinarity and modeling

In an article published in 2002, we proposed with Claudine Schmidt-Lainé that among their multiple applications in scientific, in technological and in management approaches, models can also be also "hyphens" between disciplines in interdisciplinary work[6]. Criticisms of Walras' mathematical theory of economy presented notwithstanding, this work is a good example of the role of models in combining mechanical concepts with economical one. Poincaré's letter is also an example, where he shows that it is necessary to have a good knowledge of mathematics, not necessarily in technical details, but at least in basic concepts. For example, the theory of dynamical systems has to be better known than it is today and to not be dramatically reduced to linear ODE (Ordinary Differential Equations) symbolic solving, as it is often the case. This theory enables us to construct a thinking framework about a large class of problems and it can be presented by using common language and illustrated by simple graphs. It can be seen as a universal language perhaps over time and for discussing how reality changes over other dimensions [LIO 97]. Poincaré's letter is once again a good example. It is the same for the theory of control, which can be easily introduced.

However, as already mentioned, mathematics are limited when describing some phenomena or objects, for example, human behaviors. It is also more generally true for animal behaviours. Knowledge coming from different disciplines to model a complex reality needs to combine appropriate knowledge and data. Knowledge may be partially formalized (local mathematical models) or constituted by computer software (e.g., geographic information systems). Multi-agent modeling and related software consist of associate proper procedures in order to be operational for practical uses. Many examples may be cited, among them the works realized at the Cirad in Montpellier in the field of agronomics (http://cormas.cirad.fr/fr/reseaux/equipe.htm), and, concerning marine activities, the software developed in the Geomer Lab [CYR 05]. Moreover, there is an opportunity to develop distributed artificial intelligence, which is another modeling tool, particularly for behavioral modeling or to simulate decision processes and the consequences of decisions. Finally, spectacular applications exist for the "Companion Modeling Approach" which is devoted to assisting project realizations in the field [BOU 05, ETI 11]: computer scientist can develop a model *in situ* thanks to a specific platform, for example constructing on site

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[6] Schmidt-Lainé Cl., Pavé A., *Op.Cit.*, and, also: [SCH 08].

a model of a village encompassing farmers, resources, environmental and social management, integrating all other necessary components, simulating the effects of decision, modifying the model as needed to refine the choices between a set of possibilities, etc.

Modeling climatic changes and their effects is another example, more commonly known than the previous one, where coupling global circulation model (GCM) and ecological models enables to simulate different scenarios according to hypotheses concerning greenhouse gas emissions, both to evaluate the effects on ecosystems and, conversely, the role of ecosystems in climate change. Many references can be found in the intergovernmental panel on climate change (IPCC) reports.

Although the notion of complexity is not yet stabilized, we could adopt an intuitive one: on the one hand a set of many interrelated entities, where relationships are nonlinear, and on the other hand a system which exhibits a "complex" behavior, such as a chaotic one. Historically, this notion has been established by studying the statistics of ideal gas properties (for instance temperature or pressure), which have been deduced from the physical behavior of a great number of molecules constituting the gas (ideal gas kinetics theory). However, to observe complex dynamics, numerous entities are not necessary. For example, for one population with non-recovery generations, modeled by a discrete time non-linear equation can exhibits chaos (see Figure 8.2), or for a continuous time model, 3 state variables are necessary and sufficient. Since the 1990's a great effort has been made to simulate animal behavior and their consequences. For example "Collective Artificial Intelligence" or social structures emerging from elementary agents responding to simple rules. This was the case for ant societies [DRO 93, KAT 11] and also fish shoals. However, aside from these cases, we have difficulties in modelling the emergence of properties linked to complex systems, particularly hierarchically organized ones [PAV 03, PAV 06]. Finally, socio-ecosystems, mixing human societies and ecological systems, can obviously considered complex systems. Modeling them requires interdisciplinary effort, and conversely might lead to a better understanding of these systems.

However, it is important that we also consider simple reasoning and solutions, as it may be capable of some astonishing predictions in economics or in ecology. So, systems are so complex that considering only simple subsets, or only to be few relationships (moreover often assumed linear) may lead to false conclusions. We have to make “the choice of complexity” by relativizing such conclusions, avoiding such approaches, or better still to build models, which take into account this complexity.

Ultimately, we have to insist that the role of models in the emergence and the elaboration of concepts, theories and methods shared by divers disciplines, such as the notion of complexity, is under debate [DEF 15]. The viability of systems, proposed by J.P. Aubin [AUB 10], includes possible regulations, and applications in ecosystem studies are becoming increasingly considered, for example this recent article on a marine ecosystem [GOU 15].

Models have become transverse objects and are often embedded in systemic approaches, which are a common methodology as presented in Chapter 1. Modeling is now a common methodology shared by many scientific and technological domains, which is the result of much hard work and reflection. For example, during 1989 a scientific committee, whose president was the eminent mathematicians Kahane J.P., proposed a report to the CNRS entitled: “Interactions of mathematics”. During the Autumn of 1990 the interdisciplinary research programme on the environment created a scientific committee named “Methods, Models and Theories” and its respective research group and some years later the CNRS supported another interdisciplinary programme on “Modeling and Numerical Simulation”. Other examples could be cited. Earlier, we described some negative reactions on the part of the scientific community, which considered that modeling either had a limited interest or was reserved to an “elite”. Curiously, that was not the opinion most mathematicians, who interested were by the concrete applications of their works. After 25 years the consequences were assessed: the common, shared and transverse status of modeling was acquired. Never, we have to be careful with its use [BOU 14], to pinpoint its limits, particularly in a predictive capacity, to recognize that determinism is not synonymous with predictability, and that a lot of amazing behavior can be exhibited by nonlinear models. There is wealth but also risk. Finally, all of these advances have revitalised the theoretical effort which was for a time neglected at the benefit of empiricism. A good theory is the best way to promote efficient applications, empiricism is at least, better than to do nothing however, and can result in the origin of new theories.

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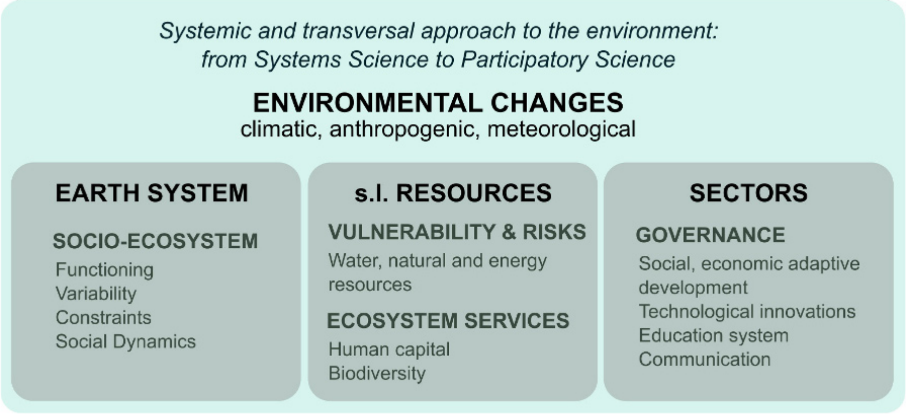

Systemic and transversal approach to the environment: from Systems Science to Participatory Science

ENVIRONMENTAL CHANGES
climatic, anthropogenic, meteorological

EARTH SYSTEM

SOCIO-ECOSYSTEM
Functioning
Variability
Constraints
Social Dynamics

s.l. RESOURCES

VULNERABILITY & RISKS
Water, natural and energy resources

ECOSYSTEM SERVICES
Human capital
Biodiversity

SECTORS

GOVERNANCE
Social, economic adaptive development
Technological innovations
Education system
Communication

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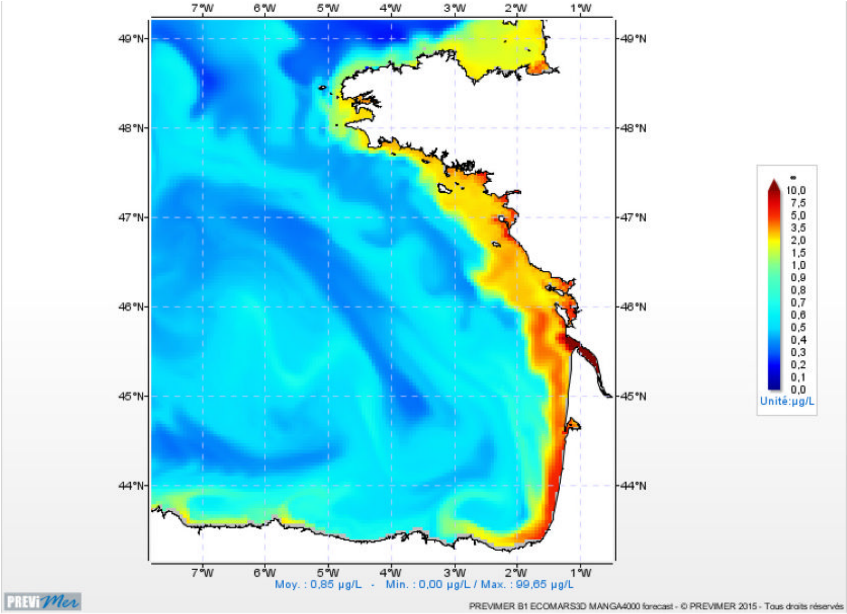

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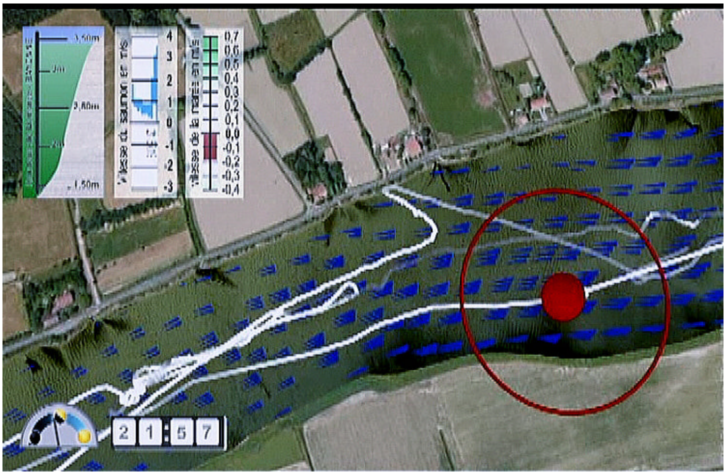

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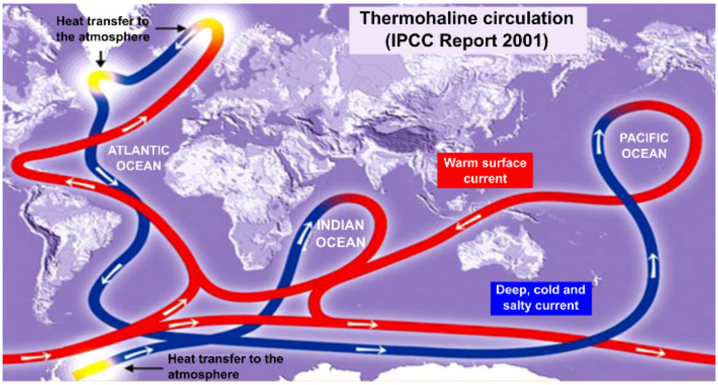

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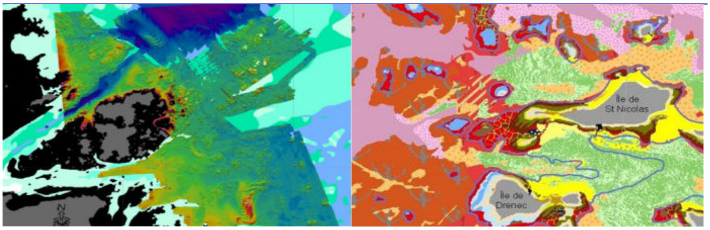

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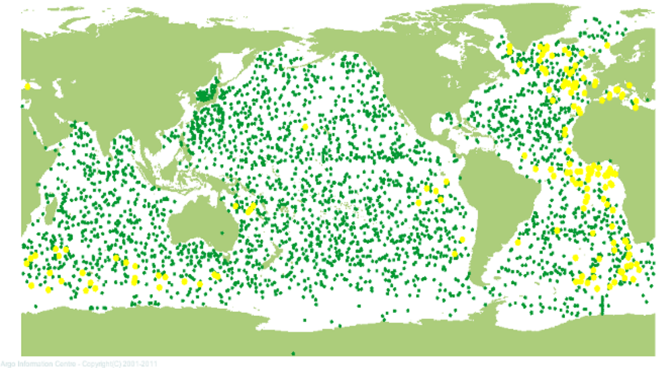

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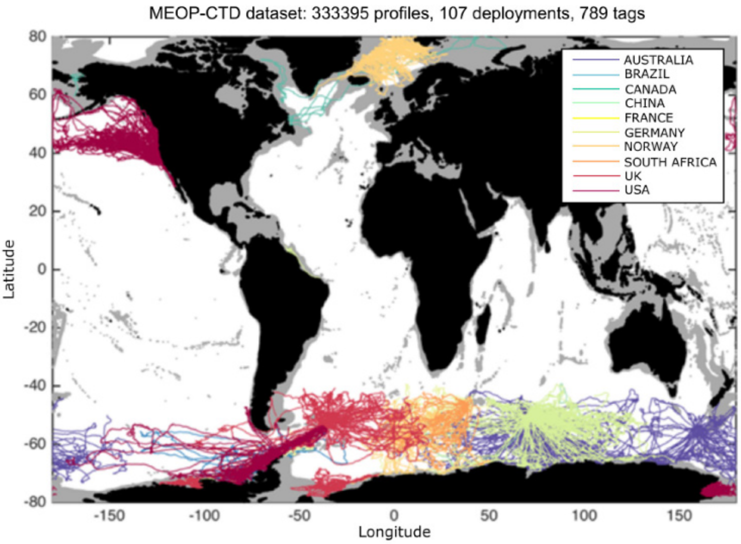

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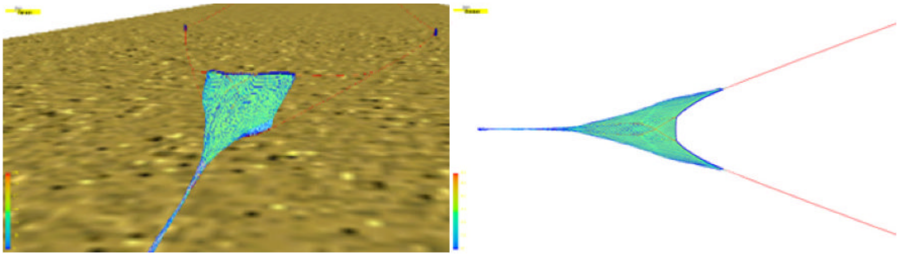

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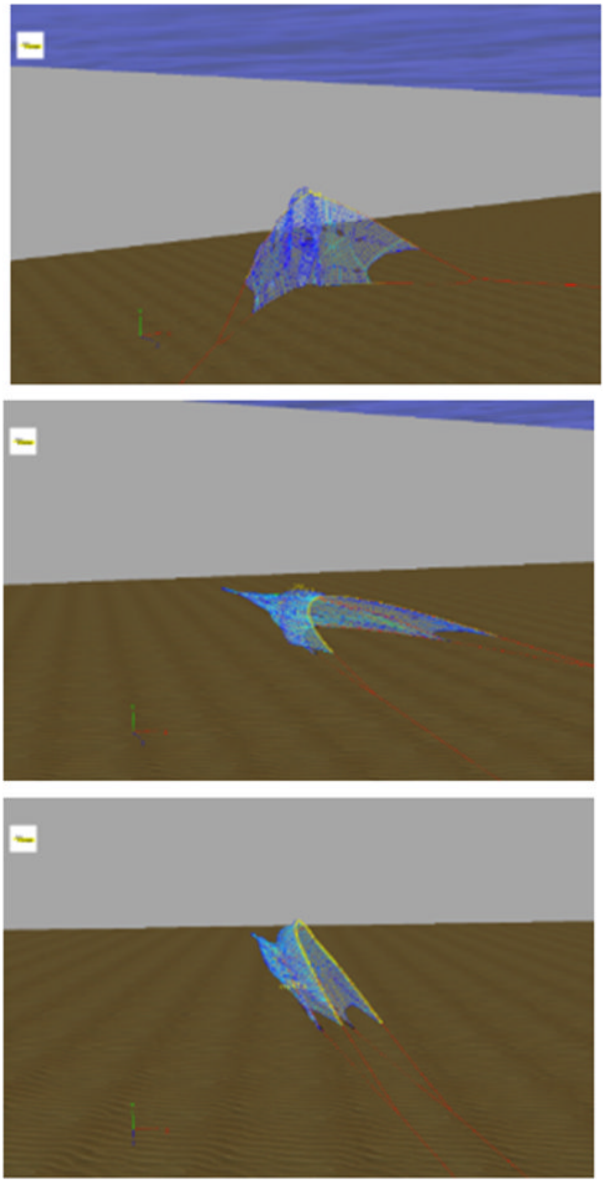

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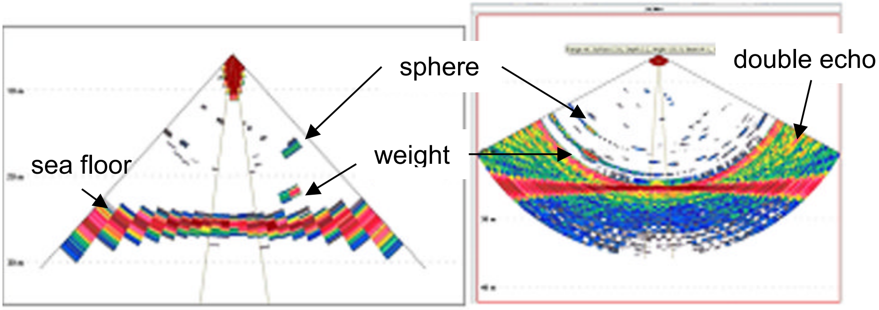

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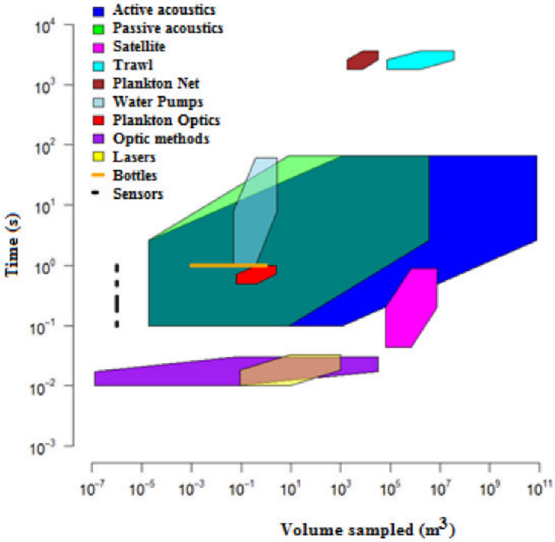

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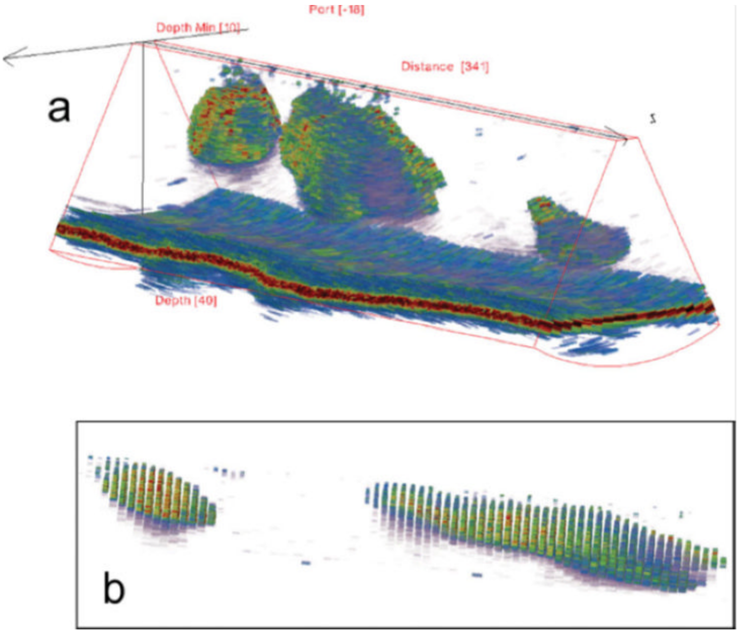

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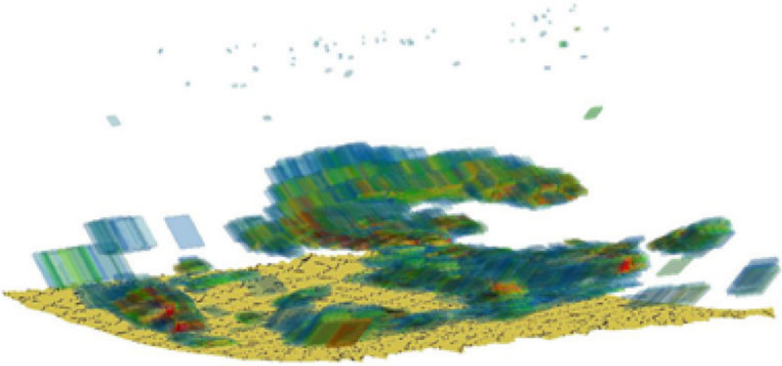

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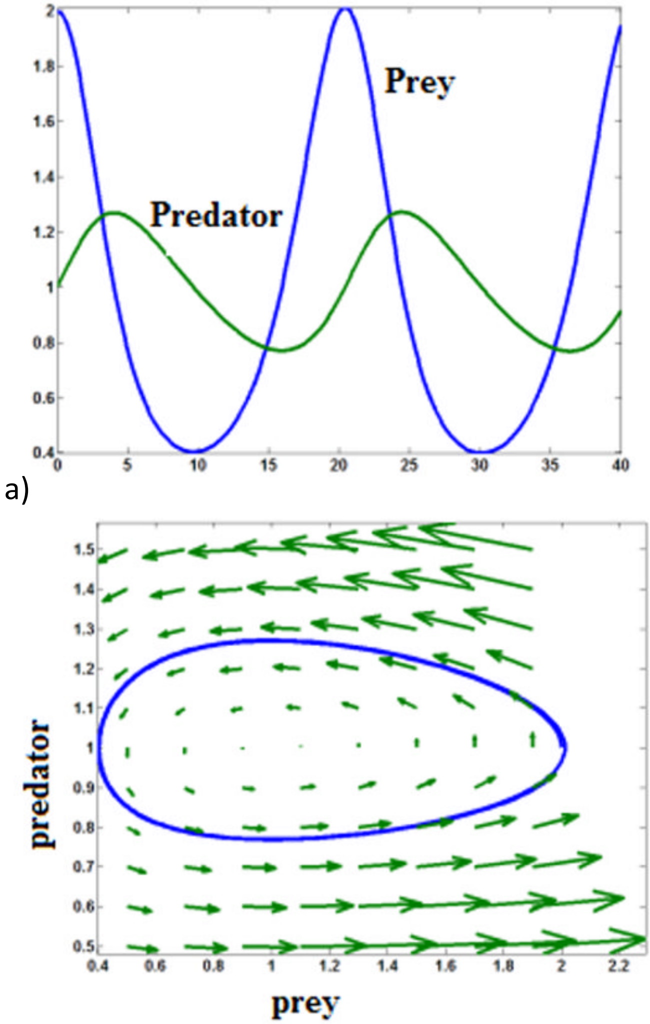

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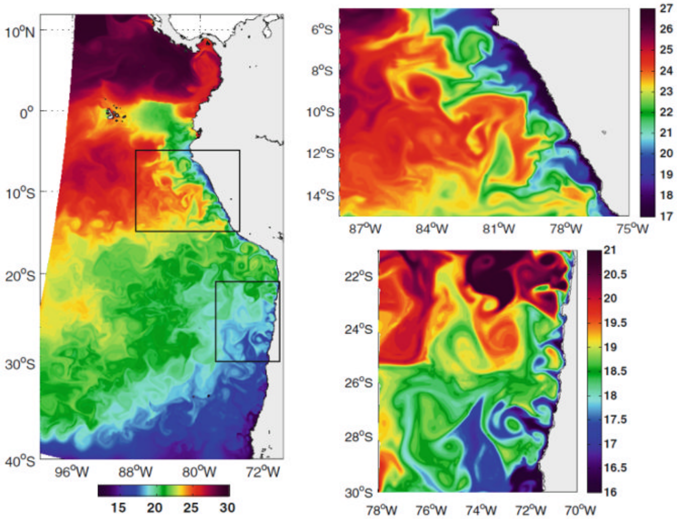

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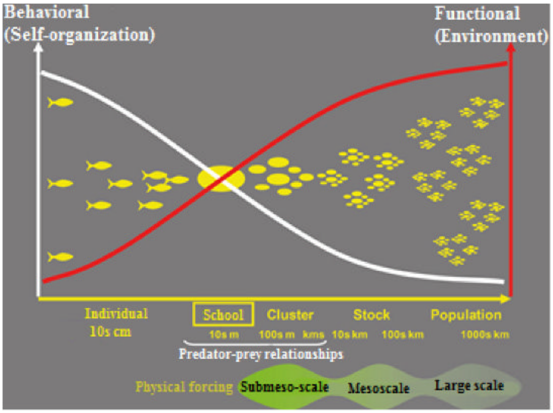

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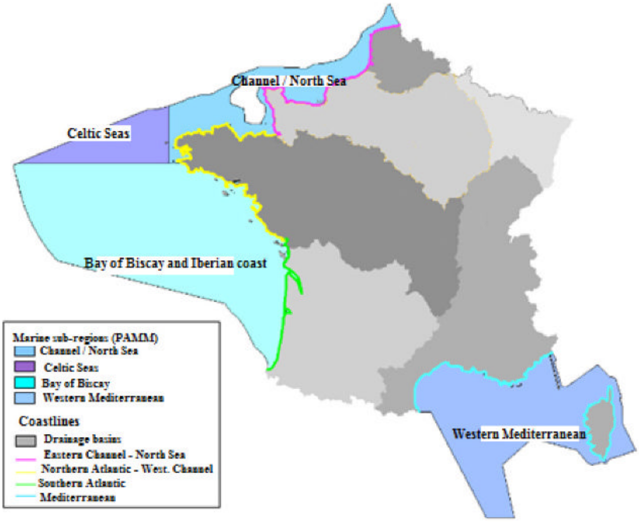

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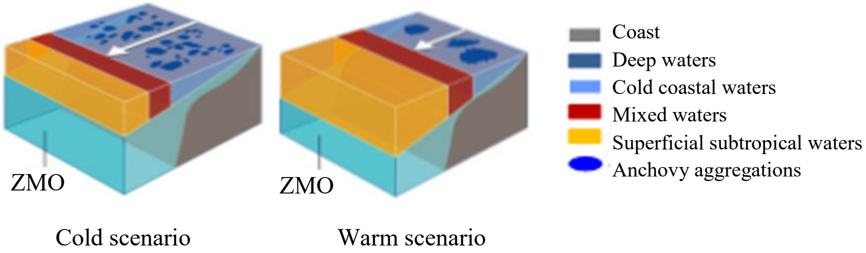

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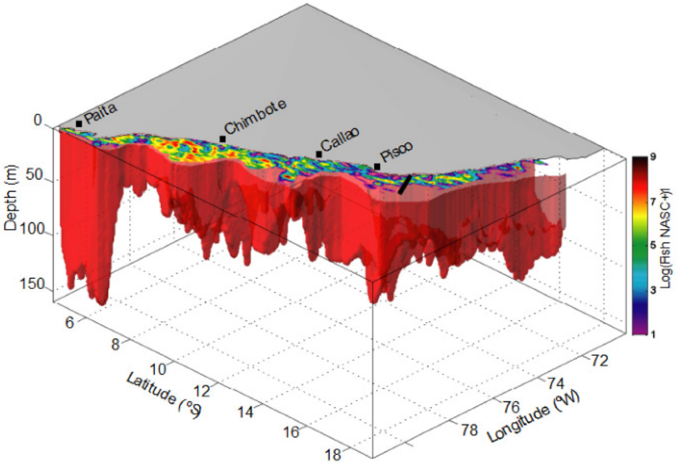

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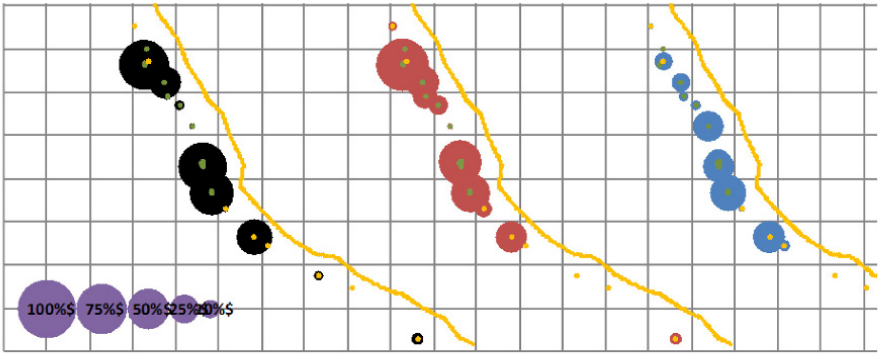

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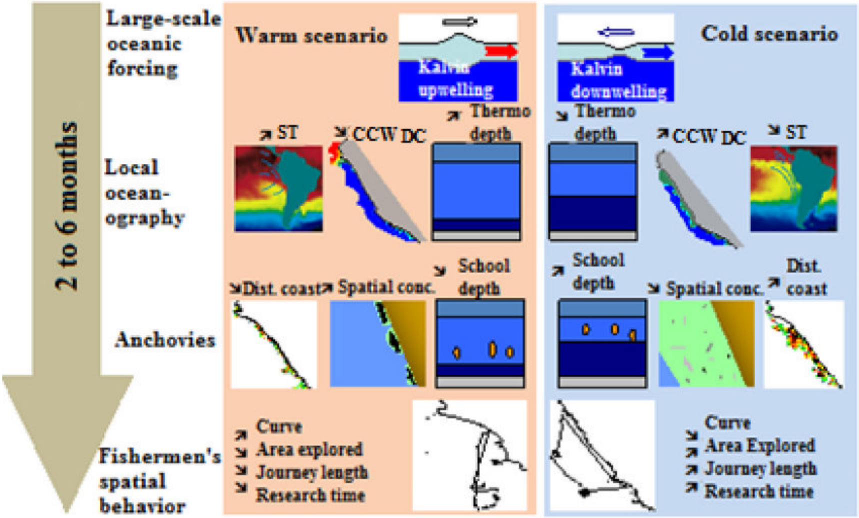

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