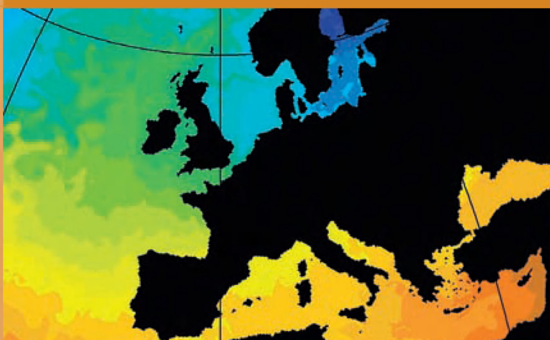
Marine Board Special Report

Climate Change and Marine Ecosystem Research

Synthesis of European Research on the Effects of Climate Change on Marine Environments

September 2011



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Climate Change and Marine Ecosystem Research

Synthesis of European Research on the Effects of Climate Change on Marine Environments

Marine Board Special Report

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Executive Summary

It is now commonly accepted that climate change poses one of the main challenges faced by society in the coming decades. Changes in patterns of air temperature, precipitation, extreme weather events, and the impacts of such changes on terrestrial environments, often form the focus of public and political concern. The marine environment and marine ecosystems are also being impacted by climate change, with consequent impacts on all terrestrial environments (not just coastal) and thus on society itself. Although there is no certainty regarding the precise nature and rate of future climate change, even the more moderate of the predicted scenarios is expected to further alter the marine environment, with major environmental, economic and social consequences.

Scientific research has contributed to a significantly improved knowledge and understanding of the current and future potential impacts of climate change on the marine environment. However, this knowledge has rarely been adequately communicated beyond the scientific community and, as a result, the impacts are not well known or understood by politicians, policy makers and the general public. This gap in the knowledge and understanding of the impacts of climate change on the marine environment between scientists and non-specialists forms the main focus of the CLAMER project (European Framework Programme 7 Coordinated Support Action on Climate Change and Marine Ecosystem Research). It starts from the premise that those charged with making difficult decisions on whether and how to implement measures to adapt to the inevitable changes which are taking place, need access to the best scientific knowledge, translated into a format that they can understand and use. Moreover, the general public also need to understand the risks and implications of climate change impacts. Only through adequate knowledge and understanding of the potential consequences of climate change can the public support decisions made by public representatives on appropriate adaptation measures, which may require significant investments of public funds.

In the past 15 years, successive European Union Framework Programmes (EU FP) have supported broad-ranging and multidisciplinary research on how climate change affects marine systems at various spatiotemporal scales, ranging, for example, from long-term global effects of CO_2 concentrations on the biosphere, to the immediate effects of local temperatures on the metabolism of bacteria. European scientists have achieved major advances within various fields and have contributed extensively to the working groups and synthesis reports of the Intergovernmental Panel on Climate Change (IPCC). Furthermore, much has been learned from regional climate research initiatives, for example, in the Baltic Sea (BALTEX), the North Sea (BASIN, RECLAIM) and the Mediterranean (MEDCLIVAR).

As part of the CLAMER project, marine scientists drawn from a broad range of disciplines have provided a summary overview of recent research on climate change impacts on the marine environment (with a particular focus on EU-funded research) and identified key scientific gaps and priorities for future research. This synthesis report brings together, in a consistent format, the analyses and recommendations of these experts according to thematic and regional categories. It illustrates beyond reasonable doubt that climate change has already impacted on all of the oceans and seas of Europe and beyond. It also identifies the clear variation in type and extent of impacts which can be found across Europe's regional seas. Most of the observed changes discussed in this report, thought to be predominantly a consequence of climate change, can be categorised as follows:

- Physical changes in the seas and oceans (e.g. sea-level rise, sea temperature increase and stratification);
- Melting of Arctic sea-ice and associated impacts (e.g. changes in the Arctic foodweb and trans-Arctic migrations);
- Changes in abundance and distribution of marine organisms and populations (e.g. fish, such as cod, haddock and herring, populations of which have extended northward and eastward at high latitudes);
- Shifts in seasonal migration patterns of marine species (e.g. shift from seasonal migration for spawning and feeding to overwintering of the fish species dorado (*Sparatus aurata*) and salema (*Sarpa salpa*) in a warming Black Sea);
- Cumulative effects of multiple stressors (e.g. impacts arising from, or compounded by, a combination of climate change, ocean acidification, hypoxia, fisheries and eutrophication); and
- Socio-economic consequences of all of these changes (e.g. impacts on commercial fisheries and tourism, coastal inundation and erosion, etc.).

As presented in this report, a panel of European scientists (many of which are CLAMER project partners) have identified important gaps in scientific knowledge which must be urgently addressed to improve both the understanding of marine climate change and its impacts and also the accuracy of predictions of future patterns of change (see Executive Summary Boxes A and B).

In order to formulate better adaptive strategies to address the consequences of climate change, it will be essential to:

- Improve methods to reduce the uncertainty of climate change projections;
- Ensure the accuracy of measurements and predictions by means of an integrated monitoring and observation network; and
- Further improve the exchange of knowledge within the scientific community and between scientists, policy makers and the public at large.

It is clear from this report that much progress is still needed to improve the understanding of the impacts of climate change and to more accurately predict future changes and impacts. Attribution and prediction of climate impacts require that the dominant processes across all spatial and temporal scales should be identified and considered. However, most studies on climate change impacts on the marine environment focus only on a limited part of the full spatiotemporal range, i.e. limited to a particular scale in space or time. All relevant research disciplines (i.e. meteorology, oceanography, biogeochemistry and ecology) should be involved to cover full cascading chains. To improve the accuracy of the projections on the impacts of climate change on marine systems, the cascading chains under focus must be linked to the interacting scales in time and space of the socio-economic systems which govern the responses of society. Therefore, multidisciplinary approaches will need to consider the most appropriate range in spatiotemporal scales and include the social, economic and humanities sciences in order to further understand and predict the inevitable impacts of climate change on marine environments and to develop truly integrated and complete adaptation responses.

In this report, the analyses of progress and gaps in research on impacts of climate change on the marine environment are presented according to thematic (e.g. sea-level rise, coastal erosion, etc.) and regional (e.g. Baltic, Atlantic, etc.) categories. A separate chapter is devoted to each identified theme, which includes, in each case, a list of critical research gaps and future research priorities. These represent a key output of the report and are summarised in Executive Summary Boxes A and B below.

Executive Summary Box A.
Climate Change and European Marine Ecosystem Research Gaps and Priorities per Theme

Themes	Research Gaps and Priorities
Sea-level Changes	• Improve understanding of ice sheet break-up processes; • Integrate modelling of ice sheet changes into global climate models; • Improve understanding of coastal sea-level forcing mechanisms and couple it with the regional variability in climate models; • Develop a robust and efficient monitoring system for mass changes in Greenland and Antarctica; • Develop reliable techniques to forecast regional / local sea-level rise.
Coastal Erosion	• Increase research into relative sea-level trends in relation to future storm tracks; • Develop and undertake a detailed assessment of the extent of coastal erosion in the EU at appropriate temporal and spatial scales; • Improve the societal understanding of coastal erosion and of the difference between coastal protection (defending property) and protection of the coastal ecosystem (which may involve sacrificing coastal property).
Temperature Changes	• Identify and reduce the sea surface temperature (SST) and sea-ice-related uncertainty in climate modelling systems; • Increase the resolution and number of coupled regional atmosphere - ocean circulation models; • Improve the parameterization of dominant processes for accurate SST simulation in coupled climate models, both at global and regional scales; • Develop reliable 3D baroclinic ocean climate models for climate study.

Executive Summary Box A. Climate Change and European Marine Ecosystem Research Gaps and Priorities per Theme	
Themes	**Research Gaps and Priorities**
Ice Melting	• Improve understanding of properties of snow cover on sea-ice; • Improve the assimilation of observation data in models of the Arctic sea-ice cover, in particular by relating ice physical parameters to electromagnetic properties (observed by satellites) in the development of forward models; • Improve the understanding of the interaction between the ocean and ice melt in order to quantify the role of changing oceanographic conditions in sea-ice melting.
Storm Frequency and Intensity	• Develop and use wind data sets which describe intensity and frequency of storms in a consistent manner; • Increase the efforts to analyse regional sea-level in relation to changing storm surges.
Changing Stratification	• Investigate if increasing atmospheric supply of nutrients could potentially offset the reduced oceanic vertical supply; • Improve the ability to predict the knock-on effects of altered productivity throughout marine ecosystems, including in complex ecosystems with many trophic levels; • Consider the effects of altered stratification in the broader context of how other ocean properties are altered - in particular the depth of the mixed layer – as part of a holistic assessment of the cumulative climate change effects on the ocean.
Thermohaline Circulation Changes	• Increase understanding of the key factors determining thermohaline circulation changes and possible collapse, and determine: - Changes in freshwater input to the North Atlantic resulting from global warming, - All thresholds that could lead to a collapse of the thermohaline circulation (THC), - The risk of exceeding a threshold for THC collapse for a given warming; - The consequences of collapse in the THC; • Determine how predictable the THC system is using today's generation of climate models and how these predictions can refine climate forecasts (particularly on the decadal scale).
Riverine Discharge and Nutrient Loads	• Improve the understanding of the interactive effects of floods, global temperature increases and coastal biogeochemistry; • Couple regional climate change scenarios with river basin, nutrient transfer and coastal ecosystem models, to test the interacting effects of global climate change with scenarios of regional socio-economic change; • Create a better understanding of the possible responses of the coastal ecosystems to changing riverine nutrient loads, both quantitatively and qualitatively.
Ocean Acidification	• Significantly improve the understanding of the impacts of ocean acidification on marine taxa; • Increase attention towards acclimation and adaptation, both at the level of the individual organism, and at the community level;

Executive Summary Box A. Climate Change and European Marine Ecosystem Research Gaps and Priorities per Theme	
Themes	**Research Gaps and Priorities**
Ocean Acidification	• Address the synergy between simultaneous changes of temperature, oxygen and pH; • Improve the representation of biological responses to climate change and ocean acidification in regional and global models.
Ocean deoxygenation and coastal hypoxia	• Characterize the spatial and temporal dynamics of oxygen in both open ocean and coastal environments; • Identify the drivers of oxygen depletion and distinguish natural variability from anthropogenic impacts; • Establish a global observation system that continuously monitors oxygen concentrations at high resolutions, which is linked to other physical and biogeochemical parameters as well as to climate observations; • Improve existing models to better predict the frequency, intensity and duration of future hypoxia events.
Impacts of Climate Change on Marine Eutrophication	• Increase the amount of consistent measurements of pelagic primary production; • Address the virtual lack of data on benthic primary production in shallow seas; • Improve the knowledge to differentiate between the many factors which simultaneously affect rates of both growth and loss of microalgae; • Improve understanding of nutrient load impacts on primary production, and identify and quantify trophic transfers between primary and secondary producers to support the development of realistic and ecologically sound management strategies for sustainable use of coastal seas in a changing environment.
Biological Impacts	• Link biodiversity with ecosystem modelling and ecology with biogeochemistry to improve prediction and risk analysis of climate change impacts on biological communities and ecosystems; • Further develop the application of individual based models (IBMs) in climate change predictions; • Tackle the lack of knowledge about the ability for marine organisms to adapt and evolve to climate change on relevant timescales; • Drastically improve the level of detail in the understanding of the impacts of fishing on the abilities of marine populations and ecosystems to respond to climate change; • Ensure systematic and sustained observation on long-term and large-scale changes in distribution of key organisms and biodiversity to keep track of change, understand risk and allow adequate mitigation.
The Baltic Sea	• Develop a system approach for Baltic Sea climate change research, which may include developing a fully coupled Baltic Sea earth system model (atmosphere-hydrological-catchment-ocean-ice-wave-biogeochemical-SPM-larvae-fish models), providing high quality multi-model coupled ensembles for the Baltic Sea climate simulations, investigating the stability and predictability of the system and developing scenario-based predictions in decadal and centennial scales; • Further improve existing Baltic Sea observing systems for supporting the system approach of Baltic climate change research, especially for biogeochemical parameters;

Executive Summary Box A. Climate Change and European Marine Ecosystem Research Gaps and Priorities per Theme	
Themes	**Research Gaps and Priorities**
The Baltic Sea	• Improve understanding of existing Baltic Sea climate change processes, and the relative importance of internal and external factors which will give a solid base for scenario-based predictions; • Solve key issues in using ecological models for climate research such as the reconstruction of past ecosystem changes including regime shifts, development of ecosystem forecast at seasonal and decadal scales and eintegration of the internal budget balance in long-term ecological models.
The North Sea	• Develop a better systematic observation and process understanding of atmospheric and oceanic parameters, and increase the temporal and spatial coverage of monitoring and research on the major biotic components (plankton, benthos, and fish); • Improve Global Circulation Models (GCMs) to capture the decadal (NAO) and multi-decadal (AMO) scale variations in ocean climate, and develop regional downscaling models based on different GCMs; • Extend biophysical modelling of single species beyond the egg and larval stages to better predict climate-driven changes on marine fish populations; • Improve lower trophic level ecosystem models, placing more emphasis on pelagic-benthic coupling of marine systems and improve the linkages between models of the upper trophic web and biogeochemical and nutrient-phytoplankton-zooplankton-detritus (NPZD) models; • Strengthen research efforts on the growth physiology of key species and their life stages, as well as on the physiological effects of acidification on multiple stressors.
The Arctic Ocean	• Significantly improve the provision of basic data from key regions of the Arctic Ocean, in particular on lower trophic levels and processes and better seasonal and spatial coverage, to validate current models which must also be improved with regard to physical forcing; • Improve pan-Arctic integration and holistic understanding of the circular Mediterranean-type Arctic Ocean, which implies increased coverage of ice-strengthened research vessels, more emphasis on permanent instrumentation, and an increased number of stations that can be used throughout the year; • Improve knowledge on temperature-dependent respiration and metabolism at low temperatures, and stage-structured models for key zooplankton stages in order to simulate their ability to conquer new geographical areas; • Develop a greater and better integrated and internationally coordinated research effort on the entire Arctic Ocean, e.g. through a joint action of the Arctic Council, the European Polar Board and/or International Arctic Science Committee (IASC); • Improve the understanding of how physical and chemical oceanography shape the dynamics of ecosystems, determine the new and harvestable production and the biogeochemical cycling (including exchange with the atmosphere) and pelagic-benthic coupling; • Develop management tools to evaluate the state of Arctic environments in relation to climate change and increased stress by a resource-demanding world economy.

Executive Summary Box B.
Climate Change and European Marine Ecosystem Research Gaps and Priorities per Region

Region	Research Gaps and Priorities
The North Atlantic	• Drastically improve the understanding and model predictability with regard to changes in ocean–atmosphere interactions and atmospheric teleconnection patterns, such as the Atlantic Multi-decadal Oscillation (AMO) and the North Atlantic Oscillation (NAO), and their potential effects on future climate change; • Ensure that the North Atlantic is a key component of an integrated global ocean observing programme by addressing current perceived short-comings such as the lack of continuous time series of key ocean–climate variables which is preventing progress in modelling climate feedbacks; • Improve biogeochemical models to take into account the full complexity of marine ecosystems, in particular in relation to the complex biodiversity and functioning of microbial systems and their feedback to biogeochemical cycles; • Expand research on the impact of acidification to include non-calcifying organisms, and ecosystem components and processes such as nutrient speciation and availability, trophic interactions, reproduction, metabolism, diseases, etc. which may impact on all organisms but most critically on primary producers; • Improve the scientific basis for fisheries management through improved research and monitoring of fish stocks as part of the implementation of a whole-ecosystem approach to understanding the effects of climate change.
The Mediterranean Sea	• Improve the understanding of the impacts of climate change on the structural and functional biodiversity (including marine microbes and viruses), ecosystem services, and biogeochemical cycles of the Mediterranean; • Improve understanding of existing climate change features using the North Adriatic Sea and the Ligurian Sea Gulf of Lion as a reference for the impact of rising temperatures on the cold water Mediterranean regions; • Improve knowledge of the present-day changes occurring in the deep-sea Mediterranean and their impacts; • Implement identified Mediterranean sites investigated for the L-TER long-term ecological monitoring, including sites and observatories in the deep sea; • Identify species and areas for environmental conservation in order to limit the impact of climate change on species with cold water affinity; • Improve the understanding of the synergistic effect of direct anthropogenic impact and climate change on Mediterranean habitats and functions;
The Black Sea	• Develop a better understanding of the interplay between the natural and anthropogenic impacts of climate change, coastal and interior basin ecosystems, and the well-being of people by means of systematic observations; • Improve monitoring of social and natural system indicators to develop reliable scenario models that will serve as a basis for designing appropriate management strategies and decision making processes towards sustainable use of ecosystem goods and services in the Black Sea, i.e. identifying ecosystem properties that are most vulnerable to abrupt and dramatic state changes in response to climate change, and the climatic and ecological determinants of such changes; establishing which system properties can be used to forecast system resiliency, etc.

Executive Summary Box B. Climate Change and European Marine Ecosystem Research Gaps and Priorities per Region	
Region	**Research Gaps and Priorities**
The Black Sea	• Develop predictive models for a better understanding of how climate change and variations affect hydrographic structure and circulation (e.g., stratification, thermal regimes, and current patterns) and their impacts on the nutrient and organic matter input, energy and nutrient exchanges, biological diversity, structure and function of the food web, and primary and secondary production; • Introduce a research programme on the impacts of acidification in the Black Sea.

1. Introduction

Climate change poses, without doubt, one of the main challenges faced by society in the coming decades. Changes in weather patterns, air temperature and precipitation, extreme weather conditions as well as the impacts of such changes on terrestrial environments, have become cause of considerable public and political concern. The marine environment and marine ecosystems are also being impacted by climate change with important consequences for all terrestrial environments (not just coastal) and therefore society itself. However, many of the impacts on the marine environment are not well known or understood by the general public and decision makers.

Over the past 15 years, both EU Member States and the European Union have funded important research efforts to understand and evaluate the impacts of climate change. This research has led to important advances in scientific knowledge and understanding of climate change processes and implications. Unfortunately, research results have not been sufficiently well synthesised, translated and communicated to trigger adequate policy responses, in particular with respect to the marine environment. In addition, the general public still largely underestimate the scale and socio-economic consequences of marine ecosystem change linked to climate change, and the potential socio-economic consequences of such change.

The CLAMER project builds upon the realization that there is a gap between what is known through research and what policy makers and the public know and understand about the impacts of climate change on the seas and oceans. This gap needs to be filled to catalyse the formulation and acceptance of necessary climate change mitigation and adaptation measures for the marine environment. The overarching aim of the CLAMER project is to raise the awareness of citizens to EU research results on the impacts of climate change on the marine environment, including their socio-economic consequences.

This CLAMER Science Synthesis, published as a Marine Board Special Report, aims to: (i) highlight the crucial role of oceans in regulating the climate system and in carbon cycling; (ii) provide a summary overview of relevant scientific knowledge, in particular that arising from European research, of the impacts of climate change on European marine environments; and (iii) identify key scientific gaps and priorities for future research. Amongst others, the report shows that European research projects have significantly contributed to the scientific understanding of the impacts of climate change on the marine environment and the associated socio-economic consequences in Europe and beyond.

This report presents a collection of contributions from European experts involving, through the CLAMER project, coordinators of major European marine ecosystem research activities of the last decade. The research and projects they represent have collectively involved thousands of scientists, including Europe's top scientists in the relevant fields, and covered the major regional seas of Europe. Given the disparity of the contributions, the report's style, emphasis and level of detail may vary from chapter to chapter. Moreover, the report is not a comprehensive scientific review, but a broad, high-level integrated source of information for policy makers and advisors, non-climate or marine scientists and interested public, ready to be used both to inform policy and to develop derived communication products within and beyond the CLAMER project.

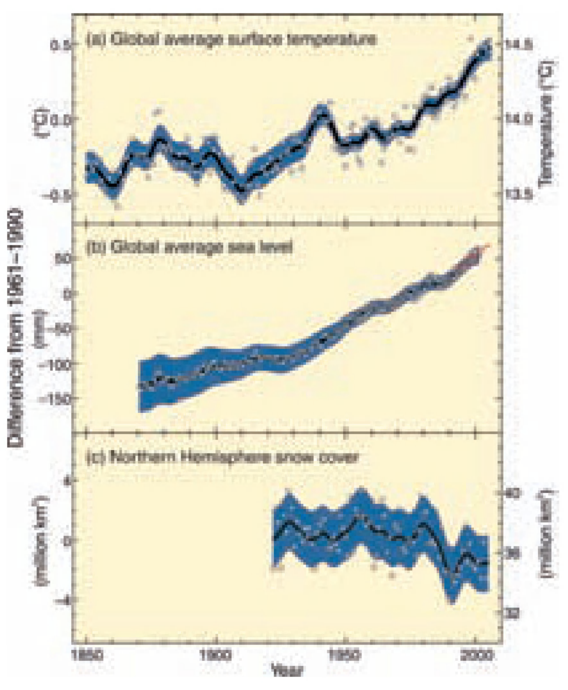

Figure 1. Observed changes in (a) global average surface temperature; (b) global average sea-level from tide gauge (blue) and satellite (red) data; and (c) Northern Hemisphere snow cover for March-April. All differences are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). (From IPPC Fourth Assessment Report, 2007)

2. What are the Main Observed and Expected Impacts of Climate Change on the Marine Environment?

2.1 Sea-level Changes

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2.1.1 Observations

Sea-level change poses significant risks to European coastlines. Changes in local mean sea-level and sea-level extremes are presently the primary concern for policy makers. However, changes in the seasonal cycle and the tidal signal may also be important at particular locations.

Global mean sea-level is primarily driven by the addition of heat (steric component) and mass (mass addition component) to the oceans, the former through the atmosphere, the latter by melting ice-sheets and glaciers. Indirect anthropogenic contributions to sea-level rise such as groundwater withdrawal, surface water diversion and land-use changes may also contribute significantly to the observed sea-level rise. The effect of salinity is, at global scale, of secondary importance.

The global mean sea-level signal is spatially variable because it is affected by the response of the earth's crust to the removal of ice-sheets and the distribution of the added fresh water and heat through the oceanic circulation. The wide range of values in this spatial distribution has the consequence that even small projected changes of global mean sea-level rise pose significant risks at some parts of the world. There are regions, like the Mediterranean Sea, where salinity changes are as important as temperature changes and distort the global signal.

It is important to differentiate the various quantities that contribute to sea-level rise by monitoring global thermal expansion and mass addition separately. It is also important to differentiate between global sea-level rise as a quantity of climate interest and local sea-level change which is primarily of practical interest. The global signal is dominated by measurements in the open ocean but what matters is the variations of sea-level near the coasts where other processes in addition to those described above dominate the global signal. Most of these processes are likely to be affected by climate change. Thus, changes in atmospheric pressure and wind distribution, oceanic circulation, local temperature and salinity, sediment supply and sediment compaction in estuaries, land movements caused by removal of mass from the earth's crust and tectonic movements are all contributing to the locally observed sea-level.

Global estimates of sea-level rise for the past century have been around 1.8±0.3 mm yr^{-1}. The same sea-level rise values have been claimed for the period 1961-2008. Higher values of around 3.3 mm yr^{-1} are found on the basis of altimetry records for the period from 1993 onwards.

Observed sea-level trends vary considerably around Europe (see Figure 2). At the coasts of the Scandinavian countries sea-level goes down or where it goes up it does so at reduced rates in relation to the global mean. The reason for this is that land is moving upwards due to the removal of ice-sheets after the last glacial period that ended about 10,000 years ago. The southern North Sea tide gauges show, for the period 1901-2008, trends most of which are consistent with the global mean value, within error bars around the global mean for the period. Higher values (2.4 to 4.5 mm yr^{-1}) are estimated for the period 1971-2008. A significant contribution to these higher values has been the increase in the winds associated with the NAO between 1960 and the early 1990s. The sea-level trend values for the UK show large variability in values (-0.7 to 2.7 mm yr^{-1}) with a best estimate of 1.4 mm yr^{-1}. The Atlantic stations of the UK as well as those on the Atlantic coasts of mainland Europe show values smaller than those at the western part of the Atlantic and the global mean. The Mediterranean Sea also shows smaller than the global mean trends of around 1.2 mm yr^{-1} for the past century. Changes in the atmospheric forcing over the Atlantic during winter linked with the North Atlantic Oscillation (NAO) have significantly contributed to the observed spatial pattern of changes. By contrast the Black Sea shows higher than the Mediterranean Sea-level trends for the past century consistent with the values found for the global mean sea-level. In conclusion the distribution of sea-level trends around Europe is not uniform and sub regional spatial patterns are evident.

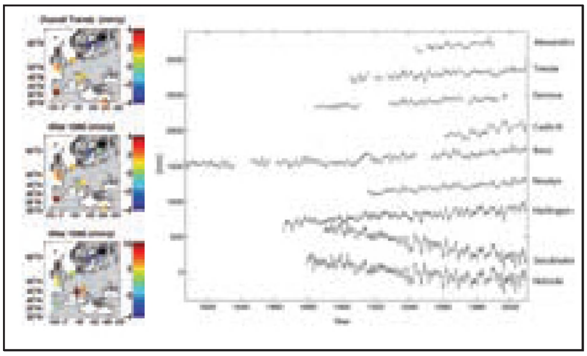


Figure 2. Long term trends of sea-level rise in major European cities: yearly values of sea level in various European coastal locations and Alexandria (right) and resulting estimated linear trends (left). (From Andrew Shaw and Mikis Tsimplis based on data from the Permanent Service for Mean Sea Level website, http://www.psmsl.org/)

2. What are the Main Observed and Expected Impacts of Climate Change on the Marine Environment?

It is unclear whether sea-level has been rising before the industrial period. In any case the anthropogenic perturbation of the system is expected to have accelerated sea-level rise. Some evidence of acceleration at the beginning of the 20th century is evident but the data is sparse and there is a possibility that this was a regional acceleration due to changes in the atmospheric and oceanic circulation in the Atlantic as most of the observations for the period come from this region.

Changes in the extremes of sea-level have been detected in northern and southern European coasts. These changes are consistent with the observed changes in mean sea-level at each location. Thus, as mean sea-level goes up the local extremes increase by the same amount. The agreement in the changes in extreme sea-levels and mean sea-level lead to the conclusion that there have not been significant changes in the strength of the storms that cause the sea-level extremes.

2.1.2 Future Projections

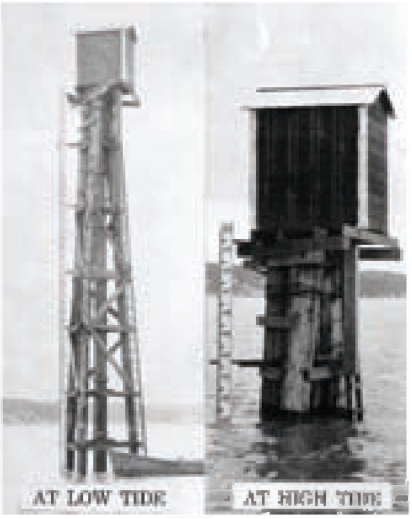
Projections for global sea-level are presently based on climate models or empirical estimates. Projections based on climate models are formed by the addition of two components. The first is the steric component (volume expansion through heat addition) which is believed to be reliable and which is constrained to values lower than 60 cm for all IPCC scenarios until the end of the 21st century. The second component is that of mass addition (addition of water mainly from melting ice) and is calculated separately from the models. There is significant uncertainty attached to the role of non-linear ice-sheet breaking processes and there is also a lack of ground truth measurements to test models of these processes. The uncertainty involved in the estimation of the sea-level rise contribution as a result of water addition from ice-sheets is between 0 to 2 m for the end of the 21st century. The lower values correspond to situations where snowfall and melting are the primary mechanisms. The upper estimates are based on assumptions that the non-linear breaking-up mechanisms of ice sheets dominate the mass addition to the oceans process. Empirical estimates based on the projected atmospheric temperature change in climate models support the higher projected values and suggest changes in the range of 0.8-1.8 m. None of the methods widely used has the resolution or skill to provide estimates for regional or local sea-level, thus high resolution regional models forced with downscaled atmospheric forcing have been developed over the last five years. However, climate models have been focusing on approximating the oceanic circulation. Only recently has the sea-level parametrisation come under scrutiny. Thus, models can give the steric changes and also the contribution from circulation changes. There is no estimate of the mass addition in climate models and this very significant component must be added separately. Therefore, local estimates of sea-level change must combine the steric and circulation components from climate models with the independent mass addition estimates. Uncertainties should also be considered cumulatively although it is clear that freshwater mass addition will affect the oceanic circulation.

Various approaches have been adopted by governments mostly based on ‘expert judgement’ achieved through the formation of different groups of scientists. Thus, for the Dutch coasts a range of 0.4-1.05 m up to 2100 (excluding land subsidence) has been suggested. In the UK, the government provides four scenarios (High++, High, Medium and Low) with a High++ scenario that gives a range between 0.9-1.9 m for the UK coasts. This categorisation depicts the climate model outputs on the one hand and the empirical projection on the other hand. They note that ‘the top of the range is very unlikely to occur in the 21st century’. In Venice, local flood protection construction is undertaken on the assumption that mean sea-level change will be constrained to less than 60 cm.

2.1.3 What Has Been Done to Better Understand Sea-level Changes?

The integration and improvement of the various oceanic, atmospheric and land forcing observational techniques, the monitoring networks and the physical understanding of the various processes all contribute to better understanding of the various components of sea-level change. These would be too many to list here.

Research focused on understanding sea-level rise has been going back several decades. Several national and international projects aimed at standardising, quality controlling and utilising sea-level observations have been run and several are still running. A milestone in the development of an observational database of mean monthly coastal sea-level data was the establishment in 1933 of the Permanent Service of Mean Sea-level presently at NERC Liverpool. Another milestone has been the establishment of the Global Sea-level Observing System (GLOSS) which aims to have 290 tide gauges evenly distributed around the globe operating at high standards. The operation of dedicated altimeters to sea-level study namely the ERS 1 and 2 missions by the European Space Agency and the TOPEX/POSEIDON, Jason 1 and Jason 2 missions by NASA and CNES have revolutionised the way sea-level is understood by providing near global spatial coverage. The addition of the GRACE mission enables the estimation of the



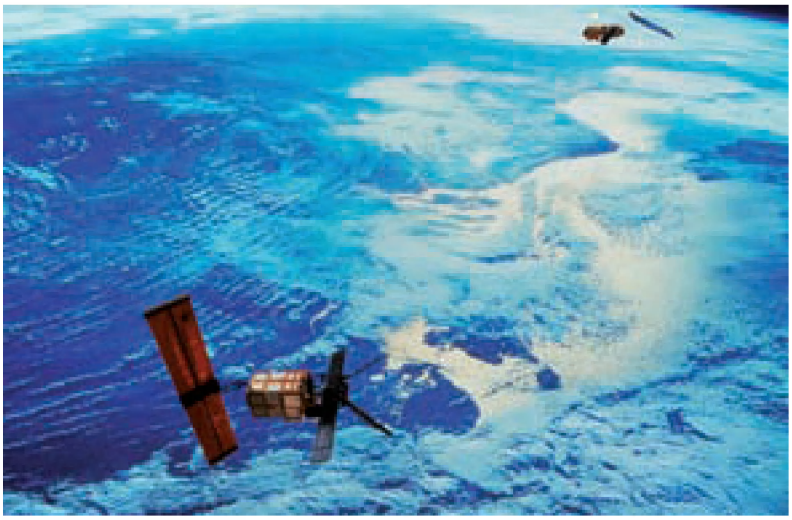


Figure 3. Sea-level is traditionally measured by tide gauges (left - historical tide gauge at Anchorage, Alaska) and since modern space research capabilities also using satellites such as Envisat (right - ©ESA).

mass of the oceans. This together with the Argo floats programme enables the separation of the mass and volume change components of the oceans. However an Argo float programme with instruments monitoring the deeper parts of the ocean will be needed to include steric variations from the whole water column.

Presently the two major issues related to global sea-level rise, relate to monitoring and understanding the behaviour of ice-sheets and developing reliable techniques for obtaining estimates for regional and local sea-level rise as evidently a global mean value is not of much use for coastal protection purposes.

Several projects are presently focusing on ice-sheets and integration of these processes to models. On top of important national dedicated projects, the GRIMICE, Ice2Sea (EU FP7), IceBridge (NASA), SeaRISE, together with the development of dedicated satellite missions to measure the changes in the mass of the Greenland ice-sheets like ICESat and ICESat2 (NASA) and CryoSat (ESA), represent a considerable investment in an attempt to constrain the mass addition contribution to sea-level rise. The development of knowledge of past sea-level behaviour during deglaciation periods may help in resolving the role of non-linear processes. Confirming the existing records by geological evidence or by digitization and analysis of existing sea-level records not yet quality controlled and analysed are worthy exercises which are not substantially funded.

The focus of the research is primarily at global scales and there is much less investment at the international scale in understanding regional variability despite its importance for coastal planning. National agencies of various countries have filled in the gap by developing programmes focusing on understanding regional and local sea-level change.

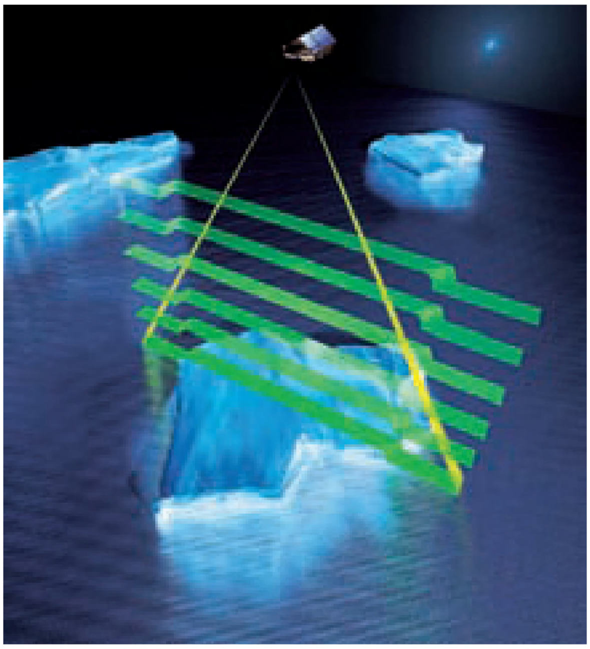


Figure 4. CryoSat-2 is Europe's first operational satellite dedicated to studying the Earth's ice, measuring from its polar orbit the thickness and extent of polar ice, showing how the polar regions are responding to climate change. (©ESA - S. Corvaja, 2010 and AOES Medialab)

2.1.4 Socio-Economic Consequences of Sea-level Rise

Sea-level rise poses significant threats for the population of low-lying areas of the world. The experience of The Netherlands, where a significant proportion of the country has been below mean sea-level for several centuries, demonstrates that existence against advancing sea-level is possible. However, for several low-lying island areas the option of protection is probably too expensive and thus there is a risk of extinction for some low-lying island states and a risk for several million people living near the sea, the relevant infrastructure and the coastal ecosystems. Immediate socio-economic consequences include increased flooding and associated damages, increased erosion of coastal areas, contamination of ground water by salt water and loss of arable land. Vulnerable ecosystems like saltmarshes and mangroves are at risk. Human development will need to adjust and populations will need to be relocated.

The importance of the socio-economic consequences depends on the speed at which sea-level will increase and the level at which it will stabilise. It also depends on the ability of the affected states to provide protection for their coasts. It may be financially more rational to protect marginal seas by regulating their opening to the global ocean than relocating populations and relevant infrastructure. The Baltic and the Mediterranean Sea could be such areas although the former is at a lower risk due to the upward land movements. Such projects will require international cooperation and planning. However, it is obvious that the higher projections discussed would be financially so expensive for coastal states that these eventualities will need to be discussed and their environmental impact assessed.

2.1.5 Research Gaps, Priorities and Key Recommendations

Various issues, including the following need to be addressed:

- The development of a robust and efficient monitoring system for mass changes in Greenland and Antarctica;
- Understanding the relative importance of ice-sheet breaking up processes;
- The integration of modelling of ice-sheet changes into global climate models;
- The resolution of whether sea-level accelerated at the beginning of the 20th century;
- The contribution of waters deeper than 1,000 m to steric sea-level changes;
- Improve the understanding of coastal sea-level forcing mechanisms and coupling them with the regional variability in climate models.

2.1.6 Conclusion

It is highly unlikely that the ice-sheet contribution to sea-level rise issue will be resolved soon, especially if the non-linear breaking up mechanisms are important. The limits of knowledge in understanding and projecting sea-level changes requires the development of financially feasible, practical international portfolios of solutions involving states, regions and populations under threat with clear starting points coupled to observed changes in sea-level rise rates.

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2.2 Coastal Erosion

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2.2.1 Observations

Coastal erosion refers to landward movement of the shoreline prompted by the loss of sediment alongshore or offshore. Erosion is, however, only one element of a complex system of morphological responses of the shoreline to variations in energy (from waves, tides, wind and water currents), sediment supply, relative sea-level and human intervention (Figure 5).

Climate change has potentially important implications for the coastal sedimentary system as a result of: (i) changes in the magnitude/frequency of storms; and (ii) relative sea-level change. Importantly, the coastal response to such changes is often influenced by local geological setting and is therefore highly site-specific. Even without climate or sea-level change, coastlines are dynamic features at various spatial and temporal scales.

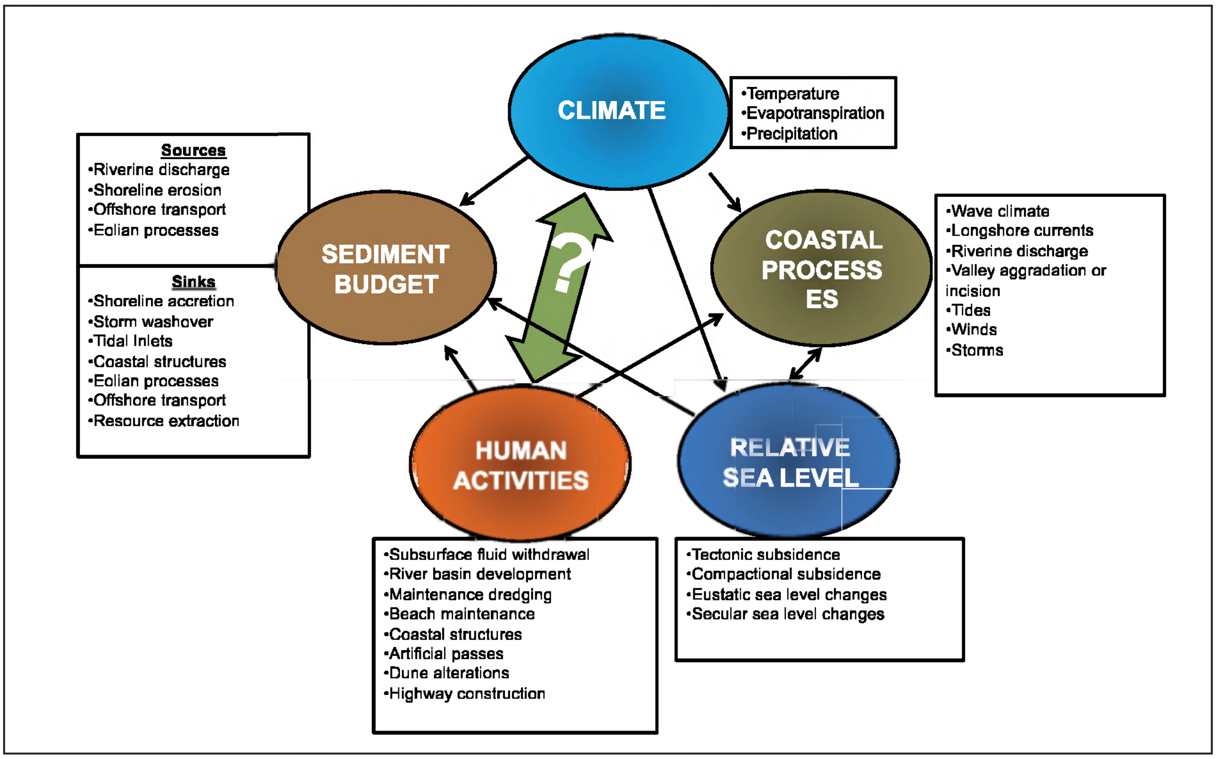

Figure 5. Relationship between shoreline movement and climatic influences (adapted from Pilkey *et al*., 1990)

Episodic extreme events such as storms often produce the most dramatic coastal erosion events, although many natural coasts recover to pre-storm conditions in months, years or decades after such events. Isolating the influences of climate and sea-level change at societal relevant timescales (decades to centuries) is problematic (Pilkey & Cooper, 2004). In general terms, rising sea-level is associated with shoreline retreat; a worldwide dominance of erosion over accretion has been widely reported and attributed to global sea-level rise. The rate and pattern of shoreline response to sea-level rise is, however, moderated by many site-specific factors such as the slope of underlying bedrock and the nature of pre-existing coastal landforms. If adequate sediment exists, coasts can even advance under rising sea-level.

There is a broad trend in relative sea-level behaviour across Europe as a result of interactions between vertical land movements (isostasy) and ocean volume changes (eustasy), with a general relative sea-level fall in the north (due to postglacial land uplift) and sea-level rise in the south. Superimposed upon this broad pattern are regional and local variations imposed by tectonic movements (particularly in the Mediterranean) and subsidence (in the vicinity of large deltas and estuaries). Similarly, there is a broad trend in sediment supply, with southern Mediterranean coasts being supplied with sediment from contemporary rivers, while northern coasts often comprise relict glacial sediment and inputs from contemporary coastal erosion.

Shorelines can experience erosion as part of a long term trend, or through episodic adjustment to storms. The former is progressive while the latter may occur on retreating, stable, or advancing coasts.

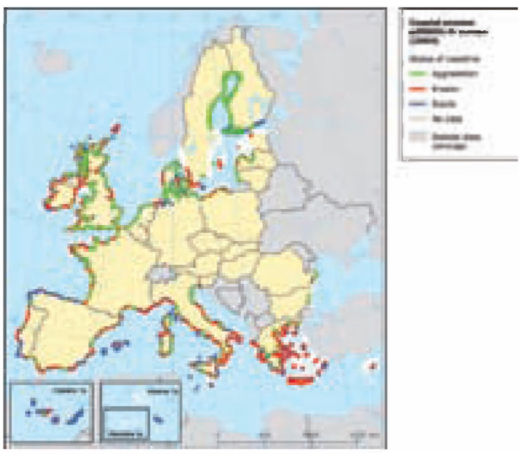

Figure 6. Coastal erosion trends in Europe (EEA, 2004 – based on EU FP6 Eurosion project's data)

2.2.2 Past Trends and Future Projections

Assessment of the erosional status of a coast largely depends on the scale of measurement. It is usually expressed in m yr^{-1} and measured over a few decades, but there is no standard procedure. There are few regional assessments of past and current coastal status in Europe and relatively few local assessments. The EU FP6 Eurosion project presented a crude diagram at European scale of areas of erosion, accretion and stability. It is unclear how this diagram (Figure 6) was derived and on what temporal and spatial scale of measurement it is based. Like all such diagrams, it is somewhat problematic in that several areas that are labelled as accreting have reported serious erosion problems. Only 15 % of the European coast was identified as eroding by the Eurosion study.

Future climate change projections include changes in storm intensity and frequency. In areas likely to experience more frequent or intense storms, an increase in the occurrence of erosional events is to be expected. The projected acceleration in global sea-level rise as a consequence of increased water volume, will likely involve an increase in the rate and extent of landward shoreline migration in southern Europe while in northern Europe areas that are experiencing land uplift may find that sea-level rise now exceeds the rate of land uplift, leading to relative sea-level rise for the first time in millennia. This would increase the extent of coastline subject to coastal erosion.

The most important control on future shoreline trends is the human response to erosion. Two common responses are commonly identified: retreat or defend. Retreat involves allowing the shoreline to respond to changes in external factors and thus find a new equilibrium. This may involve loss of infrastructure or property through erosion as the coastline adjusts, but the coastal ecosystem is maintained as a sustainable and functioning system. Defence is commonly approached either by hard sea defences or 'beach recharge'. Both are commonly employed to protect property, but have negative environmental consequences and perpetual financial costs. They are, however, often easier to implement than retreat policies that involve loss of property.

Across Europe, various forms of coastal defence structure have been emplaced. The EEA's 2006 State of the Coast Report highlighted the high degree of hard engineered intervention around the European coast while a review of beach nourishment in Europe under the SAFE project (Hamm *et al.,* 2002) highlighted the widespread extent of beach nourishment. The EEA report also demonstrated a marked increase in the urbanisation of the coastline, which is likely to increase the demand for defence as a response to erosion. Despite the adoption of the principle of 'working with natural processes' (Cooper & McKenna, 2008) in the EC Recommendation in ICZM, without a major shift in the regulatory framework, the future trend is certain to involve an increase in the extent of coastal defence works.

2.2.3 What Has Been Done to Better Understand Coastal Erosion?

Understanding the current and future patterns of coastal erosion requires knowledge of the current sedimentary context. Numerous geological studies have shown the current European coastal environment to be influenced by low contemporary sediment supply and a long period (3,000–4,000 years) of comparatively low rates of sea-level change. This has enabled many parts of the European coast to mature and achieve dynamic equilibrium with ambient conditions. In the past century, there has been an accelerating trend of human occupation of the coast, engineered interventions in coastal processes, and reduction in sediment supply by dam construction (particularly, in the Mediterranean and Black Sea) and shoreline armouring. This has coincided with an acceleration in sea-level rise and enhanced atmospheric circulation (with more intense storms and changes in storm tracks).

A number of past EU FP projects (e.g. EPOCH, Impacts, Storminess) attempted to understand the relationship between coastline response and sea-level rise and/or storminess at various temporal scales. The site-specificity of response was a common conclusion, although some regional trends in storm tracks could loosely be linked to a regional scale coastal response on the Atlantic coast. In particular, the role of extreme storms on coastal behaviour was highlighted and it was noted that the effects could last for decades, masking the long-term trend.

A number of ongoing European studies aim to better understand the dynamics of coastal response to storms. EU FP7 NESTS is investigating net seaward transport of sediment during coastal storms while EU FP7 MICORE is assessing the morphological impacts of past storms and identifying areas of the European coast at risk from storm-induced erosion.

In the context of contemporary eustatic sea-level rise, there are several global initiatives to measure and model global sea-level rise and create regional projections by incorporating local isostatic influences. EU FP7 SUBCOAST, for example, is monitoring and forecasting subsidence hazards in coastal areas of Europe. EU FP7 THESEUS is developing an early warning system for storm impacts.

A number of studies (e.g. Coast3D) have shown how poorly numerical models predict coastal behaviour, and the impossibility of accurate quantitative predictions of coastal behaviour at relevant spatial and temporal scales has been widely demonstrated. Surprisingly, some new projects (e.g. EU FP7 SIMCOAST) continue to develop coastal morphodynamic models in the unrealisable hope that they might improve predictions. An important, yet widely unappreciated fact, is that only qualitative estimates of future shoreline behaviour are possible and this requires geomorphological assessment of coastal behaviour.

Concern over coastal erosion has also prompted studies of a variety of 'alternative' shoreline defence methods. EU FP7 THESEUS is assessing the utility of 'ecologically friendly' coastal defences. EU FP7 EVERANS is evaluating the efficiency of artificial reefs by numerical modelling while EU FP7 NATARISE is investigating swash-groundwater interactions with a view to assessing beach drainage as an erosion-prevention method.

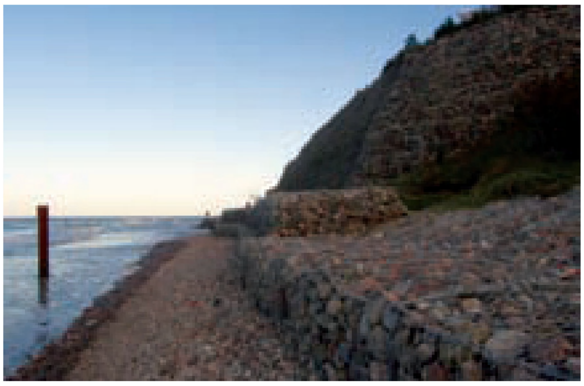

Figure 7. Protection of cliffs against erosion by geotextile and gabion structures in Gdansk, Poland. (©Simon Claus for the EU FP7 Project THESEUS)

2.2.4 Socio-Economic Consequences of Coastal Erosion

The major socio-economic consequences of coastal erosion relate primarily to loss of property and are thus interlinked with the human response to erosion (defend or retreat). Each response has associated costs and benefits that accrue in spatially and temporally variable ways.

Permitting coasts to adjust to sea-level rise and storminess (the retreat option) maintains the coastal ecosystem and its associated services, as they simply migrate. There is no requirement for future human intervention in the coastal sedimentary system and such an approach is therefore sustainable. The human costs of such a response may, however, involve loss of property and associated impact on property owners. The potential for migration is in many cases restricted by existing coastal defences, whose removal or abandonment has been undertaken in a few instances of 'managed realignment', but which in most cases is very difficult under existing regulatory systems.

Defending coastal property by protection works promotes coastal squeeze, leading to loss of habitats, particularly in the intertidal zone (beaches and tidal flats) but also at the landward limit of coastal dunes. This has negative implications for the coastal landscape and for recreation and conservation. Coastal squeeze also increases the degree of exposure of sea defence structures to wave action and requires their future strengthening. Hard defences require ongoing maintenance. Defence by beach recharge maintains the intertidal habitat artificially. It too has ongoing maintenance costs and requires a suitable source of beach material.

A number of European projects are attempting to provide decision-support to coastal authorities by developing methods to assess vulnerability. They include EU FP7's CLIMSAVE, PEGASO and DINAS-*COAST*, which attempt to integrate the physical, ecological and socio-economic implications of coastal change. In most cases, they are hampered by a lack of reliable assessments of past and future coastal erosion.

2.2.5 Research Gaps, Priorities and Key Recommendations

Assessment of the future behaviour of the European coast relies on linked research into relative sea-level trends and future storm tracks. In some cases this information is available at the sub-regional level, but in most cases it is not. There is a need for a detailed assessment of the extent of coastal erosion in the EU, with due regard to the temporal and spatial scale of measurement. This requires an understanding of the sedimentary status of the coast, but could contribute to a qualitative assessment of the future state of the coast as has been undertaken in the UK through the FutureCoast initiative in shoreline management planning. Implicit in this is a move away from the 'one-size-fits-all' approach to modelling coastal behaviour.

There is an urgent need for a better societal understanding of what 'coastal erosion' means and of the difference between the concepts of 'coastal protection' (defending property) and protecting the coastal ecosystem (which may involve sacrificing coastal property). The existing regulatory system militates in favour of protection of property and this is likely to continue. There is therefore a need for research into ways to achieve sustainable coasts through more widespread adoption of the 'retreat' option by management authorities.

Figure 8. Effects of coastal erosion can affect homes and property as illustrated by the landslide of 18 May 2008, Hoskin's West, Barton-on-Sea, UK (Courtesy Mrs. Page)

2.2.6 Conclusion

Coastal erosion can be progressive, episodic or both. It is part of a natural sedimentary system of adjustment and is not in itself problematic. When property is threatened, erosion is seen as a problem. In general terms, there is likely to be an increase in the rate and extent of coastal erosion as a result of sea-level rise and changes in storminess. Only qualitative prediction of the effects can be made because there is a high degree of site-specificity in coastal behaviour. If progress is to be made in promoting the uptake of 'retreat' as an adaptation response, work is required to change the regulatory system within which coastal management operates.

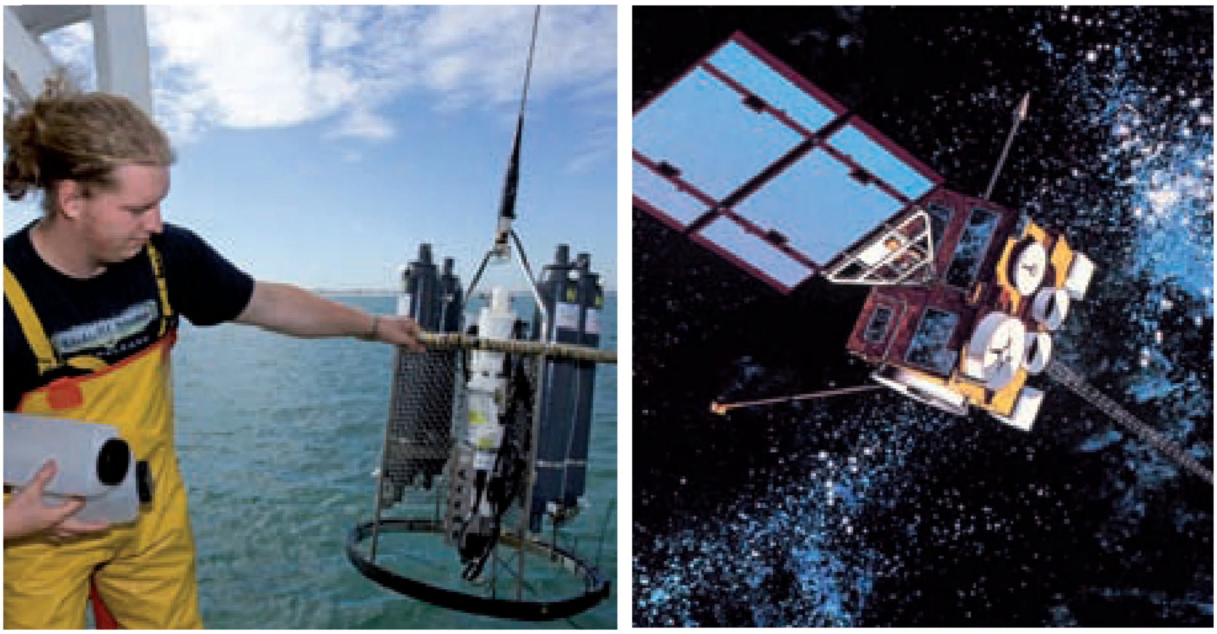

Figure 9. There are a variety of techniques for measuring Sea Surface Temperature (SST) including from ships (left), floats and fixed weather buoys. Since the early 1980s weather satellites right have been increasingly utilized to measure SST and have allowed its spatial and temporal variation to be viewed more fully. Away from the immediate sea surface, general temperature measurements are accompanied by a reference to the specific depth of measurement. (Left: ©VLIZ/Misjel Decleer; right: ©NOAA)

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2.3 Temperature Changes

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2.3.1 Observations

2.3.1.1 Global and North Atlantic

The observed sea temperature change has been identified for the last 150 years, both in decadal and centennial scales. For the global and North Atlantic Ocean, the change of the Sea Surface Temperature (SST) has been well documented in the fourth IPCC Assessment Report (see also Figure 1). At the centennial scale, the global mean SST has increased with a rate of 0.004˚C yr^{-1} during 1850-2005, 0.007˚C yr^{-1} during 1901-2005 and 0.019˚C yr^{-1} during 1979-2005. The warming trend for the North Atlantic is 0.0025˚C yr^{-1}, which is less than the global trend. In addition to the trend, the North Atlantic SST shows a 65 to 75 year variation (0.4°C range), with a warm phase from 1930 to 1960 and from 1990 to now, and cool phases from 1905 to 1925 and from 1970 to 1990, which is the most prominent multi-decadal scale signal in the World Oceans (Kerr, 2000).

2.3.1.2 Regional Seas

The warming trend has been much more significant in the European regional seas than in the North Atlantic. The SST has increased in the last 150 years with a trend of 0.006°C yr^{-1} for the Baltic and 0.004°C yr^{-1} for the North Sea and Mediterranean Sea. The warming has been speeding up especially in the last 25 years, which is about 10 times faster than the average rate of increase during the past century. Based on satellite observations, it is estimated that during the 25 year period from 1982 to 2006, the global SST increased at a rate of 0.01°C yr^{-1}, but at 0.03-0.06°C yr^{-1} for the North Atlantic and European Seas (Coppini *et al.,* 2010). Long-term *in situ* observations also support this finding. Figure 10 shows the SST and air temperature change in the Baltic-North Sea transition waters for the past 100 years (Madsen *et al*., 2009). The 10 year running mean SST has increased by more than 1°C since 1980, which is significantly larger than the decadal variability during 1900-1980.

The annual maximum and minimum SSTs are important indices for understanding biodiversity and fishery changes. The German MARNET buoy data show that the annual maximum SST at Kiel lighthouse had a warming trend of 0.15°C yr^{-1} during 1987-2007 while the

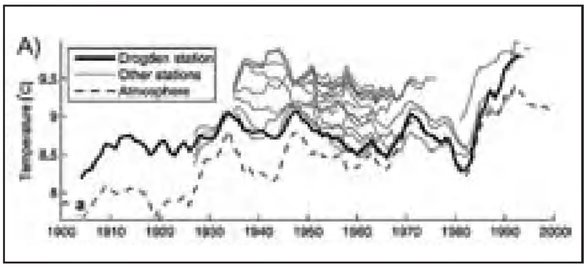

Figure 10. Ten-year running mean sea surface temperature at Drogen (solid) and other stations in Baltic-North Sea transition waters. The 2 m air temperature at Drogen is given as dashed line. (From Madsen & Højerslev, 2009)

annual minimum SST showed little trend. For the Baltic Sea, it is observed that the number of warm days has increased and the number of cold days decreased.

The water temperature change in European seas has shown complicated spatial-temporal patterns which should be further exploited. For example, in many cases, trends in winter SST are different from trends in summer SST. Warming is also found in subsurface layers. The North Sea winter bottom temperature has increased by 1.6°C during the past 25 years (Dulvy *et al.,* 2008). In the western basin, the Western Mediterranean Deep Water (WMDW) warmed during the last 50 years, interrupted by a short period of cooling in the early 1980s. The latter is reflected in the cooling of the Levantine Intermediate Water between the late 1970s and mid-1980s. A recent study (Vargas-Yáñez *et al*., 2010) also re-confirms the warming trend in the deep layer of the Western Mediterranean, with an increase of 0.002°Cyr^{-1} for the water column between 600 m water depth and the bottom.

The Black Sea showed a somewhat different pattern of temperature change during the 20th century. Recent work by Shapiro et al. (2010) found that the deep waters of the Black Sea experienced general cooling over the 20th century with a linear trend of –0.86°C, which was particularly strong from the beginning of the century to the late 1960s. The western shelf did not show a definite trend, except during the last 15–20 years when warming was evident in the SST time series. The changeover between cooling and warming trends took place in the 1990s and coincided with the dramatic regime shift in the Black sea ecosystem.

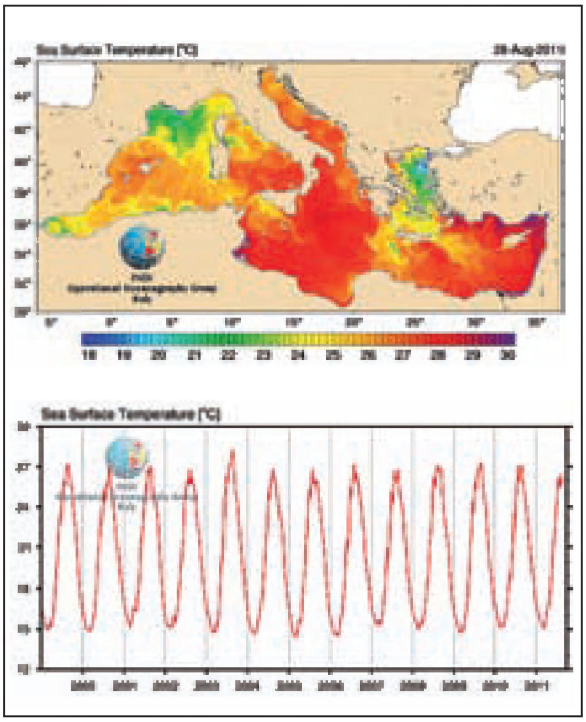

Figure 11. Sea Surface Temperature [°C] forecast for 28-Aug-2011 (above) and Sea Surface Temperature [°C] basin mean evolution since 1999 (below) for the Mediterranean Sea. (From INGV Operational Oceanography Group, Italy and EEA)

2.3.2 Future Projections

Projections of future climate changes are based on the application of either coupled or non-coupled atmosphere-ocean circulation climate models together with emission scenarios that have been developed based on assumptions of different kinds of future human behaviour. It was found that the current trend of SST warming is likely to continue to the end of the 21st century with increases of 2°C for global mean SST. A future weakening of the Meridional Overturning Circulation (MOC) may cause reduced SST and salinity in the region of the Gulf Stream and North Atlantic Current.

Scenario simulations using downscaled regional climate models and 3D baroclinic ocean models suggest, by the end of the 21st century, a mean annual warming of 2 to 4°C in the Baltic SST (BACC, 2008; Madsen, 2009). The increase would be strongest in May and June and in the southern and central Baltic. The future year-to-year variability of mean sea surface temperature was projected to increase in the northern basins owing to the melting of ice. Similar studies in other regional seas suggest a mean SST change of 1.7°C in the North Sea (Ådlandsvik, 2008), 1.5°C in the Mediterranean and 5°C for the Bay of Biscay (Alcock, 2003).

2.3.3 What Has Been Done to Better Understand Temperature Change?

A number of EU and national projects and initiatives have contributed to better understand temperature change both in the global oceans and in European regional seas. The focus of these projects has been on: (i) preparation of the Fifth IPCC Assessment Report (AR5); (ii) the Global Monitoring for Environment and Security (GMES) contribution to marine climate; (iii) regional climate research initiatives and projects; and (iv) national projects on marine climate change.

2.3.3.1 Preparation of the IPCC Assessment Report 5

A European consortium EC-Earth, has been formed to advance European research on Earth System modelling. EC-Earth performs climate projection simulations (CMIP5) as the input to the AR5 report by using European Earth System Models (IFS cy31r1 / OASIS3 / NEMO / LIM). The work has also been supported by the EU FP7 projects, ENSEMBLE and COMBINE. One focus of EC-Earth work is to make better decadal and centennial projections by reducing the uncertainties from ocean and ice components, e.g. improving ocean initial fields and coupling with ice, etc.

Progresses in 2010 have been reported in the COMBINE project. A new ocean re-analysis, based on the NEMOVAR assimilation scheme, has been completed. It will be used to provide ocean initial conditions to the COMBINE decadal forecasts; a new configuration of the ocean/sea-ice model was implemented, including the dynamic-thermodynamic multi-category sea-ice model GELATO and coupled to the NEMO3.2 global ocean mode. A few decadal prediction experiments have been performed and prediction skills analyzed for various climate parameters such as sea surface temperature and upper-levels heat content. Impact of different ocean re-analysis on decadal climate prediction has been investigated and different strategies have been studied aiming at dealing with systematic errors in a coupled ocean-atmosphere forecasting system.

2.3.3.2 GMES Contribution to Marine Climate

Well-calibrated ocean models and high resolution, quality controlled long-term observation products and model-based re-analysis products are essential for marine climate research. GMES projects MERSEA, ECOOP, BOSS4GMES and MyOcean have focused on developing solid ocean models, assimilation schemes, pre-processed long-term satellite and *in situ* observations and reanalysis products for both Global and European regional seas. A ¼ degree resolution, 20 year global ocean re-analysis is now made by EU project MyOcean, using well calibrated global operational ocean-ice model and data quality controlled by MyOcean satellite and *in situ* Thematic Assembly Centres.

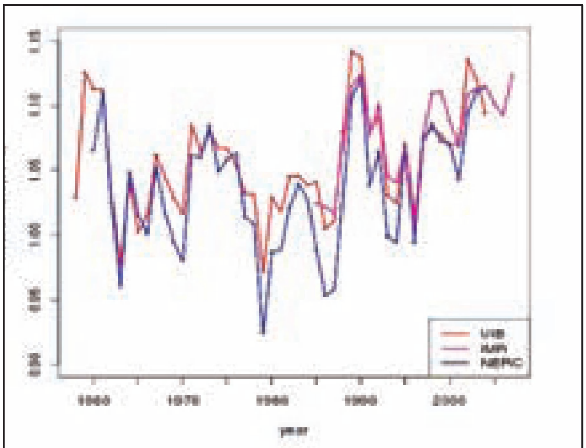

Figure 12. North Sea annual mean heat content from University of Bergen (UiB, Norway), Institute of Marine Research (IMR, Norway) and National Environment Reserach Council (NERC, UK) models (From the European Coastal Sea Operational Observing and Forecasting System, EU FP6 ECOOP Project Report, 2010)

Similar ocean re-analysis for the European regional seas, but with higher resolution, will be made available by MyOcean in 2011. In addition to the model-based re-analysis, re-processed long-term observation products of SST, sea-ice, sea-level, chl-a and 10m winds will also be available based on satellite and *in situ* measurements.

Regional sea marine climate projection simulations were made for the Baltic Sea and North Sea in the EU FP6 project ECOOP. Different regional climate models have been compared and show a good consensus for heat content simulations (Figure 12). The use of well calibrated, two-way nested 3D baroclinic operational ocean models for climate simulation in this region has been an important advancement for the investigation of the long-term Atlantic-North Sea-Baltic Sea water exchange.

2.3.3.3 Regional Climate Research Initiatives

At the regional scale, more detailed features of sea temperature change have been studied by regional projects such as BALTEX, MedCLIVAR and SESAME. MedCLIVAR is an ESF-funded networking activity, aiming at reconstruction of Mediterranean past climate evolution, description of patterns and mechanisms characterizing its space-time variability, understanding of regional climate dynamics and identification of the forcing responsible for observed and future changes. BALTEX is a major Baltic Sea climate change initiative. One major outcome of the BALTEX Programme on climate change research is the BACC (BALTEX Assessment of Climate Change for the Baltic Sea Basin) project, a joint initiative of BALTEX and HELCOM (Baltic Marine Environment Protection Commission).

2.3.4 Research Gaps, Priorities and Key Recommendations

Research gaps for ocean temperature change remain both in observational and modelling studies. Due to observational uncertainty associated with limited data sampling, changing measurement techniques and analysis procedures, it remains a challenge to characterize the pattern and amplitude of SST trends in centennial scale for certain regions. There is a continued need for refining and improving the development of homogeneous gridded SST data sets in centennial scale to reduce the observational uncertainties.

In order to make sensible projections of sea temperature for future climate scenarios, the controlling factors of European sea temperature need to be understood. Moreover, reliable 3D baroclinic ocean climate models and methods for estimating and reducing uncertainties in the projection need to be developed.

A large part of the North Atlantic sea temperature natural variability can be explained by the Atlantic Meridional Overturning Circulation (MOC) which has a non-stationary relationship with the North Atlantic Oscillation (NAO). During the 21st century, there may be a gradual weakening by about 20 % in the MOC. One research priority is, therefore, to accurately estimate the possible change of deep convection and related atmosphere-ocean-ice interaction in the Nordic and Arctic Oceans.
Long-term changes of temperature in the regional seas have complicated aspects, especially in the semi-enclosed seas. In addition to the long-term variability caused by climate forcing (winds, waves and heat fluxes), the change of SST in the Baltic and North Sea is also affected by other factors, such as stratification, downward heat transport, water exchange with the

North Atlantic, inter-basin water exchange, feedbacks induced by changing ice, change of river runoff patterns, precipitation and turbidity. Some of the above processes have not been resolved in the present regional sea climate models. It is, therefore, important that the regional ocean climate models should: (i) have a sufficiently high resolution to resolve exchange between rivers-coastal-shelf-open water masses; (ii) be well calibrated; (iii) be able to resolve dominant ocean climate processes (including internal ocean processes and coupling ones, e.g., wave-ocean-atmosphere-ice-light coupling); and (iv) meet conservation requirements.

Until now, only a very limited number of downscaling regional sea climate scenarios have been used. Owing to the large uncertainties in the regional sea climate projections, more ensembles are required for climate projection simulations.

2.3.5 Conclusions

Long-term temperature change in the ocean surface has been well-documented based on satellite and *in situ* observation. Subsurface and deep water temperature changes in regional seas have also been observed. EU and regional initiatives and projects, e.g. EC-Earth, COMBINE, ENSEMBLE, GMES, MERSEA, Euro-Argo, ECOOP, MyOcean, BALTEX, SESAME, MedCLIVAR, MEDATLAS, and ESA ECV projects, have contributed to build up steadily the observation and modelling platforms, including products and methods for ocean climate research. However, challenges remain in explaining the dominant factors and processes in regional sea temperature change. The role of river run-off, waves, mixing scheme, light attenuation and ice in the regional marine climate simulations should be further exploited. The number of coupled regional AOGCMs is still limited. The resolution in ocean climate models needs to be further enhanced.

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2.4 Ice Melting

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2.4.1 Sea-ice Extent

During the last decade we have seen dramatic changes in the Arctic sea-ice cover. Summer sea-ice extent reached a record low (at least within the satellite record since 1970) in 2007, with 2002, 2005, 2006, 2008, 2009 and 2010 being the other low points on the scale (see Figure 13). The trend in summer sea-ice extent over the last 30 years is more than -11 % per decade with an apparent acceleration in recent years. However, Arctic winter sea-ice extent is reducing at a substantially slower rate (~3 % per decade) with January 2011 as the lowest January (at least since 1970).

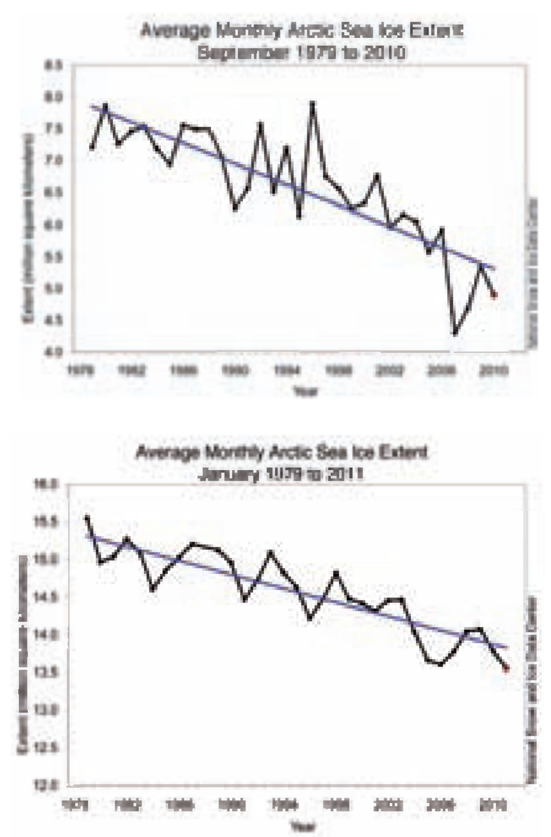

Figure 13. Monthly September ice extent for 1979 to 2010 shows a decline of 11.5 % per decade (left) and monthly January ice extent for 1979 to 2011 shows a decline of 3.3 % per decade (©National Snow and Ice Data Center)

Markus *et al.* (2009) concluded that for the entire Arctic, the melt season length has increased by about 20 days over the last 30 years. Largest trends of over 10 days per decade are seen for Hudson Bay, the East Greenland Sea, the Laptev/East Siberian seas, and the Chukchi/Beaufort seas.

Figure 14 (left) shows the sea-ice extent at the 2010 summer minimum along with the median ice extent for the period 1979-2000. Ice is missing in most regions of the Arctic with the Beaufort and Chuchki seas showing some of the largest reductions. Figure 14 (right) shows the corresponding winter distribution in January 2011. Here the largest reductions relative to the 1979-2000 median are in the eastern Canadian Arctic, The Greenland Sea and the Sea of Okhotsk.

2.4.2 Sea-ice Thickness

Results of recent investigations also show that the remaining ice is much thinner and that by 2008 the ice cover of the Arctic primarily consisted of seasonal ice or first-year ice. Instead of covering just over 50 % of the Arctic Ocean during the winter of 2004, multiyear ice covered only a third (~34 %) of that area in 2008 (Kwok *et al.,* 2009). As a result, seasonal ice became the dominant ice type in the Arctic Basin. Within the data release area (DRA) of declassified submarine sonar measurements (covering ~38 % of the Arctic Ocean), the overall mean winter thickness of 3.64 m in 1980 can be compared to a 1.89 m mean during the last winter of the ICESat record, an astonishing decrease of 1.75 m in thickness (Kwok & Rothrock, 2009). Furthermore, relative to the submarine data used for the years 1958-1976, the ICESat data show that the average thickness at the end of the melt season has decreased by 1.6 m or some 53 % of the thickness in approximately 40 years.

With the large decline in multi-year-ice in recent years, the volume growth of ice during the winter season has increased, since first-year-ice typically grows to about 2 m thickness whereas multi-year-ice on average grows between 1 and 1.5 m from its end of summer thickness.

2.4.3. Sea-ice Drift and Deformation

Using drift buoy data from the International Arctic Buoy Program, Rampal *et al.* (2009) found that sea-ice mean speed and deformation rate has increased substantially over the period 1979-2007. An increase in mean speed of 17 % per decade for winter and 8.5 % per decade during summer was found. Their results also showed exceptionally large deformation rates affected the Arctic sea-ice cover during both winter and summer of 2007.

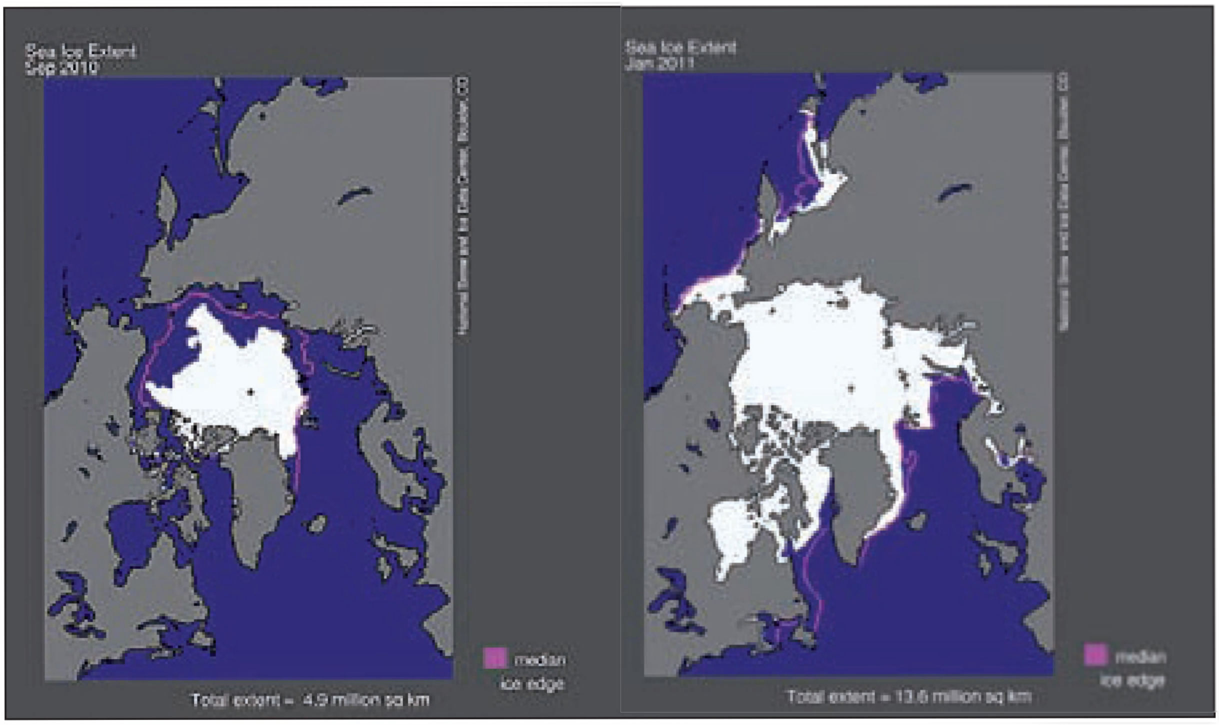

Figure 14. Left: Arctic sea-ice extent for September 2010 was 4.9 million square kilometers (1.89 million square miles). The magenta line shows the 1979 to 2000 median extent for that month. The black cross indicates the geographic North Pole (©National Snow and Ice Data Center). Right: Figure 2b. Arctic sea-ice extent for January 2011 was 13.55 million square kilometers (5.23 million square miles). The magenta line shows the 1979 to 2000 median extent for that month. The black cross indicates the geographic North Pole (©National Snow and Ice Data Center).

2.4.4 What Has Been Done to Better Understand Ice Melting?

The EU FP6 DAMOCLES project (Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies) represented a major European effort towards understanding the increased rate of melting of Arctic summer sea-ice. The project focused on reducing the uncertainties in our understanding, modelling and forecasting of climate change in the Arctic and their impacts. The Arctic over the last 2-3 decades has warmed more than other regions of the world, and the sea-ice cover has decreased significantly in the same period. A key question of both scientific and societal relevance has therefore been whether the Arctic perennial sea-ice will disappear in a few decades (or even faster, as predicted by some state-of-the-art climate models). DAMOCLES was specifically concerned with the potential for a significantly reduced sea-ice cover, and the impacts this might have on the environment and on human activities, both regionally and globally. Major progress was made in several fields ranging from improvements in high tech *in situ,* airborne and satellite observation systems, assimilation of observations in a full Arctic atmosphere-ice-ocean system and studies of potential socio-economic impacts of the rapid changes in the Arctic.

Figure 15. Polar researchers and research vessel Polarstern (©Alfred Wegener Institute for Polar and Marine Research, Germany)

The DAMOCLES project was concerned with developing capabilities, and although substantial progress was made during this project as well as during the International Polar Year (for which DAMOCLES was a substantial contribution), many of the collected datasets are still being analysed. However, results are already being incorporated in operational and semi-operational activities under GMES (Global Monitoring for Environment and Security) such as the Marine Core Service, MyOcean, which has a specific Arctic marine forecasting centre that builds on DAMOCLES research. ESA's PolarView GMES project and EUMETSAT's Ocean and Sea-ice Satellite Application Facility have also both benefitted substantially from DAMOCLES research.

2.4.5 Socio Economic Consequences of Sea-ice Melting

A clear impact of reduced Arctic ice cover with obvious socio-economic implications is the increased potential for accessing the various resources abundant in the region such as hydrocarbons and minerals. The disappearance of seasonal ice cover may also allow for the opening up of new seasonal shipping routes through the Arctic resulting in major reductions in the maritime transportation times from Europe to Asia. At the same time it would also create new routes for invasive species to be transported by ships or for migration of species between Atlantic and Pacific Oceans (such as *Neodenticula* diatoms *and* grey whales). Such migrations might have important impacts on fisheries and aquaculture activities. In addition we have already seen a strong increase in Arctic tourism which is expected to continue increasing as new areas become accessible during longer periods each summer.

Reduced ice cover in the form of shorter ice seasons and weaker ice will also significantly influence the hunting and travel capabilities of indigenous peoples living in the Arctic.

2.4.6 Research Gaps, Priorities and Concluding Remarks

During the International Polar Year (IPY), significant progress was made in many areas of sea-ice research, but many areas still need further investigations.

Snow cover on sea-ice is identified as a key area for future research. Physical properties of snow and sea-ice strongly affect the exchange of energy between the atmosphere and the ocean in the Arctic, because they act like a blanket on the ocean. One of the key properties is the surface albedo, the ability of the surface to reflect sunlight. The albedo is rather well known for winter and spring, when the surface is cold and dry, while it undergoes rapid and strong changes connected to summer melting. Variability in snow properties is also the major contributor to the remaining uncertainty in satellite remote sensing measurements of ice concentration and sea-ice thickness. Satellite remote sensing may have unexploited potential to provide additional quantitative information on a number of snow parameters.

Figure 16. Melting ice in the Arctic is leading to weaker ice, reduced sea-ice cover and shorter ice seasons (©Katja Guilini)

Assimilation of observation data in models of the Arctic sea-ice cover is another area where more research is required, in particular in the development of forward models relating ice physical parameters to electromagnetic properties that can be observed by satellites.

Finally, interaction between the ocean and ice melt is a third area that requires further attention in order to quantify the role of changing oceanographic conditions in sea-ice melt. While significant progress in the development of autonomous observation systems has been made, a systematic collection of data using these instruments needs to continue for several years to come.

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2.5 Storm Frequency and Intensity

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2.5.1 Introduction

When talking about storms, one has to discriminate between the different types of storms, ranging from tropical storms – tropical depressions, hurricanes, typhoons and other names are in use – to baroclinic storms forming along the polar front, to mesoscale storms such as Polar Lows or 'medicanes' over the Mediterranean Sea. They all have in common that they are *wind*-storms, as opposed to *rain*-storms. Sometimes they result in very severe damage to infrastructure, buildings, forests, and can have large economic impacts; on the sea they excite storm surges as well as ocean waves.

Figure 17. Storm at sea (©Mick Mackey)

Storms are also engraved in our cultural fabric, as ubiquitous risks in coastal regions and on the sea, but also as punishment for sinful societies (Pfister *et al.*, 2010). No wonder that perceptions of 'more intense storms' are an integral part of the public narrative about climate change, even if this is scientifically much less clear, as we will see below.

In the following we will summarize the knowledge about changing wind storms in Northern Europe – with respect to both baroclinic storms as well as North Atlantic Polar Lows.

2.5.2 Observations

While determining the presence of a storm is not really difficult, the construction of wind data sets which homogeneously describe intensity and frequency of storms is much more of a challenge (see also Figure 18).

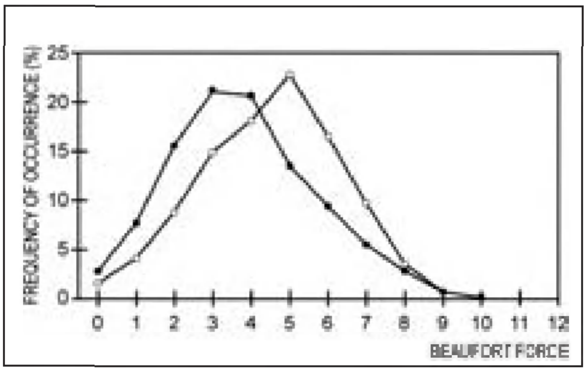

Figure 18. An example of an inhomogeneity in wind observations: Frequency distribution of wind estimates on the Beaufort scale, derived from voluntary ship reports in the English Channel after 1949. The solid dots are derived from 24,442 reports from ships without an anemometer, whereas the open dots stem from 981 observations made when an instrument was available. All 24,442 + 981 reports are visual assessments of the sea state. (Modified from Peterson & Hasse, 1987)

Conventional data sets such as ongoing weather analyses, as well as re-analyses generated by, for instance, NCEP or ECMWF and operational reports from ships of opportunity suffer from changes in data density and observational practice. This is also true for local observations of wind as a result of changing instrumentation, observers and surroundings, so that conclusions about changing wind statistics based on wind observations are almost always questionable (Peterson & Hasse, 1987).

However, some proxies of wind statistics have been constructed, which are suitable for describing changing conditions of baroclinic storms (WASA, 1998). These proxies are based on pressure readings or high water tide variations.

Using intraseasonal statistics of geostrophic winds (gradients derived from triangles of pressure readings; Schmidt and von Storch, 1993) and other proxies in Central Europe (Matulla *et al.*, 2008), the larger North Sea and Baltic Sea (Alexandersson *et al.*, 2000; BACC, 2008; Figure 19) as well as the Adriatic Sea (Matulla *et al.,* 2011), it was found that strong wind statistics did undergo large decade-long variations, some of them related to the NAO. However, these variations do not establish a long-term trend but rather an irregular series of upward and downward trends. In particular no development reminiscent of the development in regional air temperatures with recent accelerations could be detected. In other words, to date there is no trend in baroclinic storm activity detectable in Northern Europe that can be attributed to climate change.

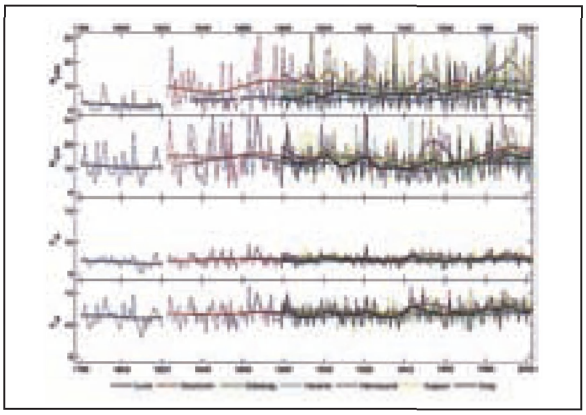

Figure 19. Four different annual storminess indices derived from station pressure records in the Baltic region. From top to bottom: (i) Np980 – number of low pressure observations below 980 hPa; (ii) NΔp/Δt – number of events when the absolute pressure tendency exceeds 16hPa/12h; P95 and P99 – the 95 and 99 percentiles of pressure differences (hPa) between two observations. The thin lines show annual variations and the smooth thick lines show variations at the decadal time-scale. (BACC, 2008)

When constructing homogeneous changing storm statistics with regional climate models, forced by large-scale re-analysis, a consistent assessment emerged, namely that considerable decadal variations prevail but no indications exist for the presence of anthropogenic signals (Weisse *et al.,* 2009).

The formation of North Atlantic Polar Lows has also been reconstructed using regional climate models exposed to large-scale re-analysis forcing. The frequency undergoes strong year-to-year variations but also no systematic change (Zahn & von Storch, 2008).

Damage-based proxies have turned out to be contaminated by various non-climatic factors, and should be avoided when assessing changing storm conditions (Pielke *et al.,* 2008).

2.5.3 Future Projections

For both baroclinic storms and Polar Lows, various scenarios have been developed for Northern Europe. These scenarios are based on a two-step modelling approach: firstly, regular, relatively coarse grid global

Figure 20. Hurricane Katrina was the 11th hurricane in the Atlantic in 2005 (left) leading to enormous devastation in New Orleans (Louisiana, USA). (Left: ©NASA Earth Observatory; right: ©AP Photo/U.S. Coast Guard, Petty Officer 2nd Class Kyle Niemi)

models are used, which are then downscaled using regional limited area models. A robust finding in all these scenarios is that the change in frequency and intensity of baroclinic storms is weak at best; strong storms will possibly undergo a stronger increase than moderate storms (Ublrich *et al.*, 2009). For the North Sea, an overall small increase is expected (Woth, 2005, Pryor *et al.*, 2006), and in the Baltic Sea the results are statistically inconclusive (BACC, 2008), which is consistent with the current absence of a detectable anthropogenic signal. The Polar Lows are expected to move poleward, and become considerably reduced (Zahn & von Storch, 2010).

2.5.4 Socio-Economic Consequences of Increased Storm Frequency and Intensity

Compared with other climate-induced impacts, the socio-economic consequences of changing storm conditions may be lower, simply because these changes are rather limited in extent and developing only slowly. One exception may be storm surges, which will be exaggerated by rising sea-levels.

It is, however, obvious, that present storminess represents a major climate risk in Northern Europe and elsewhere on the continent. Relying on too short and fragmented records describing the storm risk has not always led to adequate measures for managing the risk and, if needed, the consequences of a strong storm event. The case of New Orleans, hit by tropical storm Katrina in 2005, provides a good, albeit non-European, example of the consequences of misjudgements of risk and insufficient management in case of failures of protective efforts.

An interesting socio-economic detail is that part of the insurance industry has a tendency to claim massive upward changes of storminess, in spite of better knowledge, which some consider biased and reflecting vested economic interests. Such biases appear common in a postnormal situation, as climate science finds itself in, and analytical efforts from cultural and social sciences are needed to mitigate such effects (von Storch, 2009).

2.5.5 What Has Been Done to Better Understand Increasing Storm Frequency and Intensity?

Both the European Union and the United Nations are now taking seriously the predicted climate change scenarios of the IPCC. Of particular relevance to Coastal States is the predicted increase in the intensity and frequency of powerful storm events characterized by larger peak wind speeds and consequently, larger waves which causes concerns for both offshore and on-shore safety. For that reason, a number of national, regional and pan-European research efforts have looked at the potential risks associated with more frequent and more intense storms over the last decade. For example, the BALTEX Assessment of Climate Change for the Baltic Sea Basin (BACC) has provided an authoritative assessment of the issue in the Baltic Sea catchment.

Other projects and initiatives touch upon changes in storm frequency and intensity as part of wider climate change research, sometimes also linked to their impacts on the marine and coastal environment. The EU FP6 CENSOR project, for example, addressed impacts of changes in storm frequency and intensity as part of a wider investigation aimed to enhance the detection, compilation and understanding of climate variability and El Niño southern oscillation and its effects on coastal marine environments and resources.

The EU FP6 ENSEMBLE project, which ran until 2009, developed a common ensemble forecast system to allow a quantitative risk assessment of climate change and climate variability, with an emphasis on changes in extremes, including changes in storminess and precipitation, and the severity and frequency of drought, and the effects of 'surprises', such as the shutdown of the thermohaline circulation.

The EU FP7 MICORE project (Morphological Impacts and Coastal Risks induced by Extreme storm events) is probably the best example of a European scale project dedicated entirely to the issue of storm events.

The MICORE project investigates the knowledge necessary to assess the present day risks and to study the economic and social impact of future severe storm events. The project will also develop operational predictive tools in support of emergency response to storm events. Together, these elements will have an important strategic impact on the safety of the people living in coastal areas. The project will also investigate with stakeholders and end-users the possibilities of producing EU-wide guidelines for a viable and reliable risk mitigation strategy. MICORE will produce an up-to-date database for each partner country that will include: an historical review of storms; an inventory of data related to the forcing signals; quantification of the morphological response of coastal systems to storms and to sequences of storms; an assessment of socio-economic impact; and a description of existing civil protection schemes and interventions.

2.5.6 Conclusions and Remaining Questions

The issue of changing storm conditions in Europe has received considerable attention, even if more studies are needed for assessing recent and ongoing change and its consistency with the changes envisaged by the scenarios of an anthropogenically changed climate. When sufficiently long and homogeneous (proxy-) data are used, strong variations on the yearly and decadal scale emerge, but hardly a systematic change which could be linked to the ongoing change in regional temperatures. For the more distant future, model scenarios point to some intensification of storm activity, in particular related to strong storms.

Unfortunately, the issue is often muddled by analyses, that employ inadequate data sets, which are either fragmented or provide too short a record. Remaining questions deal with the construction of proxies for baroclinic storms in summer over land, with the reconstruction of 'medicanes' in the Mediterranean Sea, and the present and possible future impact of ocean waves in some European marginal seas. Concerning storm surges, as one of the major risks associated with baroclinic storms, more careful regional analysis of regional sea-level change is needed.

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2.6 Stratification Changes

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2.6.1 The Role of Stratification

The productivity of the coastal seas and offshore waters around Europe is largely driven by photosynthetic carbon fixation by microscopic phytoplankton. The growth of phytoplankton is fuelled by light for photosynthesis, regulated by water temperature, and requires the supply of nutrients to construct the cellular building blocks which drive phytoplankton physiological processes.

These plant nutrients – ranging from nitrate to trace elements such as iron – are primarily supplied from deeper waters underlying the sunlit euphotic zone. The main supply mechanisms are from vertical mixing of colder nutrient-rich waters either by mixing (due to tidal stirring and/or wind mixing) or by upwelling (the upward flow of an ocean current). The magnitude of vertical nutrient supply may be limited by the existence of a vertical gradient in water density, often in the upper 50 to 100 m of the ocean. This density gradient is set by vertical differences in both the temperature (warmer waters are less dense) and salinity (fresher waters are less dense), and is termed stratification. The stronger the degree of stratification, the more difficult it is to mix deeper nutrient-rich waters into the euphotic zone (Figure 21). This in turn places an upper limit on the primary productivity of surface waters.

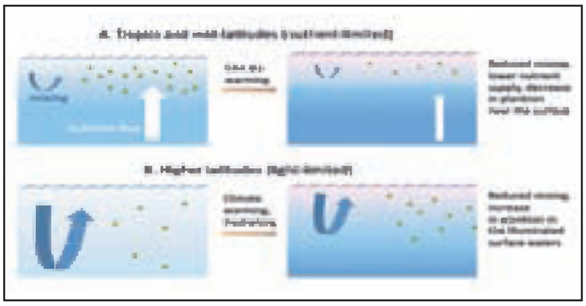

Figure 21. Predicted phytoplankton response to increased temperature in ocean surface waters: (a) in the tropics and at mid-latitudes, phytoplankton are typically nutrient-limited, and satellite data tie reduced biological productivity to upper-ocean warming and reduced nutrient supply; (b) at higher latitudes, the opposite biological response to future warming, and extra freshwater input, may occur – in these regions, phytoplankton are often light-limited; reduced mixing would keep plankton close to the surface where light levels are higher. At present, projections of future trends relating to warming are more robust than those relating to freshening. (Adapted from Doney, 2006)

2.6.2 Future Projections

Stratification of the upper ocean plays a pivotal role in setting the productivity of the upper ocean, which in turn provides the input of energy into most pelagic and many benthic ecosystems. It is thought that the differential warming of the surface and subsurface ocean layers will result in a greater density gradient between the surface waters (which will warm most) and the underlying waters (Levitus *et al.*, 2009). A further indirect effect of warming will be to increase the melting of ice at high latitudes and the alteration of regional patterns in precipitation (IPCC AR4, 2009). Both of these changes will reduce the salinity of surface waters and hence increase the vertical salinity gradient, which helps to set the density stratification of the upper ocean.

2.6.3 Better Understanding How Climate Change will Alter Stratification

Model simulations have investigated how climate change may alter stratification in both offshore (i.e. beyond the continental margins) and nearshore waters. The former are generally stratified over the annual cycle whereas the latter exhibit seasonal stratification. The projections of modelling experiments, using general circulation or coupled ocean atmosphere models (e.g. Sarmiento *et al.*, 1998; Matear & Hirst, 1999) reveal that stratification is predicted to increase in the wind-mixed open ocean (Figure 21). Similarly, in the strongly tidally-stirred continental margins (i.e. excluding seas such as the Baltic and Adriatic), modelling simulations (Holt *et al.,* 2010; Figure 22) predict an increase in stratification of around 20 % (c.f. 20 to 50 % for the open ocean). In addition, the timing of the seasonal onset of stratification in nearshore waters is projected to be around five days earlier in the annual cycle than in the present day (Holt *et al.*, 2010). Holt *et al.* also reported a comparable temporal extension of 5-10 days prior to the erosion of seasonal stratification later in the annual cycle. These predictions point to a decrease in the vertical nutrient flux on both the continental shelf and also at the particularly productive shelf break (Sharples *et al.*, 2009). The underlying mechanisms for increased stratification differ for offshore oceanic versus onshore coastal waters. In the open ocean, increased stratification will be driven by warming water temperatures in low latitudes, and by warming and freshening (due to more ice-melt and altered precipitation versus evaporation) at high latitudes (Figure 21). In contrast, the main driver of increased stratification in strongly tidally-stirred inshore waters is thought to be due to a climate-change mediated alteration of the phasing of the seasonal heating cycle, which will subsequently affect the energy flux of the internal tide (stronger stratification increases energy flux) and the mixing (vertical diffusivity is inversely proportional to squared buoyancy freq) (J. Sharples, pers. comm.).

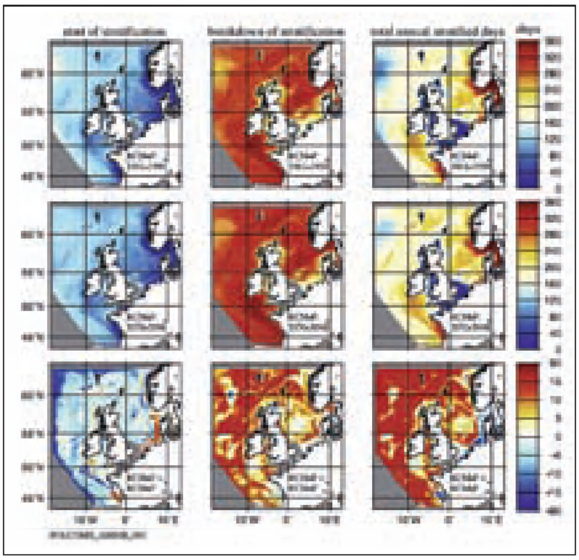

Figure 22. Mean timing of seasonal stratification from RCM-P (i.e. recent past - 1961-1990), RCM-F (i.e. Future Scenario - 2070-2098) and the difference between them. The figure shows days of the year (1st January is day 1) when persistent seasonal stratification starts and ends, and the total number of stratified days. (From Holt *et al.,* 2010)

2.6.4 Broader Ramifications of Increased Stratification

In the open ocean and coastal waters, increased stratification will reduce the upward supply of nutrients and trace elements. Mathematical models predict that this will result in reduced primary productivity at low latitudes (Sarmiento *et al.*, 2004). However, at high latitudes, productivity is predicted to be enhanced (Polovina *et al.,* 1995), since stocks of nutrients are often not completely depleted by phytoplankton, whose growth rate is limited by the depth of the surface mixed layer (Figure 21). As climate change modelling experiments also predict a shoaling of the mixed layer depth (e.g. Sarmiento *et al.,* 1998; Matear & Hirst, 1999), this may lead to greater surface ocean productivity at high latitudes. Thus, the offshore high latitude band of European waters may be characterised by a climate-change mediated increase in pelagic productivity, whereas in the very South of Europe there may be a future decrease in productivity. In the waters of the continental shelf, from the shelf break onshore, productivity may decrease based on a lengthening of the period of stratification by around 15 days during the phytoplankton growth season (Holt *et al.*, 2010). As there is compelling evidence that these productive inshore waters service major fisheries (Sharples *et al.,* 2009) climate change may result in less rich fisheries in inshore and low latitude offshore waters.

2.6.5 Research Gaps and Priorities

- A reduced nutrient supply from the ocean interior may alter the balance between the relative roles of atmospheric versus oceanic supply of nutrients. The atmosphere supplies increasingly large amounts of nitrogen and iron to the ocean in the Anthropocene (Duce *et al.,* 2008). Such a supply could potentially offset the reduced oceanic vertical supply.
- There will be knock-on effects of altered productivity throughout the marine ecosystems, which are difficult to predict, and increasingly so in complex ecosystems with many trophic levels.
- Although the effects of altered stratification are important, they are best viewed in the broader context of how other ocean properties are altered, in particular the depth of the mixed layer. Assessing the cumulative climate change effects on the ocean requires a holistic approach.

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2.7 Thermohaline Circulation Changes

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2.7.1 Observations

The most important current affecting Western Europe is the Gulf Stream (see Figure 23). This increases temperatures on the western seaboard of Europe by up to several degrees. The Gulf Stream is a key component of the thermohaline circulation, which is a global circulation pattern that is driven by density differences caused by variations in salinity and temperature. These variations arise from heating and cooling of the surface waters and/or influxes of more or less saline (dense) water. Evaporation and sea-ice formation increase salinity whereas ice melt, runoff and precipitation decrease salinity. The circulation is driven by cold dense water sinking primarily in the North Atlantic. This sinking draws surface water north from the tropics, which evaporates en route making it denser. When this water meets the cold water coming from the Arctic in the Greenland and Labrador Seas it becomes even denser and sinks. The sinking water then travels south as a Deep Western Boundary Current eventually entering the Southern Ocean. Here upwelling brings deep water back to the surface, hence closing the loop and creating what has been termed the 'ocean conveyor belt'.

The Mediterranean also has a thermohaline circulation. Strong evaporation in the east as well as winter cooling causes dense water to sink and move to the west. This is enhanced by dense water formation in the Gulf of Lion and the Adriatic during winter months. These denser waters flow out at the Straits of Gibraltar and are replaced by Atlantic water that flows into the Mediterranean as a surface flow.

2.7.2 Future Projections

There has been some concern that climate change could reduce the rate of water and heat transport in the thermohaline circulation and thus lead to a dramatic cooling of parts of Scandinavia and the UK. This could be created by a freshening of sub-Arctic waters related to increasing Greenland ice melt. In the Mediterranean the dense water formation transports oxygen to the deep waters and prevents their stagnation – a process that has happened repeatedly in the past. However, it is dependent on cold dry spells in southern France during winter to create the dense sinking water; these may occur less frequently in a warmer climate.

2.7.3 What Has Been Done to Better Understand Thermohaline Circulation Changes?

National funding agencies have recognised the importance of understanding the thermohaline circulation for some time and a number of projects have been funded

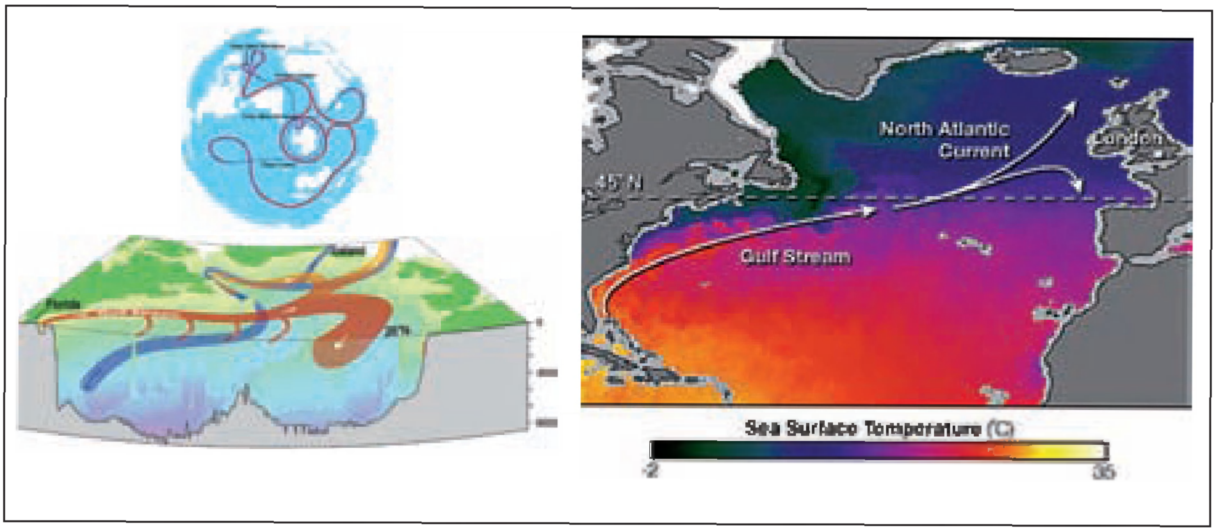

Figure 23. Summary of the path of the Thermohaline Circulation (THC) or Great Ocean Conveyor (left above: global perspective; middle: North Atlantic subsection) and Gulf Stream (left below and right) in the North Atlantic. Blue paths (left) represent deep-water currents, while red paths represent surface currents. The Gulf Stream is visible as a warm water current travelling northward along the coast of North America and eastward into the central Atlantic Ocean. As it continues its journey heat from the ocean is lost to the atmosphere, warming the air above it. (Left above: courtesy AVGA; left below: from Church, 2007; right: map by Robert Simmon, NASA)

such as the UK led RAPID and RAPID-WATCH projects. This project is dedicated to measuring and monitoring the Atlantic thermohaline circulation and has been funded since 2001 by the UK with participation from Norway, The Netherlands and the USA. The project initially installed 19 moorings across the Atlantic at 26.5°N and these have been recovered and redeployed each year since 2004, thus providing a continuous time series in which interannual variations in the strength of the thermohaline circulation can be measured. Such work is able to place into context earlier estimates of thermohaline change which relied on sporadic ship-based estimates of the flow, for example, Bryden *et al.* (2005) who calculated a weakening of the circulation by up to 30 % over the past 40 years. Whether this is an alarming finding or not will be clarified as the RAPID/RAPID-WATCH mooring measurements reach a statistically-significant length with which to confidently isolate meaningful signals from the natural variation (by 2014 a decade-long continuous series will exist). Initial results (Cunningham *et al.*, 2007; Kanzow *et al.*, 2007) have confirmed the ability of the mooring system to monitor the MOC to a high degree of accuracy. In Germany, a 10-year programme was established in 1996 to monitor the dynamics of thermohaline variability and of ocean uptake of CO_2. Cruises and moorings were concentrated in the subpolar North Atlantic where the bulk of the deep-water is formed.

Studies of the thermohaline circulation were not directly funded under EU FP6. The EC did fund a range of climate change projects but none of these specifically addressed this issue. DYNAMITE explored the dynamic mechanisms of the North Atlantic Oscillation/ Arctic Oscillation (NAO/AO) and the El Niño-Southern Oscillation (ENSO). DAMOCLES investigated changes occurring in the Arctic including the connections between ice, ocean and atmosphere. MERSEA developed a system for operational monitoring and forecasting of ocean physics, biogeochemistry and ecosystems both globally and specifically for the Arctic Ocean, Baltic Sea, Mediterranean Sea and North-East Atlantic. The SESAME project examined the coupled climatic / ecosystem entity in the Mediterranean and Black Seas, and assessed changes in these areas over the last fifty years.

In the EU FP7 project THOR (Thermohaline Overturning – at Risk?) has been funded and runs from 2008-2012. THOR will establish an operational system that will monitor and forecast the development of the North Atlantic THC on decadal time scales and assess its stability and the risk of a breakdown in a changing climate. In THOR, the combined effect of various global warming scenarios and melting of the Greenland ice-sheet will also be thoroughly assessed in a coupled climate model. THOR builds upon techniques, methods and models developed during several projects funded within EU FP5 and FP6 as well as many nationally funded projects. The project will contribute to Global Monitoring for Environment and Security (GMES), to Global Observing Systems such as to the Global Ocean Observing system (GOOS), and to the International Polar Year (IPY).

The international Argo project has established a global network of over 3,000 profiling floats. These are providing around 100,000 observations each year, throughout all the ice-free deep-ocean areas of the world. This data will result in the systematic measurement of the physical state of the upper 2,000 m of the ocean and enable scientists to measure seasonal and year-to-year changes in the ocean and to detect changes in the ocean caused either by the global warming of the atmosphere or by the onset of climate events like El Niño. Europe contributes through the EU FP7 Euro-Argo project, which began in 2008.

Figure 24. Deployment of an Argo float. The international Argo project has established a global network of more than 3,000 profiling floats. (©Euro-Argo)

The EU FP7 project MyOcean brings together, amongst others, national meteorological services, the European Environment Agency and the European Maritime Safety Agency (EMSA) to define and to set up a concerted and integrated pan-European capacity for ocean monitoring and forecasting. The areas it is aimed at are: Maritime Security, Oil Spill Prevention, Marine Resources Management, Climate Change, Seasonal Forecasting, Coastal Activities, and Monitoring Ice-sheet surveys, Water Quality and Pollution.

2.7.4 Socio-Economic Consequences of Thermohaline Circulation Changes

The impacts of a complete or partial shutdown of the thermohaline circulation have been modelled over the last few years following earlier concern raised by scientists. The results show that an abrupt shutdown before 2100 is unlikely, and that the global impacts of any slowing in circulation before then are likely to be offset by temperature increases related to greenhouse gas build up. However, locally some areas could be adversely impacted such as the western margin of Europe which may suffer both cooling and a rise of sea-level. The IPCC AR4 Working Group II Report (2007) lists the potential impacts for Europe following a rapid shut down of the thermohaline circulation (see Information Box 1).

Information Box 1. Main Types of Impact for Europe Following a Rapid Shut-down of the Meridional Overturning Circulation Relative to the 'Pre-industrial' Climate (after Parry *et al.*, 2007)

- Reductions in runoff and water availability in southern Europe; major increase in snowmelt flooding in western Europe.
- Increased sea-level rise on western European and Mediterranean coasts.
- Reductions in crop production with consequent impacts on food prices.
- Changes in temperature affecting ecosystems in western Europe and the Mediterranean (e.g., affecting biodiversity, forest products and food production).
- Disruption to winter travel opportunities and increased icing of northern ports and seas.
- Changes in regional patterns of increases versus decreases in cold- and heat-related deaths and ill-health.
- Movement of populations to southern Europe and a shift in the centre of economic gravity.
- Requirement to refurbish infrastructure towards Scandinavian standards.

2.7.5 Research Gaps and Priorities

Key open questions include[1] :

- What changes in freshwater input in the North Atlantic will result from global warming, considering the existing uncertainty, e.g. due to uncertain estimates of Greenland meltwater runoff, ignored so far in most models, and due to possible changes in ENSO?
- What is the risk of exceeding a threshold for THC collapse for a given warming?
- What other thresholds exist (e.g. a local shutdown of convection in the Labrador Sea, rather than a full THC collapse)?
- What consequences would result for marine ecosystems?
- How would climate over land be affected by a collapse scenario? Would it result just in a reduced warming, or a warming followed by abrupt cooling? Would there be associated precipitation changes?
- How predictable is the system using today's generation of climate models and how can these predictions refine climate forecasts (particularly on the decadal scale)?

2.7.6 Conclusion

Potential changes in the thermohaline circulation have grabbed the public attention following the release of the film 'The Day After Tomorrow' in 2004. This film was only very loosely based on facts but very clearly reveals how film makers, and the media more generally, are much better at getting messages to the public than scientists.

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[1] Partially taken from Ramsdorf (http://www.pik-potsdam.de/~stefan/thc_fact_sheet.html)

2.8 Riverine Discharge and Nutrient Loads

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2.8.1 Observations

Riverine nutrient discharges depend on freshwater discharge and concentrations. Freshwater discharge is mainly climate driven. Human interventions like channel deepening have increased the water flow and decreased the natural water retention capacity of river systems. On the other hand, the building of dams and weirs, aimed at regulating freshwater flow and keeping a minimum water level for shipping, has reduced water flow. Strong increases in nutrient concentrations and in the concomitant nutrient loads have been observed since the middle of the last century (Figure 25 A & B). Industry, agriculture (the use of organic and inorganic fertilizers) and canalization were major factors driving the increase in nutrient concentrations. Legislation has led to a decrease in emissions, e.g. due to the implementation of water treatment and a ban on phosphorus containing detergents (Figure 25).

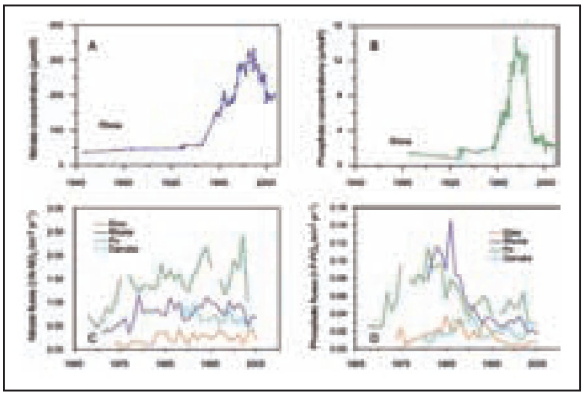

Figure 25. Long-term changes in nitrate (A) and phosphate (B) concentrations in the Rhine are compared with changes in the specific nitrate (C) and phosphate (D) fluxes in large Mediterranean and Black Sea rivers since 1960. Rhine data before 1950 are taken from van Bennekom and Wetsteyn (1990, Neth. J. Sea Res 25: 75-87). (Data after 1950 are taken from the Dutch monitoring Program for the Station Lobith at the German Dutch border; data for the Mediterranean and Black Sea rivers are from Ludwig *et al.,* 2010)

2.8.1.1 Northern Europe

In several European rivers nutrient loads reached a maximum during the mid 1980s and have decreased since then. However, regional differences do exist. Some major continental rivers like the Rhine and Elbe showed a continuous decrease of about 2 % per year (see OSPAR Quality Status Report 2010 and Wadden Sea Quality Status Report 2009) (Marencic & de Vlas, 2009). Interannual differences in nutrient loads are closely related to differences in freshwater discharge with a superimposed trend.

2.8.1.2 Southern and Eastern Europe

Before 2,000 continuous time series on nitrate and phosphate loads in Mediterranean and Black Sea rivers are scarce. Observations mostly refer to scientific studies that were limited in time, making it difficult to catch the long term evolutions. Only for the large rivers (Rhone, Po, Ebro, Danube), more or less complete reconstructions during the last 50 years can be found (Figure 25 C & D). However, although these rivers represent only a very restricted number of observations in space, trends in their nitrate and phosphate loads seem to be representative of many other rivers in the Mediterranean and Black Sea drainage basin (Ludwig *et al.*, 2009). Trends are comparable with the evolution in northern Europe (see above), although the recent decline in nitrate seems less pronounced. Compared to north European rivers, a clear need of continuous time series on dissolved silica has been identified, as this parameter is mostly missing in monitoring programmes of rivers. The rivers discharging to the Black Sea, such as the Danube River, display marked changes in the 1990s because of the political changes in this region, but now follow the general trends of most other large European and Mediterranean rivers (Ludwig *et al.*, 2009).

2.8.2 What Has Been Done to Tackle and Better Understand Riverine Nutrient Loads?

2.8.2.1 Climate Change and Water Discharge

Several EU projects, such as PRUDENCE and ENSEMBLES, have studied the effect of global climate change on the regional climate of Europe. According to the Fourth IPCC Assessment Report (IPCC, 2007), most climate models suggest that annual mean temperatures in Europe are likely to increase more than the global mean. The warming in northern Europe is likely to be largest in winter while that in the Mediterranean area is likely to be largest in summer. The lowest winter temperatures are likely to increase more than average winter temperature in northern Europe, and the highest summer temperatures are likely to increase more than the average summer temperature in southern and central Europe. Annual precipitation is very likely to increase in most of northern Europe and decrease in most of the Mediterranean area. In central Europe, precipitation is likely to increase in winter but decrease in summer. Extremes of daily precipitation are very likely to increase in northern Europe. The annual number of precipitation days is very likely to decrease in the Mediterranean area. The risk of summer drought is likely to increase in central Europe and in the Mediterranean area. Increasing temperatures in summer will lead to drier soils. This, Combined with more extreme precipitation events, will increase the chances of floods during summer (Christensen & Christensen, 2003).

Because of the ongoing trend of warmer and drier conditions increasing the pressure on water resources, the Mediterranean has been identified as a hot spot for climate change (Giorgi, 2006). Therefore, many international efforts, such as the MedCLIVAR programme, focus on this region in the fields of climate research. Decreasing precipitation trends during the second half of the last century have been detected as a general pattern in the Mediterranean region (e.g. Xoplaki *et al.*, 2004) and most Mediterranean rivers show clear negative trends in their annual discharge records. According to Ludwig *et al*. (2009), this decrease may have decreased the riverine freshwater discharge into the Mediterranean between 1960 and 2000 by at least 20 %. Also at regional scales, decreasing trends have been reported for about the same years. For example, in coastal rivers of southern France, the reduction was estimated to about 20 % for the period 1965-2004 (Lespinas *et al.*, 2009).

2.8.2.2 Nutrient Discharge

The Global *NEWS* project has increased our knowledge on factors determining the nutrient loads in the global coastal ocean. Global *NEWS* is an international, interdisciplinary scientific taskforce, focused on understanding the relationship between human activity and coastal nutrient enrichment (http://marine.rutgers.edu/globalnews/index.htm). A primary goal of Global *NEWS* is to construct and apply the next generation of spatially explicit, global nutrient export models, linking the resulting river loads to quantitative assessments of coastal ecosystem health. A general increase in future riverine nutrient loads to the coastal ocean is expected (Seitzinger *et al.*, 2010). In Europe, the EU EURO-LIMPACS project aims to predict effects of climate change on freshwater ecosystems. Also, the EUROCAT research project aimed to develop a quantifiable framework of analyses for the improved planning and management of entire river basins to improve the quality of coastal seas with regard to nutrient loads.

In the Mediterranean, a systematic compilation of data on water discharge and nutrient loads has been started on behalf of UNEP-MEDPOL (Ludwig *et al.*, 2003) and was further completed (and enlarged to the Black Sea drainage basin) in the framework of the EU SESAME project. The general objectives of this integrated project are to assess and predict changes in the Mediterranean and Black Sea ecosystems as well as changes in the ability of these ecosystems to provide goods and services. River nutrient loads are hence understood as one of the potential drivers of past and future ecosystem changes in coastal waters.

2.8.3 Future Projections

2.8.3.1 Northern Europe

Changes in precipitation and freshwater discharge are region-dependent hampering general statements. For Germany, Huang *et al*. (2010) expect a decrease in river flow in summer and autumn of between 8 and 30 %, and an increase of up to 18 % in winter by the middle of the 21st century. EURO-LIMPACS summarized the effects of climate change on cold and temperate eco-regions. Rivers in cold eco-regions belong to the least impacted aquatic ecosystems in Europe. The main human impacts result from atmospheric pollution (particularly acidification) and intense forestry. Organic pollution and eutrophication are more local problems. The impact of climate change, however, is likely to be severe. Extension of the ice-free period and increased water temperature will lead to enhance primary production and eutrophication, desynchronised life cycles and will cause physiological problems for cold-adapted species. Rivers in temperate eco-regions have been deteriorated owing to a multitude of impacts.

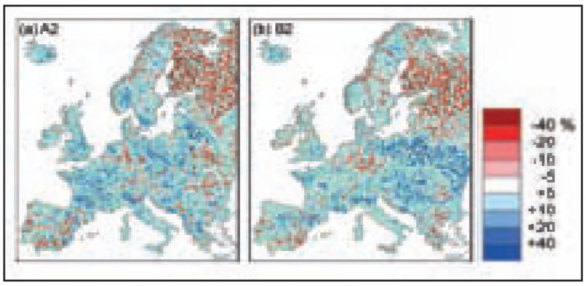

Figure 26. River floods: relative change in 100-year return level of river discharge between scenario (2071-2100) and control period (1961-1990) for the 3.9°C (left) and 2.5°C (right) scenarios.
Note: only rivers with an upstream area of 1,000 km² or more are shown. (From EC JRC PESETA Final Report)

For decades organic pollution was most significant, while nowadays hydromorphological degradation (straightening, dams, and removal of riparian vegetation) is most widespread. Climate change will have some impacts on river hydromorphology, e.g. through more frequent floods, but will mainly affect river biota through increased temperatures. The effects of these changes on nutrient dynamics within rivers and export river basins are manifold and complex. Andersen *et al.* (2006) estimated for a Danish lowland river basin an overall increased nitrogen export of about 7-9 % by the end of the 21st century, despite increased river basin retention. Johnson *et al.* (2009) predict reduced riverine discharges and increased nitrogen concentrations for two British rivers. Despite large uncertainties this study also predicts slight increases in riverine nutrient loads to the coastal zone (~10 %). Increased summer floods are expected. Inundation of floodplains will increase the riverine nutrient loads during such events (Banach *et al.,* 2010).

2.8.3.2 Southern and Eastern Europe

Projections of the river freshwater and nutrient budgets into the near future can only rely on modelling. Climate has a dominant control on water discharge and the reliability of future trends strongly depend on the reliability of the underlying climate scenarios. According to Ludwig *et al.* (2010), the decreasing trend of this parameter in the Mediterranean area of the last decades is predicted to hold in the future. In 2050, the Mediterranean may have lost more than one quarter of its freshwater input from rivers compared with 1960. This scenario is associated with an average precipitation decrease of about 4.5 mm per decade, whereas other studies even predict a more drastic reduction in precipitation (e.g. 7.3 mm per decade in Mariotti *et al.,* 2008). Ludwig *et al.* (2010) also simulated the possible evolutions of riverine nutrients. Here, socio-economic development is a more important driver than climate change and the predictions were consequently associated with the four contrasting scenarios that were defined in the Millennium Ecosystem Assessment (Carpenter *et al.*, 2006). Future trends remain in the envelope of the observed variability during the last 50 years, both for the large rivers and, when extrapolated to the basin scales, also for the entire Mediterranean and Black Sea. Societal attitudes to environmental problems have a strong impact on these budgets, in particular in the case of nitrate. At regional scales, however, the budgets can considerably change. In the northern parts of the Mediterranean drainage basin, they uniformly tend to decrease, but they may strongly increase in the south and east because of increasing demographic pressure (Figure 27).

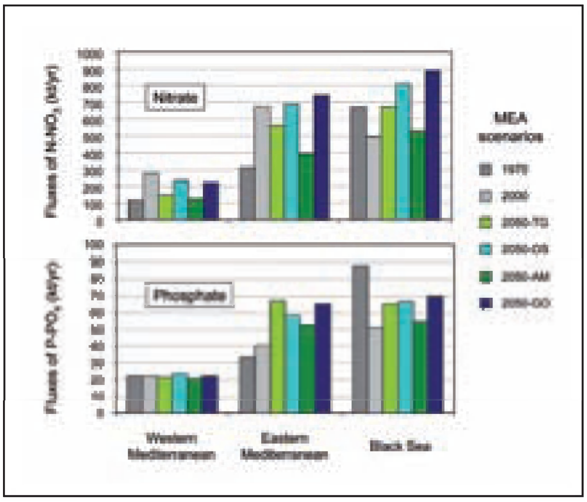

Figure 27. Comparison of the past and future river nutrient inputs into the Mediterranean and the Black Sea which were predicted by Ludwig *et al.* (2010) according to the 4 socio-economic scenarios defined in the Millennium Ecosystem Assessment: Global Orchestration (GO), Order from Strength (OS), Adapting Mosaic (AM) and Technogarden (TG).

2.8.4 Conclusions

For northern Europe, all regional climate models predict a general increase in precipitation. The combination with higher temperatures will lead to lower flow in summer and higher flows in winter (up to ~20 %). The estimated increase in total nutrient loads will be in the order of 10-20 %. These changes are smaller than the present interannual variations in riverine nutrient loads. The eutrophication history of the river Rhine demonstrates that economical pressures and political decisions have a much larger potential to change riverine nutrient loads compared to the above prediction. Thus, political and economic constraints have and will have a large impact on water quality in European waters. Long-term trends in nutrient loads due to global changes can be counteracted by political decisions.

For southern and eastern Europe, the Mediterranean drainage basin is characterized by a general evolution towards warmer and drier conditions which already started in the past and which are expected to continue in the near future. Decreasing freshwater discharges by rivers are a consequence. In the drainage basin of the Black Sea, this trend is not yet visible in the past, but likely to occur in the future as well. Given the importance of water resources for local economies in the Mediterranean region, this will increase the anthropogenic pressures on rivers. Average nutrient loads are moderate compared to many northern

European rivers (at least for nitrate), but generally follow similar trends (strong reductions of phosphate since the 1980s, constant values or slight reductions for nitrate since the 1990s). As in northern Europe, societal behaviour and political decisions may continue these trends, but only if this is not counterbalanced by demographic evolutions and/or enhanced economic development.

2.8.5 Socio-Economic Consequences of Changes in Riverine Discharge and Nutrient Loads

The expected increase in riverine nutrient loads can be counteracted by appropriate political decisions. Wetlands have a huge natural capacity to ameliorate nutrient fluxes e.g. by sedimentation of particulate matter or by denitrification. They also play an important role in buffering flash floods, which can be expected to increase due to regional climate change. Therefore, these wetlands have to be protected and extended in response to upcoming changes. Water use in the Mediterranean drainage basins should take into account the general lowering of the water resources, favouring agricultural and economic practices which are less water demanding and thus compatible with the scarceness of water in many parts of this region.

Figure 28. Wetlands at the Danube delta. Wetlands have a huge natural capacity to ameliorate nutrient fluxes for example by sedimentation of particulate matter or by denitrification. (Courtesy Thisfabtrek.com)

2.8.6 Research Gaps and Priorities

Interactive effects of floods, global temperature increase and coastal biogeochemistry with changes in coastal ecology are still poorly understood. For example, increased DOC export may support toxic marine blooms. A major challenge is to couple scenarios of regional climate change with river basin models nutrient transfer and coastal ecosystem models with the aim of testing the interacting effects of global climate change with scenarios of regional socio-economic change (e.g. Thieu *et al.* 2010). This also needs a better understanding of the possible responses of the coastal ecosystems to the changing riverine nutrient loads, both quantitatively and qualitatively. In the Mediterranean, water discharge of rivers is often strongly influenced by anthropogenic water use, which may have also contributed to the decrease in water resources. Predicting this negative feedback in a general trend towards drier conditions is an important challenge for hydrologists.

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2.9 Ocean Acidification

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2.9.1 Introduction

Since the beginning of industrialization, the ocean has taken up approximately one third of total anthropogenic CO_2 emitted to the atmosphere (Khatiwala *et al.* 2009). Carbon dioxide is a weak acid and the continued uptake of anthropogenic CO_2 triggers changes in ocean carbonate chemistry and pH referred to as ocean acidification (Calderia and Wicket, 2003). At present, the mean pH of ocean surface waters is already 0.1 units (equal to 30 %) lower compared to pre-industrial times and a decrease by 0.4 units (equal to 120 %) is projected by the year 2100 in response to a business-as-usual emissions pathway (Caldeira and Wickett, 2003). This change in pH drives profound changes in carbonate chemistry and is likely to affect the structure and functioning of marine ecosystems (Fabry *et al.,* 2008). In the following, we will discuss the chemical basis of ocean acidification (Orr, 2010) and present examples of environments, as well as ecosystems which are particularly at risk. For a comprehensive overview of the field of ocean acidification research encompassing chemistry, biology and biogeochemistry, as well as past, present and future patterns and predictions, please refer to Gattuso and Hansson (2010).

In the modern ocean, the overwhelming fraction of $CaCO_3$ is precipitated by organisms in contact with oversaturated waters as skeletal material. The decrease in pH and in saturation state with respect to $CaCO_3$ is expected to have profound consequences for marine biota. Two major forms of $CaCO_3$ are synthesized by marine organisms (Figure 30; Cooley & Doney, 2009): calcite and the more soluble aragonite. In addition, magnesium carbonates of varying composition, and thus solubility, are present in many crustacean shells and some algae. Aragonite is found in molluscs, including in the pelagic pteropods, but also in coral skeletons. Examples of calcite forming organisms include coccolithophores (autotrophs) and most foraminifera (heterotrophs). Note that some bivalves secrete shells made of alternating layers of aragonite and calcite. The mechanism of calcification varies between organisms and is still poorly understood. Organisms that exert low biological control over calcification directly deposit calcium carbonate along their inner shell walls;

they thus depend on the carbonate concentration of the environment to successfully synthesize their shells. Other organisms exert a high biological control over calcification by confining the process to an intracellular compartment (e.g. calcification vesicle in foraminifera or coccolithophores). This involves gradually accumulating intracellular stocks of carbonate ions.

Whatever the calcium carbonate form, in the modern ocean Ω reaches 1 at depths located well below the ocean surface. The depth of the saturation horizon reflects the interplay between air-sea gas exchange, biological processes and large scale ocean circulation. It is deepest in the North Atlantic and shoals gradually as water masses age along the path of the large scale meridional overturning circulation towards the North Pacific. The horizon is relatively shallow in the Southern Ocean and in the Arctic Ocean where cold temperatures are favourable to carbon dioxide dissolution.

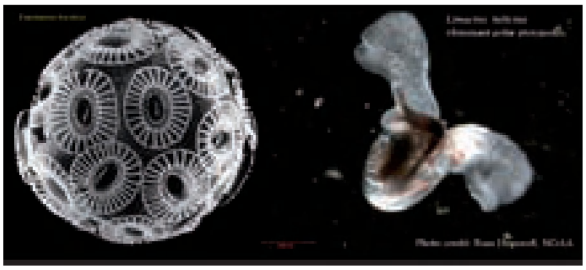

Figure 30. Calcareous shell-forming organisms. Left: electronic miscroscope view of *Emiliania huxleyi*, a coccolithophore, with its calcite liths, which an approximate size of 20 micrometers. Right: camera view of *Limacina helicana*, a pteropod with its aragonite shell with an approximate size of a few millimetres. (©Rus Hopcraft, NOAA)

2.9.2 Socio-Economic Impacts of Ocean Acidification

A lowered pH has direct and indirect effects on marine life, not only for calcareous organisms but more generally on the physiology of many organisms (respiration rate, blood chemistry, growth rate, reproduction). As a result, ocean acidification is expected to have significant impacts on marine ecosystems, including exploited ecosystems, with potentially declining harvests and fisheries revenues from shellfish, their predators, and coral reef habitats. Thus, anticipating the economic consequences of ocean acidification is becoming a major concern for commercial fisheries. A first tentative assessment has been made by Cooley & Doney (2009) (also, see Cooley 2010) for the US fisheries, first-sale revenues of which amount to approximately USD 4 billion. Although regionally focused, this study provides evidence of how acidification could perturb fisheries *sensu lato*. While the molluscs appear most vulnerable to direct effects of ocean acidification, a decline in those species could cause problems for predators above them on the trophic network.

2.9.3 Ocean Acidification is Detectable

Changes in the ocean CO_2 system seem to be detectable from time series observations around the world. The increase in surface ocean fugacity of CO_2 follows the atmospheric signal at station HOT (Hawaii Ocean Time-series) located in the northern oligotrophic Pacific, as well as at stations BATS (Bermuda Atlantic Time-series Study) and ESTOC (European Station for time series in the OCean), both located in the North Atlantic oligotrophic gyre. At ESTOC CO_2 fugacity increased by 1.7±0.7 µatm yr^{-1} in surface ocean waters and the atmosphere, leading to a decrease in pH of -0.0017 ± 0.0003 units yr^{-1} (Gonzáles-Dávila *et al.*, 2010) over the period 1995 to 2004. A more important drop in pH is reported for Iceland sea waters where the winter surface water pH decreased by 0.0024 units yr^{-1} (Olaffson *et al.*, 2009) between 1985 and 2008. The difference between rates reflects the variability of chemical characteristics between warm tropical waters (high buffer capacity) and cold northern Atlantic waters (low buffer capacity). Please refer to the section on the Arctic Ocean for further details. European projects CARBOOCEAN, EuroSITES and EPOCA contributed to the funding of these observational programmes. ESTOC is part of a larger network of ocean observatories including a total of nine stations. Building and maintaining the capacity for long-term observation of the marine environment is key to assessing impacts of global climate change and ocean acidification on marine ecosystems.

2.9.4 Impacts on Marine Organisms and Ecosystems

Numerous experiments report a reduction in calcification rates for many organisms to occur before undersaturation is reached (Ω > 1) (see Fabry *et al.,* 2008 and Doney *et al.*, 2009 for a recent synthesis). A data compilation on the biological and biogeochemical responses to ocean acidification was recently published by EPOCA and EUR-OCEANS, two European Commission funded programmes (Nisumaa *et al.,* 2010). A careful analysis of results reveals a contrasting picture. For example, while Riebesell *et al.* (2000) report reduced calcification in the coccolithophore *Emiliania huxleyi,* Iglesias-Rodriguez *et al.* (2008) observed an increase in $CaCO_3$ production in the same species. These differences have been explained in terms of genetic variability between strains (Langer *et al.*, 2009). Recently Irie *et al.* (2010) suggested that an increase in calcification, and thus more heavily calcified coccolithophores, reflects an optimal growth strategy. This hypothesis has the potential to reconcile observations from the paleo-record and contemporary laboratory experiments.

Studies published so far have yielded contrasting results. On the one hand, ocean acidification can directly damage marine organisms such as corals or molluscs, through perturbation of metabolism, reproduction, development, intracellular chemistry, and immunity. Fishes are also potentially affected via the alteration of the formation of otoliths, statoliths, and gastroliths. On the other hand, experiments show that planktonic organisms, but also crabs, lobsters, shrimps, show increased calcification in high-CO_2 seawater. Calcification is, however, not the only biological function impacted by ocean acidification. Experiments have shown photosynthesis to increase in some phytoplankton species (Rost *et al*., 2008) and changes in seawater pH interact with the N cycle in many ways (Hutchins *et al*., 2009).

To predict impacts of ocean acidification on a given marine ecosystem is a major challenge (Gehlen *et al*., 2010). Furthermore, ocean acidification does not occur in isolation and its interaction with global climate change needs to be assessed. Ecosystem impacts are expected to be important, although little is known on the time scale of adaptability of marine organisms and about the resilience of marine ecosystems. For example, a decrease in pH has been reported to damage tropical and cold water corals, which support crucial benthic habitats. Preliminary estimates show significant economic consequences of ocean acidification for US commercial fisheries (Cooley & Doney, 2009).

2.9.5 Can We Learn from the Past?

Paleostudies reported contrasting evidence of impacts of ocean acidification. According to Gibbs (2006), 55 million years ago, during the Paleocene – Eocene Thermal maximum, CO_2 conditions in the atmosphere were comparable to those expected at the end of this century for a pessimistic scenario of anthropogenic CO_2 emissions. During this period species of benthic foraminifera either disappeared (dissolution of calcite tests) or survived by building stronger calcium carbonate shells. However, the rate of increase of CO_2 in the atmosphere was much lower during this paleo event, compared to present, which makes a big difference. Conclusions drawn from the analysis of past situations might thus not be applicable to present conditions.

2.9.6 Research Gaps and Priorities

The inorganic chemistry of the carbonate system is well understood and incorporated in state-of-the-art biogeochemical ocean general circulation models. Projections of the future evolution of ocean carbonate chemistry in response to various emission scenarios allow us to investigate potential socio-economic consequences of societal development options in terms of ocean acidification with a good level of certainty. However, our understanding of the responses of marine life forms to ocean acidification is still at its infancy. Acclimation and adaptation will need increased attention, both at the level of the individual organism, as well as on the community level. The synergy between simultaneous changes of temperature, oxygen and pH will also need to be addressed. Finally, the improved representation of potential biological responses to climate change and ocean acidification in regional and global models is a clear challenge for the scientific community.

Figure 31. Anticipating the economic consequences of ocean acidification is becoming a major concern for commercial fisheries (©Andreas Karelias/iStock)

Information Box 2. The Chemical Basis of the Carbonate System

The surface ocean exchanges gases with the overlying atmosphere across the air-sea interface. These gases are soluble in seawater. Their solubility increases with decreasing temperature. Colder waters, such as those of the polar regions are thus naturally oxygen and carbon dioxide rich. Unlike oxygen, carbon dioxide (CO_2) not only dissolves in, but also reacts with water according to

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2\,H^+ \qquad (1).$$

At the average modern ocean seawater pH (8.1) bicarbonate (or hydrogenocarbonate HCO_3^-) predominates over carbonate (CO_3^{2-}). Reaction (1) results in an increase of [H^+] and thus a drop in pH ('ocean acidification'). Acidification of ocean water goes along with a decrease in the concentration of carbonate ion (CO_3^{2-}) and of the saturation state with respect to carbonate minerals ($CaCO_3$). This can be represented as the titration of CO_3^{2-} ions by CO_2 :

$$CO_2 + CO_3^{2-} + H_2O \leftrightarrow 2\,HCO_3^- \qquad (2).$$

Bicarbonate ions (HCO_3^-) react with calcium (Ca^{++}) ions dissolved in seawater to form $CaCO_3$ according to the reaction:

$$2HCO_3^- + Ca^{++} \leftrightarrow CaCO_3 + H_2O + CO_2 \qquad (3).$$

The formation of $CaCO_3$ generates CO_2, which has the potential to be transferred to the atmosphere. Reaction (2) is reversible, implying that when water masses get undersaturated with respect to $CaCO_3$ the latter dissolves. The solubility of $CaCO_3$ (Zeebe and Wolf-Gladrow, 2001) is dependent on pressure, salinity and temperature. It increases with increasing pressure (depth) and decreasing temperature. It is described by the stoichiometric solubility product Ksp, Ksp = $[Ca^{++}]sat \times [CO_3{=}]sat$, where $[Ca^{++}]sat$ and $[CO_3^{-2}]sat$ are the concentrations at saturation in seawater (Mucci, 1983). To define the calcium carbonate saturation we calculate Ω, $\Omega = ([Ca^{++}] \times [CO_3^{-2}]) / Ksp$. Theoretically, when $\Omega > 1$ $CaCO_3$ precipitates, and reversely when $\Omega < 1$ $CaCO_3$ The saturation horizon is defined by the depth at which W = 1 (see Figure 29).

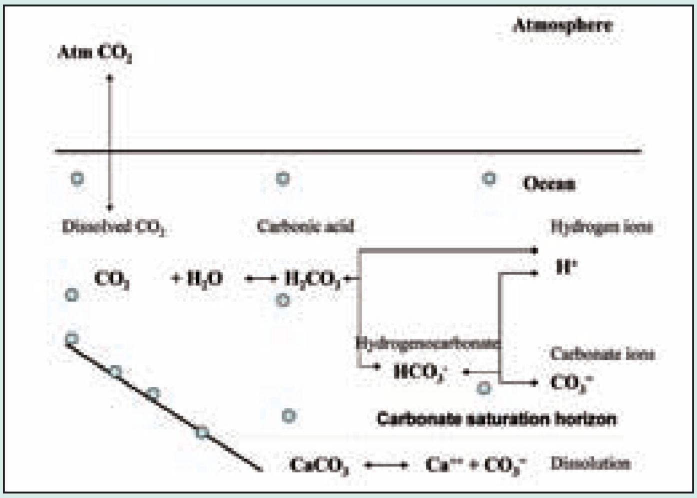

Figure 29. Chemical basis of the carbonate system in seawater. Calcareous shell-forming plants and animals (blue circles) can develop in waters which depths are shallower than the carbonate saturation horizon. Reversely calcium carbonate dissolution is active in waters deeper than this horizon.

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2.10 Ocean Deoxygenation and Coastal Hypoxia

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2.10.1 Introduction

The knock-on effect of climate change on seawater oxygen levels has only recently gained attention, but the consequences could be substantial (Diaz & Rosenberg, 2008, Keeling *et al*. 2010). Climate change can affect the concentration of oxygen in marine ecosystems in several ways. Oxygen is less soluble in warmer water, and hence, an increase in global temperature will decrease the inventory of oxygen within the ocean. Combined with changes in wind and precipitation patterns, higher temperatures will also increase stratification, thereby reducing the downward oxygen transport to deeper waters and seafloor ecosystems (see Chapter 2.6). Moreover, higher seawater temperatures enhance the respiratory and metabolic rates of organisms, thus stimulating the biological demand for oxygen.

The loss of dissolved oxygen from the open ocean, so-called ocean de-oxygenation (Keeling *et al.* 2010), is typically distinguished from the increased prevalence of low-oxygen conditions in coastal and shelf waters, referred to as coastal hypoxia (Diaz & Rosenberg, 2008). Changes in the oxygen content of the ocean interior will be driven mainly by climate effects, such as a decrease in oxygen solubility, increased stratification, weakened ventilation, and increased biological respiration (Keeling *et al*., 2010). In addition to these climate effects, the coastal zone is affected by another component of global change, that is, the increased nutrient delivery from land. Human activity has greatly accelerated the flow of nutrients to estuaries and coastal ecosystems over the past half century, thus leading to increased primary production in the coastal zone (see Chapter 2.11). This results in a larger supply of organic material to deeper water layers and sediments, stimulating respiration and causing a lower oxygenation in bottom waters (Diaz & Rosenberg, 2008; Conley *et al*., 2009).

The sensitivity of marine organisms to changes in seawater oxygen levels is highly non-linear (Vaquer-Sunyer & Duarte, 2008). Organisms are not very sensitive as long as the oxygen levels remain adequately high. Once the oxygen levels drop below a certain ‘hypoxia’ threshold, organisms suffer from a variety of stresses, ultimately leading to disappearance of the species when oxygen levels become too low. The conventional reference level for hypoxia is ~60 μmol kg^{-1}, though thresholds vary widely between different organism groups, with crustaceans and fish being the most sensitive. Early stages of hypoxia are typically missed until obvious signs, such as mass mortality of fish, indicate that thresholds have been passed. Once the oxygen drops below ~5-10 μmol kg^{-1}, conditions become suboxic, and all multicellular life disappears. When the oxygen levels go towards zero, the water is termed anoxic.

Figure 32. Patterns of coastal ecosystem decline in response to hypoxia (design: Sabine Luedeling, www.medieningenieure.de)

2.10.2 Observations and Future Projections

Has the oxygen loss from the ocean already started? The average ocean O_2 concentration is ~178 µmol kg^{-1}, while the predicted decline in the average ocean O_2 concentration over the next century ranges between 2-12 µmol kg^{-1} (1-7 %). Owing to the substantial spatial, seasonal and interannual variability, one needs sufficiently long time series of oxygen concentrations are required before trends can be shown with appropriate statistical significance. Despite these limitations, several studies have been able to show a long-term trend in oxygen concentrations, providing evidence that changes in O_2 levels are occurring, most notably in the North Pacific and the tropics. Although, anoxia is rare in the water column of the modern ocean, there are wide expanses within the Pacific, Indian and Eastern tropical Atlantic that exhibit hypoxic conditions. A major concern is that these so-called Oxygen Minimum Zones will expand in the near future. Recent analysis of oxygen data in the tropical and subtropical ocean (40N-40S) reveals that the hypoxic zone has increased horizontally by 4.5 million km^2 over the last three decades and that it has also expanded vertically (Stramma *et al.,* 2010).

A similar picture emerges for coastal hypoxia observations. Hypoxia is a natural phenomenon in some coastal systems, such as basins with restricted water circulation (e.g., fjords, Black Sea), or in shelf regions subject to the upwelling of oxygen-depleted and nutrient-rich subsurface water (e.g. Northeast Pacific, Namibian shelf and Indian shelf). Alongside this natural hypoxia, there is strong evidence for a global increase in the frequency, extent, intensity and duration of coastal hypoxia linked to human activities (Diaz & Rosenberg, 2008). A recent survey shows that the number of coastal sites where hypoxia has been reported has increased by 5.5 % per year over the last three decades (Vaquer-Sunyer & Duarte, 2008). Although this rate of increase rate partially reflects increased monitoring efforts, there is an unambiguous increase in the occurrence of coastal hypoxia.

Climate simulations over the next few centuries predict an overall decline in the oxygen concentrations, an expansion of the mid-depth oxygen minimum zones, and an increased prevalence of coastal hypoxia. These models indicate that the ocean's oxygen content will respond rather sensitively to global ocean warming. Only part of the predicted decline in O_2 levels corresponds to the decrease in O_2 solubility in warmer water; the remaining part is a result of changes in circulation and effects on biological processes. The total de-oxygenation is predicted to be about 2 to 4 times larger than that which would be expected based on solubility decrease alone (Keeling *et al.,* 2010). The most important cause for this is the effect of climate change on the stratification of the surface ocean at high latitudes, enhanced by increased temperatures and a decrease in surface water salinity driven by an intensified hydrological cycle.

Figure 33. An underwater winch system is deployed in the deep anoxic waters of the Gotland Basin (Baltic Sea) as part of the Gotland Deep Environmental Sampling Station (GODESS) as part of the EU project HYPOX. This instrument allows high frequency and high resolution profiles of oxygen and other biogeochemical parameters throughout the water column. Such measurements are instrumental for a better understanding of coastal hypoxia. First time series results show a remarkable dynamics of the oxic/anoxic transition zone with strong implications for water column biogeochemistry and nutrient recycling. (Courtesy of Ralf Prien, Leibniz Institute for Baltic Sea Research, Germany)

2.10.3 Impact on Biogeochemistry and Ecosystem Functioning

Both ocean de-oxygenation as well increased prevalence of coastal hypoxia can potentially have widespread consequences for both ecosystems and global geochemical cycles. Oxygen plays a central role in the biogeochemical cycling of carbon, sulfur, and nutrients such as nitrogen and phosphorus, as well as other chemical elements. When the Oxygen Minimum Zones extend, the ocean will lose more and more fixed nitrogen via denitrification, which could limit global ocean productivity (and hence, the fish stocks that depend on this). On the Indian continental shelf, increased production of N_2O was reported as a consequence of intensifying anoxia (Naqvi *et al.*, 2000). Global expansion of hypoxic zones thus may lead to an increased marine production of this greenhouse gas. Bottom water hypoxia also leads to major changes in the biogeochemical cycling of carbon and nutrients in marine sediments. In coastal areas, the release of nutrients from the sediment under hypoxic conditions initiates a positive feedback loop with increased nutrient availability, enhanced primary productivity, and hence, increased oxygen consumption by micro-organisms that live on the algal biomass produced. Such a positive feedback has been suggested as the cause of increased and sustained hypoxia in the Chesapeake Bay (Kemp *et al.*, 2005) and the Baltic Sea (Conley *et al.*, 2009).

Figure 34. Dead bivalves (*Crassostrea gigas* & *Cerastoderma glaucum*) in a hypoxic zone of a harbour flushing basin after drainage in Oostende, Belgium (©Ana Trias Verbeeck)

Hypoxia has major consequences for the functioning of coastal ecosystems, leading to ‘dead zones’ characterized by the absence of benthic fauna and fish. Well known examples include the Gulf of Mexico and the East China Sea, and in European waters, the Adriatic Sea, the German Bight, the Baltic Sea and the northwestern shelf of the Black Sea. Typically, these are all major fishery areas and of economic interest (Diaz & Rosenberg, 2008). Until now, the formation of these dead zones has primarily been linked to coastal eutrophication fueled by riverine runoff of fertilizers and atmospheric N deposition (input of reactive nitrogen species from the atmosphere to the biosphere) linked to the burning of fossil fuels. However, the combination of sustained eutrophication with future climate change could intensify hypoxia to new levels with a corresponding increase in ecosystem impacts.

2.10.4 Ongoing Research in Europe

To better understand dynamics, drivers, and consequences of oxygen depletion, the EU-funded project HYPOX has started to deploy and install observatories for continuous oxygen monitoring. Target sites are located in open and coastal seas as well as land-locked water bodies that differ in oxygen availability as well as in sensitivity towards change. HYPOX monitoring activities are complemented by field campaigns as well as modelling studies to understand the driving forces of hypoxia formation and to gain predictive and decision-making capabilities from the obtained monitoring data.

The BONUS project investigates the mechanisms leading to hypoxia in the Baltic Sea and will quantify the consequences in terms of ecosystem changes. Special emphasis is on the interplay between hypoxia and the availability and regeneration of nutrients. Modelling tools are used to better understand the temporal and spatial variability of Baltic Sea hypoxia taking climate change into account. Eventually, HYPER aims to provide guidelines for future monitoring practices and to assess economic costs and ecological benefits of nutrient management.

To be able to document changes in the global open ocean, the EU-funded Eurosites project has integrated nine deep-ocean observatories and upgraded their sensing and data flow capabilities. A sensor to quantify oxygen consumption plays a central role for the upgrade of observatories in order to better understand ocean oxygen dynamics and the role of water column respiration.

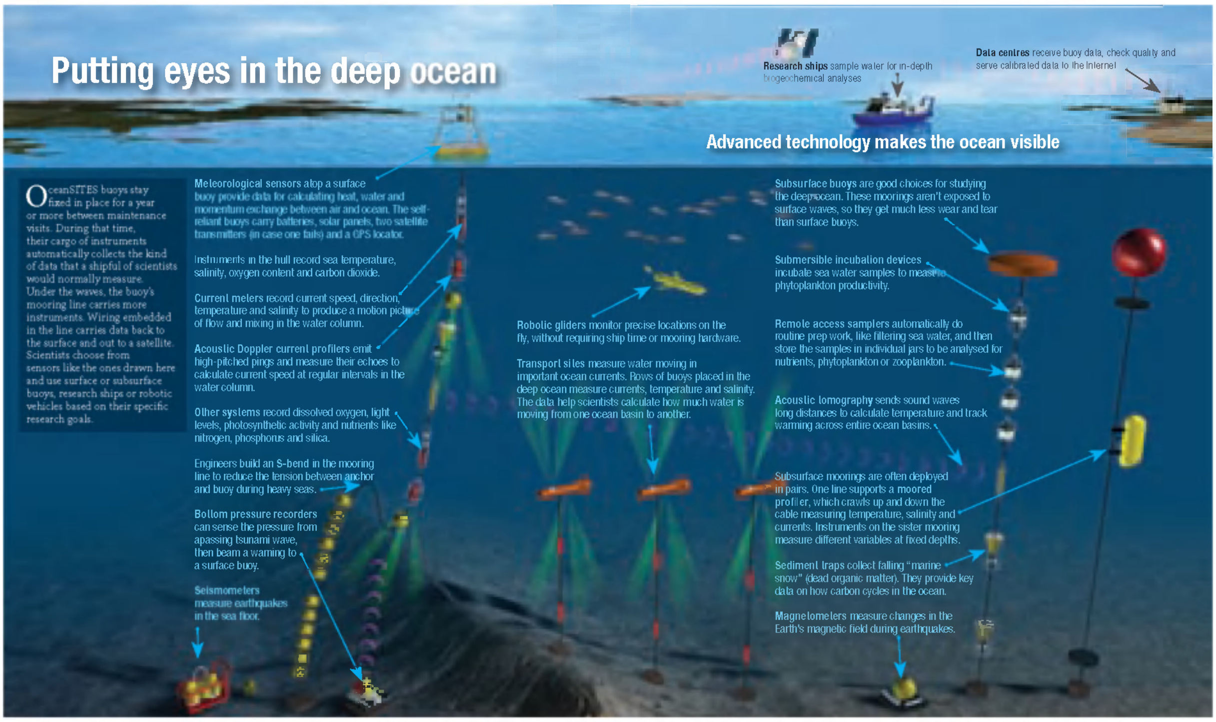

Figure 35. Illustration of ocean observation tools and technologies (courtesy OceanSITES)

2.10.5 Research Gaps and Priorities

Clearly, both ocean de-oxygenation and increased coastal hypoxia are predicted to have a strong impact on the future functioning of marine ecosystems. Therefore, future research must:

- Characterize the spatial and temporal dynamics of oxygen in both open ocean and coastal environments;
- Indentify the drivers of oxygen depletion; and
- Separate natural variability from anthropogenic impacts on changes in oxygen levels.

A combination of field observations, process studies and modelling will be needed to address these questions.

On the observational side, a global observation system is required that continuously monitors oxygen concentrations at high resolution, linked to measurements of other physical and biogeochemical parameters as well as climate observations. Drifting observing platforms such as the Argo (including the Euro-Argo) floats (www.argo.net, www.argos-system.org, www.coriolis.eu.org) are increasingly incorporating oxygen-sensors (Gruber *et al.* 2007). Stationary deep sea observatories equipped with oxygen sensing capabilities will help to quantify changes and long term trends in ocean oxygenation. Such deep-sea observatories should be deployed in regions where oxygen concentrations are expected to directly respond to climate change (e.g. areas of deep water formation, oxygen minimum zones).

Further expansion of coastal hypoxia will depend on how strongly climate change will impact O_2 solubility, water column stratification and biological respiration, and how effective measures to reduce nutrient run-off from land will be. To predict the outcome of this interplay between climate change and coastal nutrient management, a thorough understanding of the feedback mechanisms between oxygen availability and nutrient cycling in coastal environments will be needed.

Cabled observatories will be particularly useful to follow the seasonal and temporal changes in bottom water oxygen concentrations in coastal and land-locked water bodies. Based on such observations, integrated modelling efforts are needed to better predict the frequency, intensity, and duration of future hypoxia.

Information Box 3. Importance of Long Term Deep Ocean Observatories

The ocean observing system consists of a combination of remote and *in situ* sensing platforms including satellites, research vessels, ships of opportunity, marine research stations, Argo floats and fixed monitoring buoys. Marine observatories provide the backbone of this ocean environment observing capacity as they record key variables *in situ* at fixed locations in the ocean and at regular intervals over extended time periods. Such long-term time-series datasets from the marine environment are of critical importance to facilitate:

- Monitoring of the rate and scale of environmental change, including climate change and biodiversity loss;
- Effective policy making and sustainable management of the seas and oceans;
- Detection of hazards and events;
- Understanding ocean, earth and climate system processes.

Deep ocean observatories are basically platforms suspended in the ocean or located at the seafloor, fitted with multiple sensors that continuously monitor key parameters at a certain geographical location at greater depths (generally below 1,000 m). They can sometimes be left in the ocean for periods of more than a year before they require maintenance. This makes them much more cost efficient than ship based observations.

Deep ocean observatories have become indispensable tools in marine/climate research because there is a substantial lack of high resolution data which is essential to improve models, detect and predict episodic events as well as short and long term trends such as an increasing temperature, changes in stratification or decreasing in oxygen concentrations. At the same time, these observatory systems provide a warning system for extreme events such as earthquakes and tsunamis.

In Europe, the focus is currently on the creation of large observation networks through initiatives such as Euro-Argo, EuroSites and OceanSites and EuroGOOS that combine different existing observatories and collect their data in a single place, making it easier for scientists to access and combine different datasets. While securing long-term support for existing observatory sites, further integration of existing observatories and the measurement of more of the vast expanse of the open ocean will be critical in the future. At the same time, research should focus on improving existing sensors and developing more sophisticated ones so that more parameters and more complex properties of the ocean can be measured.

For more information, please visit: www.oceansites.org, www.euro-argo.eu, www.eurogoos.org, www.eur-oceans.eu.

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2.11 Marine Eutrophication

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2.11.1 Observations

Eutrophication is the movement of a water body's trophic status in the direction of more plant biomass, by the addition of artificial or natural substances, such as nitrates and phosphates, through fertilizers or sewage, to an aquatic system. Coastal eutrophication has become a wide-spread phenomenon during the past decades (Rosenberg, 1985; Nixon, 1995; Cloern, 2001; Schindler, 2006). In large river basins and sea areas of Europe, 50-80 % of the total Nitrogen (N) pollution is caused by run-off from agricultural land, whilst households and industry still tend to be the most significant source of Phosphorus (P) pollution (Figure 36). The effects of climate change, for instance through changing precipitation patterns, can influence terrestrial-derived nutrient delivery to the coastal seas via changes in river flow (see also 'Riverine discharge and nutrient loads').

The effects of changing precipitation patterns on delivery of nutrients may also be magnified by land use practices. For example, nitrate tends to build up in soils during dry years, largely as a result of reduced uptake of soil nutrients by crops, and is flushed into streams at much larger rates during subsequent wet years. If future precipitation regimes are more variable, this could increase the net impacts to coastal areas affected by nutrient over-enrichment and eutrophication (Scavia *et al.,* 2002).

In addition to increasing nutrient loads, higher freshwater discharges can further influence estuarine ecology by decreasing water residence times in the main estuarine channels (Struyf *et al.,* 2004). The effects of climate change will vary within coastal ecosystems. For the Baltic Sea, for example, common to all of the four different climate change scenarios from the Swedish Regional Climate Modelling Programme (SWE-CLIM) is a general trend of reduced river flow from the south of the Baltic Basin together with increased river flow from the north (Graham, 2004).

Higher discharges may apparently improve water quality by diluting nutrient concentrations and increasing oxygen concentrations, masking the increasing total loadings of nutrients in freshwater and brackish reaches of estuaries (Struyf *et al.*, 2004). Under certain circumstances, eutrophication may result in hypoxic (low oxygen) conditions in aquatic ecosystems. The EU FP7 project HYPOX monitors oxygen depletion and associated processes in aquatic systems that display different responses in oxygen status or sensitivity towards change, including seasonally or locally anoxic land-locked systems (fjords, lagoons, lakes) subject to eutrophication.

Modelling efforts within the EU FP6 project CARBO-OCEAN have shown that the increase of primary production due to eutrophication could counter the effects of ocean acidification on surface water carbonate chemistry in coastal environments (Borges & Gypens, 2010).

2.11.2 Stoichiometry

Whether primary production by phytoplankton is N or P limited is broadly dictated by the relative availabilities of N and P in the water compared to the stoichiometric need for average cell growth (the so-called Redfield ratio of 16:1). A new line of research was developed within the EU FP6 CARBOOCEAN project, on non-stoichiometric carbon cycle modelling, where the assumed 'Redfield concept' of constant ratios of $P:N:C:\Delta O_2$ in most biogeochemical ocean models was abandoned. Nutrient availability, in turn is determined by the ratio of external N:P in inputs to the ecosystem, preferential storage, recycling, or loss of N or P in the ecosystem, and the amount of biological N fixation (Vitousek & Howarth, 1991). In contrast to N and P, the silica concentration in estuaries is only indirectly influenced by human pollution. Diatom communities require about equal amounts of N and Si. Diatoms are an essential element of coastal water food chains. Increased N-concentrations can lead to a succession from phytoplankton communities dominated by diatoms to phytoplankton communities dominated by species that are not taken up by higher trophic levels (Schelske *et al.,* 1983; Smayda, 1997).

Over the past two decades, a strong consensus has evolved within the scientific community that nitrogen is the primary cause of eutrophication in many coastal ecosystems around the world (Howarth & Marino, 2006). Even though N is probably the major cause of eutrophication in most coastal systems in the temperate zone, optimal management of coastal eutrophication suggests controlling both N and P, in part because P can limit primary production in some systems, at least during parts of the year (Dodds, 2003; Howarth & Marino, 2006). Impacts of climate change on coastal marine eutrophication will, therefore, not only be determined by the amounts of nutrient supply but also by the relative concentrations in the freshwater discharges.

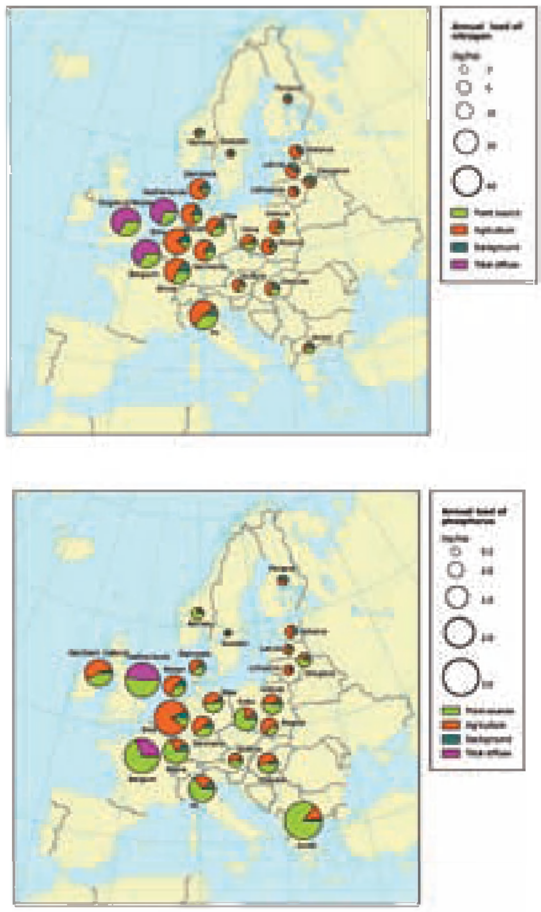

Figure 36. Total area-specific annual load of (above) phosphorus (kg P/ha/year) and (below) nitrogen (kg N/ha/year) in selected European river catchments and countries. The P load is highest in countries and catchments with high population density and a high proportion of agricultural land. In countries/catchments such as Belgium and the Odra and Po catchments with high population density and without nutrient removal at the majority of wastewater treatment plants, point sources generally account for more than two thirds of the load. The N increases generally with increasing agricultural activity, is 2 to 3 times as high in north-western Europe than in the Nordic countries and Baltic States, and agricultural or diffuse losses (agriculture plus background) account for more than 60 % of the total load. (EEA, 2005)

2.11.3 Impacts on Food Webs

Eutrophication usually results in an increased production and biomass of phytoplankton and micro-phytobenthos (e.g. Cadée & Hegeman, 2002; Beman *et al.*, 2005; Smith, 2006; Philippart *et al.*, 2010). The response of individual algal species, however, depends on their specific life-history traits such as growth curves and storage capacities (Grover, 1997; Roelke *et al.*, 1999). For example, eutrophic conditions are predicted to favour relatively large phytoplankton species that, due to their larger storage capacity, are better competitors under high and pulsing nutrient regimes (Sommer, 1984; Stolte *et al*., 1994; Grover, 1997), while the biomass of smaller algae is primarily controlled by microzooplankton grazing (Thingstad & Sakshaug, 1990).

Basic knowledge on growth as a function of multiple stresses, such as limitations of light and macronutrients, was acquired in the EU FP5 IRONAGES project, for four of the five major marine taxonomic phytoplankton groups (Veldhuis & de Baar, 2005). IRONAGES also established a comprehensive database for ocean biogeochemical cycling, including nutrients and particle fluxes. Although the emphasis is on quantifying the impact of ocean acidification on marine organisms, the EU FP7 EPOCA project is also devoting much effort to measuring key climate-relevant biogeochemical processes such primary production.

In most shallow coastal seas, phytoplankton and microphytobenthos are an important food source for macrozoobenthos (sediment-dwelling invertebrates of > 1 mm). Living phytoplankton is sifted out of the water by filter-feeding bivalves at rates in the order of 1 to 10 m^3 m^{-2} d^{-1} (Riisgaard *et al*., 2004). Dead phytoplankton cells (detritus) as well as microphytobenthos are mostly eaten by deposit-feeding bivalves, gastropods and polychaetes (Beukema *et al*., 2002). On the scale of estuaries, Herman *et al*. (1999) showed that between 5 % and 25 % of the annual primary production is consumed by macrozoobenthos. Pathways of fluxes depend, however, on the trophic state of the estuary. High organic enrichment appears to favour filter feeders, whilst deposit-feeding organisms predominate in areas with a low supply of organic matter (Pearson & Rosenberg 1987). It is, therefore, to be expected that climate-induced changes in primary production will be reflected in macrozoobenthic biomass, filtering capacity and community structure.

Macrozoobenthic communities generally support a suite of consumers, of which estuarine birds are amongst the most conspicuous. Bird numbers on a particular site depend not only on the conditions at that site, but also on conditions elsewhere in the species' distribution range (e.g. Goss-Custard *et al*., 1995). However, because the quality of a given estuary, the 'carrying capacity' for birds is determined by the local feeding conditions (Goss-Custard *et al*., 2002), changes in these conditions will also affect local bird numbers (West *et al*., 2005). Reorganization of plankton communities might also have dramatic socio-economic impacts through effects on commercial fisheries in coastal and shelf seas. A number of workers have demonstrated an empirical relationship between primary production, fish growth (e.g., Rijnsdorp & van Leeuwen 1996) and fisheries yield (e.g. Nixon, 1992; Tatara, 1991; Iverson, 1990; Larsson *et al*., 1985; Nielsen & Richardson, 1996).

The impacts of climate change, including the consequences of changes in primary productivity, on shellfish and fish stocks are further explored in the FP7 project, RECLAIM, for the North-East Atlantic and North Sea and the INTERREG project SUSFISH for the Irish Sea. The MarinERA project ECODRIVE brings together climatologists, modellers, planktologists, fisheries experts and ecophysiologists with the aim of assessing and modelling historical and projected future changes in the trophodynamic structure and function of the North Sea ecosystem. ECODRIVE aims to advance our predictive understanding of the impacts of various drivers of ecosystem change including those acting via climate change and variability as well as those acting more regionally via anthropogenic forcing such as fisheries exploitation and eutrophication.

Figure 37. Foam on the beach during windy days in the spring, caused by the decaying remains of the brown slimy algae *Phaeocystis globosa* after a bloom in Den Hoorn, Texel, Netherlands. Since the 1970s, the amount of Phaeocystis in the Atlantic Ocean and the North Sea rose due to the discharge of too many nutrients. (©Karen Rappé)

2.11.4 Research Gaps and Priorities

Observed correlations between variations in nutrients, primary production and higher trophic levels do not necessarily indicate cause and effect. Other changes that have occurred simultaneously, such as those driven by climate (light, circulation and temperature) and anthropogenic impacts (fishing, pollution, acidification and introduction of non-native species), may have affected growth and loss rates of microalgae. Understanding the impacts of nutrient loads on primary production, and identifying and quantifying trophic transfer between primary and secondary producers will be essential for developing realistic and ecologically sound management strategies for sustainable use of coastal seas in a changing environment. With an emphasis on the European Marine Strategy Framework Directive, the EU FP7 MEECE project is developing decision support tools to provide a structured link between such management questions. The INTEREG project SUSFISH will produce guidelines for future fisheries management, ensuring sustainable development of the shellfish industry in Ireland and Wales for the next 50-100 years.

In spite of the complexity of coastal food webs, changes in the relative proportion of functional groups of higher trophic levels were found to be consistent with the changes which are predicted to occur following an increase in primary production (Nielsen & Richardson, 1996; Philippart *et al.*, 2007). Within Europe, discharges of both N and P from households and industries have decreased significantly during the past 30 years, whereas the input from agriculture has generally remained at a constant level. With regard to P, these changes are mainly due to improved purification of urban wastewater across the EU (EEA, 2005). Reduction of nitrogen and phosphorus discharges in Europe and the US (National Research Council 2000; Boesch, 2002) has also resulted in an expected decrease of phytoplankton biomass (e.g. Philippart *et al.*, 2010), a decline in macroalgae, and the return of seagrass beds (e.g. Cardoso *et al.*, 2010). Based on these observations, it appears likely that climate-induced changes in nutrient loads will affect primary producers and coastal communities.

As concern over the impacts of climate change intensifies, a clear picture of major changes in plankton ecosystems over recent decades is emerging. Changes in plankton abundance, community structure, timing of seasonal abundance and geographical range are now well documented, as are knock-on effects on commercial fisheries. Ongoing plankton monitoring programmes around the world will act as sentinels to identify future changes in marine ecosystems. Despite the eminent role of primary production in setting the upper limit to carrying capacities of coastal and shelf seas, consistent measurements of pelagic primary production are limited (e.g. the EU FP6 TENATSO project sampled at one site only in the data poor tropical North-East Atlantic Ocean), whereas data on benthic primary production in shallow seas are very limited. Crucial to identifying future changes, will be the maintenance of time-series on microalgae such as the Continuous Plankton Recorder, efforts of key European marine science institutes in coastal waters, and the funding of projects that continue to mine the unique data sets that these time-series provide (Hays *et al.*, 2005).

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2.12 Sediment Changes

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2.12.1 Introduction

When considering climate change most people look at a time scale that is, seen from a geological point of view, equal to just the blink of an eye. Scenarios for expected change are often discussed in terms of several tens to maybe a few hundreds of years. Natural changes in climate, on a geological time-scale, however may easily take many thousands of years. Glacial-interglacial cycles are a well studied example of these long-term geological cycles. These longer-term time scales have a pronounced effect on sedimentary processes. During glacials, global sea-level is much lower (150 metres or more) than today (an interglacial period) since a large amount of water is not stored in the ocean basins, but in ice caps on land. At the same time, the lower temperatures have an impact on the weathering of the sediments and thus the sediment supply (i.e. the colder it is, the slower chemical weathering occurs). Differences in precipitation also affect such weathering. Firstly less/more rain results in less/more river run-off, and therefore less/more sediment being transported to coastal areas by these rivers. Secondly, more snow during glacials results in larger ice caps on the continents which result in more and larger glaciers eroding more sediments. These glaciers carry sediments onto the continental shelves and onto the continental slope much more efficiently than rivers do.

All these sedimentary processes strongly affect the continental margin, which is defined as the zone running from the present day coastal area (where a large part of the human population lives) across the continental shelf (the present day shallow coastal seas), down to the continental slope and continental rise into the abyssal plain (the deep-ocean basins). So changes in sedimentary processes due to glacial-interglacial cycles affect a zone that is of great importance to the present day human population.

2.12.2 Observations

Various EU funded research projects (e.g. ENAM, ENAM-II, OMEX, OMEX-II, STEAM, and STRATAGEM) have studied the (variations in) sedimentary processes along the European continental margin. In short, all of these projects indicate that the present day continental margin is strongly affected by past glacial-interglacial cycles. During glacials, large glaciers erode considerable amounts of sediments and rapidly bypass the continental shelf, especially at high latitudes (e.g. Norway). So the sediments are directly transported from the continent towards the continental slope and rise. At lower latitudes, glaciers may not always cross the shelf and rivers take over sediment transport. Rivers may deposit large amounts of this material onto the continental shelf. Sand and gravel deposits found in the North Sea, for instance, are (reworked) relic deposits of past river systems. During glacials, however, (a large) part of this material is transported further towards the continental slope. Erosion during the glacial periods is not only increased by the activity of glaciers, but also by the lowered temperatures, resulting in a less abundant plant cover in the areas to the north.

Once the sediments are deposited on the continental slope and rise, they do not necessarily stay there. Sedimentation rates are often that high that the sediments contain a considerable amount of water. This results in a loosely packed sediment column that is easily brought into motion, for instance by an earthquake or gravity due to the formation of a slide plane by increased pore pressure resulting from sediment loading. The sediment packages begin to slide downhill, resulting in the formation of slides, slumps, debris flows etc. In this manner, several thousands of cubic kilometres of sediment can be moved within just a few hours. A well known example of this is the Storega Slide, a complex of three slides located on the Norwegian margin. The last of these slides occurred about 8,000 years ago, well after the end of the last glacial period. The water mass displaced by the movement of this slide is thought to have resulted in a tsunami that has affected the coastal areas of present day Britain and the mainland of Europe, indicating that glacial sedimentary processes can still have their effect long after the glacial period has ended.

From the examples above, it is clear that the morphology and sediments of the continental margin as we know it today is largely shaped by the erosional and sedimentary processes active during past glacial periods.

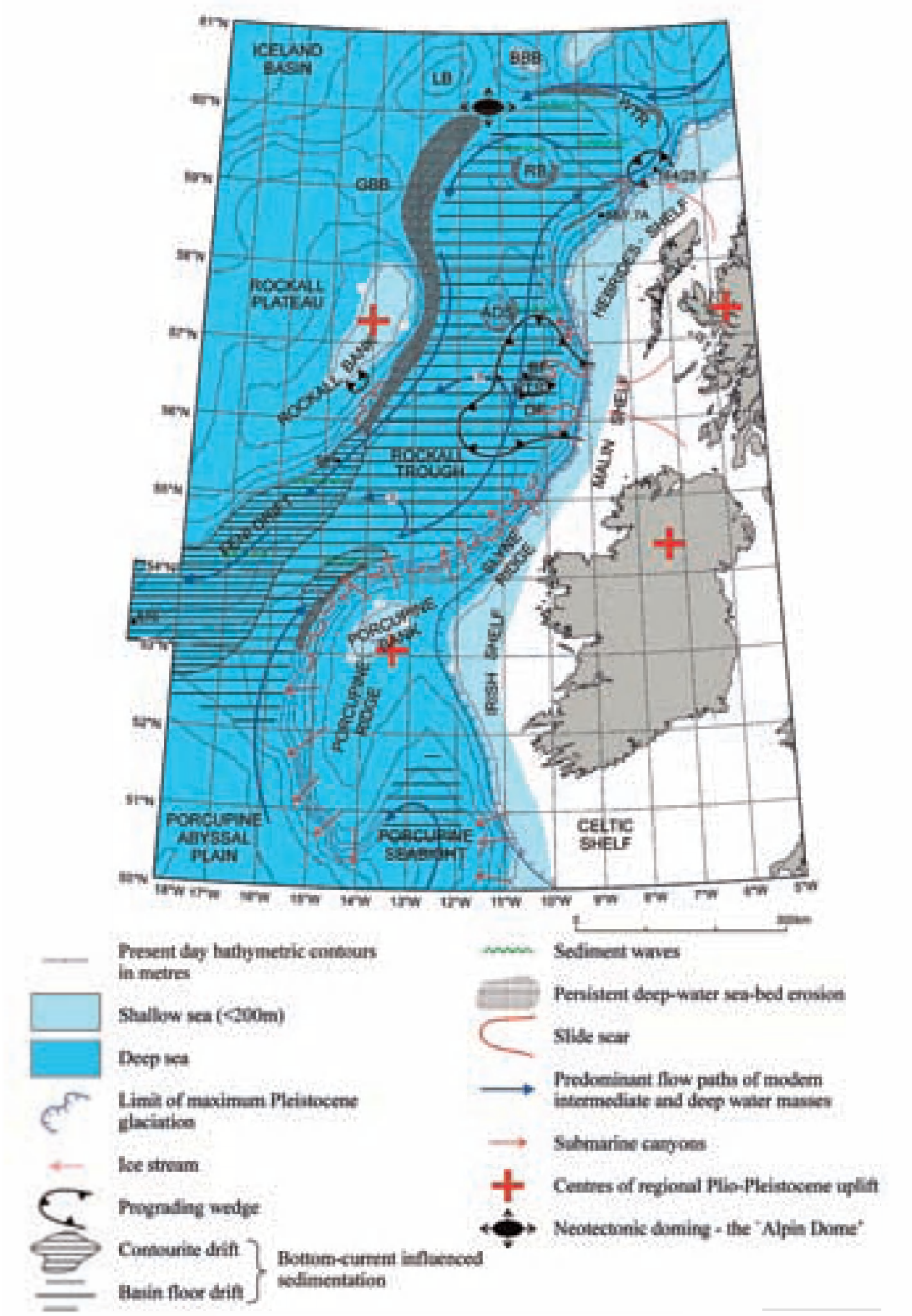

Figure 38. Paleogeography of the Irish/British continental margin for the Late Early Pliocene to Holocene period. (From de Haas *et al.*, 2002)

2.12.3 Future Projections

The climate cycles discussed in this section occur at a time scale well outside the time span of human life, or even several generations. There is no reason to believe that there will not be another glacial period sometime in the future, but it is not possible to say when this new ice age might begin. It is expected that the same type of erosional and sedimentary processes will start shaping the continental margin.

2.12.4 Socio-Economic Consequences of Climate Change Impacts on Sedimentation

As the duration of the erosional and sedimentary processes discussed in this section are much longer than the human life span, changes in these processes will not have any direct consequences for people living today, nor for the next few generations. However, the long-term effects of changes in climate from glacial to interglacial and back, certainly do have an impact on society as we know it today.

The present day morphology of the European coastline and the rest of the margin, but also of the mountainous areas (through erosion by large glaciers) is largely influenced by glacial-interglacial cycles. Also the surface sediments, especially those in the near coastal areas, are largely influenced by the last glacial period and the changes in sedimentary processes resulting from changes in climate (temperature, precipitation) and the sea-level rise initiated during the onset of the present interglacial. In this manner, the glacial-interglacial changes do influence the location of where we now live (largely in flat coastal areas and fluvial basins, the latter tend to fill in during sea-level rise), practice agriculture (through type of sediment and thus type of soil) and source building materials (for instance marine sand deposits used as road building material).

Ongoing glacial rebound (the sinking of the earth's crust at one location and its rising at another following the disappearance of the kilometres thick Scandinavian glaciers) also causes a relative rise or fall in sea-level and thus in coastal development. Moreover, instability of quickly deposited and, therefore, water-rich glacial sediments on the continental slope may result in large mass wasting events (slides, debris flows) causing a tsunami, forming a potential hazard to coastal areas.

2.12.5 What Has Been Done to Better Understand Impacts of Climate Change on Sediment Changes

Various EU-funded and other European projects (e.g. ENAM, ENAM-II, OMEX, OMEX-II, STEAM, STRATAGEM) have studied glacial-interglacial climate cycles and the related (changes in) sedimentary processes. In some only scientific institutes were involved, while in others (such as STRATAGEM) a significant contribution has been made by the oil industry through the provision of extensive datasets. These programmes have mostly dealt with the long-term climate fluctuations and the related large-scale (both in time and space) sedimentary processes.

2.12.6 Research Gaps, Priorities and Key Recommendations

We have a considerable way to go to improve our understanding of how climate change will alter sediment changes in European marine and coastal environments. Although the large scale climatic fluctuations and related sedimentary processes and deposits are fairly well understood, there still is a gap in our knowledge regarding potential natural hazards (the exact nature of all sediments on the European continental slope and rise and possible occurrence of large scale slides resulting in tsunamis or otherwise affecting the coastal zone) involved in this. Key questions of obvious societal relevance include: are there areas prone to sliding? If yes, to what extend (volume and timing)? If it happens, what is the potential threat to the coastal zone?

2.12.7 Reference

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2.13 Biological Impacts

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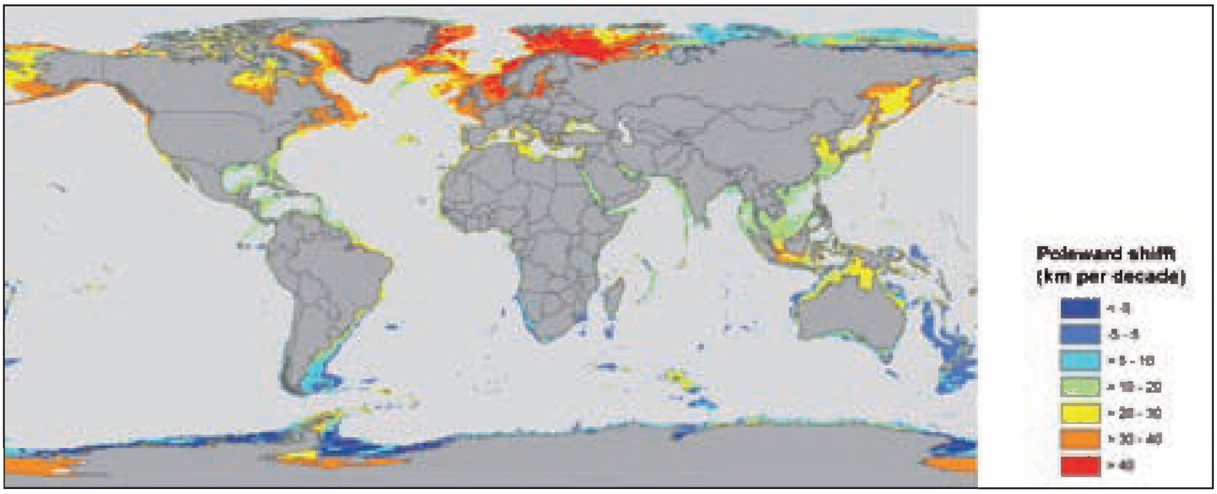
2.13.1 Introduction

Impacts of climate change on the biology of European waters are present at all levels of biological organization, from the molecular to the ecosystem. Temperature, in particular, exerts a strong control on biological processes, and consequently, even small changes in temperature can have important consequences for biochemical processes, cell biology, physiology and whole organism functioning, and thus for ecosystem functioning in general. Changing water temperatures can affect the relationships between temperature and size, between temperature and growth, between temperature and fecundity, and between temperature and energy flows. Yet the details are different for different species, which makes prediction of consequences of temperature change at the ecosystem level difficult. Because the response is often species–specific, not only do species distributions change, but also species assemblages. Such a change in the community composition may affect the stability and resilience of the ecosystem as a whole.

Temperature change is an important direct driver of many changes in the marine environment. However, a change of the water temperature has also many other ensuing effects, which are discussed elsewhere in the report, such as changes in circulation, stratification and oxygenation. These other aspects of climate change also have considerable biological impacts. For example, the melting of sea-ice is an important change in the Arctic - where biological communities depend on primary production from sea-ice algae that flourish underneath the sea-ice.

The metabolism of a given organism is typically adapted to a certain temperature window, and so with increasing water temperature, one can expect that, in the northern hemisphere, species will generally move northward. The southern limit of the range of cold-adapted species will move polewards, as well as the northern limit of warm-adapted species. Such shifts in distribution patterns have already been documented for a number of marine species and communities, especially in plankton and vertebrates. For instance, Pereira *et al.* (2010) recently estimated the poleward shift for demersal fish species and found rates in the North Atlantic of more than 4 km per year (Figure 39). Such changes in distribution patterns are the most important direct biological effects of climate change at the ecosystem level.

Figure 39. Projected rate of range shifts in marine organisms caused by climate change from 2005 to 2050 (52, 63). Latitudinal shift of demersal species (excluding areas > 2,000 min depth because of undersampling of the deep-sea region). (From Pereira *et al.*, 2010)



In this chapter we concentrate on changes in plankton, benthos and higher trophic levels. Life in the pelagic or in the benthic environment is very different. One complicating factor is that during their lifespan, marine organisms can be exposed to a variety of water types and temperatures. Pelagic organisms in the plankton are displaced over considerable horizontal distances within the same water mass, but at the same time, many species migrate daily or seasonally between deeper waters and the surface. In the benthic environment, many adults remain in one fixed place, but will experience different water masses over the course of a year, while the larvae of benthic species are often planktonic. Mobile organisms like fish, squid and marine birds and mammals move between water masses and may experience very different temperature regimes during their lifetimes. All this makes a rigorous analysis of the link between temperature change and changes in biological communities very difficult.

Another confounding factor is that food webs and ecosystems are often highly non-linear systems with tipping points, and so, stochastic events - such as introductions of new species - may drive systems from one stable state to another. Such changes may have important economic consequences when commercial species, ecosystem engineers or charismatic species (seals, dolphins, whales, …) are affected. Finally, a troublesome problem relates to the current lack of appropriate monitoring and ocean observation tools in order to sufficiently detect and document the ongoing biological changes at the species and the system level. For instance, to document changes in the species distribution patterns with sufficient coverage or to accurately assess changes in global phytoplankton productivity.

Figure 40. Plankton sampling (©VLIZ / Misjel Decleer)

2.13.2 Effects of Climate Change on Plankton of European Seas

2.13.2.1 Abundance

Primary Production

In general, both observations and model simulations suggest that climate change will likely lead to increased vertical stratification and water column stability in the ocean, reducing nutrient availability to the euphotic zone and thus reducing the productivity of both primary and secondary producers.

The climate – plankton link in the ocean is found most strongly in the tropics and mid-latitudes, where there is limited vertical mixing because the water column is stabilized by thermal stratification. In these areas, the low levels of surface nutrients typically limit phytoplankton growth. Climate warming should further inhibit mixing, reducing the upward nutrient supply and lowering productivity. In the high latitudes, the reduced mixing and nutrient supply can be compensated by an increase in the residence time of particles in the euphotic zone. Observations in support of these hypotheses include a 6 % reduction in global oceanic primary production between the early 1980s and the late 1990s, based on chlorophyll data from two satellites (Gregg *et al*., 2003), and a controversial report of a 1 % decline per year in global phytoplankton abundance over the last century (Boyce *et al.,* 2010). Observations at higher latitudes reflect the compensation mechanism mentioned above, as chlorophyll in the North-East Atlantic has increased since the mid-1980s. Model predictions for the period to 2050 and 2090 range from a small global increase in primary production of between 0.7 % and 8.1 %, with very large regional differences (Sarmiento *et al.*, 2004) to a 15 % decrease of global primary production at 4xCO_2 levels, balanced between an increase in high latitudes due to a longer growing season and a decrease in lower latitudes due to a decrease in nutrient supply (Bopp *et al.,* 2005). The latter study suggests that climate change leads to more nutrient-depleted conditions in the surface ocean, favouring small phytoplankton at the expense of diatoms, whose relative abundance is reduced by more than 10 % at the global scale and by up to 60 % in the North Atlantic and in the sub-Antarctic Pacific.

Secondary Production

The impact of climate change on secondary productivity has not been assessed at the global scale, but Richardson (2008) provides a general review of the potential climate warming impacts on zooplankton. Some patterns can be deduced from recent observations at regional scales. Shifts in zooplankton biomass have been observed in the North Atlantic and elsewhere, but the spatial and temporal coverage of these data is limited. A perhaps surprising observation is that the more eurythermal, and specifically, the heat-tolerant species of the intertidal, appear to be more vulnerable to climate change as they may live closer to their physiological limits (Harley *et al.,* 2006). This pattern may also hold true for latitudinal gradients, with low-latitude species living nearer to their thermal limits than higher-latitude species.

In relation to the impacts of climate variability and climate change on marine zooplankton, the North Atlantic copepod community has been most studied. Increased regional water temperatures in the North-East Atlantic have triggered a major re-organisation of zooplankton species composition and biodiversity. Helaouet and Beaugrand (2007) proposed that temperature changes alone could have triggered the observed rapid changes, thus suggesting that impacts of climate change at the biome level are responsible for the fate of these species. As noted, changes in relative dominance have consequences for the food web that a particular zooplankton species supports. For example, declines in the relative importance of *Pseudocalanus* sp. in the Baltic Sea, driven by a warming hydrographic environment, have been linked to changes in fish stock size and condition. Isla *et al.* (2008) investigated the physiological response of *Pseudocalanus* sp. under different degrees of warming of the Western Baltic Sea, and detected an increase in instantaneous mortality rates and a reduction in the net growth efficiency with temperature. They anticipate that a temperature rise will negatively affect *Pseudocalanus* sp. and, and as a result, the fish stocks in the Baltic Sea.

Finally, changes in freshwater runoff can also induce changes in plankton production downstream. An increased influx of freshwater not only reduces the salinity of coastal waters but also enhances stratification of the water column, thereby decreasing nutrient supply from below. In contrast, flood events are associated with an increase in productivity as more nutrients are washed into the sea. While diatoms seem to be negatively affected by increases in river discharge, dinoflagellates have been observed to profit from the increase in stratification and availability of humic substances associated with riverine input. Modifications in rainwater runoff and accompanying changes in salinity and resource supply will therefore affect the composition and, potentially, the productivity of the phytoplankton community in coastal waters.

2.13.2.2 Distribution Changes

Climate change is expected to drive species ranges towards the poles. There are limited observations or modelling results on distributional changes in phytoplanktonic communities as a result of climate change. Beaugrand *et al*. (2002) have documented biogeographical shifts of calanoid copepod communities in recent decades, with the warm-water species extending northwards and the cold-water species retreating northwards. The changes that have taken place in these northern European waters are sufficiently abrupt and persistent to be termed as ‘regime shifts’ with a northward shift in the distribution of many plankton and fish species by over 10 degrees of latitude (or over 1,000 km) being observed over the past fifty years (Figure 41). Note that these shift rates are significantly larger than those reported for terrestrial species. Interestingly, zooplankton distributions in the Northeast Atlantic have showed asynchronous changes at the same time, which may suggest that the observed distribution shifts are not just the result of warming (about 1°C), but are influenced by significant circulation changes in the Labrador Current and the north-flowing European shelf break current (Richardson, 2008).

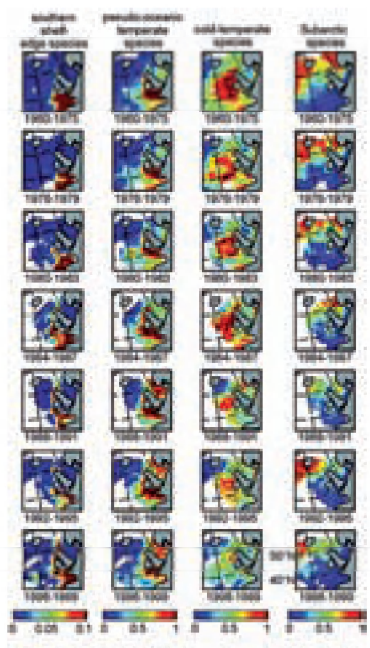


Figure 41. Long-term changes in the mean number of species per association from 1960 to 1999 (From Beaugrand *et al.,* 2002)

Furthermore, the timing of zooplankton blooms seems to be profoundly affected by climate change. In general, for zooplankton that have their maximum abundance in spring/ summer, the pattern is 'earlier when warmer', while species that peak in late summer and autumn the pattern is 'later when warmer'. In the North Sea, meroplankton have advanced their appearance by 27 days in the past 45 years, dinoflagelates peak about 23 days earlier, and copepods about 10 days earlier (Edwards & Richardson, 2004). However, diatom peaks in spring and autumn have remained relatively static, because their reproduction is triggered principally by increases in light intensity. This suggests that the combined effect of phenological and distributional changes will affect the trophodynamics of the marine ecosystem, through for example, predator-prey mismatches (Edwards & Richardson, 2004).

2.13.3 Effects of Climate Change on the Benthos of European Seas

2.13.3.1 Introduction

Benthic communities (i.e. those communities of organisms living on or in the seafloor) are an accepted descriptor of the health of the marine environment and their analysis is often incorporated in legal requirements to evaluate the state or 'health' of marine ecosystems (e.g. the Marine Strategy Framework Directive of the EU). Parameters such as the number of species or their diversity (e.g. the Shannon-Wiener index) and evenness have long been used for these purposes. In recent years, it has become increasingly clear that these descriptors are giving only partial information as they ignore the exact identity of species or the stage in the life cycle that individuals are in. This requires new research on how to best to fulfil legal requirements which aim at setting baselines against which effects of climate change can be evaluated. More importantly, the benthos, as with other biological communities, represents a dynamic component of marine ecosystems, which limits the use of static descriptors.

Effects of climate change on benthic communities can be expected because of direct and indirect effects of increasing CO_2 concentrations in the atmosphere, resulting in temperature changes and increasing acidity. Rising atmospheric temperatures will increase the heat content of the oceanic surface water and will create a number of effects including, increased frequency of extreme events (heat waves, storms), increasing stratification with changes in productivity and lower oxygen concentrations, changes in land-ocean exchanges, and socio-economic changes (fisheries and aquaculture, tourism, transport, exploitation of non-living marine resources). Besides climate change, the increasing concentrations of CO_2 in the atmosphere also induce seawater acidification. The effects of these changes on biochemical and physiological processes in benthic populations are different in different species and at the different stages of the life cycle. As a result, they are not well known and form the subject of current research. Many benthic populations are either sessile or have restricted movements as adults, but the larvae can be present in the plankton for long periods of time and can be transported over considerable distances.

Another impact of climate change will be the rise in sea-level due to melting of land-based glaciers and the expansion of seawater as it warms up (warm water occupies more space than cold water). Both factors will cause destruction of coastal habitats such as salt marshes in temperate regions and mangroves in the tropics and in areas where no retreat of these communities is possible, e.g. because of coastal protection. Sea-level rise will also cause flooding of existing coastal lowlands in areas that are not protected by dykes or when dykes are no longer capable to protect the land behind them. The newly flooded coastal areas will provide more habitat for shallow water benthos and other coastal communities.

There has been long-standing debate on whether benthic communities are random assemblages of species or have some structure that emerges from the interactions of the constituent species with each other and with the environment. In the first case, effects of climate change at the community and ecosystem level may be idiosyncratic and unpredictable. However, it is increasingly recognized that not all species are of equal importance to the stability of an ecosystem and considerable attention has been given to so-called system engineers, species that change their physical environment and thereby change also the habitat of other species. The disappearance or introduction of system engineers will, therefore, have a much greater impact on an ecosystem than the disappearance or introduction of random non-engineering species from the assemblage.

Another discussion concerns the question of whether all species perform unique and therefore irreplaceable functions in the ecosystem. The appearance or disappearance of any species would then change the functioning of the ecosystem. This is especially relevant for considering the effects of introduced or invading species. The opposite view is that only a restricted number of functions need to be fulfilled and that the exact identity of the species fulfilling those functions is not important. Moreover, any function (or niche) that re-

Figure 42. Marine biological research is labour intensive and requires highly skilled experts (right: ©Marine Board-ESF / Aurélien Carbonnière; left: courtesy Mike Thorndyke)

quires a species will in time also be filled with a species. If this is the case in general, effects of climate change may be dampened by one species replacing another which gets lost from the system.

EU research on the effects of climate change on benthic communities and ecosystems has been limited (e.g. BIOCOMBE), although several on-going projects deal with it in more detail (EPOCA, HYPOX, HERMIONE). Much existing information has been brought together through the activities of the Network of Excellence MarBEF (Marine Biodiversity and Ecosystem Functioning) (Heip *et al*., 2009). The Integrated Project HERMES (Hot-Spot Ecosystem Research on the Margin of European Seas), though not specifically aimed at detecting climate change effects, has provided a wealth of new information on benthic systems along the continental margins of Europe. Changes in deep-sea benthos linked to climate change have been reported from only a few areas in Europe.

In this overview we have chosen to discuss three main processes: distribution changes, effects of catastrophic events, and the introduction of exotic species. We then describe these issues by geographical region as the effects of a number of coinciding processes are often dependent on geography.

2.13.3.2 Effects of Temperature and Weather

Very little is known about the potential effects of changing temperature and weather conditions, especially storms, on benthic communities. Although changes in food input, through changes in climate or nutrients or both, are considered to be the primary cause of changes in the benthos, low temperatures are considered to have a large-scale direct effect on both sublittoral and intertidal communities (see Clark & Frid, 2001). During severe winters (with a mean temperature of 2°C or more below the long-term mean) on the Balgzand tidal flats in the Dutch Wadden Sea, one third of species displayed increased mortality rate. Conversely, during a period with eight mild winters in succession, overwintering mortality was diminished (Beukema, 1992), which resulted in a more stable infaunal biomass. In the short-term, a severe winter means a pronounced stress for the intertidal flat fauna with reductions in species numbers and abundance, but this reduction only persists for 1 to 2 years as reproductive success on tidal flats tends to be extremely good during the summer following a severe winter (Beukema, 1992), probably because of the effect that cold winters have on the balance of infaunal predators and their prey. For instance, it was observed that the abundance of the predator *Nephtys* was reduced following a cold winter, and this reduced predation led to increased prey (deposit feeder) biomass the following year (Beukema *et al*., 2000).

Clark and Frid (2001) also discuss the studies from the benthic community at another intertidal area from Norderney in the German Wadden Sea. This community has been affected by severe winters, with the sublittoral being more affected than the littoral (Dörjes *et al*., 1986). During the severe winter of 1978–1979, one third of the sublittoral benthic community disappeared, and the regeneration of the community over the next few years resulted in an assemblage with a completely different species composition (Dörjes *et al*., 1986). The greatest change in community structure appeared between 1980 and 1981, and it was suggested that cold winters were a greater cause of changes in the community than summer temperatures or storms. At Norderney, mild winters between 1987 and 1992 may also have induced changes in the benthos, and it was suggested that there was a synergistic effect of mild winters and eutrophication acting together, with high biomasses resulting from cold-sensitive species thriving on the increased food input. Thus, mild meteorological conditions, probably acting in conjunction with eutrophication, have resulted in an increased total biomass since 1989 (Dörjes *et al.*, 1986). Kröncke *et al.* (1998) found a strong relationship among abundance, biomass, and the North Atlantic Oscillation (NAO) index at Norderney, which suggested that changes in the benthos induced by winter temperatures could be ultimately linked to changes in the NAO (NAO – benthic abundance r = 0.73). The best correlations between the NAO and benthic parameters were found during the cold period of the year, suggesting that the NAO acted through winter temperatures. Thus, most of the interannual variability in macrozoobenthos could be explained by climate variability (Kröncke *et al.,* 1998).

Mass mortalities resulting from extreme high temperatures have been observed frequently over the last decades. A well studied example occurred late in the warm summer of 2003 in the Western Mediterranean, when an anomalous warming of seawater gave rise to the highest seawater temperatures ever recorded in the region, between 1 and 3°C above the mean and maximum average values. As a consequence, massive mortality events were observed for at least 25 benthic macro-invertebrate species (mainly gorgonians and sponges) in the entire northwestern Mediterranean region, affecting several thousand kilometers of coastline.

2.13.3.3 Changes in Distribution

Shifts in distributions of benthic populations in European waters have been reviewed in the LargeNET project of the EU Network of Excellence MarBEF. There are very few well documented cases on distribution shifts of benthic species over sufficiently large areas and long enough time. Most studies are local and often restricted to a single station or a small area. Although they can give detailed information on changes at a particular location, such studies suffer from the confounding effect of many different and interacting influences. In coastal areas in Europe, the foremost problem is the simultaneous occurrence of higher temperatures, well documented for certain areas, and eutrophication, both of which are related to long-term changes in the North Atlantic Oscillation. As benthic populations often feed on plankton, either as larvae, juveniles or adults, changes in the plankton will also have potentially large impacts on benthic communities. Examples are the Balgzand series from the Western Wadden Sea and the Northumberland and Skagerrak stations in the North Sea, extensively discussed by Clark and Frid (2001). These North Sea time series show important shifts in species composition over time, some of which can be explained by changes in food supply linked to changes in pelagic productivity, which, in turn, are associated with changes in weather patterns controlling the timing of the spring bloom and thus the amount of primary production occurring during a particular year. Changes in food supply were also found to drive the intertidal infauna of the Wadden Sea. Another rich marine data set is the Helgoland Roads time series collected at Helgoland Island in the German Bight of the North Sea. Over 30 benthic macrofaunal species have been newly recorded at Helgoland over the last 20 years, with a distinct shift towards southern species (Wiltshire *et al.*, 2010).

A good example of a detailed analysis that covers large temporal and spatial scale changes are the studies on the rocky shore fauna in the UK, as summarized by e.g. Hiscock *et al.* (2004) , Mieszkowska *et al.* (2005) and Hawkins *et al.* (2008). Hawkins *et al.* (2008) analysed the changes in geographic distributions and population abundance of species detected on rocky shores of the North-East Atlantic over the last 60 years. This period encompassed the warm 1950s, a colder period between 1963 and the late 1980s, and the recent period of accelerating warming to levels above those of the 1950s. These studies show range extensions and increases in the abundance of southern species, and corresponding retreats and decreases in the abundance of northern species. A good example is the changing distribution of two barnacle species, the northern *Semibalanus balanoides* and the southern *Chthamalus stellatus* in southern England (Figure 43).

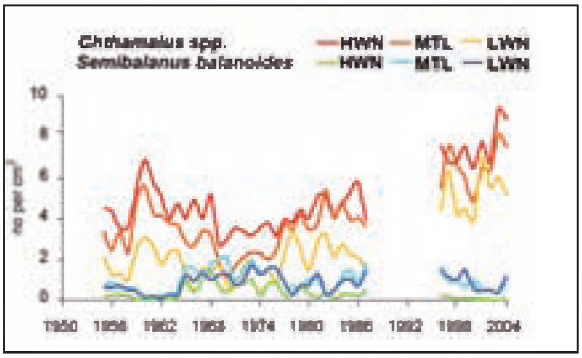


Figure 43. Long-term changes in northern (*Semibalanus*) and southern (*Chthamalus*) barnacle species from the coasts for Devon and Cornwall (from Mieszkowska *et al.* 2005)

Chthamalus has become much more abundant over the years and *Semibalanus* has disappeared from the higher levels of the intertidal zone.

The rate at which the biogeographic limits of southern intertidal species are extending northwards and eastwards towards the colder North Sea is up to 50 km per decade. As an example, the purple topshell, *Gibbula umbilicalis,* has extended its northern range limit along the north-east coast of Scotland by over 55 km and by over 125 km along the eastern English Channel since the 1980's, far exceeding the global average of 6.1 km per decade in terrestrial systems (Parmesan & Yohe, 2003).

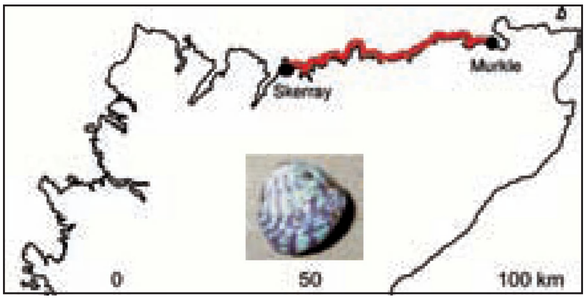


Figure 44. Northern range extension of *Gibbula umbilicalis* with about 70 km in northern Scotland (from Mieszkowska *et al.* 2005)

Large spatial changes have also been illustrated by the distribution shifts of several important bivalve species, as studied in the EU project, BIOCOMBE. A clear pattern was observed for *Macoma balthica* (Baltic clam) and the three European mussel species, *Mytilus trossulus*, *M. edulis* and *M. galloprovincialis*. These species have all showed clear northward distribution shifts over the last decades. The ecophysiology of certain key species was analysed in order to explain the observed shifts. The respiration rates, and to a lesser extent the growth rates, differed between the genetically distinct groups (thus forming ecotypes) of both mussel and clam populations. Ecophysiological performance indicators (such as respiration and growth) showed clear latitudinal patterns (north to south), as well as temperature and salinity gradients. The optimum performance of the southern *M. galloprovincialis* lies around 25°C, while that of the northern *M. trossulus* is around 16°C, with *M. edulis* taking an intermediate position (optimum performance at around 20°C).

The consequence of a temperature change along the European coastline will thus be a shift of the ecotypes of both key species. Predictions are that the observed northward range shifts of mussels will continue with future warming, with an average speed of approximately 10 km per year. Moreover, the prediction is that in the next 50 years the genetically divergent group of *M. balthica* in the Bay of Biscay will disappear.

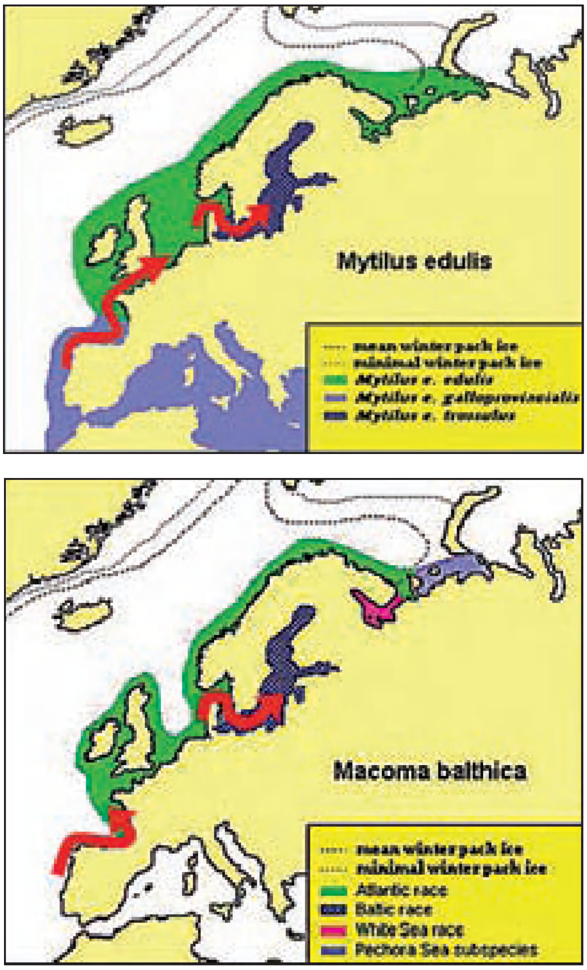


Figure 45. Shifts in distribution of three mussel species (above) and the baltic clam *Macoma balthica* (below) in Europe over the last decades (red arrows)

2.13.3.4 Invading Benthic Species

The effects of climate change on the success and spread of invading non-native species is discussed elsewhere in this report. The introduction and spread of non-native species has been the subject of numerous studies in Europe. Classical and well studied examples from the benthos are the so-called Lessepsian migration of various Red sea species through the Suez Canal to the Mediterranean, the outbreak of the green algae *Caulerpa taxifolia* and *Caulerpa racemosa* in the Mediterranean, the introduction of Ponto-Caspian species in the Baltic and the expansion of the Japanese oyster *Crassostrea gigas* in the Wadden Sea and along the southern North Sea coastline. Climate change may stimulate the introduction of exotic species in cases where the reproduction or survival of the invader is limited by its temperature or salinity tolerance. The effects of an increasing number of 'new' species in existing communities are diverse, and often not well known. The dynamics of species introductions have temporal scales of decades and assessing the long-term effects of invading species requires long-term monitoring programmes. Often, the new invader seems to achieve an equilibrium with existing species after an initial outbreak, such as happened in the well documented case of the Japanese brown alga *Sargassum muticum* in Western Europe. In some cases, such as for the polychaete *Marenzelleria* in the Baltic, the invader occupied a niche not yet filled by other species, in this case the deeper sediment layers. This new species therefore also introduced a completely new ecosystem function in the Balthic, deep bioturbation, with the potential of changing the biogeochemistry of the entire system.

2.13.3.5 Deep Sea Benthic Biodiversity

The Deep Sea, the largest habitat on the planet, is also gradually changing. Through measurements made by Argo floats it has now been shown that the heat content of deeper waters (up to 2 km) is increasing, while also oxygen minimum zones are expanding. Deep Sea benthos will respond to these changes, even to very small changes in bottom temperatures, as has been shown for the Mediterranean by Danovaro *et al.* (2001, 2004).

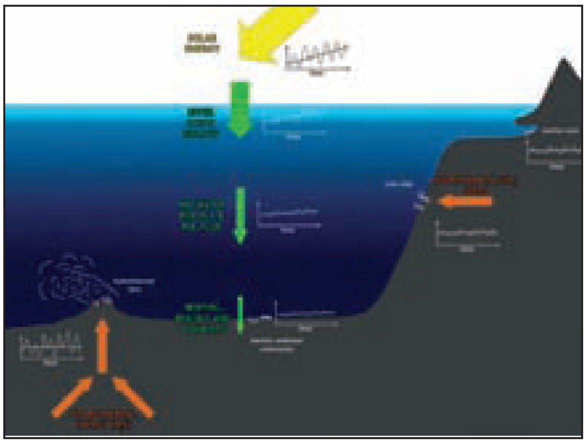


Figure 46. Schematic diagram illustrating forcing factors that influence temporal processes in 'normal' sedimented parts of the deep-sea and in chemosynthetic systems. In the first case, temporal changes are forced ultimately by climatic oscillations. In the second case, they are forced by geological processes that affect fluid flow. (From Heip *et al.,* 2009)

Perhaps the most direct impact is expected through changes in surface productivity, which is sensitive to climate change, as stratification increases and phytoplankton distributions shift, resulting in a change in the nature of primary productivity and its export to the deep sea. However, given the specific adaptation of deep-sea organisms to stable and cold temperature, even minor shift in temperature as those expected from deep-water warming could have a major impact. Unfortunately, our knowledg on deep sea benthos is scarce and very few long-term data sets exist that would allow evaluation of the effects of climate change on benthic deep sea communities. These data sets have been discussed in the DeepSets project of the EU Network of Excellence MarBEF (Heip *et al.*, 2009).

The Deep Atlantic

One time series dataset has been obtained in the North Atlantic, where temporal changes in deep-sea communities at the Porcupine Abyssal Plain (PAP), at 4,850 m water depth, have been studied since 1989. From this series, it has been shown that intra-annual changes reflect seasonal productivity cycles, and decadal-scale changes at the PAP are linked to the North Atlantic Oscillation. These oscillations lead to changes in the amount and quality of particulate organic carbon (POC) that is exported from the surface layer to the sea floor. These changes in food quantity and quality probably explain the 'boom-bust' cycles (rapid abundance increases followed by declines) observed in the megafaunal holothurians, *Amperima rosea* and *Ellipinion molle,* during the period from 1996 to 2005. The rise to dominance of *A. rosea* during 1996 has been called the 'Amperima event'. Increases in holothurian densities led to a dramatic increase in the extent to which surface sediments, and particularly deposits of phytodetritus (organic detritus derived from surface primary production), were reworked.

The response of other benthic groups over those years was mixed. The changes in density of *Amperima* and other holothurians are reflected in the time series of foraminifera. The densities of foraminifera were significantly higher in the post-Amperima event period (1996-2002) compared to the pre-Amperima event period (1989-1994). Their species composition also changed over this period, as well as their behaviour. In 1996, following a phytodetritus pulse, the miliolid, *Quinquiloculina sp.*, migrated to the sediment surface, grew and reproduced before migrating back into deeper layers as the phytodetrital food became exhausted. Densities of nematodes and, to a lesser extent polychaetes, increased significantly between 1989 and 1999. Ostracods showed a significant decrease while most other taxa, including the copepods, did not exhibit significant temporal changes in abundance. Macrofaunal polychaetes exhibited a more muted response to changes at the Porcupine Abyssal Plain (PAP). Although their abundance increased significantly before and during the Amperima event, it was not on the same scale as that observed in the megafauna. Moreover, only certain taxa and trophic groups responded.

The Deep Arctic

In the Arctic, the Hausgarten Station near Svalbard has provided the first long-term time series of the benthos in the region. Work by the Alfred-Wegener Institute demonstrated a small but important temperature increase between 2000 and 2008 at 2,500 m depth in the Fram Strait between Svalbard and Greenland. Within the MarBEF project DEEPSETS, a five-year (2000-2004) time-series study of nematodes at this site revealed shifts in nematode abundance and community composition, reflecting changes in food availability. For the larger organisms, a towed camera system revealed a significant decrease in megafauna densities at 2,500 m water depth. These changes have yet to be fully analysed in relation to changes in productivity and circulation.

The Deep Mediterranean

DEEPSETS research has shown that the eastern Mediterranean is periodically subject to stochastic flux events that deliver large amounts of food to the sea floor, abruptly turning the 'desert' into an 'oasis.' This event-driven character of the eastern Mediterranean was illustrated by the very high phytopigment concentrations in the Ierapetra Basin during 1993. These were linked to significant changes in the hydrography of the Cretan Sea after 1992, involving an increasing outflow of nutrient-rich water masses into the Levantine Basin, resulting in enhanced biological productivity and organic matter flux to the seabed. In 1993, this enhanced flux caused significant changes in the abundance and composition of the meiobenthic assemblages as well as of the planktonic and macrobenthic communities.

Deep-sea nematode diversity can be strongly and rapidly affected by temperature shifts. The abrupt decrease in temperature (of about 0.4°C) and modified physico-chemical conditions that occurred between 1992 and 1994 in the Eastern Mediterranean caused a significant decrease in nematode abundance and a significant increase in diversity. This temperature decrease also resulted in decreased functional diversity and species evenness and in an increase in the similarity to colder deep-Atlantic fauna. When the temperature recovered (after 1994-1995), the biodiversity only partially returned to previous values. It can be concluded from this that deep-sea fauna is highly vulnerable to environmental alteration, and that deep-sea biodiversity is also significantly affected by very small temperature changes (Danovaro *et al.*, 2004).

2.13.4 Effects of Climate Change on the Higher Trophic Levels of European Seas

2.13.4.1 Introduction

Climate change impacts the performance of individuals at various stages in their life history via changes in physiology, morphology and behaviour. Climate impacts also occur at the population level via changes in transport processes that influence dispersal and recruitment. Community-level effects are mediated by interacting species (e.g. predators, competitors, etc.), and include climate-driven changes in both the abundance and the per capita interaction strength of these species. The combination of these proximate impacts results in emergent ecological responses, which include alterations in species distributions, biodiversity, productivity and microevolutionary processes.

The complexity of the life cycles of many marine high trophic levels (fish, mammals, birds) presents an additional difficulty. At the individual level, for example, impacts may differ between phase stages, while at the population level, connectivity between the habitats of the different life stages may be differently affected. Despite this, there is now significant evidence of observed effects of climate change in every continent (Barange & Perry, 2009), although the majority of studies come from mid and high latitudes in the Northern Hemisphere.

2.13.4.2 Physiological Responses

Most marine animals are cold-blooded, and therefore their metabolic rates are strongly affected by external environmental conditions. Many macrophysiological studies have found that organisms transferred into conditions different from those to which they have been adapted, function poorly compared with related organisms previously adapted to these new conditions. Thermal tolerance is also non-linear, with optimum conditions at mid-range and poorer growth at temperatures that are too high or too low. Thermal tolerance changes markedly with latitude, with a narrower range of tolerable temperatures in species inhabiting high and low latitudes, and a wider range from intermediate species. Pörtner *et al.* (2001) found that temperature-specific growth rates and fecundity declined at higher latitudes, and that optimum temperatures decrease with increasing body size. Marine fish are expected to be more resilient to increases in oceanic CO_2 (and subsequent decreasing pH) than plankton, molluscs or corals although processes such as egg fertilization, reproductive biology and early life survival may be affected.

Figure 47. Atlantic cod, an important economic resources, is one of the species that is affected by changing sea temperatures (©Karen Rappé)

2.13.4.3 Population Responses

Distribution Changes

Climate change plays a major role in defining the habitat and distributions of marine and aquatic fishes through its influences on the physical properties of marine and aquatic environments. The environmental tolerances (bio-climate envelopes) to which populations have evolved then interact with these climate-controlled environmental conditions to determine the preferred or suitable habitats and distributions of marine and aquatic organisms.

Large-scale distribution shifts in marine ecosystems are a feature of pre-anthropocene climate change and can thus be regarded as natural. Perhaps the best contemporary example occurred during the period of warming which affected the North Atlantic from the 1920s to 1940s. Atlantic cod, haddock, redfish and Greenland halibut all expanded northwards, with cod spreading 1200km farther north than its previous distribution. Such shifts involved benthic invertebrates as well as demersal finfish. In general, species adapted to warmer waters expanded their distributions northwards, whereas species adapted to colder waters retracted their distributions northwards (Drinkwater, 2006).

Species with greater mobility and migratory characteristics respond most quickly to variability in habitat. Over 90 years, the timing of animal migration in UK waters followed decadal trends in ocean temperature, being later in cool decades and up to 1–2 months earlier in warm years. In the North Sea, warm-adapted species have increased in abundances since 1925, and seven out of eight have shifted their ranges northward by as much as 100 km per decade. Some of these shifts are extremely fast, averaging over 2 km yr^{-1}. In the pelagic environment shifts are not only horizontal but also vertical, with species responding to warming trends by moving towards deeper cooler waters (Perry *et al.*, 2005; Dulvy *et al.*, 2008).

Abundance Changes

Changes in the abundance and biomass of marine populations are caused by changes in their recruitment and growth rates, and ultimately by the productive capacity of their environment. Changes in temperature can have direct impacts on fish abundance and biomass by stressing the physiological systems of individuals, and indirect effects on fish abundance through their influences on growth and recruitment. Populations at the poleward extents of their ranges increase in abundance with warmer temperatures, whereas populations in more equatorward parts of their ranges tend to decline in abundance as temperatures increase.

Higher individual growth rates translate to greater productivity for an entire population, with the most productive stocks associated with higher bottom temperature and salinity conditions. This relatively simple picture becomes more complicated, however, when food availability is also considered. Since increasing temperatures increase the metabolic demands of fish, it is possible that increased food supplies along with increasing temperatures may lead to faster growth and improved recruitment success for populations at equatorward locations in their range. Beaugrand *et al.* (2003) found that an index of plankton prey explained 48 % of the variability in North Sea cod recruitment, with periods of good recruitment coinciding with higher abundances of its preferred prey. The hypothesis is that, for cod in the North Atlantic, increasing temperatures improve recruitment for stocks in cold water, but decrease recruitment for stocks in wamer water. When food supply is good, however, stocks in southern areas may be able to overcome this increased metabolism due to the warmer temperatures, and capitalise on their increased food resources to increase growth rates.

Phenological Changes

There is concern that marine trophodynamics may have already been radically altered by ocean warming through predator-prey mismatch. Beaugrand *et al.* (2003) showed how fluctuations in plankton abundance in the North Sea affected larval cod survival due to a mismatch between the size of prey and cod larvae. The timing of *Macoma balthica* spawning in north-western Europe is also temperature dependent. Recent warming trends have led to earlier spawning but not earlier spring phytoplankton blooms, resulting in a temporal mismatch between larval production and food supply (Philippart *et al.*, 2003).

2.13.4.4 Food Web Impacts from Plankton to Fish

Climatically driven changes in species composition and abundance alters species diversity, with implications for ecosystem functioning. Understanding linkages between species diversity and ecosystem function is a general research gap in marine ecology and is wide-open to investigations in the context of climate change. Direct and indirect impacts on the food web are observed and expected, but the relative importance of each type of impact depends on whether webs are structured from the top down, from the bottom up or from the middle (e.g. Frank *et al.*, 2007), and whether this dominance is affected by human and environmental forcing. Most common is to observe synchronised changes in several trophic levels, without a clear cause-effect relationship. For these reasons, models that analyze climate impacts on food webs have low predictive capacity.

2.13.4.5 Regime Shifts and Other Extreme Ecosystem Events

One of the most recently accepted mechanisms through which climate variability and change interact and affect ecosystem dynamics is based on the concept of 'regime shifts'. A common definition of this term usually involves the notion of multiple stable states in a physical or ecological system, a rapid transition from one semi-permanent state to another, and a direct link to climate forcing. Whilst regime shifts in marine ecosystems are generally attributed to climate forcing, they can also result from overfishing, pollution or a combination of these factors. An important consideration is that biological responses to shifting climatic conditions can be non-linear (e.g. a change in regime), even though the underlying abiotic changes may be linear stochastic. This sensitivity of ecosystems to amplify climatic signals may suggest that gradual changes in future climate may provoke sudden and perhaps unpredictable biological responses as ecosystems shift from one state to another (Hsieh *et al.*, 2005). Given their potential consequences, large-scale regime shifts are particularly significant.

De Young *et al.* (2008) present a conceptual framework to enhance our ability to detect, predict and manage regime shifts in the ocean and conclude that the ability to adapt to, or manage, regime shifts depends upon their uniqueness, our understanding of their causes and linkages among ecosystem components, and our observational capabilities. Because the likelihood of climate-driven regime shifts increases when humans reduce ecosystem resilience, for example by removing key functional groups of species, age groups, trophic levels, or adding waste and pollutants, a primary issue remains whether ecosystem resilience will be sufficient to tolerate future anthropogenic climate change.

Of interest, in the context of global climate change, are separate sets of non-linear biological events that can be generated, not by linear climate influence but by greater storminess. Saunders and Lea (2008) have demonstrated a high correlation between sea surface temperature and hurricane frequency and activity in the Atlantic Ocean, altering the frequency of disturbance regimes in coastal ecosystems, and leading to changes in diversity and hence ecosystem functioning.

2.13.4.6 Anticipated Impacts of Climate Change on Fish Production and Ecosystems

General impacts to marine and aquatic systems as a result of large-scale changes related to temperature, winds, and acidification can be predicted, in some cases with a high degree of confidence. These impacts will occur on a variety of time scales from rapid (a few years) to slow (multiple decades) (Barange & Perry, 2009).

There is high confidence that increasing temperatures will have negative impacts on the physiology of fish because of limited oxygen transport to tissues at higher temperatures. This process forms the physiological basis for the observed and predicted changes in distributions and recruitment. It may be more significant for high latitude and polar species, many of which have low tolerances for temperature changes.

These constraints on physiology will result in changes in distributions, and likely cause changes in abundance as recruitment processes are impacted by temperature and circulation patterns. Strongest and most rapid changes will be to those stocks at the edges of their species' ranges, such that stocks will move poleward. These responses will be most rapid for highly mobile pelagic species which has already been demonstrated in Europe for small pelagics in the English Channel and Norwegian herring in the NE Atlantic. Less mobile, often demersal, species have also been observed to move poleward or to deeper depths and cold upwelling centres. If changes in climate conditions persist, then demersal species will also alter their distributions and migration patterns. However, because habitat for demersal species often includes particular bottom features they are likely to alter their distribution patterns more slowly than pelagic species.

Figure 48. Fish catch onboard a research vessel for fisheries research (©Mick Mackey)

Changes in the timing of life history events are expected. Short-life span rapid turnover species are those most likely to experience such changes. Earlier spring plankton blooms may be expected for some species. This will result in mismatches between early life stages of fish and their prey, with recruitment failures and declines in abundance as consequences.

At intermediate time scales of a few years to a decade, temperature-mediated physiological stresses and phenology changes will impact the recruitment success and, therefore, the abundances of many marine and aquatic populations. The earliest impacted species are again likely to be those with shorter life-spans and faster turnover rates, since biomass of species with longer life-spans tends to be less dependent on annual recruitment. These impacts are also likely to be most acute at the extremes of species' ranges, and may manifest themselves as changes in fish distributions. Changes in abundance will alter the composition of marine and aquatic communities, with possible consequences to the structure and productivity of these marine ecosystems. Since these processes involve many unknowns, predicting impacts and directions for any specific case can only be done with low confidence. Predicting net community impacts such as total biomass or productivity may be done with intermediate confidence, however, because of compensatory dynamics among the members within the various functional groups that make up that community.

Increasing vertical stratification is predicted for many marine areas. It is expected to reduce vertical mixing and to therefore reduce nutrient supply to the productive photic layers, thereby decreasing productivity. In addition, increasing stratification is predicted to alter the balance between pelagic and benthic recycling of material, favouring the pelagic pathway and pelagic fishes at the expense of the benthos. This will drive changes in species composition and affect the timing of life cycle processes.

Predicted impacts to marine systems at long (decadal) time scales are dependent upon predicted changes in net primary production in the oceans and its transfer to higher trophic levels, about which there is low confidence. Future net primary production may increase in some high latitudinal regions because of warming and reduced ice cover, but decrease in low latitude regions because of reduced vertical mixing and replenishment of nutrients and changes in circulation and direct human impacts. The result is that primary production may increase in some areas but decrease in others, with the net global impact probably not larger than 10 %. Empirical observations of changes in net primary production over the past few decades have actually shown a decrease, but also with large regional variability. Changes in regional production and species composition will have impacts on all other trophic levels, including marine mammals, in particular those whose ranges are already restricted with little opportunity for expansion.

A number of models have been recently developed to predict marine resource production as driven by climate change scenarios. These models range in focus from individual, to population, community, and ecosystems, and attempt to address questions at different temporal and spatial scales. Habitat models have also been developed. This approach, generally called bioclimatic envelope modelling, uses the relationships between climatic variables and species distributions to predict future distributions according to projected changes in climate variables. Using this technique, Cheung *et al.* (2010) simulated changes in distribution of 1,066 species forced by projected changes in physical conditions from a climate model. This has been used to predict changes in global fisheries catch potential using empirical relationships between potential catch, habitat area and primary productivity (Figure 49). The study shows that low latitude countries will lose potential yield, while higher latitude countries will gain potential yield and their fisheries might benefit.

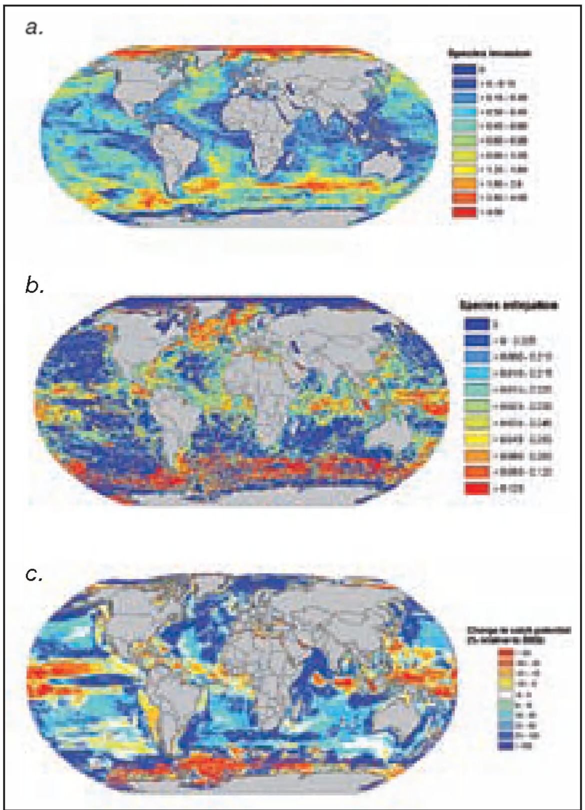


Figure 49. Projected changes in species distribution and maximum fisheries catch potential by 2050 under the SRES A1B scenario simulated using the dynamic bioclimate envelope model and empirical relationship predicting catch potential from primary productivity and species' range: (a, b) rate of species invasion (a) and local extinction (b) (redrawn from Cheung *et al.,* 2009); (c) percent change in maximum catch potential by 2055 relative to 2005 (10-year average) under the SRES A1B scenario (redrawn from Cheung *et al.,* 2010).

The impacts of fishing on the abilities of marine populations and ecosystems to respond to climate change are poorly known. Fishing makes marine populations more sensitive to climate variability and change by removing older age classes and spatial sub-units, and by changing life-history traits such as reducing the age-at-first spawning. Fishing also decreases the mean size and trophic level, and increases the turnover rates, of marine communities, and causes marine ecosystems to change towards stronger bottom-up control. The net result is that marine systems become less resilient and more susceptible to the stresses caused by climate variability and change (Perry *et al.*, 2010).

The ability for marine organisms to adapt and evolve to climate change, on the relevant time scales, is also generally unknown. Rapid adaptation and evolution, at least to fishing-induced stresses, can occur on relatively rapid time scales of a few decades (Jorgensen *et al.,* 2007).

Figure 50. The impacts of fishing on the abilities of marine populations and ecosystems to respond to climate change are poorly known (©Clicks/iStock)

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3. How Does Climate Change and Ocean Acidification Affect the Marine Environment in Different Regions in Europe?

3.1 Impacts of Climate Change on the Baltic Sea

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3.1.1 Observations

3.1.1.1 Changes in Physical Conditions

Changes of major controlling factors of the Baltic Sea system, the Major Baltic Inflow (MBI) and river runoff in the past century, have been studied thoroughly (e.g. Feistel *et al*. 2008; Graham *et al*. 2009). No major trends in the centennial and basin scales have been found for the MBI and river discharge. However, changes have been identified in the decadal and sub-basin scales. There exists 3 major stagnation periods (1922-1933, 1952-1961 and 1977-1992) in the 20th century. These periods were interrupted by the MBIs and featured by decreased salinity, temperature and increased anoxic conditions in the bottom waters. The MBI, however, does not show a trend related to climate change. It was also found the annual river discharge to the Eastern Baltic Sea has been lowered during the latest 50-75 years but the winter river discharge has been increased.

Major long-term changes of Baltic Sea physical conditions have been identified as increased water temperature, decrease of sea-ice and changing water level. The Baltic Sea has been in a relatively warm period after the end of the Little Ice Age in 1870. Since then, climate in the Baltic Sea has been steered by both natural variability and anthropogenic activities. The latter have become more and more significant due to increasing green-house gas emissions and river load discharge in the last century. The studies on observed climate change made before 2007 has been well reviewed in the BACC report (BACC, 2008), which is a joint venture of the BALTEX Program and HELCOM (Baltic Marine Environment Protection Commission) as an example of a dialogue between the scientific community and environmental policy makers.

At the basin scale, the Baltic Sea atmosphere-ocean system follows the global warming trend since 1880, but with a more rapid warming of about 50 % and 30 % more for the SST and air temperature over the sea, respectively. The warming has a large spatial-temporal in-homogeneity. In air, the warming is 40 % larger on average north of 60°N than south of 60°N. For SST, two significant warming periods have been identified, one is 1930-1960 and the other in the last 30 years. The recent warming is much more prominent than the first one. In the central Baltic, *in situ* observation shows an abrupt SST warming (1.7˚C) in 1998-2001, and SST has stayed at the 2001 level since then. Based on remote sensing SST, an increase in annual mean sea surface temperature of 0.3-1.4˚C, depending on the location, has been observed during 1990-2004. The warming of Baltic SST is characterized by a significant seasonal difference. The summer warming is two times more than in other seasons. Another feature is that no major trend of SST can be found before the 1980s although the air has experienced a significant warming. The warming of the last 30 years is also coincident with the positive NAO index, which brings more warm westerly flow to the Baltic region.

Baltic Sea subsurface and deep water temperature has been identified with a regime shift at a much earlier time. Fonselius and Valderrama (2003) analysed data from deep monitoring stations for 100 years of observations (1900–2000) and found that deep water temperatures were significantly lower in the first half of the 20th century than in the second half. Based on the *in situ* observations after 1990 in lower than 70 m water depth, it was found that deep Baltic Sea temperature has been steady before 2000 but experienced a significant warming (1-3˚C) since then. The research indicates that the deep Baltic Sea has a different temporal regime than the upper layer. The interaction between the two layers, however, has not been fully studied.

As a consequence of the increasing SST in the last 30 years, the evaporation also increases, which leads to a 4 % increase of humidity. No general trend is observed for the last hundred years for the Baltic Sea annual mean precipitation and river runoff, although positive trends are observed for the winter time since 1950s. During the last 30 years, the mean runoff has a positive anomaly relative to the 100 year mean. This corresponds to a decrease of surface salinity in the Baltic in the same period. The surface salinity has reversed the declining trend since 2004. For the deep Baltic Sea, the salinity has steadily decreased in the Bothnian Bay and Sea during the last 100 years. Other areas e.g. the Golf of Finland, the Baltic Proper and the northern Baltic, however, experienced salinity increases since 1990.

The warming signal is also detected in sea-ice change. From ice extent measurements, it was found that the shift towards a warmer climate took place in the latter half of the 19th century. There is a general decrease in the duration of the ice season, where the largest decrease was 14–44 days in a century, based on a time series at 37 Baltic coastal stations (Jevrejeva *et al.*, 2004). The lowest maximum ice extent was observed in the winter 2007/2008.

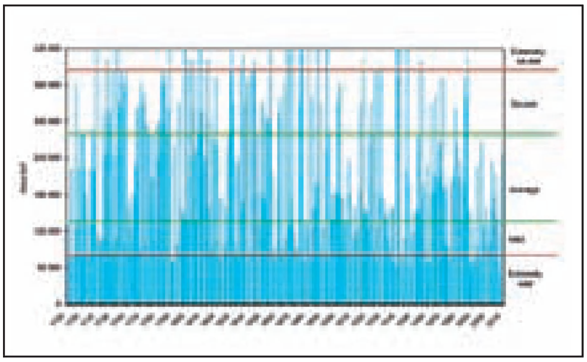

Figure 51. The maximum extent of ice cover in the Baltic Sea on the winters 1719/20 – 2009/10 (Courtesy of FMI / Source: HELCOM).

The sea-level change in the Baltic is mainly dominated by the isostatic and eustatic global sea-level rising effects, combined with changed winds. The isostatic uplift varies from approximately zero in the southern Baltic Sea to a maximum uplift in the Bothnian Bay of about 10 mm yr^{-1} (Johansson *et al.,* 2002). The magnitude of the eustatic sea-level change is 1–2 mm yr^{-1}. Consequently, the net sea-level rise was estimated to be about 1.7 mm yr^{-1} in the Southeast Baltic Sea while it reverses to –9.4 mm yr^{-1} in the Northwest Gulf of Bothnia. The eustatic sea-level rise has accelerated during the last decades.

Due to the regional geological structure, wave and hydrodynamic conditions, coastal erosion has been one of the major environment problems in the southern and eastern Baltic Sea coasts. An increasing trend of coastal erosion in the last 50-100 years has been observed. For example, on the Polish coast, the average coastal retreat in the period 1875–1979 was 0.12m yr^{-1}, increasing to 0.5 m yr^{-1} in the period 1960–1983, and 0.9 m yr^{-1} in 1971–1983. In Latvia, over the past 50–60 years, long-term cliff erosion has occurred at the rate of 0.5–0.6 m yr^{-1}, reaching a maximum of 1–1.5 m yr^{-1} along certain stretches of the coast. Since 1980/1981, the rates of erosion along the Latvian coast have increased to 1.5–4 m yr^{-1}. A similar situation has also been observed along the coast of Lithuania. In Estonia, there has been increased activity of both erosion and accumulation processes in recent decades (BACC, 2008).

Extra evidences have been revealed from a study by Hansson (2010). The time series of water temperature, ice extent, runoff, salinity and oxygen concentrations in the Baltic Sea has been reconstructed for the last 500 years. Changing winter climate is studied. It is found that the last 500 years are characterized by long periods of either mild or cold winters, and that the transitions between them have been rather rapid. Current warming level has occurred twice in history. During the warm periods, the decrease of freshwater flow into the southern Baltic is higher than the increase in the northern Baltic. This leads to a saltier Baltic.

3.1.1.2 Changes in the Biogeochemical Environment

Climate change affects the Baltic Sea ecosystem through the changing physical environment, light conditions and biogeochemical environment. Major long-term changes have been observed in water transparency, coastal erosion, eutrophication, anoxic conditions, biodiversity and ecosystem regime shift.

The light attenuation, among these factors, is the only one which has a two-way link with physical and ecological parameters. On one hand, primary production largely depends on light conditions; on the other hand, the phytoplankton biomass is likely to have a high influence on water transparency, at least in summer. This may in turn change the speed of warming in the surface.

Decrease in summer time water transparency was observed in all Baltic sub-regions over the last one hundred years (Lundberg, 2005; Fleming-Lehtinen & Kaartokallio, 2010). Such a decrease may be regarded as an indication of increasing eutrophication in the Baltic Sea. The decrease of water transparency was most pronounced in the northern Baltic Proper (from 9 m to 5 m) and the Gulf of Finland (from 8 m to 4 m). A more recent decrease over the past 25 years was most pronounced in the Western Gotland Basin, Northern Baltic Proper and the Gulf of Finland. On the other hand, in the Kattegat and Eastern Gotland Basin, the decreasing trend ceased during the past 20 years and since then the water transparency remained at about the same level. In the Arkona Sea and Bornholm Sea the water transparency has increased during the last two decades.

Oxygen deficiency in the Baltic Sea has been observed for the last 40 years. During 1970-2000, the total area with oxygen concentrations < 2 ml l^{-1} enlarged from < 12,000 km^2 to 70,000 km^2, which corresponds to 5-27 % of the bottom area of the Baltic (Conley *et al.,* 2002). It was also found that the oxygen condition today in the Baltic cannot be compared with any other period since the 16th century (Hansson, 2010). Going back over one thousand years, however, widespread oxygen depletion has been identified recently by a BONUS project INFLOW. This may imply a complicated role of climate change in oxygen depletion. In addition to climate change, the anthropogenic loads have been regarded as another major reason which leads to today's oxygen conditions. Although the loads have started to diminish already in the 1970s, the improvements in water quality are slow.

Linked with the changing physical and biogeochemical environment, the middle and high trophic levels in the Baltic Sea ecosystem also experienced dramatic changes (BACC, 2008). Between the early 1970s and the early 1990s the number of species has decreased in the Åland archipelago, while faunal abundance and biomass have increased above 30 m. Between 20 and 40 m depths, the trend has been similar in inner areas, while the outer, more exposed areas have been in better condition. About 40 % of the species composition has changed since the 1970s and a shift from suspension feeders to deposit feeders has taken place.

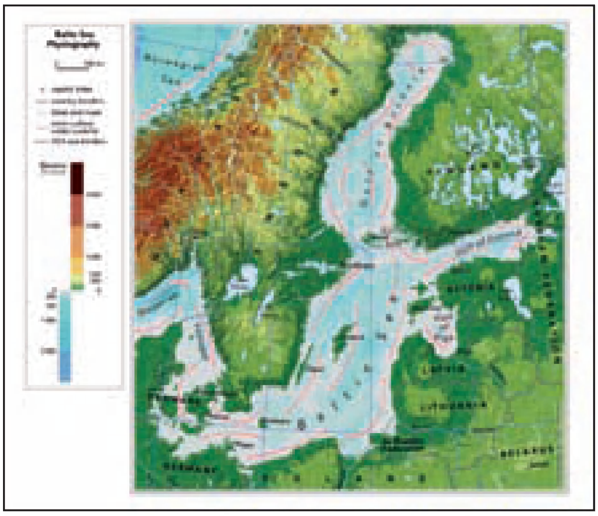

Figure 52. Baltic Sea physiography (depth distribution and main currents) (©EEA)

Ecosystem regime shift has been observed in most parts of Baltic Sea in the mid-1980s (Möllmann *et al.,* 2008; Diekmann & Möllmann, 2010). These regime shifts have important management implications, as they can cause significant losses of ecological and economic resources. Such knowledge is applied to develop an ecosystem-based approach which provides quantitative stock forecasts for Baltic cod and suggests adaptive management actions to mitigate negative effects on future fisheries production under climate change (Lindegren *et al.,* 2010).

3.1.2 Future Projections

Projections for future climate of Baltic Sea and its impact have been investigated by using coupled Atmosphere-Ocean General Circulation Models, Regional Climate Models, regional 3D ocean-ice models and coupled regional atmosphere-ocean-ice models. Considering the complexity of the Baltic Sea system and the limited quality and number of existing coupled regional atmosphere-ocean-ice models, the results from the projection simulations should be used with caution.

These results indicate a continued increase in temperature both in the atmosphere and the sea. The results from the existing ensemble of GCMs differ for the Baltic Sea warming of the air. For example, the warming in the northern Baltic basin from the late 20th century to the late 21st century could range from as low as 1°C in summer (lowest scenario for summer) to as high as 10°C in winter (highest scenario for winter). Downscaling studies using RCMs also indicate increases in temperature during all seasons for every sub-region of the Baltic Sea basin. Combined results show a projected warming of the mean annual temperature by some 3 to 5°C for the total basin. Corresponding changes in temperatures would be 4 to 6°C in winter and 3 to 5°C in summer.

For the future, increased winter precipitation may emerge later in this century over the entire area, while summers may become drier in the southern part – but this expectation is uncertain for the time being. Northern areas could generally expect winter precipitation increases of some 25 to 75 % while the projected summer changes lie between -5 and 35 %. Southern areas could expect increases ranging from some 20 to 70 % during winter while summer changes would be negative, showing decreases of as much as 45 %.

Regarding the oceanographic response to the projected climate change in the atmosphere, studies show that mean annual sea surface temperatures could increase by some 2 to 4°C by the end of the 21st century. Different from the seasonal trend of air temperature, summer SST change may be significantly larger than the winter SST change. Ice extent in the sea would then decrease by some 50 to 80 %. Due to increased rainfall and precipitation, the average salinity of the Baltic Sea will decrease. However, the range of salinity decrease is largely uncertain due to uncertainties in predicting the exact balance between future rainfall, evaporation and river runoff.

Land uplift and the global mean sea-level rise will dominate future changes of mean sea-level in the Baltic Sea

(Meier *et al.,* 2004). In the Fourth IPCC Assessment Report (AR4) a global mean sea-level rise of 0.18-0.59 cm by the end of this century relative to 1980–1999 is suggested for the SRES emission scenarios (IPCC, 2007). It is, however, emphasized that contributions from changes in ice dynamics and uncertainties in carbon-cycle feedbacks are not included. Recent new studies have shown that larger sea-level increases by 2100 cannot be ruled out. By including melting of Greenland and Antarctic ice in the projection (Pfeffer *et al*., 2008), as well as the long-term statistical relation between global mean sea-level and mean temperature (Rahmstorf, 2007, Grinsted *et al.,* 2009), the new findings suggest a possible 0.8-1.6 m global mean sea by the year 2100 for SRES scenarios.

The AR4 reported that the North Atlantic will experience a greater increase (about 0.1 m in average) than the global average. In the Baltic Sea, high spatial variability and land uplift complicate the mean sea-level change. It is likely that, by the year 2100, some regions currently experiencing a relative fall in sea-level may instead have a rising relative sea-level. By including land uplift, the projected global average sea-level rise and the projected trends of the leading sea-level pressure component in GCM scenarios, Johansson *et al.* (2004) concluded that the past trend of decreasing mean sea-level in the Gulf of Finland will not continue in the future because the accelerated global average sea-level rise will balance the land uplift.

Regional wind changes could have additional impact on surge heights, especially for the extreme events. For instance, the 100-year surge event in the Gulf of Riga could change from the present 2 m to a future 1.9–3.3 m relative to the mean sea-level for the period 1903–1998.

Quantitative projection of the Baltic Sea ecosystem can be difficult due to the large uncertainties in the ecosystem model and major forcing factors. Nevertheless future trends of increasing temperature and decreasing salinity still make qualitative projections possible.

Accelerated eutrophication is an expected consequence of the anthropogenic climate change in the Baltic Sea since the increased freshwater runoff and precipitation determine most of the nutrient load to the Baltic Sea (HELCOM, 2009). Projected increasing river runoff and precipitation will also strengthen the stratification which may worsen the bottom oxygen condition. The increased temperatures, especially during winter months, will lead to changes in growth and reproduction parameters for fauna and flora, many of which are of boreal origin, i.e., adapted to low temperatures. The worsened eutrophication and increased runoff will further reduce the water transparency in summer, which in turn may enhance the surface warming.

The expected decrease of salinity of the Baltic Sea will have a major influence on the distribution, growth and reproduction of the Baltic Sea fauna. Considering that surface salinity ranges only 5-8 psu in a wide area covering Bonholm to the Bothnian Sea, a 2-3 psu decrease of the surface salinity in this area means a complete regime shift of the saline environment. Freshwater species are expected to enlarge their significance, and invaders from warmer seas (such as the zebra mussel *Dreissena polymorpha* or the North American jelly comb *Mnemiopsis leidyi)* are expected to enlarge their distribution area. The lower limit of approximate salinity tolerance for certain species is critical. Along the complete range of Baltic Sea surface salinity we may expect decreases of species number due to changes in species distribution areas.

3.1.3 What Has Been Done to Better Understand the Climate Change Impact in the Baltic Sea?

A number of long-term climate data sets (50-500 years) has been collected, quality controlled and reconstructed by EU and national research projects related to climate change. The national monitoring programs of all Baltic countries, now coordinated by HELCOM, provided a solid basis for establishing these climate data sets. The parameters include river runoff, precipitation, air and sea temperature, surface winds, sea-level, ice extent, temperature and salinity profiles, dissolved oxygen, water transparency and nutrients. The observations have been used in identifying the climate change signals in the Baltic Sea atmosphere, ocean and marine ecosystems. EU projects covering marine observing systems and data management, e.g. SEADATANET and EMODNET, have contributed to the establishment of a climate observation database. In the following years, long-term climate observations of Essential Climate Variables (ECVs) from remote sensing will be reprocessed with high quality and resolution through implementation of the European Space Agency Climate Change Initiative (ESA- CCI), which will add a great value to the Baltic Sea climate study.

The quality of the ocean and ecosystem models has been improved in the past years regarding their numerics, physical and biogeochemical parameterization, resolution and coupling between different models. Significant model improvements have been made in operational oceanography applications with supports from self-funded BOOS (Baltic Operational Oceanography System) activities, and EU projects starting from FP5 such as PAPA, ODON, MERSEA, ECOOP, BOSS4GMES and MyOcean. High resolution, well calibrated two-way nested Baltic - North Sea ocean-ice models have been used in Baltic Sea climate studies. Data assimilation schemes, e.g. Multivariate Optimal Interpolation, 3D Variational Method, Ensemble Optimal Interpolation etc, have been developed and implemented for the Baltic Sea ocean-ice-biogeochemical models. Multi-decadal hindcast and re-analysis of hydrodynamics and ecosystems of Baltic Sea are now started within MyOcean and the follow-on GMES marine service project.

For the research community, the EU Marine Strategy Framework Directive, EU INTERREG initiative, BALTEX (Baltic Sea Experiment) program, BACC (Assessment of Climate Change for the Baltic Sea Basin) project, BONUS and national climate change programs are major driving forces. For example, the BACC project, as a joint venture of BALTEX and HELCOM (Baltic Marine Environment Protection Commission), has demonstrated a successful dialogue between the scientific community and environmental policy makers. It integrates available knowledge of historical, current, and expected future climate change. The unique feature of BACC is the combination of evidence on climate change and related impacts on marine, freshwater, and terrestrial ecosystems in the Baltic Sea basin, which encompasses the entire catchment area. It is the first systematic scientific effort for assessing climate change in a European region. More than 80 scientists from 12 countries have contributed on a voluntary basis. The next BACC report is expected to be published in 2013.

BONUS+, jointly funded by the European Commission and national funding institutions in the Baltic States, also has a climate change related module. A total of 16 projects involving over 100 research institutes and universities were funded (euro 22 million) through a joint call BONUS+ in 2007. In 2011, during the third and final project year, analysis of the obtained data and compilation of the research outputs are ongoing. Extensive multi-disciplinary research on ecosystem function, resilience, regime shift and related social-economic impacts and management measures has been carried out. The next step, BONUS-185 call, is now in preparation phase and will be launched in the near future.

A research initiative on the ocean acidification and its impacts on the Baltic Sea has been recently started as part of EU project EPOCA. Innovative platforms for monitoring ocean acidification have been developed and tested. The impacts of ocean acidification on the cyanobacteria, benthic foraminifer Ammonia aomoriensis and Baltic cod sperm have been studied.

3.1.4 Research Gaps and Priorities

Major climate change impacts (including anthropogenic effects) have been observed in physical, biogeochemical and ecosystem levels, as rising sea-level, warming ocean, less ice, a fresher Baltic Sea in winter, accelerated coastal erosion, less water transparency, more eutrophication, anoxic condition and ocean acidification, ecosystem regime shift etc. It is still a great challenge to predict the future of these observed changes. In decadal to centennial scales Baltic Sea system is affected by both external (North Atlantic Oscillation, Arctic Oscillation, Meridional Overturning Circulation, inflow, river runoff) and internal factors (stagnation, ventilation, ecological cascade, regime shift and ecosystem resilience). The relevant importance of these factors has far from been fully understood. It is suggested that such kind of studies for the future Baltic Sea system should be scenario-based and using a system approach. The latter means, firstly, the scales, forcing and components of the system should be properly defined so that some meaningful conclusions can be reached: secondly, the tools for monitoring and simulating the system should be properly developed based on a deepening understanding of the Baltic system climate processes; and thirdly, the stability, predictability and uncertainty of the system prediction should be studied.

Important research topics include:

- Development of a system approach for Baltic Sea climate change research, which may include developing fully coupled Baltic Sea earth system model (atmosphere-hydrological-catchment-ocean-ice-wave-biogeochemical-SPM-larvae-fish models), providing high quality multi-model coupled ensembles for the Baltic Sea climate simulations, investigating the stability and predictability of the system and developing scenario-based predictions in decadal and centennial scales;
- Further optimisation of existing Baltic Sea observing systems for supporting the system approach of Baltic climate change research, especially for the biogeochemical parameters;
- Improvement of the understanding of existing Baltic Sea climate change processes, and the relative importance of internal and external factors which will give a solid base for design scenario-based predictions;
- Solving key issues in using ecological models for climate research, e.g., reconstructing past ecosystem changes including regime shifts, make ecosystem forecast in seasonal and decadal scales, internal budget balance of the ecological models in long-term integration.

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3.2 Impacts of Climate Change on the North Sea

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3.2.1 Weather and Climate

As for most European Seas, the pattern of sea temperature in the North Sea over the last century has changed from generally cold conditions in the early 1900s to a warm period from the 1920s to the 1950s, cool again through the 1960s and 1970s followed by recent warming that commenced in the mid 1980s (Johannessen *et al.*, 2004).

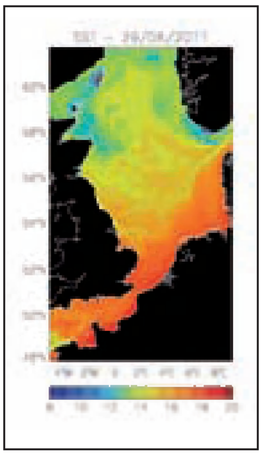
Within the past 50 years, the North Sea has experienced two climatic regime shifts (e.g. Weijerman *et al.,* 2005; Kirby & Beaugrand, 2010). The first change occurred in the late 1970s, and was distinguished by a reduced inflow of Atlantic water and cold-boreal conditions (Reid *et al.*, 2001). During the most recent change in the late 1980s, oceanic inflow increased markedly and so did sea surface temperature (Beaugrand, 2004). This warm temperate period has continued to the present day.

Air temperatures over the North Sea are expected to increase by 2°C to 3.5°C by the 2080s, with high summer temperatures becoming more frequent and very cold winters becoming increasingly rare (e.g. Hulme *et al.*, 2002; van den Hurk *et al.*, 2006). Of particular relevance to Integrated Coastal Zone Management is the predicted increase in the intensity and frequency of powerful storm events characterised by larger peak wind speeds and consequently larger waves (IPCC, 2007), although this prediction has recently been challenged.

3.2.2 Hydrodynamics

A number of recent studies have clearly demonstrated the close link between the North Atlantic atmospheric variability, represented by the North Atlantic Oscillation (NAO), and hydrodynamic changes occurring on the Northwest-European Shelf. The process is not unidirectional but contains feedbacks between large-scale North Atlantic atmospheric patterns and cross-shelf patterns of North Sea water circulation. The former influences the latter but the latter also modifies the former. Long-term changes in datasets of physical factors in the North Sea have been empirically correlated with the NAO.

Figure 53. North Sea from Space (above - ©NASA) and sea surface temperature forecast in the North Sea for 29 August 2011 (below - ©Met Office, UK). The coastal seas model sea temperatures (right) are validated against measurements taken from a large source of measurement platforms, made up from the Met Office MAWS stations, oil and gas platforms and collaborations with the Irish Marine Institute and Meteo France.



3.2.3 Biotic Changes

In the North Sea, temperature has been an important driver of changing trophodynamics for nearly 50 years (Kirby & Beaugrand, 2010). Within this period, two climatic periods, characterised by a wide-scale and rather sudden change in plankton, benthos and fish populations, stand out as exceptional (e.g. Weijerman *et al.*, 2005; Kirby & Beaugrand, 2010).

Seasonal changes in the timing of biological events in different functional groups in the plankton as a response to warming are leading to mismatches in the abundance peaks of phytoplankton and zooplankton, between zooplankton and fish, between bivalve larvae and shrimp, and between fish and seabirds (e.g. Beaugrand & Reid, 2003; Edwards & Richardson, 2004, Philippart *et al.*, 2003; Wiltshire & Manley, 2004). In the past 40 years, the warming of the North Sea has affected cod recruitment via changes at the base of the food web (Beaugrand *et al.*, 2003).

Northerly range extensions or changes in the geographical distribution of plankton and fish populations are associated with the above changes and have been related to regional climate warming (Beaugrand *et al.*, 2003; Brander *et al.*, 2003; Perry *et al.*, 2005; Dulvey *et al.*, 2008). Warmer water species of plankton, for example, have extended their range northward by 1000 km in only 40 years and colder species have retreated out of the North Sea (Beaugrand *et al.*, 2003).

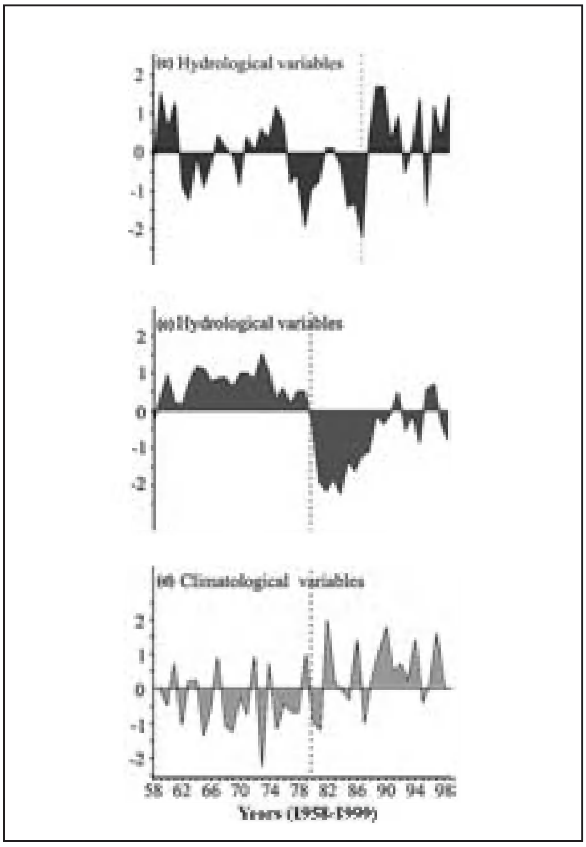


Figure 54. Changes in sea surface temperature (above), salinity (middle) and westerly wind intensity (below) in the central North Sea between 1958 and 1998. The dotted line indicates the regime shift between 1987–1988. (From Beaugrand *et al.,* 2004)

According to scientists of the MarinERA ERA-NET ECODRIVE project, two major possible transfer mechanisms have been discussed, i.e. the direct atmospheric forcing and its effects on stratification and on advection of Atlantic water through the English Channel and the northern North Sea entrance. Recently, Sundby and Drinkwater (2007) reported that the major salinity anomalies associated with decadal-scale climate pattern of the North Atlantic can result from variability in volume flux induced by the NAO.

Within the EU FP5 MAIA project, a system was developed to monitor the inflows of Atlantic water to the northern seas. This system provides a means to calculate the long-term variability of the Atlantic inflow to put short-term measurements into perspective, and can also provide reliable boundary conditions for numerical models of the North Sea. The objectives of the MarinERA ERA-NET ECODRIVE project includes the analyses of available long-term time series data on climate indices, as well as modelled (climate-forced) estimates of abiotic and biotic factors.

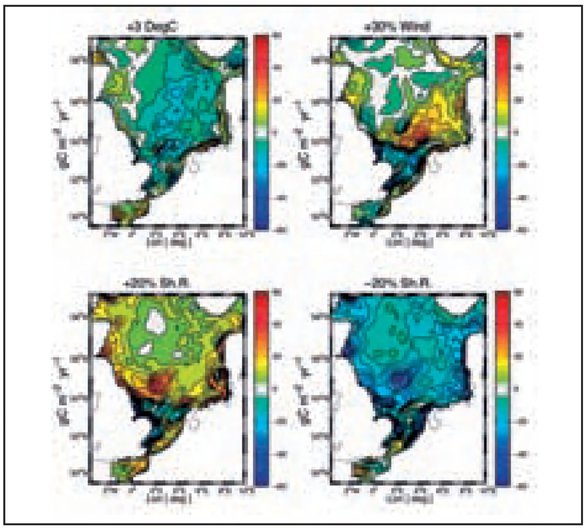


Figure 55. Changes in primary production (gCm^{-2} yr^{-1}) in response to an 3°C increase in temperature (upper left), a 30 % increase in wind (upper right) and a 20 % increase or decrease in radiation (Sh.R. bottom left and right) as predicted by the Ecosmo biophysical model (from Drinkwater *et al.,* 2009; RECLAIM)

Sardines and anchovies have moved northward in the North Sea and red mullet and bass extended their ranges north to western Norway (Brander *et al*., 2003). On average, North Sea fish have shifted also to deeper waters. For example, a demersal fish assemblage consisting of 28 North Sea species has deepened significantly at a rate of ~3.6 m decade^{-1} between 1980 and 2004 (Dulvey *et al.*, 2008). Many warm-water rocky shore snails and barnacles formerly absent or just extending into the North Sea from the warmer waters of the British west coast have spread south from the tip of Scotland along the North Sea coast of the UK (Mieszkowska *et al*., 2005).

In summary, the change in temperature in the late 1980s has established a new ecosystem dynamic regime by modifying the strength and direction of many trophic interactions and favouring jellyfish, decapods and echinoderms (Kirby & Beaugrand, 2009; Gibbons & Richardson, 2009). This strongly suggests that the North Sea ecosystem is vulnerable to variation in climatic conditions in general, and to anomalies in temperature and hydrodynamics in particular. Several processes within the North Sea food web appear to be triggered by temperature, and further increases in temperature may continue to disrupt the connectedness between species potentially leading to changes in community structures and possibly local extinctions

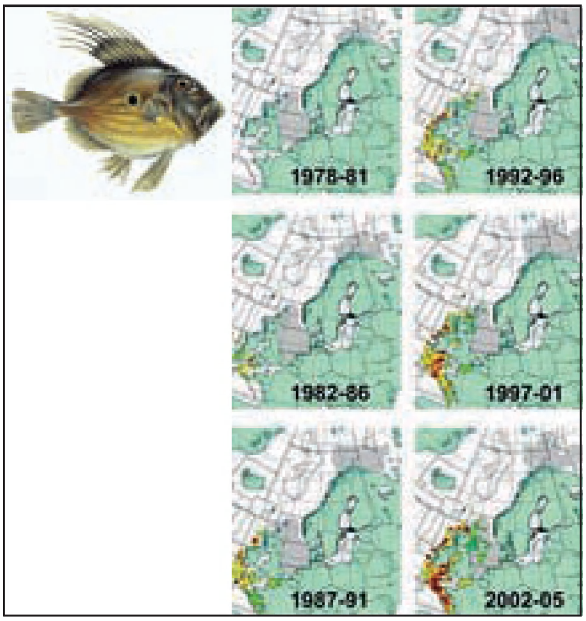


Figure 56. Change in abundance and distribution of John Dory (*Zeus faber*), a Lusitanian species, between 1978 and 2005 (From Pinnegar et *al.,* 2009; RECLAIM)

3.2.4 Socio-Economic Impacts of Climate Change in the North Sea

A first exploration of the relative roles of fishing and changes in primary production in the EU FP6 RECLAIM project suggested that fishing was found to be the primary forcing factor of ecosystem changes in the North Sea. The FP6 Network of Excellence MarBEF found that warming temperatures are contributing to an overall increase in fish species diversity in the North Sea. For many marine species, including commercially caught fish, large and co-varying fluctuations in recruit densities mainly determine the year-to-year variation in the size of the adult stocks. If the annual sea surface temperature increases further, efforts to maintain previous fishery yields from reduced stocks (due to northward movement and lowered recruitment levels) has the potential to significantly impact fisheries and have dramatic effects on the ecosystem (Brander, 2007).

The EU FP7 MICORE project will provide the knowledge necessary to assess the present day risks and to study the economic and social impact of future severe storm events and will also develop operational predictive tools in support of emergency response to storm events. One of the case-studies within this project was located at Egmond, in the Northern part of the Dutch coastline of the North Sea. The EU FP7 THESEUS project will develop a systematic approach to delivering both a low-risk coast for human use and healthy habitats for evolving coastal zones subject to multiple change factors. Specific attention will be paid to the most vulnerable coastal environments such as deltas, estuaries and wetlands, where many large cities and industrial areas are located, amongst which are the estuaries of the rivers Scheldt and Elbe along the North-West European coastline of the North Sea.

Figure 57. Future climate change predictions are likely to affect fisheries (©Evy Copejans)

3.2.5 Research Gaps and Priorities

The EU projects that focussed or included the North Sea (a.o. BASIN, RECLAIM) and the Marine Board-ESF Position Paper[2] (Philippart *et al.,* 2007) identified the following gaps in research:

- **Observations** - Gaps in systematic observations of atmospheric and oceanic parameters, including those of climate, need addressing in order to improve forecasting of ecosystems in the North Atlantic and associated shelves such as the North Sea. Monitoring research of the major biotic components (plankton, benthos and fish) should be continued and expanded. Increasing temporal and spatial coverage of data sets and inclusion of less well covered ecosystem components (benthos) is required. Such time series are invaluable for analyses of climate impacts and for the formulation and validation of ecosystem models.

- **Models** - Global Circulation Models should be improved to capture the decadal (NAO) and multi-decadal (AMO) scale variations in ocean climate, and regional downscaling models need to be developed based on different GCM to provide a realistic future projection for regional impact studies. Bio-physical modelling of single species should extend beyond the egg and larval stages in order to better project climate-driven changes on marine fish populations stemming from processes acting in various life history stages (from eggs to adults) and on the life cycle closure, and lower trophic level ecosystem models need to be improved including more emphasis on pelagic-benthic coupling of marine systems. Models of the upper trophic web need to be better linked to biogeochemical and NPZD models in order to predict the consequences of climate change for 'higher' consumers in ecosystems.

- **Species' traits** - Additional research on the growth physiology of key species and life stages, as well as on the physiological effects of acidification and multiple stressors is needed. The evolutionary adaptive capacity of marine species and populations to climate-driven change in environmental factors is poorly understood and needs to be examined.

- **Socio-economic consequences** - Better understanding and modelling of implications for fishing fleets and local economies are required, since it can be very difficult to determine how fisheries might look in the future, and what conditions they will need to adapt to.

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3.3 Impacts of Climate Change on the Arctic Ocean

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3.3.1 Introduction

The Arctic Ocean belongs to the least investigated regions of the World Ocean. Only three of its sub regions have been reasonably investigated: the Bering Strait / Chucki Sea, the Canadian Archipelago and adjacent Beaufort Sea and the Barents Sea. For the European Arctic Corridor (EAC), stretching from the eastern Greenland and the Fram Strait to the Kara Sea, good ecological knowledge is only available for the Barents Sea (Wassmann *et al.,* 2006a).

One of the major limitations to understand climate change and ecological knowledge from the EAC region is that the investigations take usually place in the productive period and only in certain regions. How the climate is changing in the EAC region cannot be easily evaluated by the few, scattered and variable time se-

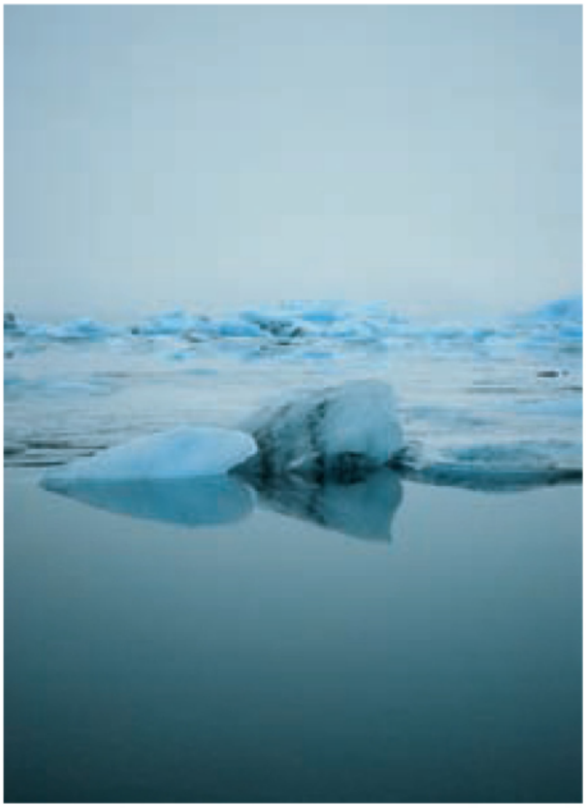

Figure 58. Ice-scape (©Karen Rappé)

ries of hydrochemistry and ecology. In a remote, vast and inaccessible region such as the EAC, the only practical method at present to address the question of production and C flux over the entire region is to apply mathematical models, developed on and validated by existing measurements on the physical, chemical and biological oceanography of the area.

There exists few model studies of the entire Arctic Ocean (e.g. Popova *et al.*, 2010; Zhang *et al.*, 2010; Slagstad *et al.*, 2011) and several are in their early stages. Some of the results presented here rely upon SINMOD, a coupled hydrodynamic-ice-chemical-ecosystem model system, the only model that specifically focuses upon the EAC region. SINMOD expands on earlier model contributions that focused upon the Barents Sea region (detailed description: Slagstad & McClimans, 2005; Wassmann *et al.*, 2006b) by extending the model domain to the Fram Strait, the northern Barents and Kara Seas and the Arctic Ocean shelf break (Figure 59). SINMOD can investigate the pelagic C flux through phyto- and zooplankton in the EAC and these can be explored over time through hind-cast meteorological or future IPCC climate scenarios. The EU FP7 Arctic Tipping Point project includes also runs of the entire Arctic Ocean.

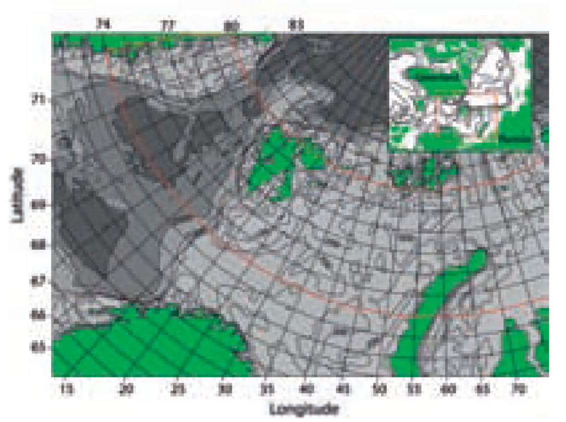

Figure 59. The European Arctic Corridor and the model domain. In the upper right the main model domain and the nested area of the European Arctic Corridor for which gross primary production results are presented. Also shown are the regions above 74 and 80°N for which separate estimates of gross primary production are provided. (From Wassmann *et al.,* 2010)

3.3.2 Observations

3.3.2.1 Change of Physical Conditions

More than 80 % of the in- and outflow of Arctic Ocean water takes place in the EAC region. The North Atlantic Current transports warm and salty water around Svalbard and through the Barents Sea and this water (subducted below lighter Arctic water) engirdle the entire Arctic Ocean as a boundary current. The major outflow of water from the Arctic Ocean is through the East Greenland Current. Understanding the physical oceanography of the EAC region is thus essential to comprehend and predict climate change in the Arctic Ocean.

The flow-through type ecosystems of the EAC are characterised by shelves, complex bathymetry and hydrography (Loeng *et al.*, 1997) that results in an ecological zonal structure. It demonstrates a striking combination of physical conditions, high latitude light regime and substantial advection of heat, salt, nutrients and biomass by the Norwegian Atlantic Current (Sakshaug *et al.*, 1995; Mauritzen *et al.*, 2011). Sea-ice can cover up to 90 % of the Barents Sea surface in winter, but there is no locally produced multi-year ice in the EAC region (Vinje & Kvambek, 1991). Thus much of the Barents Sea experiences ablation and growth of sea-ice on a seasonal basis. While ice cover has decreased significantly in the entire Arctic Ocean since 2006 (in particular in the Beaufort, Chukchi and East Siberian Seas, see Stroeve *et al.*, 2007), there has simultaneously been more ice than normal north of Spitsbergen and in the Fram Strait. The decline of sea-ice cover in the EAC region is thus not as pronounced as for the entire Arctic Ocean and this is one of the reasons that climate change is not easily detected in the EAC region. An increase of warming of Atlantic water will decrease the region where Arctic water is found and this will result in an 'atlantification' of the central regions of the EAC region, presently dominated by Arctic waters.

The interannual variability in the temperature of the Atlantic Water inflow is considerable. The total variability of the temperature in the inflow region, as recorded through the World's longest oceanographic time series, the Kola Transect, is about 2 degrees between warmer and colder phases. There is no obvious long-term increase in seawater temperature in the southern Barents Sea over the last 100 years (Loeng *et al.*, 1997), but decadal periods of warmer and colder phases exist.

3.3.2.2 Change in Biogeochemical Environment, Biotic and Ecosystem Changes

The marginal ice zone crosses most of the EAC shelves during the basically northbound progression of the spring bloom and is of particular importance for the production of organic matter (Wassmann *et al.*, 2006). The north- and southwards movement of the marginal ice zone produces a prominent, seasonal signal in the EAC region with major interannual variability. The key zooplankton species Calanus finmarchicus, typical for Atlantic water, spreads northwards in connection with warmer waters. The key zooplankton species Calanus glacialis, however, decreases its presence during warm scenarios.

As the interannual variability has been large, the time series too short and the seasonal coverage too sporadic, the effect of warming cannot be easily discerned in the EAC region. The links between observed changes and climate on biogeochemical environment remain thus less obvious compared to other regions. A clears exception is though acidification (see Information Box 4).

Northwards shifts in biogeographic boundaries are inevitable with continued warming of the Barents Sea. Recently, the boreal-distributed mussel, *Mytilus edulis*, a keystone species in temperate waters, was discovered in Svalbard after a 1,000 year absence (Berge *et al.*, 2005). This exemplifies the potential for significant and non-predictable alterations from non-native species previously excluded by the unfavourable conditions. As a consequence, the functioning of the food web of the Barents ecosystem may change by continuous warming and sea-ice retreat as well as the invasion of boreal species such as e.g. *M. edulis*, mackerel and blue whiting (*Micromesistius poutassou*) or by introduced species such as the king crab (*Paralithodes camtschaticus*). To which degree the arrival of boreal species can be interpreted as a consequence of global warming and climate change is a matter of interpretation.

The steady increase of atmospheric CO_2 has, over time, resulted in an acidification, in particular in the Arctic Ocean and out-flowing Arctic Water. For details about the on human time scales irreversible acidification of the Arctic Ocean (see Information Box 4).

Information Box 4. Ocean Acidification: the Case for the Arctic Ocean

Anthropogenic activities are at the origin of a rapid rise in atmospheric CO_2 concentrations since the late 18^{th} century to levels exceeding the natural range of the last million years. The increase in atmospheric CO_2 concentrations causes global warming and ocean acidification. Global Earth System models (e.g. coupled models including a representation of the global atmosphere, ocean and terrestrial biosphere) are used to simulate impacts of global warming and ocean acidification on marine biogeochemical cycles and marine ecosystems. Several model studies have highlighted the vulnerability of high latitude oceans to ocean acidification (Orr *et al.,* 2005; Steinacher *et al.,* 2009). This is in particular the case for the Arctic Ocean for which undersaturation with respect to aragonite is projected to occur within the next decade (Steinacher *et al.,* 2009) in response to a ‘business-as-usual’ IPCC emission scenario up to year 2100. Such drastic eminent changes in ocean carbonate chemistry are explained by the natural low saturation state of Arctic ocean surface waters and by a strong amplification of ocean acidification by climate change. As a matter of fact, sea-ice retreat and freshening in response to global warming lead to a decrease in CO_3^{2-} levels and thus in saturation state. In a study addressing the long term commitment of CO_2 emissions on ocean chemistry, Frölicher and Joos (2010) demonstrated that ocean acidification projected from ‘business-as-usual’ emissions is irreversible on human timescales. Taking into account potential impacts of ocean acidification on marine biota and ecosystems (Doney *et al.,* 2009), would call for a lower target of atmospheric CO_2 (of 450 ppm according to Steinacher *et al.,* 2009) than considering global warming only.

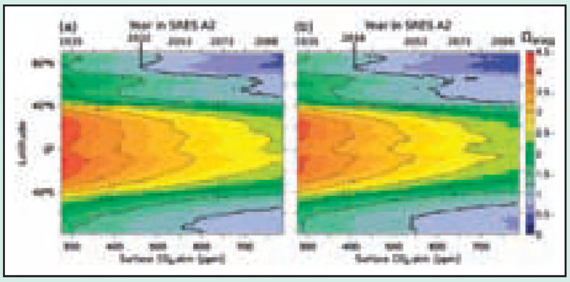

Figure 60. Projected evolution of the surface ocean carbonate system during the 21st century in response to a ‘business-as-usual’ IPCC emission scenario (SRES A2). The figure shows the evolution of the saturation state Ω for aragonite: (a) annual mean; (b) lowest monthly mean zonally averaged. The dotted line indicates the transition between oversaturation to undersaturation with respect to aragonite. Values of W < 1 indicate adverse environmental conditions for marine calcifiers building aragonite shells. The onset of undersaturation occurs by 2032 when focusing on the zonal mean. Seasonal undersaturation is projected to develop as early as 2016. (Adapted from Steinacher *et al.,* 2009).

3.3.3 Link Between Observed Changes and Climate

The annual gross primary production (GPP) in the entire EAC model domain varies from year to year, ranging between about 66 and 89, with an average GPP of 76.5 ± 5.6 C g m^{-2} yr^{-1} (Wassmann *et al.*, 2010b; Figure 61). In the more Arctic section between 74 and 80°N (Figure 61), the average GPP is not very different from that of the entire EAC model domain: 75.2 ± 7.2 g C m^{-2} yr^{1} (Figure 61). The mean annual GPP in the High Arctic EAC domain >80°N was on average 24.0 ± 3.5 g C m^{-2} yr^{1} (Figure 61).

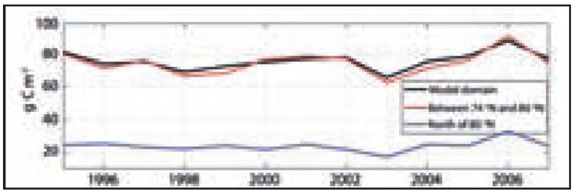

Figure 61. Variability in annual phytoplankton gross primary production (g C m^{-2}) between 1995 and 2007 for the European Arctic Corridor (Figure 59). The rates for the entire model domain (black), the region 74 to 80°N (red) and > 80°N (blue) are denoted. (From Wassmann *et al.* 2010)

Ice cover is the main cause of the variability and periods of increased (2006) and decreased (2003) GPP (Figure 61). However, in none of the three sectors of the model domain any particular trend in temporal variability of annual GPP estimates is shown, not even the High Arctic domain north of 80°N. This suggests that neither the slow but steady decrease of ice cover observed in the entire Arctic Ocean in the years 1995–2007 nor the rapid decline in 2007 had any effect on GPP in the EAC region. The GPP in the EAC region prior to 2007 appears characterised by limited interannual variability, on average 75.2 ± 10 % and 24.0 ± 16 % g C m^{-2} yr^{-1} for the EAC region (74–80 and >80°N, respectively). The decadal GPP anomalies in most of the EAC region seem small, in particular in the regions dominated by Atlantic Water. The biggest monthly anomalies were found in those parts of the seasonal ice zone (SIZ) that loose ice early in the season, a region of high GPP. In contrast, the biggest annual anomalies were encountered in the SIZ that looses ice late in the season (low GPP). When speculating where, when and how the largest relative changes in GPP can be expected in the EAC region in the near future, the GPP anomalies may be our guide. There is no significant trend of increased GPP in the time prior to 2007 and the present investigations can thus serve as a baseline for eventual future changes in GPP.

As the upper layers of the Arctic Ocean receive more light, heat and freshwater, vertical mixing processes cannot provide sufficient nutrients for phytoplankton growth. Increased light will thus increase new production only to a limited degree. Net-heterotrophy in the Arctic Ocean will increase due to: (i) increased import of mesozooplankton; (ii) increased respiration of heterotrophs (in particular microbes); and (iii) relatively small increases in primary production caused by stratification that limits nutrient supply. Primary production is thus strongly influenced by physical forcing and thus climate change, but the predicted increase in GPP is not accompanied by similarly increasing net or harvestable production in the future.

The Arctic zooplankton key species *Calanus glacialis* is a fat-rich, crucial food item for several species such as the fish capelin and the bird Little Auk (Karnowski & Hunt, 2002). Increased future water temperature will result in a decrease of *C. glacialis,* but an increase in the less fat-rich *C. finmarchicus* population.

This will have negative consequences for growth of several Arctic species. Little Auks may fail to breed successfully because of the increasing distance between the colonies and the feeding grounds. Capelin, the essential prey organisms for several fish, seals and whales, may become less fat and thus less energy is provided for the predators. The balance between *C. finmarchicus* and *C. glacialis* production in the EAC region is an essential feature, reflecting today's climate variability and will be consequential for the future C flux.

Decreased summer ice will also have negative implications for species that need ice. We may expect reduced growth and condition of ice-bound, ice-associated or ice-born animals such as ice algae, ice fauna, certain seals and the Polar bear. The most critical phase for these organisms is spring and early summer and then ice reduction will not be so strong compared to late summer when all ice will melt completely in the future.

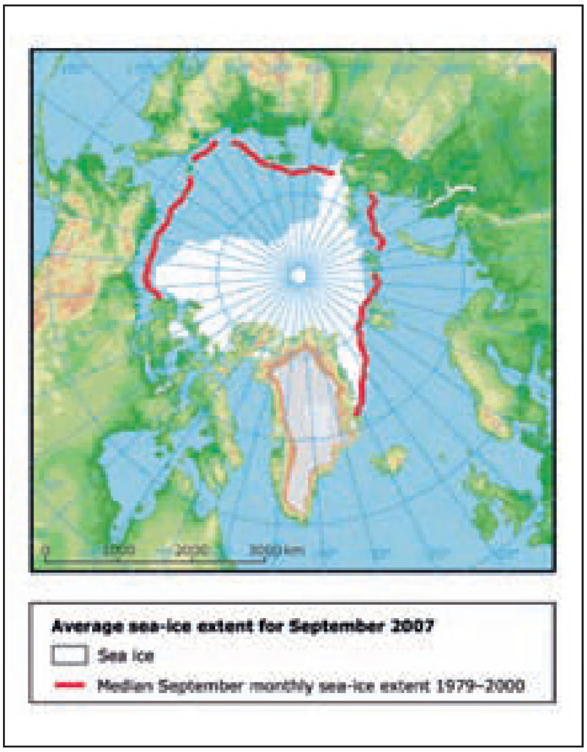

Figure 62. Arctic average sea-ice extent for September 2007. The extent of the summer sea ice in September 2007 reached a historical minimum, 39 % below the climatic average for the first two decades of satellite observations (red line) (From EEA and National Snow and Ice Data Center)

3.3.4 Future Projections

The physically-biologically coupled 3D SINMOD model was also applied to the entire Arctic Ocean (Slagstad *et al.,* 2011). Two highly relevant and timely questions related to climate change were raised: (i) how will productivity change in a warmer, future Arctic Ocean; and (ii) where will changes be observed? The model was applied in an experimental setting where a control run had atmospheric forcing from the European Centre for Medium-Range Weather Forecasts re-analysis data. In order to test how atmospheric temperature increase and retreating ice cover in the forthcoming century might affect productivity through physical processes in the Arctic Ocean, Slagstad *et al.* (2011) added a latitude-dependent air temperature increase starting at +1°C at 40°N and increasing to +2, +4, +6 and +8°C at 90°N to the temperature forcing, mimicking future projection of global warming at high latitudes. The model indicates that gross primary production increases along the temperature gradient both in the Arctic Basins and along the Eurasian shelves from approximately 10 to 40 g C m^{-2} yr^{-1} and from 30 to 60 g C m^{-2} yr^{-1}, respectively (Figure 63 A). In contrast, primary production in the Barents Sea was more or less constant (ca. 100 g C m^{-2} yr^{-1}).

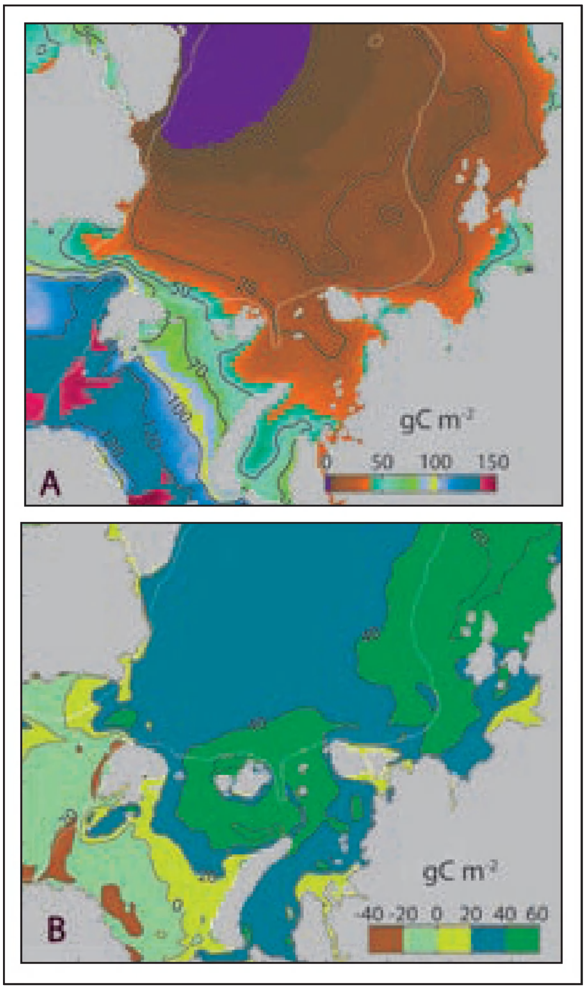

Figure 63. A. Simulated annual gross primary production (g C m^{-2}) in the Arctic Ocean (today's average). B. Difference between the simulated average annual gross primary production of today and the average annual gross primary production of the Arctic Ocean forced by an 8°C air temperature increase towards the end of this century (A2 model projection of IPPC). The difference is given in g C m^{-2}. (Redrawn and recalculated from Slagstad *et al.,* 2011)

The major findings of the model experiments are: (i) in a warmer Arctic Ocean the primary production (GPP) will double or even triple (Figure 63B); (ii) the key processes that determine primary production in a warming ocean are ice cover (light), stratification (ice melt), wind (vertical supply of nutrients) and the metabolism of heterotrophs (respiration); and (iii) primary production increases on most shelves and along the Eurasian shelf break (Figure 63B), but less on the Canadian and Greenland side. One of the surprising results from the model experiment is the minor increase in primary production in the entire Barents Sea during global warming (Figure 63B). The Barents Sea primary production is sensitive to winter and spring ice cover, but not so much to increased air temperature. Reduced ice cover will increase the primary production in the previously ice covered north, but this is compensated for by decreased production in the southern Barents Sea due to reduced supply of nutrients from deep water in the future (increased stratification).

3.3.5 Socio-Economic Impacts of Climate Change in the Arctic Ocean

Historical examination has shown that climate-induced ecosystem changes, for example those reported in the waters around Greenland and in the Barents Sea, have major consequences for fish catches. In a situation where the status of many living marine resources is precarious, abrupt ecosystem changes have major socio-economic impacts on local communities dependent, both culturally and for subsistence, on these natural resources. While climate warming will result in better access to northern and so far ice covered waters the consequences for fisheries in the European Arctic Corridor (EAC) region may be strong and probably negative in the long run. Invasion of southern species such as mackerel may change the internal balance between today's fish species. The stratification-induced decrease in harvestable production in the southwestern and increase in production in the northern and northeastern EAC region may have negative impacts on the Norwegian, but positive impacts on the Russian fisheries. A High Arctic fishery off the continental shelves is unlikely due to nutrient limitation that limits the harvestable production.

The exploitation of seals and whales may be modified in accordance with climate change. There will be a decrease in the number of seals that need ice as birth and resting places. More ice-free water however will result in more feeding space for whales. Seals may also come under pressure because of the northwards expansion of killer whales.

Economic activities dependent upon marine ecosystem services, such as Arctic tourism, may also be vulnerable to abrupt, climate-driven changes to marine ecosystems, and face major challenges in adapting to the new conditions. The decreasing ice cover already results in increasing tourism, but also in greater stress on pristine and vulnerable resources. Limits to Arctic tourism have been already introduced on Svalbard. The ban on heavy oil usage for tourist ships will exclude many vessels that presently operate there. Considering the sustainability of the region, steps have to be taken to limit tourism and to balance the socio-economic gain against ecosystem losses.

With the decrease and thinning of ice maritime transport through the Northeast and Northwest Passage and ultimately over the North Pole will become an alternative to the Suez or Panama channel or rounding South Africa or America. This would reduce transportation distances strongly and speed up the flux of goods. The first trials were actually carried out in 2010, and with success. While this would be of great benefit to the industry, the impact on the Arctic Ocean environment will be severe. First, this today more or less pristine marine environment would be exposed to traditional gas, soot, heavy metal and oil discharge that goes along with all shipping. Second, the chances for accidents with detrimental consequences are high in regions that are more or less ice covered. Third, the Arctic nations are not all prepared (oil spill equipment, tug boats etc.) to handle accidents. Fourth, handling of heavy oil at low or freezing temperatures and in thinly ice covered waters is beyond what today's technology can handle. The Northern Sea Route will come because of the economic benefits, but the socio-economic impact on Arctic societies will be significant.

Figure 64. With the decrease and thinning of Arctic sea-ice, maritime transport through the Northeast and Northwest Passage and ultimately over the North Pole will become an alternative to the Suez or Panama channel or rounding South Africa or America. This would reduce transportation distances strongly and speed up the flux of goods. While this would be of great benefit to the industry, the impact on the Arctic Ocean environment will be considerable. (©Norilsk Nickel)

Less ice cover will be favourable for marine oil and gas exploitation. It is assumed that about 25 % of the remaining oil and gas reserves of the World are to be found in the Arctic, and thus also in the Arctic Ocean region. Production costs will decrease when ice cover decreases. However, the winter distribution of sea-ice will be less affected as compared with the late summer ice cover that has received most of the World's attention. However, although the ice cover will not disappear, the ice gets thinner and also the winter ice cover may decrease due to the erosion of stratified water by low pressure passage. Less ice will also make minerals on land easier accessible and that may result in increased discharge of pollutants in adjacent coastal regions.

In the High North, management of fisheries and marine food-web exploitation by native peoples, tourism, and oil and gas extraction is nested within larger, global-scale initiatives, reducing the ability of Arctic states to adapt to change. The development of a management plan for activities in the Arctic Ocean represents a major institutional experiment on how to address abrupt changes in the Arctic marine ecosystem. The challenge lies in developing managerial models than can help discount anticipated risks and at the same time profit from emerging opportunities. Lessons could be drawn from other management systems that have experienced major shifts in recent history (for example the Bering Sea area). The success of these new models is dependent on three key factors: (i) the availability of reliable scientific forecasts on the future changes of Arctic marine ecosystem in response to climate change; (ii) the development of regionally focused resource-use models; and (iii) communication conduits to efficiently and reliably transfer this knowledge into managerial and political frameworks.

3.3.6 What Has Been Done to Better Understand the Climate Change Impact in the Arctic Ocean?

All nations that engirdle the Arctic Ocean, in particular Canada, Denmark / Greenland and Norway have invested recently in major research programmes for this region. The USA has been less active, with no fresh money for the International Polar Year (IPY). Russia currently carries out little oceanographic research activities in the Arctic Ocean, but both the USA and Russia support the RUSALCA project in the East Siberian Sea. Among the non-Arctic nations Germany carries out continuous research efforts, e.g. supporting the deep sea 'Hausgarten' time series in Fram Strait. Sweden, Poland, Spain and to a lesser degree France and the UK contributed to Arctic Ocean marine ecosystem research. Also the EU has supported Arctic Ocean research through projects such as DAMOCLES and recently EPOCA and Arctic Tipping Point. The international Polar Year (IPY), although being supported only be a few nations with fresh money, has resulted in a quantum leap in knowledge and understanding. Norway and Canada invested significantly in Arctic research during IPY. All these projects and programmes have been essential to increase our knowledge and to remove white spots from our geographic or mental maps, but despite of that they have only provided limited evidence to evaluate climate change in the total Arctic Ocean.

The obstruction of international research in the Arctic region caused by the Cold War is difficult to compensate for now that, in an era of significant climate change, we need adequate information coverage. In a recent overview by Wassmann *et al*. (2011) it became evident that only about 50 footprints of climate change for marine ecosystems could be detected for the entire Arctic Ocean region, because for major provinces such as the coast of Siberia, north of Greenland, the Fram Strait or the central Arctic Ocean no information about climate change could be provided.

Most of the marine ecological footprints of ecosystem change are provided by the larger, charismatic, fauna such as polar bears, seals and birds, while the information regarding the most important base of the food web, the plankton communities, is scant. It is obvious that much has been done and achieved, but that the work so far is not sufficient to provide the desirable evidence to answer the extensive questions raised by politicians and the general public.

3.3.7 Research Gaps and Priorities

The Arctic Ocean belongs to the region of the world that faces the most significant climate change. Simultaneously, it is the least known ocean. This dichotomy is in itself a major problem that the nations of the Northern Hemisphere need to address. Why is it that we know least about regions that are subjected to the greatest climate change and have significant influence on the living condition of billions of people in the Northern Hemisphere?

In essence, far more research has to be carried out in the North. While this is a common verdict, it has a particular relevance for the Arctic Ocean. We need more time series (to evaluate change), more spatial coverage (to obtain an overview about a highly diverse ocean), more experimental studies (to understand the responses during changing external conditions) and more emphasis on ecosystem processes. This would

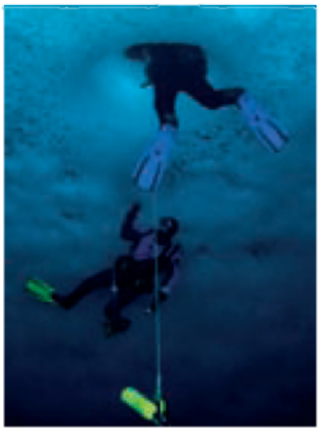

Figure 65. The Arctic Ocean belongs to the region of the world that faces the most significant climate change. Simultaneously, it is the least known ocean. To improve our knowledge we need more research. Left: coverage by ice-strengthened research vessels has to increase (©Alfred Wegener Institute for Polar and Marine Research, Germany). Right: marine scientific divers engaged in preparations for under-ice physico-chemical measurements (©Martin Sayer / NERC)

imply that the coverage by ice-strengthened research vessels has to increase, that the need for permanent instrumentation is supported and that the number of stations that can be used throughout the year is increased. Finally, we need far more validation data for ecosystem models as well as remote sensing models. Arctic Ocean research and in particular modelling work is, compared to others seas, still in its infancy. The questions raised by society correspond to the expected climatic changes, but adequate answers cannot be provided. Part of the reason is that for most nations on the Northern Hemisphere polar research means activity in Antarctica.

The application of existing marine ecosystem models provide guidelines for future primary and secondary production research efforts in the Arctic Ocean. It provides scientists and managers with a tool to maximize the effects of research efforts geared to find answers to the vital question as to which role the Arctic Ocean plays in the global climate system. To achieve more precise primary production estimates for the Arctic Ocean the models must be improved with regard to physical forcing, e.g. photosynthetic available light affected by low sun angle, an atmosphere with high probability of fog formation and a variable thickness and variable snow cover on ice. There is a need for more information on temperature-dependent respiration and metabolism at low temperatures, and stage-structured models are needed for key zooplankton stages in order to simulate their ability to conquer new geographical areas. Finally, basic data from the entire Arctic Ocean have to be obtained in order to validate the models. This essential exercise is hardly possible with the current knowledge, except for a few of the investigated regions.

The key research gaps are lack of basic data from essential regions of the Arctic Ocean, in particular lower trophic levels and processes and better seasonal and spatial coverage. In addition, more emphasis has to be given to pan-Arctic integration and an improved holistic understanding of the circular, Mediterranean-type Arctic Ocean.

The main research priorities for Arctic climate change research in the next 10-15 years must be more, better integrated and internationally coordinated research in the entire Arctic Ocean to determine how physical and chemical processes shape the dynamics of ecosystems, determine the new / harvestable production and the biogeochemical cycling (including exchange with the atmosphere) and pelagic-benthic coupling.

Recommendations for better science policy / funding / management / coordination that could improve our capacity in this area must first of all be based upon an analysis of the needs of the nations and its people of the Northern Hemisphere. This analysis may not have been adequately carried out as the emphasis on research in the Arctic Ocean appears to be not proportional to the needs of the societies of the Northern Hemisphere, which all will be strongly affected by the effects of climate change in the High North. Thus some Arctic nations need to continue their efforts while some have to strengthen it. Adjacent nations should take action to support research in the Arctic Ocean and the same holds true for international organisations such as the UN and the EU. The development of management tools to evaluate the state of Arctic environments in times of climate change and increased stress by a resource demanding World society is also important to develop in order to guarantee a sustainable development. The coordination of Arctic research is not adequate and should be strengthened. This could be achieved by a joint action of the Arctic Council, the European Polar Board and International Arctic Science Committee (IASC). In a global world no ocean is the exclusive responsibility of its coastal nations.

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3.4 Impacts of Climate Change on the North-East Atlantic

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3.4.1 Introduction

The North-East Atlantic Ocean encompasses a vast area stretching from European western shores out to the Mid-Atlantic Ridge (the Azores and Iceland are its highest points) and bounded to the north by the Greenland-Scotland Ridge (which separates the Atlantic Basin from the Nordic Seas). The seabed can be divided into three distinct zones: the shallow continental shelf region to 200 m depth, the zone of rapidly increasing depth known as the continental slope, and the deep ocean basin. The abyssal plain, the deep flat ocean basin floor is about 5,000 m deep (OSPAR, 2010).

The NE Atlantic has a major moderating effect on European weather through the benign warming effects of the North Atlantic Current which is an extension of the Gulf Stream (Figure 66). The warm surface waters release heat into the cold northern atmosphere at a rate equivalent to a hundred times the world's energy consumption, which is sufficient to warm the air over Europe by about 5°C. Indeed, the Atlantic is the only ocean where there is a net northward heat transport across the equator and is thus distinguished by relatively warm upper layer temperatures.

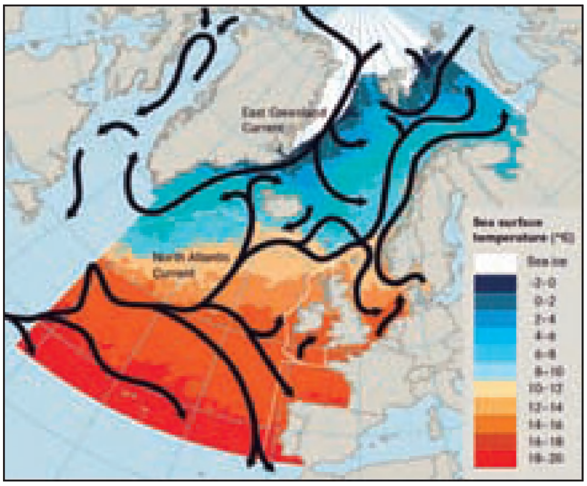

Figure 66. Sea surface temperature within the North-East Atlantic from global high resolution Mercator ocean forecasting system for 13 October 2009 (source: Mercator Ocean) (from OSPAR, 2010).

The northward movement of warm water is part of the global thermohaline circulation. The North Atlantic is important because it is one of the few areas, where new deep-water formation takes place as surface waters cool and sink in the Labrador and Greenland sea areas. Thermohaline overturning circulation prevents stagnation and hypoxia in deep waters through constant replenishment by surface waters saturated in oxygen.

Figure 67. Mace Head Atmospheric Research Station, West coast of Ireland

The oceans and the atmosphere are tightly coupled and highly dynamic systems. Heat, freshwater, gases and momentum are exchanged between the ocean and the atmosphere. Interpreting trends and variability in these properties requires an understanding of the complex interactions and feedback linking the ocean atmosphere system through study of both the atmosphere and the oceans. The predominant northwest wind patterns combined with the long Atlantic oceanic fetch ensure the delivery of high quality oceanic air to the European periphery that is a boon for European atmospheric research particularly the measurement of changing atmosphere composition and its effect on both regional air quality and global climate (O'Connor *et al.,* 2008). The Mace Head Atmospheric Research Station (Figure 67), for example, located on the west coast of Ireland is now regarded as one of the most important sites for atmospheric research in the northern hemisphere and data from Mace Head is used by climatologists around the world to predict global climate change and in the study of air-sea gas exchange in the NE Atlantic as part of numerous EC funded projects (see Table 1).

Marine climate change research in the North-East Atlantic as well as addressing ocean atmosphere system interactions also addresses the rapid changes that are taking place in marine ecosystems. Understanding these changes, including the relative roles of natural variability and anthropogenic effects, and to predict the future state of marine ecosystems requires quantitative understanding of the physics, biogeochemistry and ecology of oceanic systems at mechanistic levels against the backdrop of ocean atmosphere interactions (Hurrell & Deser, 2009).

3. How Does Climate Change and Ocean Acidification Affect the Marine Environment in Different Regions in Europe?

Climate change research in the North-East Atlantic is therefore principally focused on fundamental research into understanding the current situation, establishing robust monitoring systems to provide early warning of climate impacts over time, and improving predictive modelling capabilities with regards changes relating to: (i) biogeochemical cycling particularly ocean CO_2 uptake; (ii) temperature / salinity and thermohaline circulation; (iii) storminess, maximum wave heights and sea-level rise; (iv) biotic responses to increased temperature / CO_2, ocean acidification and other factors; and (v) mitigation and socio-economics.

Table 1 below lists the major EU-funded and other relevant projects that have addressed major climate change research issues in the North-East Atlantic. More information about individual projects can be found in the Clamer Inventory Report[3] of Relevant Climate Change and Ecosystem Research (CLAMER, 2011). The sections that follow provide a summary of some of the key findings from these projects primarily in the open ocean corresponding to OSPAR Area V (Figure 68).

[3]CLAMER Deliverable 1.1: Inventory Report of Relevant European Research – see www.clamer.eu

Table 1. Summary of the major European research projects that have contributed to a better understanding of climate change impacts in the North-East Atlantic.

Topic	FP5	FP6	FP7	Other
Ocean observing systems				
I) Thermohaline Circulation models	ASOF-N,E,W; TRACTOR	ENSEMBLES	THOR	
II) Coupled ocean-atmospheric models - GMES	Gyroscope	DYNAMITE; ECOOP; ESONET; MERSEA	EuroSITES; THOR	WCRP – Clivar; Euro-Argo
III) Ocean Biogeochemical Climate Models + reduced CO_2 exchange	Ironages; NOCES	CARBOOCEAN; MAP; EUCAARI; Quantify; Quantify TTC	Euro-Basin	GLOBEC; IGBP/SCOR - IMBER
IV) Storm Events and mean wave heights		Seamocs	MICORE	
V) Sea-level rise			Theseus; IMCORE; ANCORIM	
VI) Ocean Acidification		CARBOOCEAN	EPOCA; MEECE	
Biota				
Plankton		Eur-Oceans	Euro-Basin	SICA - Greenseas
Fish	UVAC; Codyssey	Reclaim; IN EX FISH;	Salsea-Merge; CoralFISH	ERANET - Defineit
Benthos	ACES	HERMES; Marbef	HERMIONE; MEECE; EELIAD; CoralFISH	
Society				
Socio-economics	Codyssey	FEUFAR; Marbef; HERMES, Quantify; Quantify TTC; Seamocs; ELME; IN EX FISH	CoralFISH; HERMIONE; KnowSeas; MEECE; ANCORIM	ERANET - Defineit
Mitigation - carbon capture and storage			Eco_2	

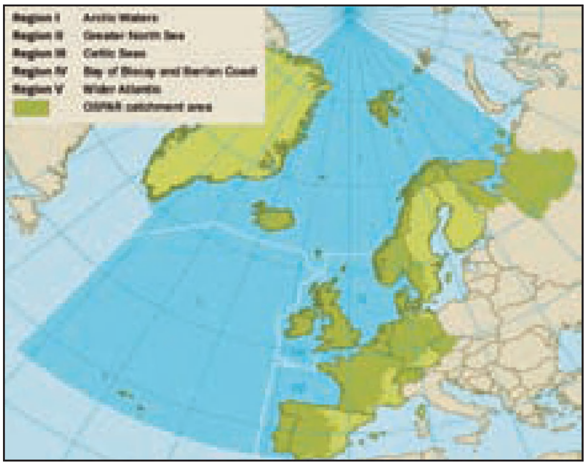

Figure 68. The principal regional divisions with the OSPAR area (from OSPAR, 2010)

3.4.2 Observations

3.4.2.1 Abiotic Changes

The North Atlantic Ocean has exhibited a linear warming trend in average Sea Surface Temperature (SST) of 0.49°C over the period 1850–2007. This warming signal can be attributed to the combined effects of an anthropogenically induced global warming trend and significant interannual to multidecadal-scale variability linked basin-scale oscillations of the ocean–atmosphere system. The dominant modes of low-frequency variability in North Atlantic SST records are linked to atmospheric teleconnection indices, namely, the Atlantic Multi-decadal Oscillation (AMO), the East Atlantic Pattern (EAP), and the North Atlantic Oscillation (NAO). Analysis of a 60-year cycle of warming and cooling in North Atlantic SSTs showed prolonged periods of anomalously warm SSTs in 1864–1880, 1893–1890, 1930–1960, and 1990–2007, with cool periods in 1881–1892, 1900–1930, and 1960–1990. This oscillation between warm and cool SST anomalies is consistent with the variations of the basin-scale AMO (Cannaby & Husrevoglu, 2009).

The overflow and descent of cold, dense water from the sills of the Denmark Strait and the Faroe–Shetland channel into the North Atlantic Ocean is the principal means of ventilating the deep oceans, and is therefore a key element of the global thermohaline circulation. Most computer simulations of the ocean system in a climate with increasing atmospheric greenhouse-gas concentrations predict a weakening thermohaline circulation in the North Atlantic as the subpolar seas become fresher and warmer and it is assumed that this signal will be transferred to the deep ocean by the two overflows. From observations it has not been possible to detect whether the ocean's overturning circulation is changing, but recent evidence suggests that the transport over the sills may be slackening. Analysis of long hydrographic records, has demonstrated that the system of overflow and entrainment that ventilates the deep Atlantic has steadily changed over the past four decades leading to sustained and widespread freshening of the deep ocean.

The frequency of severe wind events and mean wave heights have increased over the past 20 years (Alexander *et al.,* 2005). Wave height in the North Atlantic has been observed to increase over the last quarter century, based on monthly-mean data derived from observations. Empirical models have linked a large part of this increase in wave height with the North Atlantic Oscillation (NAO). The NAO index records the pressure difference between the Azores high and the Icelandic low pressure systems, with a positive index indicating a stronger pressure gradient. The NAO signal is particularly prevalent during winter, when the mean atmospheric circulation is strongest. Interannual to decadal shifts from positive to negative phases of the NAO are associated with large changes in wind speed and direction over the Atlantic and, therefore, with changes in heat and moisture transports, and in the wind- and buoyancy-driven ocean circulation.

When the NAO index shifts from low to high values, wind speeds over the North Atlantic increase by up to 4 m s^{-1}, and the latent and sensible heat fluxes from the ocean to the atmosphere increase by 150 W m^{-2} over the Subpolar Gyre in winter. The trend towards more positive phase NAO conditions over recent decades, associated with a more direct storm track across the Atlantic, has been linked to an increased intensity of westerly winds and winter storms and shifts in hydrographic properties throughout the North Atlantic Ocean. A wave model for the NE Atlantic developed by Wolf and Woolf (2006) was used to examine the sensitivity of the sea state to variation in parameters describing the relative importance of the mean wind speed and the characteristics of storm events. The intensity, frequency, track and speed of storms was found to have less effect on the monthly mean and maximum wave height than the strength of westerlies. This suggests that a recent observed increase in wave height in the NE Atlantic is more likely caused by an intensification of the background westerly atmospheric circulation than by a change in storminess.

The oceans are the main global sink for carbon dioxide (CO_2), and are estimated to have taken up 40 % of anthropogenically produced CO_2 from the atmosphere since the beginning of the industrial revolution, thus buffering the impact of increased CO_2 in the atmosphere and slowing the rate of anthropogenic climate change. The largest vertically integrated concentrations of CO_2 are found in the North Atlantic (23 % of the global oceanic anthropogenic CO_2). Observational studies have reported a rapid decline of ocean CO_2 uptake in the temperate North Atlantic in the early years of the 21st century with absorption 50 % less than in the mid-1990s. Recent data show that this CO_2 sink is slowly recovering although more long-term observations are needed to better understand this variation and its causes. The reduced uptakes rates have been linked to a decline in mixing and ventilation between surface and subsurface waters due to increasing stratification associated with changes in the North Atlantic Oscillation, exacerbated by the changing buffer capacity of seawater as the carbon content of surface waters increased. Recent observations by Watson *et al.* (2009), indicate substantial variability in CO_2 uptake by the North Atlantic on a time scales of a few years.

The uptake by the Atlantic of anthropogenically produced CO_2 has led to a reduction in the pH of surface waters causing acidification that is expected to have appreciable effects on the marine biota over this century. This situation is expected to endure for thousands of years until buffering caused by the dissolution of carbonate sediments moderates or neutralizes the effect of pH change. The most pronounced changes in acidification are seen in the North Atlantic extending down to 5,000 m, much deeper than previously thought, due to the deep water formation that occurs there. The average pH of ocean surface waters is already 0.1 units (30 %) lower than in pre-industrial times. Some of the most important drops in pH have been reported by Olafsson *et al*. (2009), in the Iceland Sea, an important source of North Atlantic deep water. Here, the winter surface water reading decreased by 0.0024 units per year between 1985 and 2008, a rate 50 per cent faster than at two subtropical monitoring stations.

Calcium carbonate occurs in two common polymorphs: aragonite and calcite. A useful measure of changes in calcium carbonate dissolution processes is therefore to monitor the boundary below which dissolution occurs - the saturation horizon. Aragonite is much more soluble than calcite, with the result that the aragonite saturation horizon is always nearer to the surface than the calcite saturation horizon. Organisms that produce calcium carbonate shells are found above the saturation horizon. In the Icelandic study, Olafsson *et al*. (2009) found that the aragonite saturation horizon is currently at 1,710 m and shoaling by 4 m yr^{-1}. Based on this rate of shoaling and on the local seafloor bathymetry, approximately 800 km^2 of seafloor becomes exposed to waters that have become under-saturated with respect to aragonite each year.

3.4.2.2 Biotic Changes

In the North Atlantic and over multi-decadal periods, changes in phytoplankton species and communities have been associated with Northern Hemisphere temperature trends and variations in the NAO index (Beaugrand & Reid, 2003). While at the interannual timescale correlations between temperature and phytoplankton are weak, due to high variance inherent in phytoplankton populations, at decadal intervals they are well correlated. Over the whole Northeast Atlantic there has been an increase in phytoplankton biomass in cooler and a decrease in warmer regions. Changes in ecosystem composition in the North-East Atlantic, that appear to be driven by climate variability, are already underway such as the shifts in plankton biomass noted by Beaugrand *et al.* (2002). Other parts of the food chain are shifting northward in response to thermal stimuli, rather than tracking the seasonal shift in primary productivity. These changes are creating a mismatch between trophic levels and functional groups with implications for ocean–climate interactions and living marine resources (Edwards & Richardson, 2004). In the warming NE Atlantic, zooplanktonic copepods have moved to the north by 10° latitude (1,000 km) within 50 years while colder water plankton has retreated in the same direction (Beaugrand *et al.,* 2002; Edwards *et al*., 2008). This represents a mean poleward movement of between 200 and 250 km per decade. The speed of this migration, due to advective processes, is more pronounced than any documented terrestrial study. The changes that have taken place in these northern European waters are sufficiently abrupt and persistent to be termed as ‘regime shifts’ (Beaugrand, 2004).

Many species of fish have also shown similar northerly range extensions in the eastern Atlantic, at estimated rates that are up to three times faster than terrestrial species. Some fish distributions have moved northwards over the past 30 years by distances ranging from ~50 to 400 km with coldwater species such as monkfish *Lophius piscatorius* moving the furthest while at the same time some have moved into deeper waters at an average rate of ~3.6 m per decade (Pinnegar & Heath, 2010).

Figure 69. Fish distributions of some coldwater species such as monkfish *Lophius piscatorius* have moved northwards over the past 30 years (©Karen Rappé)

One of the largest biogeographical shifts ever observed for a fish species is the dramatic increase and subsequent northerly geographical spread of the snake pipefish (*Entelurus aequoreus*). Prior to 2003 this fish was confined to the south and west of the British Isles, but it now extends as far north as the Barents Sea and Spitzbergen and since 2004 has increasingly featured in the diet of many species of seabirds and other marine predators (Harris *et al.*, 2007), signalling a change in the marine food web. Shifting distributions of fish, partly as a result of climate change are having an impact on the effectiveness of some fishery closure areas and on the apportionment of fishery resources between neighbouring countries (e.g. mackerel in the north-east Atlantic) (Pinnegar *et al.*, 2010)(see also Figure 70).

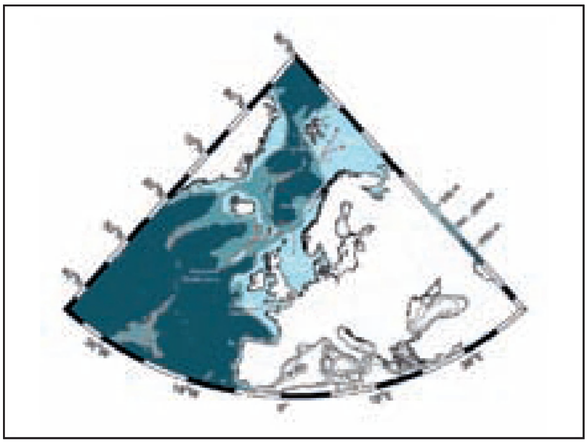

Figure 70. Likely extensions of the feeding areas for some of the main commercial fish populations in the north-eastern Atlantic under climate change. The extent of the movements is for illustrative purposes and not a quantitative estimate of distance moved. (Modified from Blindheim *et al.*, 2001; from OSPAR, 2009)

3.4.3 Future Projections

3.4.3.1 Abiotic Changes

The anthropogenic contribution to the warming signal in North Atlantic Sea Surface Temperature (SST) anomalies since 1850 was estimated as 0.41°C in 2006 and, based on future CO_2 emission scenarios, it is likely to increase over the coming years. Since 1890, the Atlantic Multi-decadal Oscillation (AMO) signal in the temperate NE Atlantic has exhibited a 60-year periodicity, with an amplitude of 0.18°C. If the cyclic nature of the AMO continues into the coming decades, the influence of long-term trends in North Atlantic SST should extend the warm phase until ~2020, when another cool period can be expected (Cannaby & Husrevoglu, 2009). The next cool phase of the AMO should appear as a warm anomaly relative to the 1961–1990 mean, because of the underlying global warming trend. The AMO clearly signifies a prevalent mode of variability in the North Atlantic climate system.

Projections relating to the frequency of storm events in the future climate are of very low confidence and are notoriously difficult to construct given the rarity of storms and their small spatial scale. Whether wave heights will continue to increase is a question which remains to be answered. The derived spatial distribution of the NAO-related sea-level variability allows the development of scenarios for future sea-level and wave height. Because the response of sea-level to the NAO is found to be variable, there is some inherent uncertainty in the use of the empirical relationships to develop such scenarios for future sea-level. Nevertheless, while it remains uncertain whether the multi-decadal NAO variability is related to climate change, the use of the empirical relationships in developing such scenarios is justified. The resulting scenarios demonstrate: (i) that the use of regional estimates of sea-level increase the projected range of sea-level change by 50 % and (ii) that the contribution of the NAO to winter sea-level variability increases the range of uncertainty by a further 10–20 cm. Wave heights are also sensitive to NAO changes. The consensus of climate models' predictions for the NAO suggest that it is likely to continue in its positive phase which means that wave heights are likely to continue to be larger than those observed in the mid-20th century with projected significant wave-height changes in the northeast Atlantic to exceed 0.4 m.

A slowdown in the Atlantic Meridian Overturning Circulation (MOC) in the 21st century is very likely. Rapid fluctuations between weak and strong modes of deep convection could be linked with abrupt climate changes across the North Atlantic region because of associated changes in the poleward flux of warm surface waters. Furthermore, mode switches in deep convection might be triggered by continued freshening north of 60°C in the Atlantic Ocean The general consensus from modelling projections is that there is likely to be a reduction in the strength of the Atlantic MOC of up to 50 % of its current strength. This will not lead to a cooling of Europe, but less warming. This is because the general atmospheric warming 'wins' over the cooling expected from a reduced MOC.

Paleoceanographic radiocarbon reconstructions undertaken to examine changes in northeast Atlantic convection since the Last Glacial Maximum demonstrate that changes in the strength of open-ocean convection have occurred periodically (Thornalley *et al.*, 2011). The authors found that during cold intervals, a reduction in open-ocean convection could be inferred associated with an incursion of an extremely radiocarbon (14C)–depleted water mass, interpreted to be Antarctic Intermediate Water. Reduced open-ocean convection in both the northwest and northeast Atlantic was found to be necessary to account for modelled perturbations in atmospheric circulation based on the timing of deep convection changes in the northeast and northwest Atlantic. In addition, isotopic measurements on multiple species of planktonic foraminifera combined with published benthic isotope records from south of Iceland were analysed in order to assess the role North Atlantic freshwater input played in determining the evolution of hydrography and climate during the last deglaciation. Thornalley *et al.* (2010) demonstrated that two major freshening events occurring during the Younger Dryas cold interval (YD, 12.9– 11.7 ka) were accompanied by a reduction in open-ocean convection, south of Iceland.

Increases in sea temperature and changing planktonic systems and ocean currents may lead to a reduction in the uptake of CO_2 by the ocean; some evidence suggests a suppression of parts of the marine carbon sink is already underway. Thomas *et al.* (2008) however suggest that air-sea CO_2 uptake may rebound in the eastern temperate North Atlantic during future periods of more positive NAO. Climate change feedbacks from acidification may result from expected impacts on marine organisms (especially corals and calcareous plankton), ecosystems and biogeochemical cycles.

3.4.3.2 Biotic Changes

Ocean acidification induced impacts on surface ocean pH and biota will probably be more severe than periods in the geological past when the atmosphere experienced elevated CO_2 levels, as dissolution processes will not have time to counteract pH changes. This is expected to cause extensive damage to shallow tropical reef communities with consequent reduction of biodiversity followed by extinctions. Some authors (Veron *et al.,* 2009) warn that should CO_2 levels reach 600 ppm that reefs will begin to erode leading to domino effects, affecting many other marine ecosystems. They suggest that this is likely to have been the path of the great mass extinctions of the past, adding to the case that anthropogenic CO_2 emissions could trigger the Earth's sixth mass extinction. Given the likely demise of tropical corals, the much deeper cold-water scleractinian coral reefs in the NE Atlantic will become increasingly, globally important as examples of surviving coral reef ecosystems. At current rates of aragonite saturation horizon shoaling, these reefs should be relatively unaffected at least until the end of the century. Increasing pH in surface waters of the Atlantic however may decrease the calcification rates of abundant calcifying phytoplankton (coccolithophores) and other marine organisms such as molluscs, echinoderms and foraminifera, or shift their distributions which could impact the $CaCO_3$ budget and ocean carbon cycle as a whole.

Beyond an anticipated slow shift in fish distributions to more northerly and deeper waters, information on the future prospects for fish communities as a result of climate change are somewhat limited, and often highly speculative (Pinnegar *et al.,* 2010). Modelling strategies for predicting the potential impacts of climate change on the natural distribution of species and consequently the response of fisheries have often focused on the characterization of a species' 'bioclimate envelope' (Pearson & Dawson, 2003). By looking at the current range of temperatures tolerated by a species, it is possible to predict future distribution, if we know how the physical environment in an area will likely change in the future. Cheung *et al.* (2011) used a dynamic bioclimatic envelope model to project distribution and maximum catch potential of 120 species of exploited demersal fish and invertebrates in the Northeast Atlantic. Addressing previous criticisms and shortcomings of bioclimatic envelope modelling, Cheung *et al.* (2011) took account of the effects of changes in ocean biogeochemistry and phytoplankton community structure that affect fish and invertebrate distribution and productivity. They showed that ocean acidification and reduction in oxygen content reduce growth performance, increase the rate of range shift, and lower the estimated catch potentials (10-year average of 2050 relative to 2005) by 20–30 % relative to simulations without considering these factors. Consideration of phytoplankton community structure further reduced projected catch potentials by 10 % highlighting the sensitivity of marine ecosystems to biogeochemical changes and the need to incorporate likely hypotheses of their biological and ecological effects in assessing climate change impacts.

3.4.4 Research Gaps and Priorities

Limitations to progress in modelling climate feedbacks include a lack of, and poor data, inadequate representation of ocean / atmosphere drivers and other processes in models (parameterisation), scaling factors and spatial resolution. Data are needed for input to and validation of models; a lack of historical measurements and time series of key variables and processes is a major restriction on progress in modelling. To address this problem there is an urgent need to implement an integrated global ocean observing programme (including the NE Atlantic) that includes continuous time series of key ocean–climate variables. Such time series need to be maintained for a sufficient length of time to enable a climate change signal to be distinguished from internal natural variability (e.g. Argo, Altimetry, RAPID MOC array, ADCP arrays, CPR)(Reid *et al.,* 2010).

The Atlantic Multi-decadal Oscillation (AMO) clearly represents a significant mode of variability in the North Atlantic climate system, with likely feedbacks for the global climate. Understanding of this process is thus basic to understanding climate variability and change. The ability of climate models to reflect past variability and to predict the future course of the AMO is basic to their ability to predict future changes in the North Atlantic. The complexity of interactions between the North Atlantic Oscillation (NAO) and ocean dynamics, particularly concerning ocean–atmosphere interactions and feedbacks and interactions between immediate and delayed responses, leave many questions relating to the effect of atmospheric teleconnection patterns on ocean dynamics unanswered. The effect of the East Atlantic Pattern (EAP) on ocean dynamics in the North Atlantic basin has received less attention than has the NAO. Because the EAP appears as the second most important component explaining SST anomalies over multidecadal time-scales in the study by Cannaby & Husrevoglu (2009), the effect of the EAP on North Atlantic ocean–atmosphere heat and freshwater fluxes and current structures requires further investigation. The incidence of storms and the strength of the westerly flow are interrelated in ways that need to be better elucidated. Understanding changes in the ocean–atmosphere interactions, and atmospheric teleconnection patters, is central to understanding the potential effects of future climate change, yet remains one of the greatest challenges facing climate science.

There is no clear scientific agreement on the key processes required to model the role of ocean biology and microbial ecology on carbon uptake and the production of radio-actively active gases. The processes involved in gas exchange and sinking fluxes, and their parameterisation are especially poorly understood and yet models are very sensitive to these parameters. A major limitation of current biogeochemical models is that they do not consider the full complexity of the ecosystem (Beaugrand, 2009). In particular, it is not yet clear how the complex biodiversity and functioning of microbial systems and their impact on biogeochemical cycles should be incorporated into models. Observed changes in ocean feedbacks have occurred with a global average (land and sea) temperature rise of less than 1°C. Further warming may increase the impacts of the oceans on climate change, and amplify feedbacks. Despite considerable progress in the development of ocean/ climate models the above limitations mean that their output and prognoses need to be viewed with caution. It should be stressed, however, that while the models are not perfect, this does not reflect on their usefulness as they are an essential tool to look into the future (Reid *et al.,* 2010).

Most research to date on the effects of ocean acidification has focused on calcifying organisms, however comparatively little attention has been devoted to the impact of acidification on non-calcifiers, and ecosystem components and processes such as nutrient speciation and availability, trophic interactions, reproduction, metabolism, diseases, etc. which may impact on all organisms but most critically primary producers (Vézina & Hough-Guldberg, 2008). Rapid modifications due to ocean acidification could have direct effects on a range of physiological processes of marine life at all stages of their life cycle. Indirect effects may influence the interactions between communities at different trophic levels and the availability of nutrients for primary producers. Elucidating the impacts on the full range of marine organisms, and in particular on higher trophic levels that rely on calcifiers for shelter and nutrition, will be complex. Nevertheless, in the coming decades it will be an extremely important focus area for marine research (Ní Longphuirt *et al.,* 2010).

A whole-ecosystem approach which includes greater research and monitoring of fish stocks, trophic interactions and impacts of acidification and climate change will improve the scientific basis for fisheries management. The adaptive ability of specific species and ecosystems, the fisheries industry, coastal communities and consumers to ocean acidification will dictate the economic costs of ocean acidification. The environmental status of all marine waters is threatened by ocean acidification. Through several international conventions, such as OSPAR (1992), and EC directives such as the Marine Strategy Framework Directive (2008), the European maritime states, have a legal obligation to protect the North-East Atlantic. A coherent network of Marine Protected Areas providing protection to vulnerable species and habitats from other pressures may improve resilience to climate change and ocean acidification.

With regard to fisheries, although our existing knowledge is in many respects incomplete it nevertheless provides an adequate basis for improved management of fisheries and of marine ecosystems and for adapting to climate change. In order to adapt to changing climate, future monitoring and research must be closely linked to responsive, flexible and reflexive management systems. This will require the design of monitoring strategies to detect critical changes in species and ecosystems that are particularly sensitive to changes in climate. On the policy side, it will be important to prepare in advance to deal with issues arising from changes in fish stock distribution or the appearance of new fishing opportunities. Access rights will be raised in international fora as the geographical distribution of stocks change. Decision rules need to be established as early as possible, preferably before changes have taken place to avoid the risk of the development of unregulated fisheries (Brander, 2010).

3.4.5 References

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3.5 Impacts of Climate Change on the Mediterranean Sea

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3.5.1 Introduction

The Mediterranean is the largest of the world's five Mediterranean-climate regions. The Mediterranean basin is ca. 3,680 km long with an average width of 700 km and is divided into the Western and Eastern basins, which are separated by the straits of Sicily (Figure 71). The Western basin (mean depth, ca. 1,600 m) consists of two deep basins: the Algero Provençal basin and the Tyrrhenian Sea. The Eastern Mediterranean includes the Ionian, Adriatic and Aegean Seas, and the Levantine basin.

The principal traits of this semi-enclosed 'miniature ocean' can be summarized as:

- Limited freshwater inputs;
- Microtidal regime;
- High oxygen concentrations;
- High deep-sea temperature (always above 12.8°C); and
- Oligotrophic conditions with low nutrient concentrations which typically decrease eastward.

The Mediterranean basin is characterised by a freshwater deficit of ca 0.9 m yr $^{-1}$ (Romanou *et al.*, 2010). The water exchange of this semi-enclosed sea is mediated by the Atlantic inflow of surface water (in the upper part of the Straits of Gibraltar; 300 m in depth), and the outflow of the deep, high-salinity, Mediterranean waters (in the deeper parts of the straits; Béthoux *et al.*, 2002). As a result of the eastward decreasing nutrient concentrations, the two basins are characterised by different primary productivities. In the Western basin, the primary production is about 350-450 mgC m^{-2} d^{-1} (Moutin and Raimbault, 2002), whereas in the Eastern Mediterranean the very low primary production (about 150 mgC m^{-2} d^{-1}; Turley *et al.*, 2000) together with the strong summer stratification of the water column and the tight microbial loop control, result in exceptionally low exports of primary organic matter to the sea bed (Turley *et al.*, 2000).

Changes in the world ocean affect the Mediterranean sooner than the world ocean itself and thus, gaining better knowledge of this ecosystem will enable the prediction of possible scenarios of the state of this basin, which will eventually lead to better management. The Mediterranean is a sensitive area, with a highly stressed ecosystem and having high species diversity.

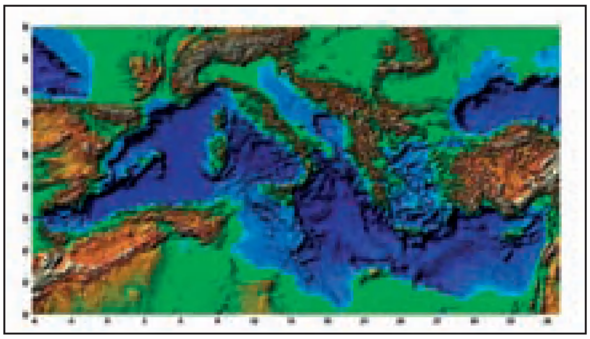

Figure 71. Bathymetry of the Mediterranean Sea

Although it occupies 0.82 % of the world's ocean surface and 0.32 % of its volume, the Mediterranean is a hot spot of biodiversity. This basin ranks amongst the best studied in terms of marine biodiversity. Species richness (ca 8500 species) accounts for 7.5 % of all described marine species (range 4-18 % according to the group considered): 67 % of Mediterranean species are found in the Western Basin, 38 % in the Adriatic Sea, 35 % in the Central part, 44 % in the Aegean Sea and 28 % in the Levantine Sea. This trend indicates a west-east impoverishment of species richness, reflecting climatic and trophic gradients. Mediterranean marine assemblages have a very limited species similarity with the Atlantic counterparts, and are typically characterised by smaller sizes.

The Mediterranean Sea is biologically diverse also because it is a warm sea at temperate latitudes, thus hosting both temperate and subtropical species, and has been further diversified by its complex geological history. In the last 5 million years the Mediterranean has formed ten distinct biogeographic regions, with probably no equals in the world (Bianchi & Morri 2000). As a result, the present marine biota of the Mediterranean is composed of species belonging to: (i) a temperate Atlantic-Mediterranean background; (ii) cosmopolitan/panoceanic species; (iii) endemic elements, comprising both paleoendemic (Tethyan origin) and neoendemic species (Pliocenic origin); (iv) subtropical Atlantic species (interglacial remnants); (v) boreal Atlantic species (ice-ages remnants, especially of the Würm glacial); (vi) Red Sea migrants (especially into the Levant Sea); (vii) eastern Atlantic migrants (especially into the Alboran

Sea) (Bianchi 1997). The shallow depth (on average ca 1450 m) and the relatively fast deep-water turnover (40-50 y vs >80 y in other oceanic systems), coupled with a high degree of endemism (about 25 % of Mediterranean species; Tortonese, 1985; Fredj *et al.*, 1992; Giaccone, 1999) induces a potential amplification of the impacts of climate change, which are expected to cause earlier changes in biodiversity in comparison with other seas. Any changes in biodiversity may affect ecosystem functioning, even in the case of invasions by a single species, and there are important consequences both for nature as well as society.

The expectation of a faster response to climate change of Mediterranean biodiversity makes this system a model for investigating biodiversity response to direct and indirect effects of temperature changes and other climate-related variables. Recent evidence undoubtedly points to large-scale warming of the Mediterranean basin (Bethoux *et al.*, 1990; Astraldi *et al.*, 1995; Bethoux & Gentili, 1996; Walther *et al.*, 2002) and there is increasing evidence that Mediterranean biodiversity is presently facing changes, which can be attributed to increasing seawater temperature (Francour *et al.*, 1994). However, the extreme richness of microclimates in the Mediterranean (ranging from climate conditions similar to those of the Northern Sea in the Adriatic to an almost tropical condition in the Eastern basin) makes any prediction at large spatial scales difficult and, indeed, most effects of climate change (or climate anomalies) on marine biodiversity have been so far identified only at regional scale.

The Mediterranean Sea is considered a hot spot for studying the impacts of global climate change at a regional scale. To this end, the EU Integrated Project SESAME has set out to study the Mediterranean and Black Seas, and the changes that are expected to affect these two ecosystems in the next 50 years. Based on this, recent research suggests that warming trends documented in historical data from the last 50 years correlate with some of the observed changes in the Mediterranean biota (Vichi *et al.*, 2009).

3.5.2 Western Mediterranean

In the Western Mediterranean, climate change is influencing the boundaries of biogeographic regions and thus the ranges of individual species and warm water marine species are extending their ranges and colonizing new regions where they were previously absent. The northward migration of conspicuous species of warmer affinities has been demonstrated in several regions (Bianchi & Morri, 1994; Francour *et al.*, 1994). The Ligurian Sea, one of the coldest areas of the Mediterranean Sea located in its northern part, displays a low number of subtropical species and a higher abundance of species of cold-temperate waters (Rossi, 1969). However, the warming of Ligurian Sea waters (Bethoux *et al.*, 1990; Sparnocchia *et al.*, 1994; Astraldi *et al.*, 1995) has favoured the penetration of warm-water species (e.g., *Thalassoma pavo*), which from 1985 onward established large and stable populations (Bianchi and Morri, 1993, 1994). However, the increasing number of tropical Atlantic species in the northern Mediterranean (Harmelin & d'Hont, 1993) can result from a combination of anthropogenic and climate changes. Recent studies identified the link between the large-scale climate changes of the North Atlantic (NAO) and the local climate variability of the North-western Mediterranean. During the 1980s, climate changes altered plankton assemblages and food webs, since high positive temperature anomalies favoured jellyfish outbreaks, which caused a strong decrease of copepod abundance (Molinero *et al.*, 2005). This study provides correlative evidence that climate change has important implications in the functioning of the Mediterranean marine ecosystems.

The largest mass-mortality event ever recorded in the Mediterranean Sea was observed in 1999 (Cerrano *et al.,* 2000; Perez *et al.,* 2000), when a summer positive thermal anomaly extended the thermocline down to a depth of 40 m (Romano *et al.,* 2000) and determined an extensive mortality of 28 epibenthic invertebrate species (Perez, *et al.* 2000). The area impacted by this climate anomaly extended from the French to the Italian coasts, and to a lower extent impacted also Corsica. Among benthic organisms, the most severely affected were sponges and gorgonians, such as Paramuricea clavata, Eunicella singularis, Lophogorgia ceratophyta, and Eunicella cavolini (Cerrano *et al.,* 2000; Perez *et al.,* 2000; Romano *et al.,* 2000; Garrabou *et al.,* 2001). Temperature anomalies, even of short duration, can therefore dramatically change Mediterranean faunal diversity. Once some species have been eradicated, other species, pre-adapted to the new conditions, can replace locally extinct species, thus hampering the ecosystem resilience to pre-impact conditions. Such a thermal anomaly impacted also the fauna inhabiting marine caves, since it determined the replacement of endemic species (mysids with cold and stenothermal characteristics) by others congeneric species with warmer affinities (Chevaldonne & Lejeusne, 2003). These events are associated with a high risk of species extinction and strongly support the view that Mediterranean marine biodiversity is already under threat because of warming of surface waters.

Finally, climate change in the Mediterranean is also favouring the frequency of epidemiological events, as most pathogens are temperature sensitive. Studies performed on the coral Oculina patagonica identified the *Vibrio shiloi* AK-1, as aetiological agent involved in the Mediterranean mass mortalities (Kushmaro *et al.,* 1998). Mass mortalities of the gorgonian *Paramunicea clavata,* scleractinian corals, zoanthids, and sponges observed in 1999 in the Ligurian Sea were indeed promoted by a temperature shift, in conjunction with the growth of opportunistic pathogens (including some fungi and protozoans; Cerrano *et al.,* 2000). Also viral life strategies could be promoted by temperature rise. Although data available in the Mediterranean are limited, the presence of morbilliviruses in monk seals has been recently identified (van de Bildt *et al.,* 1999), in this case with a major potential impact on the survival of this extremely rare and endangered species.

3.5.2.1 Adriatic Sea

During the last 30 years, in the Adriatic Sea the ichthyofauna displayed an increase of thermophilic species (Dulcic & Grbec, 2000). Fish and zooplankton species that were previously rare are becoming abundant, and others are new records for this area (Dulcic & Grbec 2000; Kamburska *et al*., in press). All these observations can be related to climate changes, which intensified after 1988 and are causing the warming of sea surface temperatures and variations in salinity of the Adriatic Sea (Russo *et al*., 2002). These changes had an impact also on other water properties (increases in storm frequency and rainfall, and changes in wind speed and direction, altered turbidity), which in turn affect the whole Adriatic Sea ecosystem (Russo *et al*., 2002). A number of phenomena such as jellyfish (*Pelagia noctiluca*) and thaliacean blooms (Boero, 1994, 1996), harmful algal blooms (by several species of Dinoflagellates) and coloured tides, which are triggered by these meteoceanographic changes, as suggested by the remarkable intensification recorded during the last 20 years (Boero, 2001). Also the frequency of appearance of mucilages (associated with a malfunctioning of the microbial loop) has doubled in the last 25 years, concomitantly with a significant increase of SST (ca 1.5°C in the northern sector; Russo *et al*., 2002). Increased surface temperatures and altered circulation and precipitation regimes have also been invoked to explain the increased frequency of bottom water hypoxia or anoxia in coastal areas of the northern Adriatic.

These phenomena, often associated with mass mortalities of fish and benthic fauna, alter food webs and might have important cascade effects on biodiversity. The Adriatic Sea, furthermore, can undergo dramatic change in the lower part of its temperature ranges. In winter 2001, the Adriatic Sea experienced a period of abnormally low surface temperatures (from 9°C to freezing) that led to mass mortalities of sardines (*Sardinella aurita*) (Guidetti *et al*., 2002), with consequent alteration of the food webs. The Adriatic basin is also the site for deep-water formation, as a result of the bora winds associated with decreased temperatures, but recent studies reported the lack of open-sea convection related with the increased temperatures (and mild winter climatic conditions). This phenomenon can alter deep-water and strongly reduce spring phytoplakyon blooms and export production (Gacic *et al*., 2002).

3.5.3 Eastern Mediterranean

The rise of sea water temperatures in the Mediterranean Sea, and particularly in the Eastern Basin, may be partly responsible for changes in the range of some species by creating maritime corridors linking the region to other seas. The entrance of alien species has determined a dislocation of the niche of autochthonous species and possibly cascade effects on the food webs (CIESM, 2002).

Most of the alien species in the Mediterranean are thermophiles originating in the tropical Indo-Pacific (Lessepsian migrations; Galil, 1993). The list of exotic animals and plants that invaded the Mediterranean, and particularly the Eastern basin, is getting longer every day (Zibrowius, 1983, 1991; Boudouresque & Ribera, 1994; Verlaque, 1994; Ribera & Boudouresque, 1995).

Despite the overall tendency towards a sea surface warming, the Eastern Mediterranean has also been characterised by an event of temperature decrease occurring at regional scale. The so-called ‘transient’ (a climatic anomaly) caused a drop in temperature of about 0.4°C and caused a drastic decrease in faunal abundance and a significant change in faunal diversity (Danovaro *et al.,* 2001). Between 1992 and 1994 a temperature shift of 0.3°C resulted in a reduction of ca 50 % of nematode diversity (and possibly of the diversity of other groups). Moreover, the extent of the impact on biodiversity was directly related with the extent of the temperature shift (Figure 72). Temperature decrease also caused a decrease of the functional diversity and species evenness (Figure 73; Danovaro *et al.,* 2004). Temperature drop increased the similarity between the species listing of the warm deep-Eastern Mediterranean and the colder deep-Atlantic nematode fauna. After 1994, when the temperature gradually recovered to pre-transient values, the biodiversity started to reverse to previous conditions. However, this process was not complete, as the species list in 1998 was still differed from the community composition observed in 1989 (Danovaro *et al.,* 2004).

These results indicate that: (i) the Mediterranean fauna is highly vulnerable to climate change; (ii) both structural and functional biodiversity of continental margins are significantly affected by very small temperature changes; and (iii) the impact of climate change on marine biodiversity might be non reversible. Moreover, these events indicate that not only coastal systems but also continental-margin ecosystems may experience abrupt climate-driven temperature shifts, which reflect changes in the prevailing surface climate conditions occurring on a regional scale (Bethoux *et al.,* 1990). Since there are close interactions between deep and coastal systems, the vulnerability of deep-sea ecosystems to climatic changes might have important implications also on the biodiversity and functioning of continental shelves.

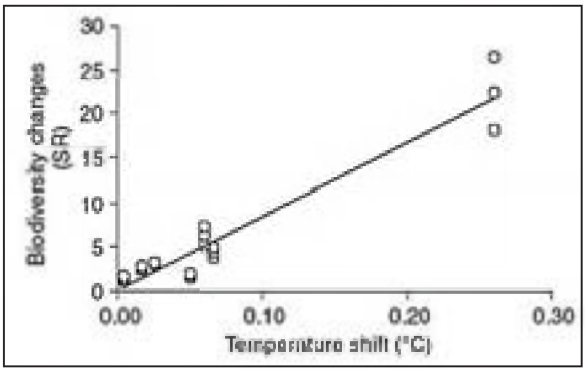

Figure 72. Relationships between temperature changes and species richness (nematodes) in the continental margins of the Eastern Mediterranean.

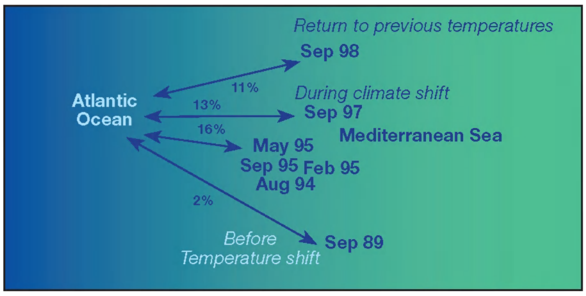

Figure 73. Multi-Dimensional Scaling analysis on changes in nematode biodiversity related with the climatic shift (transient) in the continental margins of the Eastern Mediterranean. Reported is the analysis of similarity (SIMPER) providing information on the percentage of common species between the Atlantic Ocean and the Mediterranean during climate change (water cooling) based on samples collected from September 1989 (Before T shift) to September 1998 (return to pre-change T values) (stress=0.01).

3.5.4 Plankton and Microbe Abundance: Their Role in Climate Change

A study of the composition and viability of pelagic communities of the Mediterranean Sea across the different sub-basins and straits, in relation to nutrient regimes and hydrological conditions (Lasternas *et al.*, 2010), provides evidence for clear patterns of change in the abundance and cell viability of planktonic organisms across the Mediterranean basin. More specifically, the results identify, in particular, water temperature and phosphate concentrations as key determinants of the viability of planktonic organisms in the Mediterranean, thereby supporting existing evidence that both phytoplankton and bacteria tend to be P-limited in the Mediterranean Sea (Krom *et al.*, 1991; Zweifel *et al.*, 1993; Thingstad & Rassoulzadegan, 1995; Pitta *et al.*, 2005). It became clear that the relationships between temperature and phosphate concentrations and the cell viability of various plankton components provide a basis for testing hypotheses on how climate warming may affect planktonic communities across the Mediterranean Sea.

Similarly, the evaluation of a 45-year data set of primary production (PP), a 30-year data set of phytoplankton biomass, and a 51-year data set of species composition from the Middle Adriatic (Kaštela Bay) showed an increase of phytoplankton biomass and abundance in the period from the mid-1980s to the mid-1990s. Overall, the phytoplankton community in the mid-Adriatic (Kaštela Bay) changed with time in terms of biomass as well as in community structure (Gladan *et al.*, 2009) Furthermore, evaluation of the data in relation to North Atlantic Oscillation (NAO) indices revealed that large scale atmospheric phenomena affect changes in the phytoplankton community in Kaštela Bay. It is also of interest to note that the abundances of the main phytoplankton groups showed significant relationships with sea surface temperature (SST). Diatoms showed a negative relation, while dinoflagellates were positively related to SST. The increase in dinoflagellate contribution to the phytoplankton community occurred during the period of a warm temperature event that has been well documented in the northern Atlantic. The relationship between chlorophyll-a and primary production with the NAO index reflects the NAO influence on local weather, which, through nutrient availability, affects the winter/spring bloom.

Climate change was also studied through the potential spreading of marine mucilage and microbial pathogens in the Mediterranean, as surface water warming can favour the coalescence of marine snow into marine mucilage. As marine mucilage characterizes aquatic systems under altered environmental conditions, its study is, of great value when studying climate change. EU FP SESAME project's scientists investigated, by means of molecular techniques, viruses and prokaryotes within the mucilage and in surrounding seawater to examine the potential of mucilage to host new microbial diversity and/or spread marine diseases. It was concluded by Danovaro *et al*. (2009) that the spreading of mucilage in the Mediterranean Sea is linked to climate-driven sea surface warming, as the mucilage can act as a controlling factor of microbial diversity across wide oceanic regions.

Changing climate can have direct and indirect consequences on marine viruses (virus function, viral assemblages and virus–host interactions), including cascading effects on biogeochemical cycles, food webs and the metabolic balance of the ocean. In turn, marine viruses influence directly and indirectly biogeochemical cycles, carbon sequestration capacity of the oceans and the gas exchange between the ocean surface and the atmosphere. We cannot yet predict whether the viruses will exacerbate or attenuate the impact of climate changes on marine ecosystems, but we have evidence that marine viruses interact actively with the present climate change and are a key biotic component that is able to influence the oceans' feedback on climate change (Danovaro *et al*., 2011).

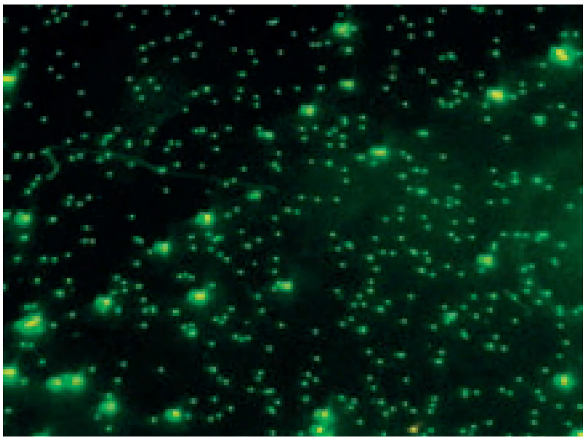

Figure 74. Epifluorescence micrograph of prokaryotes and viruses in a seawater sample stained with a fluorescent dye, SYBR Green I. Smallest dots are viruses and larger ones are prokaryotes (bacteria or archaea). With about 1 billion bacterial cells and 10 billion viral particles per liter of seawater, viruses are by far the most common biological entities in the marine environment. It is not yet possible to predict whether viruses will exacerbate or attenuate the impact of climate changes on marine ecosystems, but according to Danovaro *et al.* (2011) there is evidence that marine viruses interact actively with the present climate change and are a key biotic component that is able to influence the oceans' feedback on climate change. (©Ruth-Ann Sandaa, University of Bergen)

3.5.5 Climate Change and Non-Native Species

Recent large-scale studies have also focused on the invasion of non-native species into the Mediterranean ecosystem and how these affect ecosystem balance, as well as relating them to observed warming of the eastern Mediterranean Sea. The collection and analysis of long-term data of 149 warm water non-native species since 1924 indicates that the introduction of warm water and tropical non-native species has been exacerbated by the observed warming of the eastern Mediterranean Sea. This occurrence has accelerated after an abrupt shift in both regional and global temperatures which was detected around 1998, leading to a 150 % increase in the annual mean rate of species entry after this date. Furthermore, the abrupt temperature rise which occurred since the end of the 1990s, has modified the potential thermal habitat available for warm-water species, thus facilitating their settlement at an unexpectedly rapid rate.

The speed at which non-native species spread, as well as their response to global warming is apparently much faster than temperature increase itself, thus presenting an important warning for the future of Mediterranean Sea biodiversity. In addition to sea warming, other factors that enable and enhance biological invasions include salinity increase and oceanographic forcing (Raitsos *et al.,* 2010).

Along those lines, lists of non-native species have been created and updated since 2006, with the most recent one by Zenetos *et al.* (2010). The new findings showed that species of tropical/subtropical affinity, favoured by climate warming, are introduced and colonize the Mediterranean at a fast rate, while cold water species are settling at a lower rate. Thermophilic species, such as Indo-Pacific, Indian Ocean, Red Sea, Tropical Atlantic, Tropical Pacific, and circum(sub)tropical ones, have been found to account for 88 % of the introduced species in the eastern part of the Mediterranean, 73 % in the Central Mediterranean, and 59 % in the Western part. Finally, these species accounted for 56 % of introduced species in the Adriatic. Cold water species, i.e. circumboreal, North Atlantic, and North Pacific, make up a small percentage of the introduced species, ranging between 4 % and 22 % and being more numerous in the Adriatic than in the Eastern Mediterranean.

The net outcome is a jump in species richness. More specifically, it is clear that the introduced species have increased the biodiversity of the Mediterranean Sea, as an entity, by 6 % excluding phytoplankton and microzooplankton. The figure is even higher reaching 28 %

in fish and 9 % on average for the studied taxa. While species richness is increasing at whole basin scale, leading to a higher γ diversity, cases of local replacement have been reported (Galil, 2007), which may imply an alteration of γ diversity.

A total of 955 non-native species are known in the Mediterranean, the vast majority of them being introduced in the eastern Mediterranean (718), less in the western (328) and central (267) and east in the Adriatic (171). Of these, 134 are classified as invasive or potentially invasive; 108 in the east, 75 in the central part, 53 in the Adriatic and 64 in the Western Mediterranean.

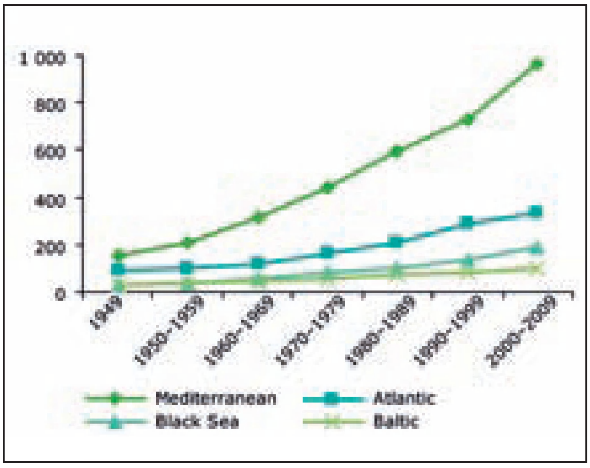

Figure 75. Number of marine, coastal and estuarine non-indigenous species in the European sea basins; the highest numbers are observed in the Mediterraean Sea (©EEA)

Other studies, conducted by Vichi *et al*. (2009), attempted to produce model projections of changes in the Mediterranean oceanography in the 21st century (according to a selected climate scenario) and investigated the impacts on marine ecosystems. From this research, it emerged that there is an introduction of non-indigenous species of tropical origin which are currently showing a wider basin-scale distribution (tropicalization), whereas indigenous species with warm-water affinity are expanding their habitat ranges northward, sometimes at the expense of the residential cold-water species (meridionalization). Sea water temperature is, thus, one of the major drivers of tropicalization and meridionalization of the Mediterranean Sea biota. The projections of future climate conditions, performed with the aid of coupled climate models and according to scenarios of socio-economic development, is a possible tool to investigate the possible future changes in the region.

The OGCM general circulation model was used to simulate the ocean conditions during the 20th century and to obtain future projections driven by the climate conditions forced with the A1B and the IPCC SRES scenario of greenhouse gas evolution. The projected changes in SST during wintertime from the results of the SXG-A1B simulation indicate a northward displacement of the isotherms, with a substitution of the 15°C isotherm by the 16°C isotherm. The 14°C threshold for Mediterranean bioconstructors is moving northward, to reach the southern French coast, where fossil records of *A. calycularis* from the Pleistocene have been found (Figure 76C). The middle Adriatic is projected to permanently lie above this threshold, favouring the establishment of warm-water species as the ones recorded on the Croatian coast and related to the warm periods of the late 90s. Recent findings indicate that *A. calycularis* is now found in the Adriatic Sea and, more generally, northward of the climatologic 14°C divide that is considered a threshold for constructional biocalcifiers.

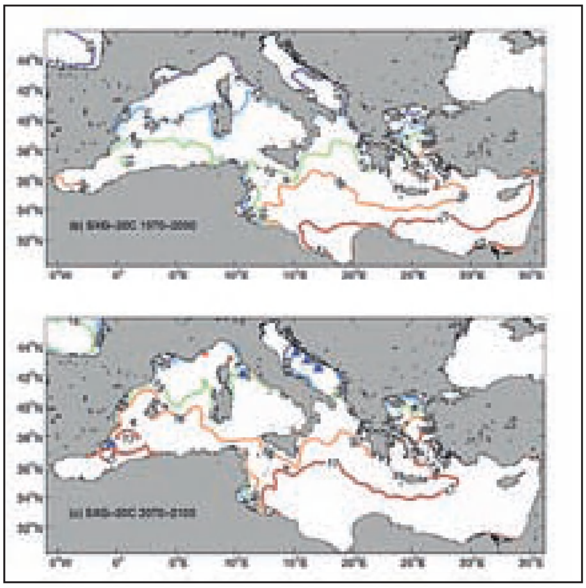

Figure 76. (A) Climatological surface temperature distribution in February from the ERA40 model simulation (1970-2001) and distributional ranges of A. calycularis (open circles, from Bianchi, 2007; see references therein). (B) February SST distribution in the present climate SXG-20C simulation. (C) Projected SST distribution at the end of the 21st century (2070-2100) from the SXG-A1B simulation. (blue triangles = recent records, Grubelic *et al.*, 2004; red + = fossil records, Zibrowius, 1995).

3.5.6 Carbon and Organic Matter Dynamics

Preliminary results from the Mediterranean Sea have shown that it has become significantly more productive and more active regarding carbon sequestration over the last 30 years or more. Regarding pCO_2, for example, the first results within SESAME indicated that values were higher in fall than in spring, while all areas studied acted as sinks for carbon in spring and sources in the fall (SESAME Activity Report 2009).

Dissolved organic carbon (DOC) represents the largest reservoir of reactive carbon on Earth and it plays a key role in the microbial food web, because it is the main source of food for heterotrophic bacteria. Consequently, its study can provide new insights into the marine carbon cycle and the role of the Mediterranean Sea in carbon sequestration. DOM concentrations in oceanic waters are mainly the result of biological activity, while its distribution is mainly driven by the circulation of water masses. Circulation changes, induced by climate change, may significantly affect DOM distribution.

An extensive study of the DOC dynamics was carried out by an in-depth investigation of the DOC vertical profiles collected in different areas of the Mediterranean Sea between 2001 and 2008. These datasets highlighted a high variability and dynamic nature of the Mediterranean DOC pool, both in the surface and deep layers.

The DOC distribution in the bottom waters clearly shows the importance of DOC in C sequestration at depth in the Mediterranean Sea. In fact, a marked increase of DOC (>60 µM) was observed in the Gulf of Lion, in the southern Adriatic Sea and in the Ionian Sea, corresponding to a minimum of AOU (<47 µM), that indicates the occurrence of deep water recently ventilated. All these regions are influenced by deep water formation. A particularly strong event of deep water formation was observed in the Western Mediterranean Sea in the winter of 2005, when very high DOC concentrations (55-76 µM) were detected in the bottom waters. An estimation of the amount of DOC exported at depth during that winter was calculated. It ranged between 0.29 and 1.15·106 g $C \cdot s^{-1}$ (0.76-3.02 Tg C $month^{-1}$). Assuming that the lowest DOC concentration observed in Mediterranean waters (34 µM) represents the refractory fraction, all the DOC exported at depth should be in the semi-labile form. This is a very large amount, which consequently highlights the importance of DOC in the global carbon cycle, both in terms of carbon sequestration and energy input for deep water ecosystems (Santinelli *et al.,* 2010).

As rivers are important sources of freshwater and nutrients for the Mediterranean, a reconstruction of the spatial and temporal variability of these inputs since the early 1960s was made by Ludwig *et al.* (2009), based on a review of available data on water discharge, nutrient concentrations and climatic parameters. It became evident that river discharges underwent marked changes during the last decades, both in quantity and composition, potentially identifying them as major drivers of the geochemical, physical and biological functioning of the marine system in this part of the world ocean. Over the 1960–2000 period, river freshwater discharge to the Mediterranean Sea decreased, while that to the Black Sea remained more or less constant. This reduction (between 1960 and 2000) mainly reflects recent climate change, and dam construction which may have reduced discharge even further. This reduction in the Mediterranean Sea is mainly derived from the large-scale evolution of precipitation and temperature and thus reflects the potential impact of climate change on river freshwater discharge. A similar decrease can also be expected for the fluxes of dissolved silica (Si), strongly controlled by water discharge and potentially reduced by river damming as well. This contrasts with the fluxes of nitrogen (N) and phosphorus (P) in Mediterranean and Black Sea rivers, which were strongly enhanced by anthropogenic sources.

Overall, the future scenarios on river discharges of water and nutrients to the Mediterranean pinpoint to the decreases in water discharge, already visible during the last 50 years, which are predicted to hold on in the future. In 2050, the Mediterranean could lose more than 1/4 of its freshwater inputs compared to 1960.

The predicted nutrient budgets for the Mediterranean remain more or less in the envelope of the observed variability during the last 50 years. Regionally, however, the distribution of the nutrient inputs may change considerably. In the North, the inventories generally tend to decrease. But in the South and the East, where populations will grow rapidly, the inventories may strongly increase.

3.5.7 Socio-Economic Impacts of Climate Change in the Mediterranean

Regarding policy issues, economic implications of managing coastal and marine environments have been discussed by assessing the results of different valuation studies implemented in the area. Lessons and policy recommendations from existing literature are inferred to guide marine resources management decisions.

The study of Remoundou *et al.* (2009) provided a summary of the major literature on valuing marine and coastal ecosystems services, and classified valuation studies implemented in the Mediterranean and Black Sea by specific goods and services. One of the main findings of this study is that there are extremely few published studies within the Mediterranean and Black Sea region, which highlights the potential for future research on coastal and marine ecosystems ability to sustain different goods and services, as a result of climate change and anthropogenic drivers in the area. Results revealed that there are substantial positive economic values attached to marketed and non-marketed services provided by marine and coastal ecosystems that justify their sustainable use and management. Although scarce, however, existing literature underlines the potential of valuation techniques as tools that can effectively intersect with, and facilitate, the formulation of stronger resource management policies that account more fully for the total economic value of the goods and services generated by marine and coastal ecosystems. Finally, the monetary magnitude of use and non-use values related to coastal and marine ecosystems signals the potential for governmental intervention and policy formulation.

Figure 77. Newly landed fish at a local port in the Costa Brava, Spain (©Maica/istock)

3.5.8 Research Gaps, Uncertainties and Relevance to EU Funding

The Mediterranean Sea is an extremely complex and diversified region, which contains ten different biogeographic sub-regions. Climate change is expected to have a major impact on the biodiversity and ecosystem functioning of this region, with special reference to the northern and colder Mediterranean sectors and on specific habitats, such as marine caves and the deep-sea floor.

Important research topics include, but are not limited to:

- Examine how climate change will affect structural and functional biodiversity of the Mediterranean Sea, how the structure (e.g. species composition, food web length, and size distribution) and functioning (e.g. biomass, production and decomposition processes, and predator–prey interactions) of Mediterranean marine ecosystems will change;
- Improve the understanding of existing climate change features, using the north Adriatic Sea and the Ligurian Sea / Gulf of Lion as a reference for the impact of rising temperatures on the cold-water Mediterranean regions;
- Improve the understanding of the current changes occurring in the deep-sea Mediterranean and on the impact of such changes;
- Implement the number of sites investigated for the L-TER (long-term ecological monitoring), including sites and observatories in the deep sea;
- Identify species and areas for environmental conservation in order to limit the impact of climate change on species with cold-water affinity;
- Improve the understanding on the impact of current climate change on Mediterranean biodiversity and ecosystem services;
- Improve the understanding of the impact of climate change on marine microbes (including viruses) and of the consequences on biogeochemical cycles;
- Improve the understand the synergistic effect of direct anthropogenic impact and climate change on Mediterranean habitats and functions.

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3.6 Impacts of Climate Change on the Black Sea

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3.6.1 Introduction

The Black Sea is a well-known example of the highly stressed and degraded marine ecosystems. In the 1970s and 1980s, it has been impacted synergistically by the effects of over-exploitation of fish resources, intense eutrophication, invasions by opportunistic species (BSC-SoE, 2008). These anthropogenic pressures have introduced major transformations on the structure and functioning of the ecosystem (Daskalov, 2003; Bilio and Niermann, 2004; Daskalov *et al.,* 2007; Oguz & Gilbert, 2007; Oguz *et al*., 2008; Oguz and Velikova, 2010). They have also been accompanied with major changes in the hydrometeorological properties in relation to changes in large-scale atmospheric systems over the Eurasia (Oguz *et al*., 2006). The climate change and variability have therefore played a major role on the Black Sea ecological changes in spite of difficulty of substantiating their relative contributions with respect to the other drivers. It is also not clear how much of the changes in the ecosystem properties are introduced by the natural mode of climate variability and by the antropogenic climate changes due to fossil-fuel combustion, land-use including agriculture and deforestation. The present section provides an overview of the changes in the physical (i.e. abiotic) and biogeochemical (i.e. biotic) properties of the Black Sea, and their possible link to the large scale atmospheric systems of the Northern Hemisphere. It further describes likely future climate change projections, socio-economic consequences of climate change, and research gaps and uncertainties, and relevance to EU funding. The data presented below are taken from BSC-SoE (2008).

3.6.2 Abiotic Changes

3.6.2.1 Temperature

The Black Sea winter-mean sea surface temperature anomaly (blue curve in Figure 78) indicate (i) a cooling phase from 1880 to 1910 of about 0.7°C; (ii) an approximately 1.0°C warming trend during 1910-1970 modulated by sub-decadal scale fluctuations; (iii) roughly 1.5°C cooling during the next 20 years (up to 1993); and (iv) an equally strong warming afterwards during 1994-2002. The latter warming trend brought the temperature back to its level at the beginning of 1970s, indicating that the Black Sea did not build up a net warming after the 1970s contrary to the North-eastern Atlantic and the North Sea. The winter-mean SST correlates well with the annual-mean SST (red curve in Figure 78) and the May-November mean temperature of the Cold Intermediate Layer below the seasonal thermocline (green curve Figure 78) that therefore suggests persistence of the winter cooling-warming signatures within the entire upper layer above the permanent pycnocline (i.e. within ~100 m depth) and during the entire year. The Black Sea SST is therefore characterized by a multi-decadal strong cooling-warming cycle with almost 2.0°C temperature changes after 1970 with respect to a weak but continuous global warming trend with ~0.4°C temperature rise (black curve in Figure 78). The warming trend observed in the winter SST during 1910-1970 is, however, consistent with the global one except its more pronounced fluctuations.

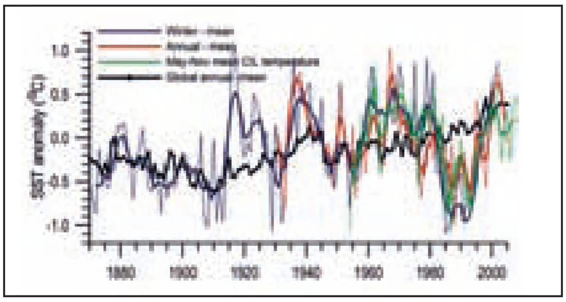

Figure 78. Time series of the basin-averaged winter and annual mean sea surface temperature anomalies, the May-November mean temperature anomaly of the Cold Intermediate Layer (CIL) located below the seasonal thermocline for the Black Sea, and the annual mean global sea surface temperature anomaly. The thin lines show the original data and the thick lines are the smoothed curves by means of five point moving averaging. The CIL is customarily defined as a layer with temperatures less than 8°C below the mixed layer and typically covers the lower part of euphotic zone. Note that the axis for the NAO index on the right is inverted.

In addition to strong interannual changes, considerable regional variability is evident by about 3°C differences between winter temperatures of the colder interior basin and the relatively warm peripheral zone and/or between the northwest and southeast sectors (Figure 79). In general, regional meteorological conditions in the eastern part favour milder winters and warmer winter temperatures in the surface mixed layer. The western coastal waters that receive the freshwater discharge from Danube, Dniepr and Dniestr rivers and are subject to more frequent and stronger cold arctic air outbreaks, correspond to the coldest part of the Black Sea (Figure 79). Thus, the southeastern part might often be roughly twice as warm than the northwestern part for both cold winter (plot in Figure 79 above) and warm winter (plot in Figure 79 below) climatological years.

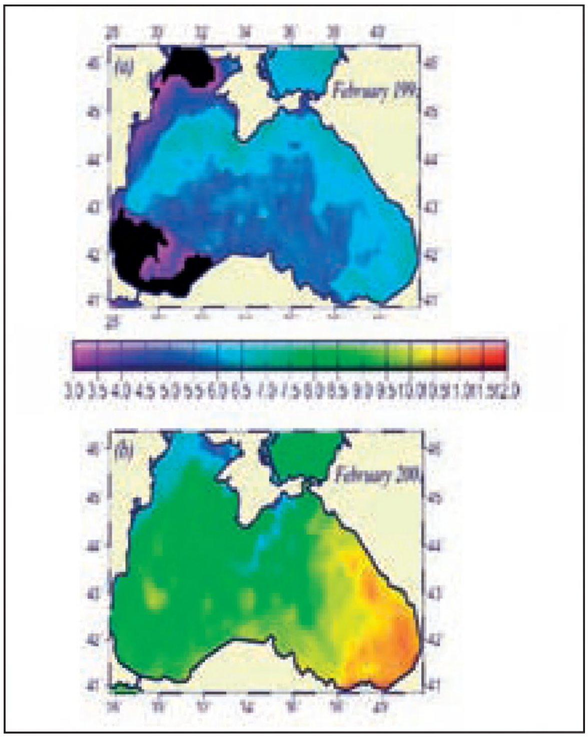

Figure 79. The mean SST distribution in February for 1993 and 2001 corresponding to one of the coldest and warmest cases in the Black Sea, respectively, during the 20th century. The SST data are obtained from 9 km monthly-mean, gridded NOASS/NASA AVHRR Oceans Pathfinder data set (From Oguz *et al.*, 2003).

Figure 80 compares the annual mean Black Sea SST with those of the Eastern and Western Mediterranean Seas. The SST in all areas undergoes to a rapid cooling from the mid-1960s to the beginning of the 1980s, after which the Western Mediterranean SST switches to a warming mode whereas the Black Sea continues to cool until 1993 and then switches to the warming mode. The Eastern Mediterranean SST represents a weak warming in the 1980s followed by stronger warming in the 1990s. A common characteristic of all the three time series is the reduction of temperature during 1992-1993 that is also observed in the global SST time series (Figure 80). This reduction is evidently related to the global cooling induced by the eruption of Mount Pinatubo in the Philippines during June 1991 (Soden *et al.* 2002). As documented by satellite measurements, peak global cooling of ~0.5°C in the lower troposphere was attained nearly 18 months after the eruption that then gradually approached to pre-Pinatubo levels at 1995.

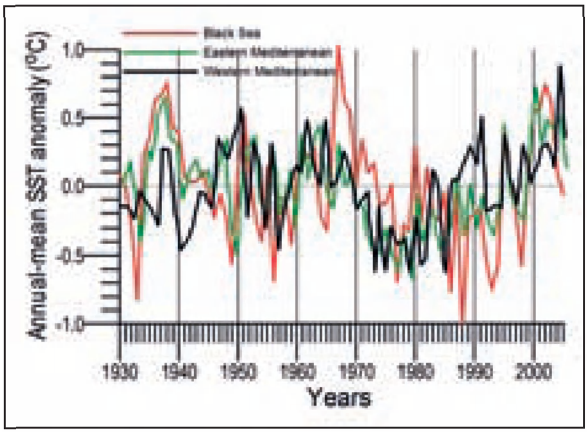

Figure 80. Time series of the annual mean sea surface temperature anomaly for the Eastern and Western Mediterranean and Black Seas

3.6.2.2 Sea-level

Based on examination of 12 long-term (1923–1999) tide gauge records around the Black Sea, the sea-level rise occurs in 2.0 - 4.0 mm yr^{-1} range over the last 60 years (Mikhailov and Mikhailova, 2008). The satellite altimeter data, on the other hand, reveal a higher rate of rise of about 7.5 mm yr^{-1} during 1993-2007. The mean rise for Tuapse (northeast coast) of 2.5 mm yr^{-1}, being comparable with the basin average conditions, is shown in Figure 81. This is slightly higher than the global average of 1.8 mm yr^{-1} from 1961 to 2003 (IPCC, 2007), 1.7 mm yr^{-1} of the Atlantic Ocean and 1.1-1.3 mm yr^{-1} of the Mediterranean. We also note a relatively minor contribution of the thermosteric effect (< 5 cm) to the overall sea-level rise (Figure 81). In fact, the sea-level due to the thermosteric effect decreased during 1970-1993 in response to excessive cooling of the sea, whereas actual sea-level has been rising. On the other hand, the thermosteric effect explains much of the observed global sea-level rise in the second half of the 20th century (Antonov *et al.* 2002).

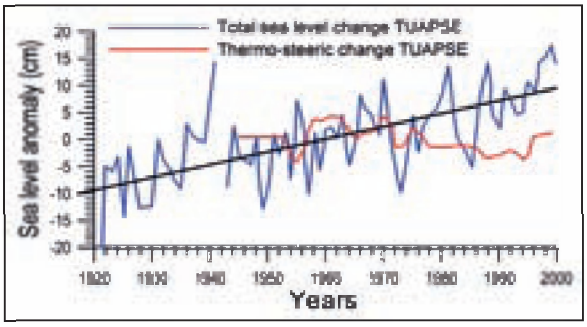

Figure 81. Sea-level anomaly changes around the mean (blue curve) and the thermosteric contribution (red curve) at Tuapse located along the northeastern coast of the Black Sea

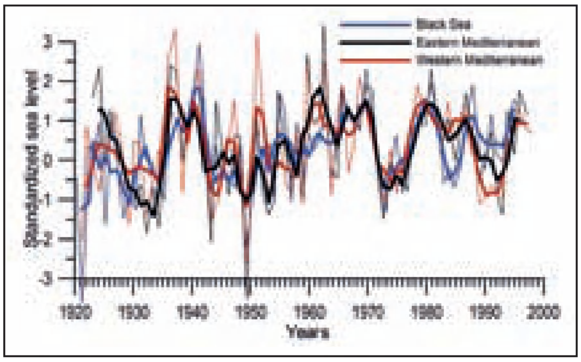

Figure 82. Detrended and standardized annual-mean sea-level time series for the Black Sea, Eastern and Western Mediterranean Seas. (Data are from Tsimplis & Josey, 2001)

Furthermore, subdecadal-to-decadal fluctuations of the detrended and standardized annual-mean sea-level time series for the Black Sea agree fairly well with those of the Eastern and Western Mediterranean Seas although the Black Sea and the Mediterranean Sea have an opposite hydrological balance (Figure 83).

3.6.2.3 Net Fresh Water Input

Temporal changes of the net fresh water input into the Black Sea (river inflow plus precipitation minus evaporation) indicate a net long-term positive trend consistent with the sea-level changes (Figure 83). The positive trend is contributed by increasing river discharge and precipitation and decreasing evaporation (Ilyin, 2010). Subdecadal-to-decadal changes in the net fresh water input also agree well with the mean detrended sea-level anomaly (Figure 83). Periods with low fresh water input generally correspond to those of relatively low sea-level that also coincides with relatively low sea surface temperature (Figure 78).

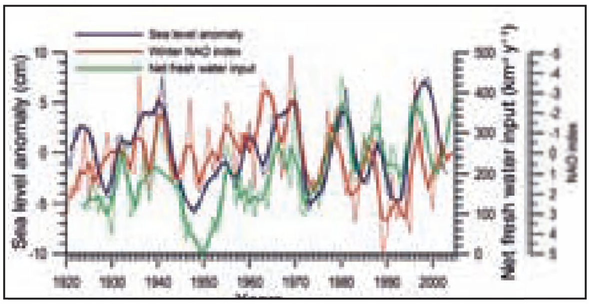

Figure 83. Time series of the detrended annual mean sea-level anomaly (blue), net fresh water input into the Black Sea defined as a the sum of river inflow and precipitation minus evaporation (green), and the winter mean North Atlantic Oscillation index (red). The thin lines show the original data and the thick lines are the smoothed curves using 3 point moving averaging. Note the inverted scale of NAO index.

3.6.3 Biogeochemical Impacts and Effects on Biodiversity

Figure 84 displays variations of long-term annual-mean oxygen concentration for the layer between σ_t ~14.45 and 14.6 kg m^{-3} density surfaces, corresponding roughly to the base of the euphotic zone, in the northeastern basin. Oxygen concentrations increase from 170 μM in the early 1980s to ~300 μM in the early 1990s, then decrease to 240 μM for another 10 years up to 2002, and slight increase again afterwards. These changes are inversely related with the subsurface summer-autumn CIL temperature changes. Relatively high subsurface oxygen concentrations observed during cold years should be associated with higher rates of ventilation of the euphotic zone and thus accumulation of more oxygen in the upper layer water column.

Cold years also characterize relatively higher phytoplankton biomass (Figure 84). Normally, years with high phytoplankton production are expected to have low oxygen concentrations due to more intense oxygen consumption associated with more intense remineralisation process. This is however not the case in Figure 84 and the positive correlation between oxygen concentration and phytoplankton biomass may suggest that the rate of oxygen production during cold years is apparently a more dominant process than its consumption due to more enhanced plankton production.

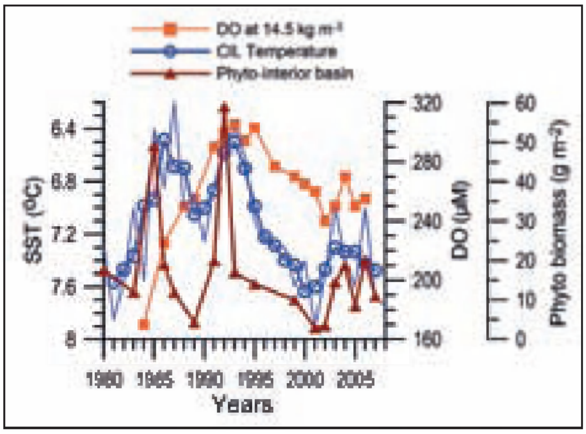

Figure 84. Changes in the average dissolved oxygen concentration within the density layer of σt ~14.45 and 14.6 kg m^{-3} density surfaces (roughly corresponding to the base of euphotic zone) in the region off the eastern coast (Yakushev *et al.*, 2005), and the summer- autumn mean CIL temperature (Belikopitov, 2005) and phytoplankton biomass (g m^{-2}) (Mikaelyan, 2005) within the euphotic zone of the interior basin.

Bacillariophyceae abundance (i.e. mostly diatoms) in western coastal waters also closely follows temperature variations. It persists with much higher abundance in relatively cold years, as clearly displayed by a linear rising trend from 1970 to 1993 in Figure 85. On the other hand, the abundance tends to decrease during the intense warming period after 1993. A similar decrease is also noted during the warming phase before 1970.

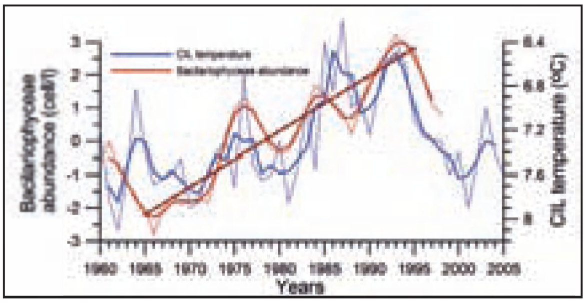

Figure 85. Time series of standardized bacilariophyceae abundance along the Bulgarian coastal waters (after Moncheva, 2005) and CIL temperature. The dash line shows the linear trend of bacilariophyceae abundance during 1965-1995 period.

Mesozooplankton biomass fluctuations of the central-eastern Black Sea are also in phase with those of temperature (Figure 86). The biomass tends to increase (decrease) in warm (cold) years.

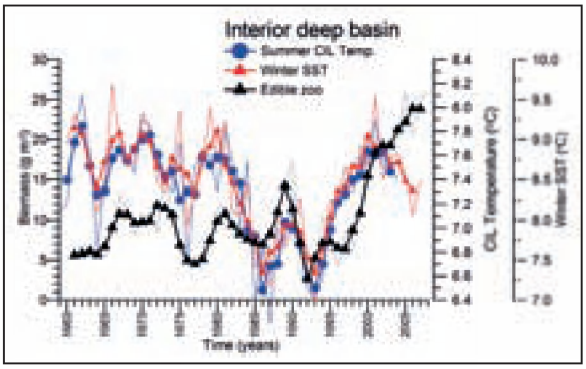

Figure 86. Time series of the annual-mean edible zooplankton biomass in the northeastern basin (g m^{-2}), and the mean CIL temperature (°C) (blue dots; after Belikopitov, 2005) averaged over all stations within interior basin and mean winter (December-March) sea surface temperature (SST) as an average of Hadley2, NCEP-Reynolds and Pathfinder5 data sets.

According to measurements along the Bulgarian coast, a boreal cold-water organism *Noctiluca scintillans* maintained a more favourable reproduction capability during cooler late-spring (May–June) temperatures following more severe winters (Figure 87). *Noctiluca* biomass therefore increased an order of magnitude during the 1970s cooling period and then declined gradually during the subsequent warming phase of the 1990s. But factors like species food competition and prey-predator interactions should also control the biomass changes in the 1980s and 1990s.

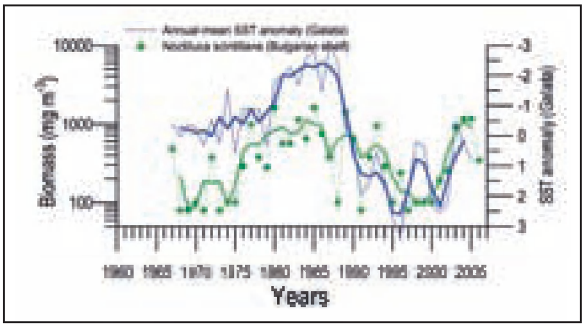

Figure 87. Time series of Noctiluca scintillans biomass in Bulgarian shelf and the annual-mean SST variations at the coastal station Galata.

A similar link exits between summer (August) surface temperature and *Mnemiopsis* abundance in the eastern Black Sea during August in the 1989-2003 period (Figure 88). A positive correlation between warm temperatures (26-27°C) and high abundances (> 2,000 ind/m^2) is clearly indicated during 1989-1991 and 2000-2001. Similarly, the cold periods (~24°C) of 1992-1993 and 2003-2004 are characterized by an order of magnitude lower abundances (~200 ind/m^2).

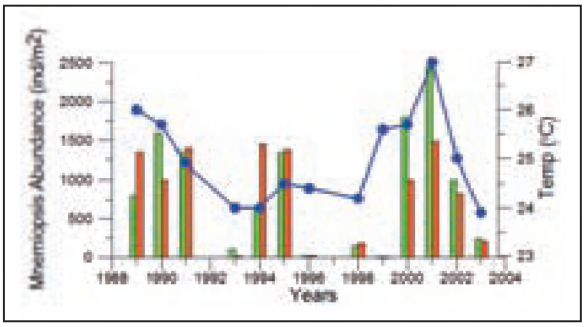

Figure 88. Time series of Mnemiopsis abundance in the eastern Black Sea offshore waters (green bars) and inshore waters (red bars) during August of 1989-2003 period, and August surface water temperature (blue dots) (from Shiganova *et al.*, 2004).

Planktivore fish stocks (mostly anchovy and sprat) have been subject to dramatic changes during the second half of the last century (Oguz, 2007). They were at relatively low levels during the 1960s prior to the depletion of pelagic piscivore stocks and dolphins. During the 1970's the stocks increased due to weakening of predator control as well as increasing level of eutrophication and thus more active biological production (Daskalov *et al*., 2007). At the end of the 1980's planktivorous fishes collapsed due to the combined effect of overfishing and the outburst of the ctenophore *Mnemiopsis leidyi* (Oguz *et al*., 2008). Even though anchovy and sprat stocks are exposed to such complex environmental controls, they nevertheless appear to be regulated by climatic changes. Figure 89 shows a clear correlation between the sum of anchovy and sprat catch increase and the climatic cooling during the 1970s and 1980s and vice versa for the 1990s. Erdogan *et al*. (2010) provided a similar correlation between anchovy catch size and monthly temperature changes during November-February and thus the number of fishing days with an optimum temperature range of 9.4-14.5°C.

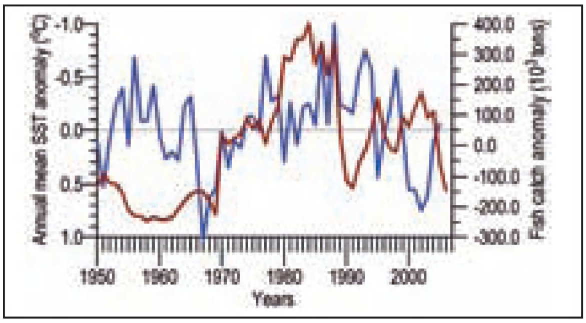

Figure 89. Time series of annual-mean basin-averaged temperature and the sum of sprat and anchovy catch anomalies. Note the inverted temperature axis on the left.

Long term data from the interior basin suggest that the share of coccolithophores within the total May-June phytoplankton biomass was about 19 % prior to 1985, and 16 % during 1985-1994, but decreased to 2.5 % after 1994 when the Black Sea shifted to the warming phase. The reduced cocolithophore populations in the Black Sea is consistent with the reduced calcification rates under global warming and ocean acidification but it may be related to, at least partly, to the decadal warming-cooling cycles associated with NAO changes.

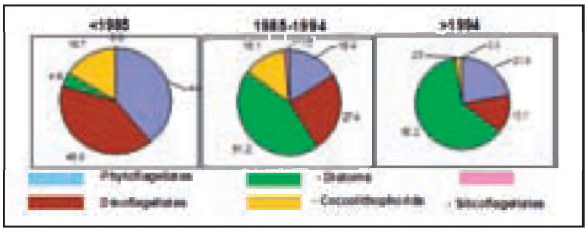

Figure 90. % share of different taxonomic groups in the total phytoplankton biomass during May-June within deep interior basin of the Black Sea for different phases of the ecosystem.

3.6.4 Link between Observed Changes and Climate

A high and significant correlation between the basin-averaged winter-mean SST and the winter-mean air temperature anomaly and the NAO index (Figure 90) provides compelling evidence for regulation of the regional hydro-meteorological conditions by large scale climatic teleconnection patterns. We refer to Figure 90 to show how the long-term (1910-1970) warming trend coincides with declining NAO index values toward more negative values whereas the subsequent cooling up to the mid-1990s is related to strengthening of the NAO toward its more positive phase. Therefore, more positive NAO values imply colder, drier and more severe winters in the Black Sea (Oguz *et al*., 2006) which is opposite to the conditions of wetter and milder winters in the north-western European seas (Osborn *et al*., 1999).

The changes in long-term detrended average sea-level reveal a negative correlation with the winter-mean NAO index (Figure 82). In general, positive NAO index values are associated with relatively low sea-level. The correlation is highest for the western Mediterranean (r = -0.48) and decreases to r = -0.37 for the Eastern Mediterranean Sea and r = -0.40 for the Black Sea. A high degree of agreement between temporal variations of biogeochemical variables and temperature also indirectly indicates a link between Black Sea ecosystem changes and large scale climate systems. Reconstructing annual temperature variations for the Mediterranean Sea and Middle East (between 30-40°N latitude and 20-50°E longitude) since 1750 also points to the role of the NAO in the region (Mann, 2002). In addition, the North Sea - Caspian pattern (NCP) is shown to explain some of the variability on the Mediterranean, Black and Caspian Seas hydro-meteorological properties (Gunduz & Ozsoy, 2005). This index is constructed based on mid-tropospheric (500 hPa) geopotential height difference between the North Sea and the Caspian Sea regions. A similar index, but based on the surface pressure differences of these two regions, is referred to as the East Atlantic – West Russia (EAWR) index. These two indices characterize motions of jet streams over Europe, and therefore represent eastward zonal extension of the NAO pattern originating in the Atlantic sector.

As pointed by Oguz *et al.* (2006), their combination explains better the Black Sea climatic variability, although the NAO constitutes the primary atmospheric system. In addition, cold air outbreaks developing in the Gulf of Genoa of the Mediterranean Sea affect the Black Sea climate in both winter and summer months once they move to the northeast over the Aegean Sea and then the Black Sea. In contrast, while the El Nino/Southern Oscillation (ENSO) phenomenon constitutes a major source of interannual climate variability over much of the globe, it has only a weak influence on the climate of the Eastern Mediterranean-Black Sea region (Price *et al.*, 1998).

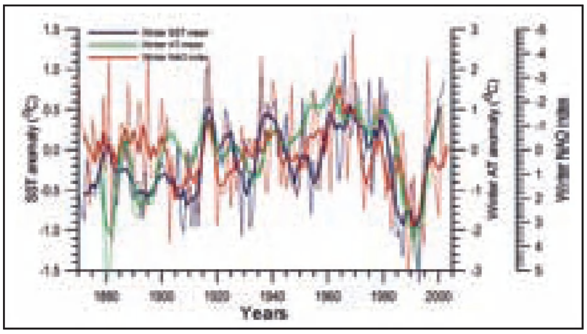

Figure 91. Time series of the basin-averaged winter mean sea surface and air temperatures, and the winter mean North Atlantic Oscillation index. The thin lines show the original data and the thick lines are the smoothed curves by 5 point moving averaging. Note that the axis for the NAO index on the right is inverted.

3.6.5 Future Climate Change Projections

No specific future climate change scenarios have been accomplished for the Black Sea yet, but the studies conducted for Europe in general and the Mediterranean and Middle East in particular by Giorgi and Lionello (2008), Evans (2009) may be used to infer the fate of the Black Sea climate towards the end of the present century. The model predictions use different projections of the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emissions. They show consistently a northward shift of the Atlantic storm tracks to higher latitudes. As a result, the Mediterranean region will exhibit a general reduction in precipitation, while northern Europe will be subject to an increase (10 - 50 %). The Black Sea lies in the transitional zone between these two regimes and thus it is hard to identify its definitive future climate state. In the case of precipitation increase, a simultaneous increase in air temperature (and thus sea temperature) is projected over the Black Sea. Otherwise, colder and drier climatic conditions will prevail in agreement with projections due to likely changes in the NAO pattern in response to the global warming described in the previous section.

3.6.6 Socio-Economic Consequences of Climate Change in the Black Sea

Marine ecosystems, particularly coastal seas, are generally regulated by multiple environmental pressures and therefore it is often difficult to separate the effects of climate change from those of eutrophication, overfishing and other site specific environmental factors. The most important socio-economic impact of climate change in the Black Sea was felt in the fisheries sector. Temperature appears to be a key environmental factor for conditioning migration and schooling behaviour of anchovy. Increasing winter temperatures adversely affected anchovy migration patterns by shortening the main fishing season from the late February to the early January (Erdogan *et al.* 2010). Disruption of the existing patterns due to climatic warming affected nearly 20,000 fishermen employed in the Turkish Black Sea fishing sector because 80 % of the Black Sea fish catch was attributed to Turkey (Shivarov, 2010).

Figure 92. Increasing winter temperatures adversely affect anchovy migration patterns by shortening the main fishing season from the late February to the early January with important effects on the employment of fishermen in Turkey (Erdogan *et al.* 2010). (©Leen Vandepitte)

These socio-economical impacts on the fishery sector followed even a more dramatic one that took place earlier at the beginning of the 1990s when the total fish catch declined from 900,000 tons in the mid 1980s to 100,000 tons. As documented by Knowler (2008), it roughly amounted to an economical loss of about USD 240 million, based on a unit catch value of USD 300/ton. Moreover, processing plant losses were roughly estimated at about USD 10 million for 50 plants in the

Black Sea region, on the basis of the costs of switching over to an alternative production line. Using the more extreme replacement cost approach, the estimate for Turkish processing plants alone suggests losses of USD 20 to 30 million. Up to 150,000 people were estimated to depend directly on the Black Sea fisheries, but income losses have been more difficult to estimate. Wages lost in processing plants alone totalled approximately USD 10 million annually (Knowler, 2008).

The Turkish coastal waters, particularly on the eastern side, include an important aquaculture industry based mainly on rainbow trout. Raising temperatures during the last decade have however increased the frequency of disease outbursts, decreased breeding efficiency and shortened their growing season. These events led to a shift to farming of new species, such as European seabass, more suitably adapted to new conditions. While this could be a solution to the local economy, it raises new environmental problems (Erdogan *et al.*, 2010).

3.6.7 Research Gaps, Uncertainties and Relevance to EU Funding

There are many knowledge gaps regarding likely impacts of climate change on the Black Sea ecosystem. The present assessment studies are limited in scope due to dispersed and often unreliable data sets. A better understanding of the interplay between the environment and well-beings of the people living in the region demands more comprehensive research in the fields of environmental and natural resources. The lack of systematic observations by the riparian countries hinders better understanding of the natural and anthropogenic climate changes and their impacts on the coastal and interior basin ecosystems. Unless critical information gaps can be closed by improved monitoring of social and natural system indicators, it will not be possible to develop reliable scenario models that will serve as a basis for decision making towards sustainable use of ecosystem goods and services.

EU funding for conducting scientific research in the Black Sea ecosystem studies in general and climate change impacts in particular have been very limited so far as compared to those provided for other European Seas. The EU FP6 SESAME project was the first and the only EU-funded project that included a climate change research component so far.

3.6.8 References

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4. Social and Economic Aspects of Climate Change Impacts on the Marine Environment

4.1 Introduction

Climate change impacts on the European marine environment in the 21st century will include sea-level rise and probably increased storminess, both of which will increase coastal flooding and erosion; ocean acidification and associated potential disruption to marine ecosystems; changes in fish distributions, and marine eutrophication. Increased runoff from rivers will affect biological production in the oceans and changes in ocean currents may also occur. These impacts which are described in more detail in chapters 2 and 3 of this report will have implications for our economy and our society which will require appropriate adaptation measures. Because of the high cost associated with these adaptation strategies, several mitigation strategies and are being considered and pursued to various extents by different countries, including investigations into geo-engineering techniques such as ocean iron fertilisation as a way to reduce pressure from elevated CO_2 concentrations resulting from human activities (see Information Box 5).

This chapter provides an overview of the main focus, key findings and gaps of recent and current European social science research focusing on the on the economic consequences of climate change impacts on marine ecosystems as discussed in Chapter 2 and Chapter 3 (see Section 4.2). However, the potential impacts of climate change on the marine and coastal environment will affect people beyond economical terms, either as a result of changes in economic activities or as a result of direct impacts on their lives and well-being, for instance through flooding or the destruction of private dwellings due to coastal erosion. How societies respond to these challenges will have an important influence on both environmental and socio-economic outcomes (see Figure 92).

For coastal economies and people who live and work in marine and coastal environments, relative sea-level rise with increased rates and extent of coastal erosion and higher frequency of flooding are likely to be the main direct impacts with important social ramifications. Their importance is underscored by the fact that about 33 % of the EU population live within 50 km of the coastline. This means that a sea-level rise of 47 cm would expose between 200,000 and 800,000 additional people annually to coastal flooding by 2100 (Hinkel *et al.*, 2010).

However, the countries in the EU most exposed to sea-level rise are not necessarily the most vulnerable, since those with higher socio-economic status will be better placed to adapt. A 5 m sea-level rise could lead to the abandonment of much of the Rhine and Rhone deltas, and the loss of Antwerp, Amsterdam and Rotterdam, whilst the London landscape would be highly modified (Tol, 2007). Venice is already experiencing marine flooding due a to a combination of subsidence and sea-level rise, and mobile flood protection gates are already being built, at a cost of 4.7 billion euros.

The impacts of sea-level rise, coastal erosion and flooding, and their social consequences, are the main focus of the rather limited research that has been conducted, to date, on the social impacts of climate change on the marine environment. There might also be other less obvious social impacts. For example, the effects of climate change on marine pathogens and biotoxins may also have serious social consequences, if human health, food security and business sustainability (e.g. in marine aquaculture production systems) are affected. In short, knowledge of the likely social impacts is, as yet, very limited, and much more research needs to be done.

At the same time, there is a rapidly increasing number of studies focusing on the socio-cultural and psychological factors that underlie people's attitudes and responses to climate change, e.g. in terms of risk perception, concern, place identity and willingness to implement or support adaptation or mitigation actions. Some of these studies analyse public attitudes towards climate change impacts on marine environments, in particular with respect to sea-level rise and flooding, which have the potential to directly affect people living in vulnerable communities. Public attitudes towards other less immediate and tangible issues such as ocean acidification have been investigated to a much lesser extent. While it is impossible to make any universal generalisations based on existing research, it is clear that there is a wide range of legitimate stakeholder perspectives on these issues.

These socio-cultural and psychological aspects are the focus of CLAMER Work Package 2 'Public Perception & Awareness - Uptake of European Research Results'. We refer to the CLAMER Deliverables of this Work Package and in particular to Deliverable 2.3. on public engagement with climate change impacts on marine environments by Chilvers & Terry from the University of East-Anglia (see www.clamer.eu for more information).

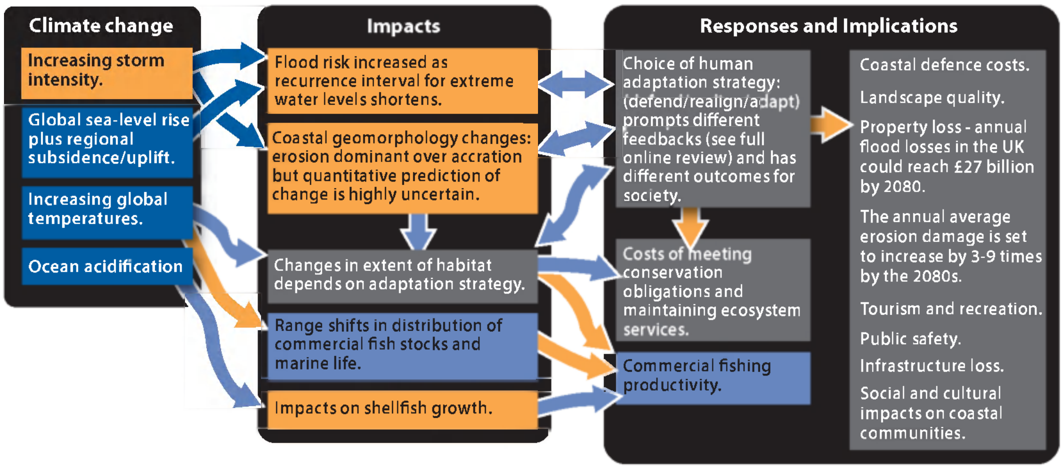

Figure 92. Key linkages between climate change impacts on the marine and coastal environment and the social and economic situation of coastal communities (adapted from the Marine Climate Change Impacts Partnership, MCCIP - http://www.mccip.org.uk/ecosystem-linkages/coastal-economies-and-people.aspx)

Information Box 5. Ocean Iron Fertilisation and Other Ocean Geo-engineering Concepts

Over the past 40 years there have been quite some waves of publicity about various schemes for large scale manipulation of the biosphere. More recently there has been the next revival, now under the label of **geo-engineering**, defined by the Royal Society (Sherpherd, 2009) as:

'The deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change.'

One of the major focus-points in ocean geo-engineering schemes is the reduction of Carbon dioxide concentrations in the atmosphere, being the most important and not readily reversible cause of man-made climate change. Among these, it is mostly iron fertilisation that has gone beyond merely concepts and has also been investigated by experiments. Other concepts for ocean geo-engineering include: (i) ocean fertilisation with Nitrogen and Phosphorus or by enhanced upwelling of nutrient-rich deep waters; (ii) deep ocean CO_2 injection; and (iii) increased CO_2 uptake by enhancing natural olivine weathering or calcite dissolution reactions.

There exists considerable **controversy about the feasibility and potential risks associated with geo-engineering,** not only with the public but also within the scientific community. Most of the geo-engineering concepts so far, are suitable mostly as learning tools for playing with global climate simulation models and providing a better understanding of feedbacks of the biosphere system. Small and medium scale experiments of limited duration remain of interest for scientific purpose and can be conducted with limited risks. However, the prospect that large-scale and long-term geo-engineering activities would be performed in complex natural ecosystems which are not yet fully understood raises important concern for possible ecological side effects.

Ocean Iron Fertilisation

In approximately 40 % of the world oceans, essential nutrients such as nitrogen, phosphorus and silicate (essential for diatoms) are in ample supply, yet phytoplankton abundance is very low. These areas are referred to as ‘High-Nutrient-Low-Chlorophyll’ regions. Studies during the 1980’s showed that, in many of these areas, low concentration of the trace nutrient iron (Fe) is the limiting factor. This observation led to the idea of adding iron intentionally to the upper ocean (iron fertilisation) to stimulate phytoplankton growth and hence the uptake of carbon dioxide from the atmosphere as a result of increased photosynthesis rates. If dead phytoplankton subsequently sinks to the bottom of the ocean this would lock away some of the carbon it has absorbed from the atmosphere.

Since the 1990s, marine researchers have been exploring iron fertilisation as a way to stimulate phytoplankton growth with initially to prove that iron is indeed the primary limiting factor, for assessing the potential of iron fertilization for sequestering atmospheric carbon dioxide in the deep ocean, and to increase marine biological productivity. However, *in situ* iron fertilisation experiments and natural iron fertilisation processes have shown that this concept will not be as cost-efficient as once thought and might result in other unintended environmental impacts (e.g. deep ocean water acidification). In addition, opponents argue that such schemes could distract from efforts to decrease anthropogenic carbon emissions.

Nevertheless, an important group of scientists believes that much remains to be learnt about the limiting role of iron and the efficiency of iron fertilisation in promoting long-term sequestration of carbon dioxide by the oceans, as well as its impact on marine ecosystems. For this reason, a new impetus on iron fertilisation research has taken shape under the form of the *In situ* Iron Studies (ISIS) consortium of ocean science institutes active in iron research, an international effort established in February 2011 to assess the efficacy of ocean iron fertilisation (OIF) in reducing the amount of carbon dioxide in the Earth’s atmosphere, as well as its potential impacts on marine ecosystems.

See http://isis-consortium.org/

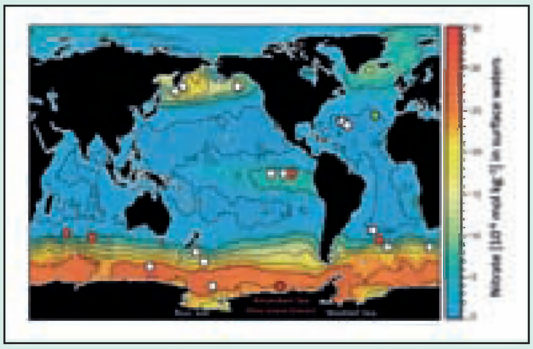

Figure 94. Chart of iron (Fe) fertilisation studies in the oceans. Background colour is the concentration of nurient nitrate in surface waters; notice the three major HNLC regions subArctic North Pacific, equatorial East Pacific and Southern Ocean. White crosses are the 13 thus far intentional Fe *in situ* addition experiments in 1993-2009 period. Red crosses are the five studies of unperturbed natural Fe fertilisations. Green crosses are not discussed.

4.2 Economic Effects of Climate Change Impacts upon the European Marine Environment

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4.2.1 Economic Impacts of Sea-level Rise and Coastal Flooding

In the absence of global mitigation efforts, sea-level rise of 80–200 cm is expected globally by 2100 as a result of ocean thermal expansion and ice-sheet melt (Rahmstorf *et al.*, 2007; Pfeffer *et al.*, 2008; Anonymous, 2008). Shutdown of the thermohaline circulation could further raise sea-level by 80 cm by 2150 (Kuhlbrodt *et al.,* 2009). Larger sea-level rise of several metres may occur beyond 2100 if major ice-sheets collapse. Hansen (2007) believes that several metres of sea-level rise could occur by 2100.

Although there is widespread attention to the physical projections of sea-level rise, there are relatively few numerical estimates of associated European economic losses. 500-1000 billion euros worth of EU assets are located within 500 m of its coastline, whilst 35 % (3.5 trillion) of total EU GDP may be found within 50 km of the coastline (Policy research cooperation, 2009). Sea-level rise of 80–200 cm could wipe out entire countries (Tol, 2007) causing massive economic damage. It would also cause large scale loss of intertidal and wetland ecosystems such as saltmarshes, which would also have economic consequences due to the loss of the unquantified ecosystem services that they provide, such as protection from storm surges and the maintenance of fish nurseries and hence healthy marine fish populations. A pessimistic 10 m eventual sea-level rise is plausible, and Europe has been identified as one of the most threatened regions in this case, with 25 % of its exposed GDP below this altitude above sea-level (Tol, 2007).

Due to their relatively high GDP, France, the Netherlands and the UK were thus considered less vulnerable by some authors (Tol *et al.*, 2006) whilst others highlighted that the Netherlands could have the highest *relative* damage costs of 0.3 % GDP. Some considered the Mediterranean and the Baltic as more vulnerable than the Atlantic coasts (Richards & Nicholls, 2009), whilst yet others considered that Ireland was especially vulnerable, with estimated adaptation costs ranging from 0.05-0.6 GNP (or USD 420 million annually) (Devoy, 2009; Hinkel *et al.*, 2010). Estonia's adaptation costs could be as high as 0.16 % GDP (Hinkel *et al.*, 2010).

Figure 95. The Maeslantkering is a storm surge barrier in the Netherlands, which automatically closes when needed for protection. It is part of the Delta Works and it is one of largest moving structures on Earth. (©AeroLinphoto, the Netherlands)

Sea-level rise may also impact on tourism destination choices. Tourism flows from changing demand scale and demand recomposition could be substantially more important than land loss from the economics viewpoint per se (Bigano *et al.*, 2008). The potential loss of entire countries (Tol, 2007) to sea-level rise has profound implications: large movements of populations from inundated areas might ensue, creating issues for governance due to the presence of 'climate refugees'.

It may be possible for mitigation to reduce sea-level rise to a limited extent in the 21st century due to the slow response of sea-level to emission reductions. However, beyond the 21st century, mitigation has a stronger role to play, partly due to the reduced risk of ice-sheet melt. By 2100, however, stabilization of CO_2 concentrations at 550 ppm would reduce economic impacts by some 10 % only (Tol, 2007). Similarly the AVOID project identified a (global) potential to avoid some 25 % of sea-level rise impacts on saltmarshes with very stringent mitigation.

Estimated costs of 9–88 cm of sea-level rise in Europe range from 40–80 million euros per year in the 2020s, to 0–2.3 billion per year in the 2080s (1995 values). These estimates consider the distribution of population and its GDP per capita, and assume adaptation (through dike construction and beach nourishment) and combine its costs with those of the residual damages due to sea floods, salinity intrusion and migration (Richards and Nicholls 2009). Hinkel *et al.* (2010) considered sea floods to be the most costly of these impacts, and estimated total annual damages of USD 17 billion in 2100 Europe resulting from a predicted 47 cm sea-level rise in 2100 in the absence of adaptation. In the presence of adaptation, Hinkel's estimate is 2.2 billion euros annually. By comparison, Europe is likely to be spending an estimated 0.88 billion euros annually between 1998 and 2015 on coastal protection.

Adaptation has generally been found to be cost-effective in European studies (Richards & Nicholls, 2009; Hinkel *et al.*, 2010), and might reduce damages by a factor of 7 to 9, or 10–100 depending on the study (Tol, 2007; Hinkel *et al*., 2010). However, these studies do not consider cost effectiveness beyond 2100 and the building of coastal protection squeezes wetlands between dikes and the sea, potentially violating the EU habitats directive.

Costs of sea-level rise impacts might be significantly underestimated because the above estimates do not include the economic consequences of lost land, such as changed consumer prices. Trade tends to re-distribute losses from affected areas to Europe as a whole (Darwin & Tol, 2001). More generally, it is important to realise that all these studies of economic impacts rely on the same methodology (contained within the FUND and DIVA models), within which the estimates depend strongly on the input parameters used and the values attributed to them. The value of ecosystem services to human well being is often omitted from the analyses, and where it is included, very uncertain monetary values are placed upon them. Bigano *et al*. (2008) used a Computable General Equilibrium model to estimate EU losses of only USD 14 million per year due to 25 cm of sea-level rise by 2050. These values are much lower than the 2 billion euro's annually proposed by Hinkel *et al*. (2010) with adaptation (or the 8 billion without) for 18 cm sea-level rise in 2050, but this study is incomplete as only loss of agricultural land is considered. Generally the literature has focused on estimating the value of assets at risk if there is no adaptation, rather than quantifying the costs of inaction or the benefits of adaptation (Policy research cooperation, 2009). Adaptation cost estimates for 2100 range from USD 2.6–3.5 billion (Hinkel *et al.*, 2010) under 47 cm sea-level rise across Europe whilst those for the Netherlands range from 30–46 billion euros for 85–150 cm sea-level rise (Aerts n.d.).

Other studies have focused on the socioeconomic consequences of individual instances of coastal flooding that might occur in the future, such as a £9 billion loss for a 1 in 75 year flood in the 2050s under a large climate change scenario for East Anglia in the UK (Mokrech *et al.*, 2008). Another UK study used Monte Carlo analysis based on the future uncertainties in sea-level rise projection given in IPCC (2007), i.e. 9–88 cm (mean 48 cm) in 2100 (Purvis *et al.*, 2008). The costs of the 1 in 200 year flood were estimated to lie between zero and £5 million annually depending on the sea-level rise. This study highlighted the danger of under-estimating impacts by overly focusing on median climate change outcomes without considering the low probability, high consequence possibilities. However, it itself uses a symmetrical probability distribution of sea-level rise about the median, whereas in reality probability distributions of climate change outcomes should be skewed reflecting the asymmetrical nature of our knowledge of climate sensitivity. The study also does not consider the role of ice-sheet melt, which would induce sea-level rise beyond the IPCC estimates (which themselves contained the caveat that ice-sheet melt was not included).

4.2.2 Economic Impacts of Changes in Storm Frequency and Intensity

More frequent and intense storms are projected for northern Europe under climate change, especially in a band running from the south of England through northern France, Denmark, northern Germany and Eastern Europe (Arnbjerg-Nielsen & Fleischer, 2009; Schwierz *et al.*, 2010). Wind damage in Europe is likely to remain dominated by rare events and interannual variability, which is projected to increase with climate change (Leckebusch *et al.*, 2007; Schwierz *et al.*, 2010). Estimates of increased damages include a rise of 21 % in the UK and 37 % in Germany (Leckebusch *et al.*, 2007); and a rise of 44 % in annual expected loss across Europe as a whole, with much larger increases in loss for longer periods (e.g. 104 % rise of the 100 year loss) (Schwierz *et al*., 2007).

Strengthening existing, or construction of new, dikes may be necessary with increased probability of flooding induced by sea-level rise and increased storminess. The attractiveness of tourist destinations may be influenced by the length of dikes. Based on the hedonic price technique, Hamilton (2007) found that the average price of accommodation in the coastal districts of Schleswig-Holstein, the most northerly state in Germany, decreases as the length of dikes increases but increases as the length of open coast increases. These observed trends have implications for revenue from tourism.

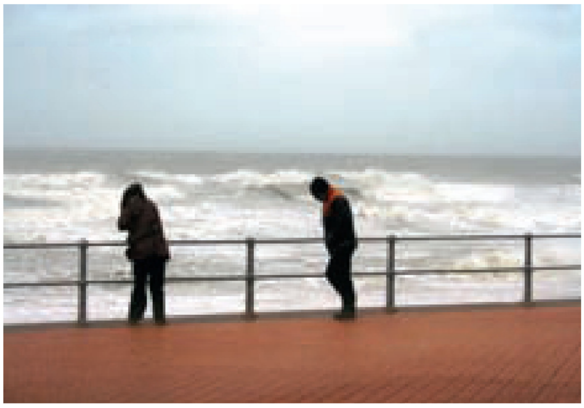

Figure 96. Storm at the beach resort Ostende in Belgium (above: ©Evy Copejans; below: ©Joost Overmars)

4.2.3 Economic Aspects of Changing Human Health Risks

Climate change induced physical and chemical changes in the marine environment influence the prevalence and potency of marine pathogens and biotoxins. Millions of euros in health costs may result from human consumption of contaminated seafood, ingestion of water-borne pathogens, and, to a lesser degree, through direct occupational or recreational exposure to marine diseases. Climatic conditions are playing an increasingly important role in the transmission of these diseases. Since the early 1970s, climate-induced physical and chemical changes in the marine environment, which in turn trigger changes in marine ecosystems (e.g. Harmful Algal Bloom (HAB) biotoxins), have rendered many fish populations increasingly susceptible to opportunistic pathogens. The fishing industry suffers from disease-induced mass fish mortalities, as well as from a decline in consumer confidence in seafood. In addition to a variety of ecological and environmental factors, rising temperatures contribute to pathogen range expansions by stimulating the growth, transmission and survival of marine parasites, thereby threatening aquaculture. Marine ecosystems are important tourist attractions for many coastal populations and climate change could lead to coral reef mortality, for instance (UNEP-WCMC, 2009).

4.2.4 Case Study: Economic Impacts on European Fishery

Allison *et al.,* (2009) adopted an indicator-based approach that consists of climate exposure, sensitivity or fisheries dependence and adaptive capacity to assess the vulnerability of 132 national economies to potential climate change impacts on their capture fisheries. Although their study indicated that most of the vulnerable countries are among the world's least developed countries such as those in Africa, northwestern South America and Asia, European fisheries will no doubt be affected by climate change as warming is believed to be most pronounced at high latitudes. Northeast Atlantic (roughly the area to the east of 42°W longitude and north of 36°N latitude) is the largest European fishing area, contributing to 70 % of the catches across all the EU countries in 2008, followed by the Mediterranean1. Climate change therefore has implications in particular for economies that depend on fisheries, as well as nations with large fishing fleets and aquaculture production such as Italy, France, Spain, the United Kingdom and Greece[4].

Fisheries account for less than 0.5 % of total economic output in northern Europe, but are relatively more important in the South (e.g. 7 % of Greek output) and in Norway, where fisheries account for 2 % of GNP and 6 % of exports. Thus there could be large regional socioeconomic impacts in areas where fisheries are negatively affected by climate change (Eide & Heen, 2002; ACIA, 2005). Fish farming comprises 51 % of fisheries output in the Nordic countries and only 2 % in Central Europe North. Climate change will impact on commercial fishing via alternations in the size of fish stocks, their distribution, catchability, and the prices of fish (ACIA, 2005; Aaheim, *et al.,* 2009) and hence the profitability of the industry. However, the industry is flexible, having become accustomed to the need to adapt to change (ACIA, 2005). Nevertheless, climate change might introduce larger or more rapid changes than can readily be accommodated.

Impacts on aquaculture could also be far reaching and are difficult to predict. Production of both finfish and shellfish may be adversely affected by increased exposure to pests and diseases. Changes in seawater temperature regimes may also affect metabolic func-

[4] Eurostat Fishery Statistics. Available at http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Fishery_statistics.

tions and growth in aquaculture species, and food availability for cultured shellfish. Finally, increased exposure to extreme weather events will have implications for the structural resilience required for aquculture installations at sea, patriculary those in exposed locations (e.g. off-shore fish cages).

Figure 96. Future climate change predictions are likely to affect fisheries (©Ana Trias Verbeeck)

Knowledge of impacts of climate change on marine biodiversity remains limited, with even the directions of changes being difficult to predict in some cases. Ocean acidification has the potential to significantly affect the life cycles of some marine fish and shellfish, putting at risk some unknown fraction of the economic value of these resources which in total amount to approximately USD 100 billion (Royal Society, 2005). It may induce a significant perturbation of the whole marine and coastal system and the ecosystem services which it provides (which includes removal of waste and pollutants, and protection of coastlines from erosion) in ways that at present cannot be foreseen. Furthermore, the marine ecosystem might experience disruption in its functioning owing to the rapid rate of climate change, or due to asynchrony between predators and prey in a system where different species alter their distributions in different ways as climate changes (Fishclin *et al.,* 2007). The oceans have already acidified by, on average, 0.1 pH units. In the absence of mitigation, this could rise to 0.4 units by 2100. However, stringent mitigation has the potential to largely halt further acidification, reducing the further increase to only 0.05 pH units (Bernie *et al.,* 2010).

Few studies have examined the economic impacts of climate change on the European fishery sector. Those that have explored this area typically adopted the causal chain approach, i.e. from global warming to fish availability to the economic impacts such as GDP. It is important to note that each of these steps is subject to substantial uncertainty (Arnason, 2007).

Owing to our incomplete knowledge of these processes, studies which estimate economic impacts of climate change on fisheries assume that the marine ecosystem remains fundamentally intact. Perturbations of +/- 25 % in fish stock availability in the Barents Sea, which is one of the world's most productive fisheries, were thought to have the potential to raise or lower north Norwegian employment by 1 % (Eide & Heen, 2002). It was noted that changes in management of fish stocks generally had a more profound impact than potential climate change impacts (Eide, 2008). However, these perturbations were the potential consequences of moderate changes of 2–3°C in sea surface temperature in the Barents Sea. The Fourth IPCC Assessment Report (IPCC, 2007) suggests that sea surface temperature changes of 4–5°C are quite likely in the region by the 2080s.

Bioeconomic studies focusing on the potential shutdown of the thermohaline circulation in the 21st century and beyond have suggested a potentially serious impact on cod recruitment in the Barents Sea, which would be insufficiently compensated for by improvements in capelin stock development, resulting in an unprofitable industry (Link & Tol, 2009; Kuhlbrodt *et al.,* 2009). Another bioeconomic study on the Iberian-Atlantic sardine (Sardina pilchardus) fishery (Garza-Gil, 2010) indicated that global warming induced rising sea surface temperature (SST) in the fishing-grounds would reduce sardine biomass, and in turn, catch levels and economic yield. Their results suggested that annual profits would decrease by 1.27 % between 2010 and 2030 under the current rate of SST warming at 0.027°C per year. Under a warmer scenario with fishing ground temperature increased by 10 %, profits were shown to drop by about 1.4 % per year over the study period. Garza-Gil (2010) also found that the Portuguese regions would suffer greater economic losses from warmer SST than the Spanish regions, as over 70 % of the total landings were Portuguese catches. On the other hand, Icelandic GDP could benefit from climate change effects on its fisheries; although the magnitude of this change (at less than 0.2 %) would likely be insignificant when compared to historical economic growth rates and fluctuations (Arnason, 2007).

Allison *et al.* (2009) has provided a framework for assessing the vulnerability of fisheries to climate change. The study of changes to ecosystems and ecosystem services, especially the relation to climate change, remains a challenge due to the uncertainties in the detailed effects and direction of change on the physical and biological processes that affect individual fisheries. The picture is also masked by the considerable stress from overfishing, habitat loss, pollution, non-native species, water abstraction and damming. Furthermore, wetlands, river basins and other ecosystems that support fisheries tend to lie downstream of other human activities (including forestry, agriculture, industrial abstraction and damming), and there are difficulties in assessing the influences of climate impacts on other natural resource sectors, thus the effects on fisheries ecosystems and livelihoods, and vice versa (Allison *et al.,* 2009).

More detailed studies on climate change impacts on fisheries at the regional scale would require the availability and higher quality data, in addition to improved understanding of the individual components of vulnerability (Allison *et al.,* 2009). Building adaptive capacity is important for countries with a significant fishery sector that may benefit from (e.g., Iceland; Arnason, 2007) or adversely affected by climate change (e.g., Norway; Eide, 2008).

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5. General Discussion and Conclusions

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5.1 Current Knowledge

5.1.1 Introduction

Over the past 50 years, European scientists have been engaged in numerous research initiatives and projects at the national, European and International level, which have contributed significantly to the understanding of human-induced climate change and associated changes in the marine environment. In the past 15 years, the European Union has increasingly supported pan-European research collaborations in this area which has resulted in a wealth of new data, information and knowledge.

The synthesis of results of EU-funded projects on climate change presented in this report demonstrates beyond reasonable doubt, that climate change has already impacted all oceans and seas of Europe and beyond. Within the past 25 years, seawater temperatures from the surface to the deep sea have increased, with enclosed seas such as the Baltic, the Mediterranean and the Black Sea warming more rapidly than the open ocean. In the Arctic, warmer waters have resulted in a decrease in the area and thickness of sea-ice. Warming waters, together with mass additions from melting ice-sheets and increased landward winds at several locations, have also contributed to sea-level rise. The combination of sea-level rise and increased winds, have contributed to the erosion of 15 % of the European coasts. Many marine species, including zooplankton, benthos and fish, have migrated northwards, resulting in local increases in biodiversity and changes in the marine food web. Some marine organisms have even been able to cross from the Pacific to the Atlantic via seasonal ice-free passages through the Arctic.

Although large climate changes occurred during the geological past, the present rates of change are unprecedented. The warming has been speeding up, especially during the past 25 years during which it has been about ten times faster than the average rate of increase during the previous century. Synthesizing the findings of European research on the impacts of climate change on marine environments reveals that the marine environment is also changing rapidly. Many of the observed changes which are thought to be predominantly a consequence of climate change (IPCC, 2007; this report and references herein) can be grouped as follows: (i) changes in the physical properties and motions of the sea; (ii) melting of the Arctic sea-ice; (iii) northward movements of marine organisms; (iv) shifts in timing of life-cycle events; (v) cumulative effects of multiple stressors; and (vi) the socio-economic consequences of all these changes.

5.1.2 Physical Properties and Motions of the Seas

Over the 1986-2006 period, the increasing **trends in sea surface temperature (SST)** for European waters, including the Atlantic, were three to six times higher than the global average rise for sea surface temperature (Coppini *et al.,* 2010). In particular, the relatively small enclosed seas, such as the North Sea and the Baltic Sea, were disproportionally affected by global warming (Belkin, 2009). Changes in water temperatures in European Seas have shown complicated spatial patterns, such as differences between winter and summer trends in SST, the occurrence of warming in subsurface layers, and the interruption of warming trends by cool periods. Scenario simulations suggest that by the end of the 21st century, the temperature of the Baltic Sea may have increased by 2°C to 4°C (Madsen, 2009), of the North Sea by 1.7°C (Ådlandsvik, 2008), and of the Bay of Biscay by 1.5°C to 5°C (Alcock, 2003).

Addition of heat to the seas increases the volume of the seawater which subsequently enhances the global mean sea-level. For the past century, global estimates for **sea-level rise** have been around 1.8 mm y^{-1} (Church *et al.,* 2010). Around Europe, the observed sea-level trends have shown considerable regional differences, most probably as a result of local circumstances such as the vertical movement of land masses and prevailing winds. In the future, sea-levels are predicted to increase on average, but there is much uncertainty on the contribution of mass addition resulting from melting ice-sheets and glaciers. Present estimates for 2100 (excluding non-linear ice-sheet breaking processes) range between 60 cm for European waters in general, up to 1.9 m for UK coasts under 'worst-case' scenarios. If major ice-sheets do collapse, then theoretically, several meters of sea-level rise could occur by 2100 (Hansen, 2007).

The sinking of cold dense water in the northern North Atlantic is the major driver of the **Thermohaline Circulation (THC),** that part of the large-scale ocean circulation which is driven by global density gradients created by surface heat and freshwater fluxes. An increase of water temperatures in the Arctic may, therefore, result in a reduction in the amount of cold water that sinks, which would subsequently slow down the THC with global consequences (Parry *et al*., 2007). In general, a reduction of the global circulation is expected to result in a further increase of temperatures and sea-level, but impacts may not be consistent at a local level, for example on the western margin of Europe, which may suffer cooling (Parry *et al*., 2007).

Most seas and oceans are characterized by a vertical gradient in water density as the result of gradients in temperature and salinity, often in the upper 50 to 100 m of the water column. The stronger the degree of this **stratification,** the more difficult it is to mix bottom and surface waters. The degree of stratification is expected to increase globally as the result of enhanced warming of sea surface (Levitus *et al*., 2009), to increase locally at high latitudes as the result of the melting of sea-ice, and to change locally as the result of changes in precipitation patterns (IPCC AR4, 2007). In open waters, increased stratification will reduce the upward supply of nutrients and trace elements from the deep waters to the surface waters with locally different consequences for the ocean productivity. Increased stratification will also deplete oxygen in deeper water layers and can lead to increased anoxia in some places (dead zones).

5.1.3 Melting of Arctic Sea-ice

Since 1970, when satellite records on **sea-ice extent** became available, the Arctic sea-ice cover in summer has declined, on average, by more than 40 % with a record low in 2007[5]. In addition, the average thickness of the sea-ice at the end of the melting season has decreased by 53 % during these 40 years (Kwok & Rothrock, 2009). The reduction of the ice is expected to reduce the growth and condition of ice-bound, ice-associated and ice-born organisms.

The shrinking of Arctic ice affects Arctic organisms with consequences for the biodiversity and ecosystem functioning of the **Arctic food web**. In the European Arctic corridor, phytoplankton gross primary productivity was found to be strongly related to ice-cover (Wassmann *et al*., 2010). Model experiments indicate that primary production could triple in a warming Arctic Ocean (Slagstad *et al*., 2011). Furthermore, the warming of the Arctic waters has been accompanied by an increasing advance of Atlantic waters to high latitudes by way of the prevailing North Atlantic current. Compared to Arctic waters, Atlantic waters are relatively species-rich and contain relatively small species of herbivores. The subsequent increase in the number of trophic levels in the Arctic food web has resulted in an increase in biodiversity and a decrease in food availability for the top predators such as seabirds, seals and whales (Wesławski *et al*., 2009).

Recently, the opening of the Northwest Passage in the polar ice has allowed marine species to travel between the Pacific and Atlantic oceans. The algae *Neodenticula seminae* has returned to the Atlantic Ocean after an absence of over 800,000 years (Reid *et al*., 2007) and can presently be found in Atlantic waters off the coast of New York (P.C. Reid, pers. comm.). A Pacific grey whale that was spotted off the coasts of Spain and Israel last year is also presumed to have migrated through the Northwest Passage (Scheinin *et al*., 2011). Because the Arctic ice is expected to reduce further during the next 100 years (Slagstad *et al*., 2011), **such trans-Arctic migrations** of marine plants and animals are likely to become more common. Based on the strong impacts of a previous invasion of Pacific organisms on the Atlantic marine communities approximately 2 million years ago, this is likely to alter the present species composition of the northern North Atlantic (Reid *et al*., 2007) with considerable consequences.

5.1.4 Northward Movements of Marine Organisms

Global warming is expected to drive many marine species towards the poles (Parmesan & Yohe, 2003) as has been observed under similar warming conditions during prehistoric times (Fields *et al*., 1993). For European seas, this expectation is corroborated by a suite of observations on **northward movements** of marine organisms as the result of recent warming. At high latitudes, fish such as cod, haddock and herring have expanded northward and eastward (Drinkwater, 2010). Blue whiting has extended northward as far as the south-western Barents Sea (Dolgov *et al*., 2010). Blue mussels (*Mytilus edulis*) have penetrated the Baltic and appeared in Svalbard following a 1,000 year absence (Berge *et al*., 2005). Warmer water groups of plankton to the west of the British Isles have moved north by approximately 1,000 km during the last 40 years (Beaugrand *et al*., 2002), whilst mid-water to surface-water fish have shown similar northerly extensions in their ranges (Brander *et al*., 2003). In the North East Atlantic, the Balearic shearwater (*Puffinus mauretanicus*) has shown a rapid northward expansion, most probably following its main prey species, the anchovy, *Engraulis encrasicholus,* and the sardine, *Sardina pilchardus* (Wynn *et al*., 2007).

Because not all species have migrated at the same speed and direction, the northward movements result

[5]See www.nsidc.org

in local changes in **community composition and species richness**. For example, Atlantic associated benthic species have expanded while Arctic species declined (Berge *et al*., 2005) and cases of local replacement have been reported for the Mediterranean (Galil, 2007). In the North Sea, the increase in southern species occurred at a higher rate than the decrease in northern ones, resulting in a local increase in biodiversity (Hiddink & Ter Hofstede, 2008; Beukema & Dekker, 2010). In the Celtic Sea, species richness of fish increased due to increases in the number of warm-favouring Lusitanian species. In the area west of Scotland, species richness decreased because the number of cold-favouring Boreal species decreased (Ter Hofstede *et al*., 2010). In the Black Sea, the numbers of new Mediterranean species that establish themselves in these waters is increasing (Shiganova & Öztürk, 2010). In the Mediterranean, species richness is increasing mainly as the result of introduction and colonization of species with a (sub) tropical affinity, favoured by climate warming (Zenetos, 2008 & 2010).

Bioclimatic models of the ranges of marine organisms in 2050 suggest **further poleward shifts** because of climate change. Average speeds of population shift for demersal species may exceed 4 km yr^{-1} in the central North Sea and the Nordic Seas. Projected shifts for pelagic species are foreseen to be more rapid than demersal species, up to 6 km yr^{-1} in the mid-Atlantic, due to the higher motility of pelagic species and larger changes in ocean conditions in the surface layer. Rates of shift can be more than double in a high-range climate change scenario compared to a low-range scenario, suggesting that limiting greenhouse gas emissions will allow more time for species to adapt to new circumstances (Pereira *et al*., 2010).

5.1.5 Shifts in Timing

Global warming has affected the **timing of life-cycle events** of many marine plants and animals. In the North Sea, for example, meroplankton has advanced its appearance by 27 days, dinoflagellates and diatoms peak 23 days earlier and copepods about 10 days earlier when compared to 45 years ago (Edwards & Richardson, 2004). Warming of the Black Sea resulted in a shift from seasonal immigration for spawning and feeding to overwintering of two fish species, namely the dorado (*Sparatus aurata*) and salema (*Sarpa salpa*) (Shiganova & Öztürk, 2010).

If sensitivity to temperature of organisms differs from one trophic level to the next, climate change may lead to a **decoupling of trophic interactions**. Such climate-induced mismatches in trophic transfer have been observed for phytoplankton and zooplankton (Beaugrand & Reid, 2003; Wiltshire & Manley, 2004), for zooplankton and fish, (Edwards & Richardson, 2004), for bivalve larvae and shrimp (Philippart *et al*., 2003), and for fish and seabirds (Durant *et al*., 2003). This reduction of food supply has had consequences for the predator species. For example, in the past 40 years, the warming of the North Sea has affected cod recruitment via changes at the base of the food web (Beaugrand *et al*., 2003).

5.1.6 Multiple Stressors

Humans impact on natural systems in a multitude of ways, yet the cumulative effect of multiple stressors on ecological communities remains largely unknown. Crain *et al*. (2008) synthesized almost 200 laboratory studies that manipulated two or more stressors in marine and coastal systems and found that cumulative effects in individual studies were either additive (equal to the sum; 26 %), synergistic (larger than the sum; 36 %), or antagonistic (less than the sum; 38 %). With regard to European seas and oceans, at least the following human impacts on marine systems are thought to be **cumulative** to the direct impacts of global warming: (i) ocean acidification; (ii) oxygen depletion; (iii) eutrophication; and (iv) fisheries.

Since the beginning of industrialisation, the ocean has taken up approximately one third of the total anthropogenic CO_2 emitted to the atmosphere (Khatiwala *et al*., 2009). As the result of the weak acidity of CO_2, the mean pH of the ocean surface waters is already 0.1 pH unit lower compared to pre-industrial times, and expected to decrease by 0.4 units by the year 2100 (Caldeira & Wickett, 2003), under a 'business as usual' scenario for global greenhouse gas emissions. This **acidification** of the ocean is expected to have profound consequences for marine biota (Gehlen *et al*., 2010), because it limits the possibilities for marine organisms to synthesize skeletal materials (Gattuso & Hansson, 2010) and enhances photosynthesis in some phytoplankton species (Rost *et al*., 2008).

The open ocean is losing oxygen as the result of a decrease in oxygen solubility, increased stratification and weakened ventilation, and an increase in biological respiration. Such **de-oxygenation** affects marine organisms if seawater oxygen levels drop below species-specific thresholds. Climate simulations over the next few centuries predict an overall decline in oxygen concentrations and an expansion of the mid-depth oxygen minimum zones (Keeling *et al*., 2010). The combination of sustained coastal hypoxia, caused by eutrophication, and climate change could enlarge the 'dead zones' in coastal seas which are characterised by the absence of benthic fauna and fish.

Coastal **eutrophication** has become a widespread phenomenon during recent decades. Nutrient-enrichment of coastal seas is related to precipitation patterns and land use (Scavia *et al*., 2002). Eutrophication generally results in an increase of primary production in coastal seas (Smith, 2006) and oceans (Beman *et al*., 2005), which may counteract the impacts of acidification (Borges & Gypens, 2010) and enhance the impacts of de-oxygenation (Kemp *et al*., 2005; Conley *et al*., 2009). Changes in primary production may further affect the biomass (Herman *et al*., 1999) and species composition of estuarine communities (Philippart *et al*., 2007), and subsequently of fisheries yields (Nixon, 1995).

Marine **fisheries** have impacted targeted and non-targeted invertebrates and fish by reducing their abundance, spawning potential and, possibly, population parameters such as growth and maturation (Dayton *et al*., 1995; Kaiser *et al*., 2007). In the northern hemisphere, global landings have shifted from large piscivorous fishes to smaller invertebrates and planktivorous fishes during recent decades, resulting in a shift in community structure at sea (Pauly *et al*., 1998). In the area west of Scotland, a potential effect of fisheries, in addition to temperature change, on the observed change in species richness can not be ruled out (Ter Hofstede *et al*., 2010). The consequent decline in population characteristics, such as age at first spawning and age distribution, and species richness is considered to make marine ecosystems more susceptible to other drivers such as climate change (Hughes *et al*., 2007; Perry *et al*., 2008).

Many seas of Europe have experienced the introduction and establishment of **non-indigenous species** as the result of migration, discharge of ballast water, and aquaculture. The impact of invasions on the functioning and resilience of the ecosystem towards climate change depends on the abundance and the role of the new species within the existing communities. Some new-comers in the Baltic and North Sea have had significant effects after previous invasions in other seas, such as the North American jelly comb *Mnemiopsis leidyi* in the Black Sea (Oguz *et al*., 2008).

5.1.7 Socio-Economic Consequences

Sea-level rise represents a threat for populations of all low-lying areas of Europe. Some countries such as the United Kingdom, France and the Netherlands, however, are considered less vulnerable as the result of their relatively high gross domestic product (GDP), which enables them to adapt through dike construction and beach nourishment (Tol *et al*., 2008; Richards & Nicholls, 2009). Sea-level rise without the building of coastal protection could wipe out entire countries, causing sea floods, massive economic damage, large movements of populations from inundated areas, salinity intrusion and loss of wetlands including the ecosystem services that they provide (Tol, 2007). In the absence of adaptation, the costs of a 44 cm sea-level rise could reach 12×10^9 Euro yr^{-1} in 2100 (Hinkel *et al*., 2010). This figure might underestimate actual costs, because it does not include the economic consequences of lost (agricultural) land such as changed consumer prices, the low probability / high consequence possibilities of flooding events, increased storminess and the role of ice-sheet melt.

The **biological pump** is the process by which CO_2 fixed by photosynthesis is transferred to the deep ocean resulting in storage of carbon for periods of decades to centuries, or even much longer, in the sediments. Permanent storage may be in the form of organic matter or calcium carbonate. Changes in temperature, ocean circulation and ocean chemistry (e.g. acidification) will affect species composition of the plankton in the open ocean and, subsequently, the removal of atmospheric CO_2 by the ocean. This biological process may enhance or dampen the impacts and socio-economic consequences of climate change as the result of the increase of greenhouse gases in the atmosphere.

Global warming and ocean acidification are expected to affect **commercial fishing** via alterations in the size of the fish stocks, their distribution, catchability and the prices of fish (ACIA, 2005; Aaheim *et al*., 2009). Although changes in management of fish stocks generally have a more profound impact than potential climate change impacts (Eide, 2008), climate change may introduce larger or more rapid changes than can readily be accommodated. Some loss of fish stocks may be compensated by stock development of other species, but this compensation may be insufficient to result in a profitable industry (Link & Tol, 2009; Kuhlbrodt *et al*., 2009). Empirical bioclimatic envelope models have projected that low latitude countries will lose potential fisheries yield, whilst the fisheries of higher latitude countries might benefit from climate change (Cheung *et al*., 2010). At present, more mechanistic models are being developed, which take into account interspecific interactions, size classes (Barange *et al*., 2010) and functional groups (Brown *et al*., 2004) or based upon the activities and dynamics of individual organisms (Vikebo *et al*., 2005), which may shed a different light on the consequences of climate change on fish stocks.

5.2 Future Knowledge

5.2.1 Introduction

The European research projects described in this report have identified important **gaps in knowledge** which, when filled, could significantly increase the understanding of the current developments and the accuracy of predictions of future patterns of climate change and its impact on marine environments. In general, the development of improved methods to reduce the uncertainty of climate change projections, a continuous follow-up of the accuracy of predictions, actual measurements by means of an integrated monitoring network, and a further improvement of the exchange of knowledge between scientists and between science and policy development, will be essential to inform and better formulate adaptive strategies to address the inevitable consequences of climate change.

5.2.2 Further Improvement of Predictions

Present research on the impacts of climate change on marine ecosystems has revealed that there are some **major environmental processes and trends of global importance whose future trajectory is unknown**, such as the Greenland melt water run-off, the strength of the Atlantic Meridional Overturning Circulation, and the efficiency of the biological pump. Projections of consequences of climate change on marine ecosystems would strongly benefit from a reduction of such uncertainties.

Current **modelling approaches** such as numerical models (used for coastal erosion) and empirical models (used for fish stocks) may not be sufficiently accurate for quantitative predictions of the consequences of climate change. Therefore, new approaches to study the effects of climate change are being explored, such as 3D baroclinic ocean climate models for projections of sea temperature and individual-based models for projections of fish stocks.

In spite of the need for local information on climate and weather developments, such as storm tracks, only a very limited number of **downscaling** regional climate models has been used, due to their large uncertainties. In addition to the enhancement of the resolution in ocean climate models, there is a clear need for **coupling** of models which describe different processes (e.g., river basin models, ecosystem models, fisheries models) with the aim of testing interacting effects, the synergy between simultaneous changes, the role of multiple stressors and possible feedbacks (Thieu *et al.*, 2010).

To improve the accuracy of the knowledge on the direction and rate of change, there is a need for further **mechanistic understanding** of possible responses to climate change of hydrological, geological, chemical and ecological properties and processes of the sea. For example, our understanding of the effects of warming on Arctic communities and the responses of marine life forms to ocean acidification is still in its infancy. Furthermore, the concepts of resilience and thresholds, and their possible consequences for projections of climate change, are only starting to be unravelled.

5.2.3 Development of a Robust and Efficient Integrated Monitoring System

Much of the present knowledge on the impacts of climate change on marine ecosystems was gained from **long-term field observations** on the hydrological, chemical and biological state of the seas and oceans. Europe-wide examples are the Permanent Service of Mean Sea-level, the Global Sea-level Observing System (GLOS), the international Argo floats program, the Global Monitoring of the Environment and Security, the Global Earth Observation System of Systems (GEOSS) and the Continuous Plankton Recorder (CPR) programme. A further integration and improvement of oceanic, atmospheric, geochemical and biological observational techniques and of monitoring networks would contribute to an improved understanding of the various components of climate change.

Major gaps in the monitoring efforts should be identified and filled. Such gaps in systematic observations are found in some geographical areas, such as the Arctic, the deep sea, and the riparian countries of the Black Sea, and in properties of marine systems. Many of the observations target the physical and geochemical properties of the seas such as temperature, salinity, currents, sea-level, pH and oxygen concentrations. In order to understand the impacts of climate change on marine flora and fauna, and the possible feedbacks, similar emphasis should be put on monitoring of biological variables such as the pelagic primary production, trophic transfer rates, migratory behaviour, and physiological stress.

5.3 Conclusions

Extensive EU-funded research has provided a **wealth of information** on how climate change affects marine systems at various spatiotemporal scales, ranging from long-term global effects of CO_2 concentrations on the biosphere to the immediate effects of local temperatures on the metabolism of bacteria. European scientists have contributed to major scientific breakthroughs, for example within the field of arctic research or on the mechanisms and consequences of ocean acidification. In addition, European scientists and consortia have contributed extensively to the Working Groups and Synthesis Reports of the IPCC, e.g. climate projection simulations by EC-Earth. Furthermore, much has been learned from regional climate research initiatives such as those for the Baltic Sea (BALTEX), the North Sea (BASIN, RECLAIM), and the Mediterranean (MedCLIVAR, SESAME).

Climate change is a global phenomenon that affects local marine ecosystems via a cascading range of physical, chemical and biological processes acting at different scales. Attribution and prediction of climate impacts require that the dominant processes across all scales should be identified and included. However, most studies on climate change impacts on the marine environment focus only on a limited part of the full spatiotemporal range, i.e. limited to a particular scale in space or time. All relevant research disciplines (e.g. meteorology, oceanography, biogeochemistry and ecology) are required to cover full cascading chains. To improve the accuracy of scenarios on the impacts of climate change on marine systems, the cascading chains under focus must be linked to the interacting scales in time and space of socio-economic systems governing the response of society. Therefore, further studies will need to include the social, economic and humanities sciences to allow the formulation and implementation of truly integrated and complete adaptation responses. We recommend increasing efforts using a **multidisciplinary approach** considering the most appropriate range in **spatiotemporal scales** to further understand and predict the inevitable impacts of climate change on marine environments.

5.4 References

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Annex 1 List of abbreviations and acronyms

Projects are given with weblink (if available)

ACES	The Atlantic Coral Ecosystem Study (http://www.ecoserve.ie/projects/aces/)
ACIA	Arctic Climate Impact Assessment
ADCP	Acoustic Doppler Current Profile
AM	Adapting Mosaic
AMO	Atlantic Multi-decadal Oscillation
ANCORIM	Atlantic Network for Coastal Risk Management
AO	Arctic Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
AOU	Apparent Oxygen Utilisation
AR	IPCC Assessment Report
ASOF	Arctic/Subarctic Ocean Fluxes
ATLANTIS	Atlantic sea-level rise: adaptation to imaginable worst case climate change
AVHRR	Advanced Very High Resolution Radiometer
AVOID	Can we avoid dangerous climate change? (www.avoid.uk.net)
AWI	Alfred Wegener Institute for Polar and Marine Research, Germany
BACC	BALTEX Assessment of Climate Change for the Baltic Sea Basin
BALTEX	Baltic Sea Experiment (http://www.baltex-research.eu)
BASIN	Basin-scale Analysis, Synthesis, and Integration (http://www.na-basin.org)
BATS	Bermuda Atlantic Time-series Study
BIOCOMBE	The Impact of BIOdiversity changes in COastal Marine Bentic Ecosystems (www.nioo.knaw.nl/projects/biocombe)
BONUS	Baltic Sea Research and Development Programme (http://www.bonusportal.org)
BOOS	Baltic Operational Oceanography System
BOSS4GMES	Building Operational Sustainable Services for GMES (http://www.boss4gmes.eu)
BSC-SoE	The Black Sea State of the Environment Report
CARBOOCEAN	Marine Carbon Sources and Sinks Assessment (http://www.carboocean.org)
CCI	ESA Climate Change Initiative
CEA	French Alternative Energies and Atomic Energy Commission
Cefrem	CEntre de Formation et de Recherche sur l'Environnement Marin, France
CENSOR	Climate variability and El Niño southern oscillation: implications for natural coastal resources and management (http://www.censor.name)
CIESM	Mediterranean Science Commission
CIL	Cold Intermediate Layer
CLAMER	Climate Change and Marine Ecosystem Research (http://clamer.eu)
CLIMSAVE	Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe (http://www.climsave.eu)
CLIVAR	Climate Variability and Predictability (http://www.clivar.org)
CMIP5	Coupled Model Intercomparison Project Phase 5 (http://cmip-pcmdi.llnl.gov/cmip5/)
CNES	Centre National d'Etudes Spatiales, France
CNRS	National Centre for Scientific Research, France
Coast3D	Coastal Study of Three-dimensional San Transport Processes and Morphodynamics (http://www.frw.ruu.nl/fg/coast3d/Welcome.html)
CODYSSEY	Cod spatial dynamics and vertical movements in European waters and implications for fishery management (http://www.codyssey.co.uk)
COMBINE	Comprehensive Modelling of the Earth System for Better Climate Prediction and Projection (http://www.combine-project.eu)
CORALFISH	Assessment of the interaction between corals, fish and fisheries in the deep waters of Europe and beyond (http://eu-fp7-coralfish.net)
CPR	Continuous Plankton Recorder

DAMOCLES	Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (http://www.damocles-eu.org)
DEEPSETS	Deep-sea & Extreme Environments, Patterns of Species and Ecosystem Time Series (http://www.marbef.org/projects/deepsets/)
DEFINEIT	Developing fisheries management indicators and targets (http://www.defineit.dk)
DINAS-COAST	Dynamic and interactive assessment of national, regional and global vulnerability of coastal zones to climate change and sea-level rise
DIVA	Dynamic Interactive Vulnerability Assessment
DMI	Danish Meteorological Institute
DOC	Dissolved organic carbon
DOM	Dissolved Organic Matter
DRA	Data Release Area
DYNAMITE	Understanding the Dynamics of the Coupled Climate System (http://dynamite.nersc.no)
EAC	European Arctic Corridor
EAP	East Atlantic Pattern
EAWR	East Atlantic West Russia
EC	European Commission
EC-Earth	Developing a European Earth System model based on ECMWF modelling systems
ECMWF	European Centre for Medium-Range Weather Forecasts
ECO2	Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (http://www.eco2-project.eu)
ECODRIVE	Ecosystem Change in the North Sea: Processes, Drivers and Future scenarios (http://www.io-warnemuende.de/ecodrive.html)
ECOOP	European Coastal sea Operational observing and Forecasting system
ECV	Essential Climate Variables
EEA	European Environment Agency
EELIAD	European eels in the Atlantic: Assessment of their decline (www.eeliad.com)
ELME	European Lifestyles & Marine Ecosystems (http://www.elme-eu.org)
EMODNET	European Marine Observation and Data Network
EMSA	European Maritime Safety Agency
ENSEMBLE	ENSEMBLE based predictions of climate change and their impacts (www.ensembles-eu.org)
ENSO	El Niño-Southern Oscillation
EPOCA	European Project on Ocean Acidification (http://www.epoca-project.eu)
EPOCH	European Programme On Climatology and natural Hazards
ERA40	ECMWF 45-year reanalysis of the global atmosphere and surface conditions 1957-2002
ERA-NET	European Research Area Network (EU FP scheme)
ESA	European Space Agency
ESF	European Science Foundation
ESONET	European Seas Observatory NETwork (http://www.esonet-noe.org)
ESTOC	European STation for time series in the OCean
EU	European Union
EUCAARI	European Integrated Project on Aerosol Cloud Climate Air Quality Interactions (http://www.atm.helsinki.fi/eucaari/)
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
Euro-Argo	European Contribution to Argo Programme (www.euro-argo.eu)
EURO-BASIN	European Union Basin-scale Analysis, Synthesis and Integration (http://www.euro-basin.eu)
EUROCAT	European Catchments - Catchment changes and their impact on the Coast
EUR-OCEANS	EURopean network of excellence for Ocean Ecosystems Analysis (www.eur-oceans.eu)

Annex 1 List of abbreviations and acronyms

EuroGOOS	The European Global Observing System
EURO-LIMPACS	Integrated Project to Evaluate the Impacts of Global Change on European Freshwater Ecosystems
Eurosion	European Initiation for Sustainable Coastal Erosion Management (http://www.eurosion.org/index.html)
EuroSITES	European Ocean Observatory Network (http://www.eurosites.info)
EVERANS	Evaluation of the Efficiency of Artificial Reefs by Advanced Numerical Simulations – Towards Environmentally Friendly Coastal Protection
FEUFAR	Future of European Fisheries and Aquaculture Research (http://www.feufar.eu)
FP	EU Framework Programme for Research and Technological Development
FutureCoast	Predicting the Future Coastal Evolution of England and Wales
GCMs	Global Circulation Models
GDP	Gross Domestic Product
GELATO	Global Experimental Leads and ice for ATmosphere and Ocean
GEOSS	Global Earth Observation System of Systems
Global NEWS	Global Nutrient Export from Water Sheds (http://marine.rutgers.edu/globalnews/index.htm)
GLOBEC	Global Ocean Ecosystem Dynamics
GLOSS	Global Sea-level Observing System
GMES	Global Monitoring for Environment and Security
GNP	Gross National Product
GO	Global Orchestration
GODESS	Gotland Deep Environmental Sampling Station
GOOS	Global Ocean Observing system
GPP	gross primary production
GRACE	Gravity Recovery and Climate Experiment
GREENSEAS	Development of global plankton data base and model system for eco-climate early warning
GYROSCOPE	Development of a real time *in situ* observing system in the North Atlantic Ocean, by an array of lagrangian profiling floats (http://www.ifremer.fr/lpo/gyroscope/)
HAB	Harmful Algal Bloom
HCMR	Hellenic Centre for Marine Research, Greece
HELCOM	Baltic Marine Environment Protection Commission (Helsinki Commission)
HERMES	Hot-Spot Ecosystem Research on the Margin of European Seas (http://www.eu-hermes.net)
HERMIONE	Hotspot ecosystem research and Man's impact on European seas (http://www.eu-hermione.net/)
HNLC	High-Nutrient, Low-Chlorophyll
HOT	Hawaii Ocean Time-series
HYPER	HYPoxia mitigation for Baltic Sea Ecosystem Restoration (http://hyper.dmu.dk)
HYPOX	*In situ* monitoring of oxygen depletion in hypoxic ecosystems of coastal and open seas, and land-locked water bodies (www.hypox.net)
IASC	International Arctic Science Committee
IBM	Individual Based Models
Ice2Sea	Estimating the future contribution of continental ice to sea-level rise (http://www.ice2sea.eu)
IceBridge	Airborne Mission for Earth's Polar Ice
ICESat	Ice, Cloud, and land Elevation Satellite
ICZM	Integrated Coastal Zone Management
IGBP	International Geosphere-Biosphere Programme

IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IMCORE	Innovative Management for Europe's Changing Coastal Resource (http://www.imcore.eu)
IMR	Institute of Marine Research, Norway
IN EX FISH	Incorporating Extreme Drivers into Fisheries Management (http://www.liv.ac.uk/inexfish/index.html)
INFLOW	Holocene saline water inflow changes into the Baltic Sea, ecosystem responses and future scenarios (http://www.bonusportal.org/inflow)
INTERREG	Interregional Cooperation Programme
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
IRONAGES	Iron Resources and Oceanic Nutrients - Advancement of Global Environment Simulations (http://www.nioz.nl/nioz_nl/d0e54483aa31c55b01a9fb11c0c23df4.php)
ISIS	*In situ* Iron Studies
JRC	Joint Research Centre
KNAW	Royal Netherlands Academy of Arts and Sciences, the Netherlands
KNOWSEAS	Knowledge-based Sustainable Management for Europe's Seas (http://www.knowseas.com)
LargeNET	Large-Scale and Long-Term Networking of Observations of Global Change and Its Impacts on Marine Biodiversity (http://www.marbef.org/projects/largenet/index.php)
LSCE	Laboratoire des Sciences du Climat et l'Environnement, France
L-TER	Long-TERm ecological monitoring (http://www.ilternet.edu)
MAIA	Monitoring the Atlantic Inflow toward the Arctic
MAP	Mediterranean Action Plan
MarBEF	Marine Biodiversity and Ecosystem Functioning (http://www.marbef.org)
MariFISH	Strengthening the links between European marine fisheries science and fisheries management (http://www.marifish.net)
MarinERA	Facilitating Cooperation between National Marine RTD Programmes in Europe (http://marinera.seas-era.eu)
MARNET	Marine Environmental Monitoring Network in the North Sea and Baltic Sea
MBI	Major Baltic Inflow
MCCIP	Marine Climate Change Impacts Partnership
MedCLIVAR	Mediterranean CLImate VARiability and Predictability (http://www.medclivar.eu)
MEDPOL	Marine pollution assessment and control component of MAP
MEECE	Marine Ecosystem Evolution in a Changing Environment (www.meece.eu)
MERGE	A Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (http://www.stanford.edu/group/MERGE/)
MERSEA	Marine Environment and Security for the European Area (http://strand1.mersea.eu.org/index.html)
MICORE	Morphological Impacts and Coastal Risks induced by Extreme storm events (www.micore.eu)
MOC	Meridional Overturning Circulation
MyOcean	Ocean Monitoring and Forecasting (http://www.myocean.eu.org)
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration, United States of America
NATARISE	Natural and artificially influenced swash-groundwater interactions experiments
NCEP	National Centers for Environmental Prediction

Annex 1 List of abbreviations and acronyms

NCP	North Sea - Caspian pattern
NERC	National Environment Research Council, United Kingdom
NIOO-KNAW	Netherlands Institute of Ecology
NIOZ	Royal Netherlands Institute for Sea Research
NOAA	National Oceanic and Atmospheric Administration, United States of America
NOC	National Oceanographic Centre, United Kingdom
NOCES	Northern Ocean-atmosphere Carbon Exchange Study
NoE	Network of Excellence (EU FP Scheme)
NPZD	nutrient-phytoplankton-zooplankton-detritus
NW	North-Western
OGCM	Oceanic General Circulation Model
OIF	Ocean Iron Fertilisation
OMEX	Ocean Margin Exchange
OSPAR	Oslo and Paris Conventions for the protection of the marine environment of the North-East Atlantic
PAP	Porcupine Abyssal Plain
PEGASO	ICZM Project for the Mediterranean and the Black Sea (http://www.pegasoproject.eu)
PESETA	Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis (http://peseta.jrc.ec.europa.eu)
PML	Plymouth Marine Laboratory, United Kingdom
POC	particulate organic carbon
POSEIDON	Monitoring, Forecasting and Information System for the Greek Seas (http://www.poseidon.hcmr.gr)
PP	primary production
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects (http://prudence.dmi.dk)
QUANTIFY TTC	Quantifying the Climate Impact of Global and European Transport Systems – Extension
QUANTIFY	Quantifying the Climate Impact of Global and European Transport Systems (http://www.pa.op.dlr.de/quantify/)
RAPID	Rapid Climate Change (http://www.noc.soton.ac.uk/rapid/rapid.php)
RAPID-WATCH	Rapid Climate Change – Extension (http://www.noc.soton.ac.uk/rapid/rw/)
RECLAIM	Resolving Climatic Impacts on fish stocks (http://www.climateandfish.eu)
RUSALCA	Russian-American Long-term Census of the Arctic
SALSEA	International Atlantic Salmon Research programme
SCOR	Scientific Committee on Oceanic Research
SEADATANET	Pan-European Intrastructure for Ocean and Marine Data Management (http://www.seadatanet.org)
SEAMOCS	Applied Stochastic Models for Ocean Engineering, Climate and Safe Transportation (http://www.maths.lth.se/seamocs/)
SESAME	Southern European Seas: Assessing and Modelling Ecosystem changes (www.sesame-ip.eu)
SIMCOAST	Numerical Simulation Tools for Protection of Coasts against Flooding and Erosion
SIZ	Seasonal ice zone
SPM	Suspended Particulate Matter
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
STRATAGEM	Stratigraphical Development of the Glaciated European Margin
SUBCOAST	Assessing and Monitoring Subsidence Hazards in Coastal Lowland around Europe (http://www.subcoast.eu)

SUSFISH	Shellfish productivity in the Irish Sea (http://www.susfish.com)
SWE-CLIM	Swedish Regional Climate Modelling Programme
THC	Thermohaline circulation
THESEUS	Innovative coastal technologies for safer European coasts in a changing climate (http://www.theseusproject.eu)
THOR	Stability of Thermohaline Circulation (http://www.eu-thor.eu)
TRACTOR	TRAcers and Circulation in the NORdic Seas region (http://www.ices.dk/ocean/project/tractor)
UiB	University of Bergen, Norway
UK	United Kingdom
UMR	Unité Mixte de Recherche
UNEP	United Nations Environment Programme
US	United States (of America)
USA	United States of America
UVAC	The influence of uvr and climate conditions on fish stocks: a case study of the northeast arctic cod
WCMC	World Conservation Monitoring Centre of the United Nations Environment Programme
WCRP	World Climate Research Programme
WMDW	Western Mediterranean Deep Water

Marine Board Member Organisations

Marine Board-ESF

The Marine Board provides a pan-European platform for its member organisations to develop common priorities, to advance marine research, and to bridge the gap between science and policy in order to meet future marine science challenges and opportunities.

The Marine Board was established in 1995 to facilitate enhanced cooperation between European marine science organisations (both research institutes and research funding agencies) towards the development of a common vision on the research priorities and strategies for marine science in Europe. In 2011, the Marine Board represents 33 Member Organisations from 19 countries. The Marine Board provides the essential components for transferring knowledge for leadership in marine research in Europe. Adopting a strategic role, the Marine Board serves its member organisations by providing a forum within which marine research policy advice to national agencies and to the European Commission is developed, with the objective of promoting the establishment of the European Marine Research Area.

http://www.esf.org/marineboard

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