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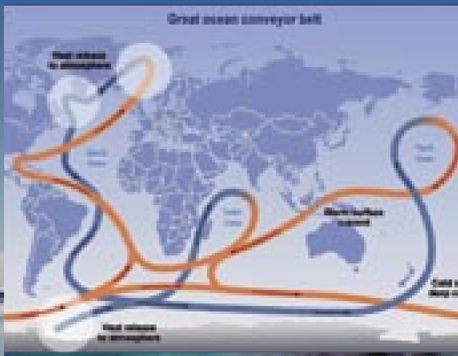
MARINE BOARD

Position Paper 9

Impacts of Climate Change on the European Marine and Coastal Environment

Ecosystems Approach

March 2007



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Impacts of Climate Change on the European Marine and Coastal Environment

Marine Board Position Paper 9

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Colonies of Phaeocystis globosa in the Wadden Sea. (Credit: J.M. van Iperen/NIOZ)

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The Marine Board operates by creating a forum for its Member Organisations, identifying strategic scientific issues, providing a voice for European marine science and promoting synergy in the management of both national programmes and research infrastructure facilities and investments.

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Foreword

The scientific evidence is now overwhelming that climate change is a serious global threat which requires an urgent global response, and that climate change is driven by human activity. The IPPC Report (2007) states that sea levels will rise by 3.1 cm every decade; the oceans have warmed to a depth of 3 km; Arctic summer sea-ice is likely to disappear in the second half of this century; up to 40% of species could face extinction; weather patterns will become more extreme; for example hurricanes and storms will become more intense. The Stern Review (2006) estimates the social and economic cost of climate change to the global economy at € 5,500 billion by 2050. The Stern Review concludes that, provided we take strong action now, there is still time to avoid the worst impacts of climate change.

Enough is now known to make climate change the challenge of the 21st century, and the research community is poised to address this challenge. The need for enhanced detection and assessment of the impacts of climate change on the oceans and their ecosystems has been emphasised in several recent publications (Stern 2006; Hoepffner, N *et al.* - JRC-IES 2006; IPCC 2007). Europe is warming at a faster rate than the global average, and the physical attributes of our seas are changing accordingly, with implications for the functioning of our regional climate and our marine environment. Therefore, in addressing the impacts of climate change on the oceans, Europe must pay particular attention to its regional seas. The diverse nature of Europe's regional seas, with the attendant diversity of expression of climate change impacts, represents a particular challenge for monitoring and management of climate change at the pan-European, regional and local levels. The changes in the marine environment will have a profound impact on the daily life of Europe's inhabitants, requiring forward planning in preparation for the changes. It is hoped that the report will contribute to this planning.

In 2005 the Marine Board established a working group of experts from different countries and disciplines, under the chairmanship of Dr Katja Philippart (NIOZ, the Netherlands), to address climate change impacts on the marine environment, with the objective of documenting the existing knowledge on, and implications of, climate change, with particular reference to **regional priorities and dimensions.**

The report of the Working Group **profiles an overview of the research needs and future scientific challenges of climate change at the both European- and regional-seas level, including the Arctic, Barents Sea, Nordic Seas, Baltic, North Sea, Northeast Atlantic, Celtic-Biscay Shelf, Iberia upwelling margin, Mediterranean and Black Sea.** The report identifies future research challenges in terms of climate change monitoring, modelling, and development of indicators. Its conclusions will support the development of future research strategies and inform the development of policy.

Throughout this position paper, 'climate change' is used to denote the recent predominantly human-induced change (principally the result of greenhouse gas emissions but also from urbanisation and deforestation) and climate variability due to random processes and natural causes such as volcanoes, solar radiation, and non-linear interactions between ocean and atmosphere (Hasselmann 1976).

On behalf of the Marine Board, I would like to thank the Working Group Chair, Dr Katja Philippart, and its expert participants, whose efforts resulted in a comprehensive overview of climate change-related impacts on Europe's regional seas. I would also like to thank SAHFOS-UK (David Johns and Priscilla Licandro) for providing, with support from the Marine Institute–Ireland, the maps of regional seas as well as graphs on long-term variation of sea-surface temperatures, and Nicolas Walter from the Marine Board Secretariat, who provided support to the Working Group.

Lars Horn
Chairman, Marine Board-ESF

Executive summary

Terms of reference

In September 2005, the Marine Board-ESF established a Working Group of experts to address Climate Change Impacts on the European Marine and Coastal Environment. The objectives of the Working Group were as follows:

1. Summarise the evidence for global climate change in the marine and coastal environment;
2. Review main anticipated impacts of climate change with regard to physical and biological features of the European marine and coastal environment;
3. Recommend to the Marine Board - ESF any future needs in terms of climate change monitoring, development of indicators, research and development to assess the impacts of climate change.

Socio-economic and mitigation issues were not within the terms of reference of this study.

Structure of the report

This is the final report of the Working Group. It summarises the current state of knowledge with regard to general and regional-specific impacts of climate change on European marine and coastal environments, including the Arctic, Northeast Atlantic, Barents Sea, Nordic Seas, North Sea, Baltic Sea, Celtic-Biscay Shelf, Iberian upwelling margin, Mediterranean Sea, and Black Sea. Results from earlier long-term studies of European seas are used to examine past changes, to put recent rapid changes into context, and to forecast likely future ecosystem responses to climate change. General and regional indicators of climate change are identified, and associated challenges for future research and monitoring are highlighted.

Evidence for climate change

Recent research, including the examination of ice cores and growth rings of ancient trees, shows that the Northern Hemisphere has been warmer since 1980 than at any other time during the last 2000 years. The observed increase in temperature under climate change was generally higher in northern than in southern European seas.

Although marine ecosystems are influenced by many factors such as eutrophication and overfishing, every region has shown at least some changes that were likely to be attributable to recent climate change. For the most northern seas, such as the Arctic and the Barents Sea, the most obvious temperature-related change is the decline in sea-ice cover. For most open seas there is evidence of geographic displacement of species populations northwards, with northern species being replaced by more southern species. Such changes not only impact on local ecosystems but also impact on the activities of the international fishing fleet when commercial species are affected.

The enclosed seas have noticeably undergone far more dramatic changes than the more open seas during the past decades. Relatively small changes in the frequency of inflow (as in the Baltic Sea) or in temperature (as in the Eastern Mediterranean and Black Sea) had a strong effect on large parts of the ecosystem, indicating the high sensitivity of these enclosed systems to climate change.

Anticipated impacts of climate change

Although there can be 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 associated major environmental and social impacts.

It is expected that within open systems there will generally be (further) northward movement of species, e.g. Atlantic species moving to more northern seas such as the Arctic, Barents Sea and the Nordic Seas, and subtropical species moving northward to temperate region such as the Iberian upwelling margin.

For seas that are highly influenced by river runoff, such as the Baltic Sea, an increase in freshwater due to enhanced rainfall will lead to a shift from marine to more brackish and even freshwater species. If enclosed systems such as the Mediterranean and the Black Sea lose their endemic species, the associated niches will probably be filled by species originating from adjacent waters and, possibly, with species transported from one region to another via ballast water.

Conclusions and recommendations

While on-going national and international actions to curtail and reduce greenhouse gas emissions are essential, the levels of greenhouse gases currently in the atmosphere, and their impact, are likely to persist for several decades. On-going and increased efforts to mitigate climate change through reduction in greenhouse gases are therefore crucial.

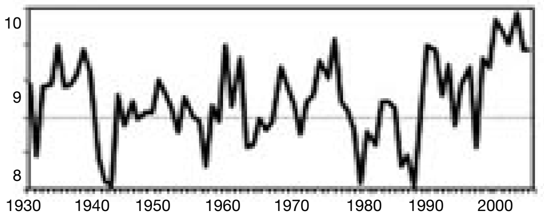
In parallel, a better understanding of potential climate change impacts (scenarios) at both regional and local levels, the development of improved methods to quantify the uncertainty of climate change projections, the construction of usable climate change indicators, and an improvement of the interface between science and policy formulation in terms of risk assessment will be essential to formulate and inform better adaptive strategies to address the inevitable consequences of climate change.

Executive summary

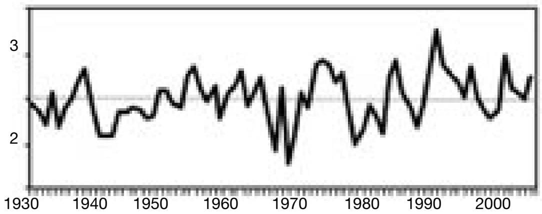
The Working Group identified specific recommendations on future monitoring and indicators and with regard to future research needs, which are described in Section 5 and Section 6 of this report, respectively. General recommendations were to:

1. Enhance evaluation of the impact of climate change on the European marine and coastal environment: this will require a concerted effort to gather, store and analyse previously and currently collected marine environmental data (e.g. common open access database and annual pan-European reporting based on national contributions);
2. Identify the nature and rate of consequences of climate change in European marine and coastal waters: this will require the maintenance of sustained monitoring efforts and use of new technologies to increase their spatial and temporal resolution;
3. Predict the consequences of climate change for our marine environment: this will require the development and measurement of parameters (e.g. indicators) which are indicative of the underlying mechanisms of climate-induced changes;
4. Predict the response and feedback of marine environments and ecosystems to climate change: this will require the improvement of regional climate models and the development of biophysical models;
5. Predict the impact on climate change on the distribution of marine organisms and on marine food webs: this will require the inclusion of knowledge on species' physiology, bioenergetics and behaviour in biophysical and ecosystem models.

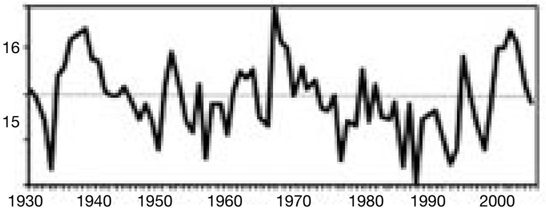
Baltic Sea



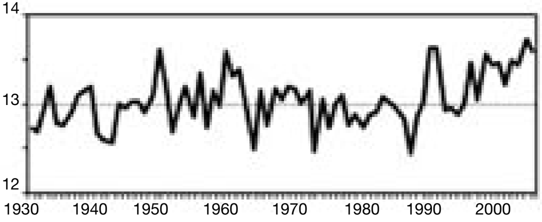
Barents Sea



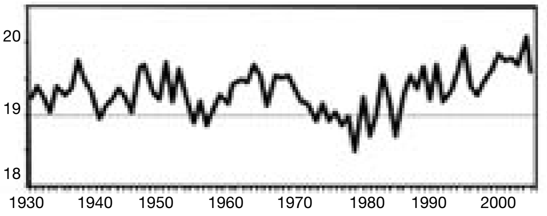
Black Sea



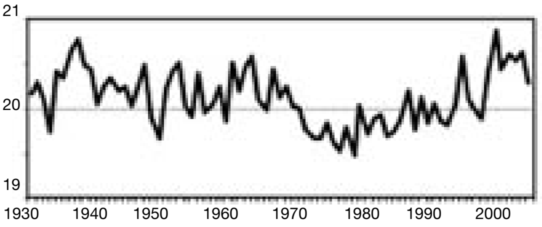
Celtic-Biscay shelf

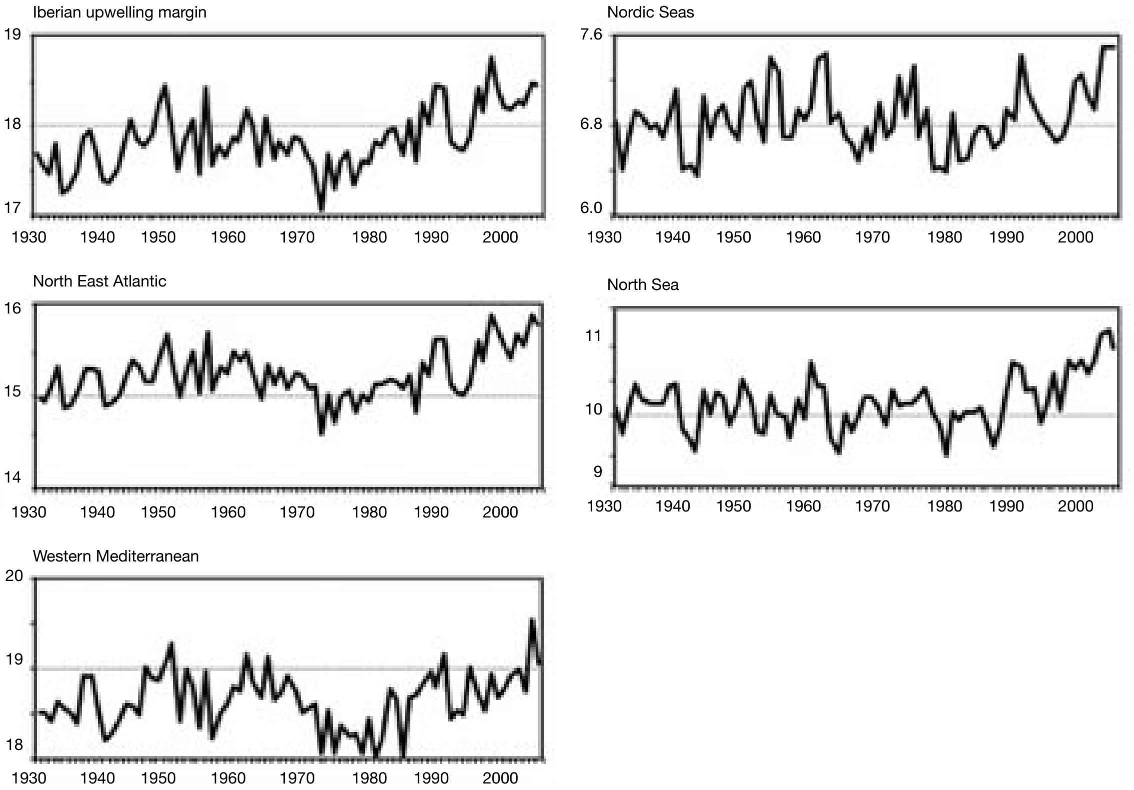


Central Mediterranean



Eastern Mediterranean





Signals: Long-term variation in area-averaged sea-surface temperatures (°C) in European marine and coastal environments based on HadSST2 data from the Hadley Centre, UK (data compiled by Priscilla Licandro/SAHFOS and Katja Philippart/NIOZ).

Potential Impact: Summary of scenarios of effects of climate change on European Seas

GENERAL TRENDS	SEA-SPECIFIC EXPECTATIONS
Increase in temperature	Higher in northern than in southern seas
Impacts on ecosystems	Stronger for enclosed than for open seas
Northward movements	Stronger in southern than in northern seas
	Stronger in open than in enclosed seas
Shifts in species composition	From northern to southern species (open seas)
	From ice-bound to aquatic species (northern seas)
	From marine to freshwater species (Baltic Sea)
	From endemic to congeneric species (enclosed seas)

1. Climate change

1.1 Global change and climate change

> *'Global climate change will affect the physical, biological and biogeochemical characteristics of the oceans and coasts, modifying their ecological structure, their functions, and the goods and services they provide'.*
>
> *IPCC (2001b)*

Our world is changing rapidly. During the last 10-15 years, temperatures throughout much of the globe have been warmer than ever recorded; Arctic sea-ice is rapidly disappearing, melting of both glaciers and the Greenland ice cap is accelerating; enormous ice sheets from Antarctica are collapsing into the sea; sea levels are rising and seas are becoming stormier, increasing the risk of coastal flooding in low lying areas including major cities; precipitation is more variable with more frequent intense rainfall events leading to extensive flooding; the duration and severity of droughts has increased; hurricane intensity appears to be greater; springtime is occurring earlier; there is a poleward shift in the distribution of many species; and the number of harmful algal blooms in coastal regions appears to have increased. Many of these events are thought to be a consequence of a predominantly human-induced **climate change.**

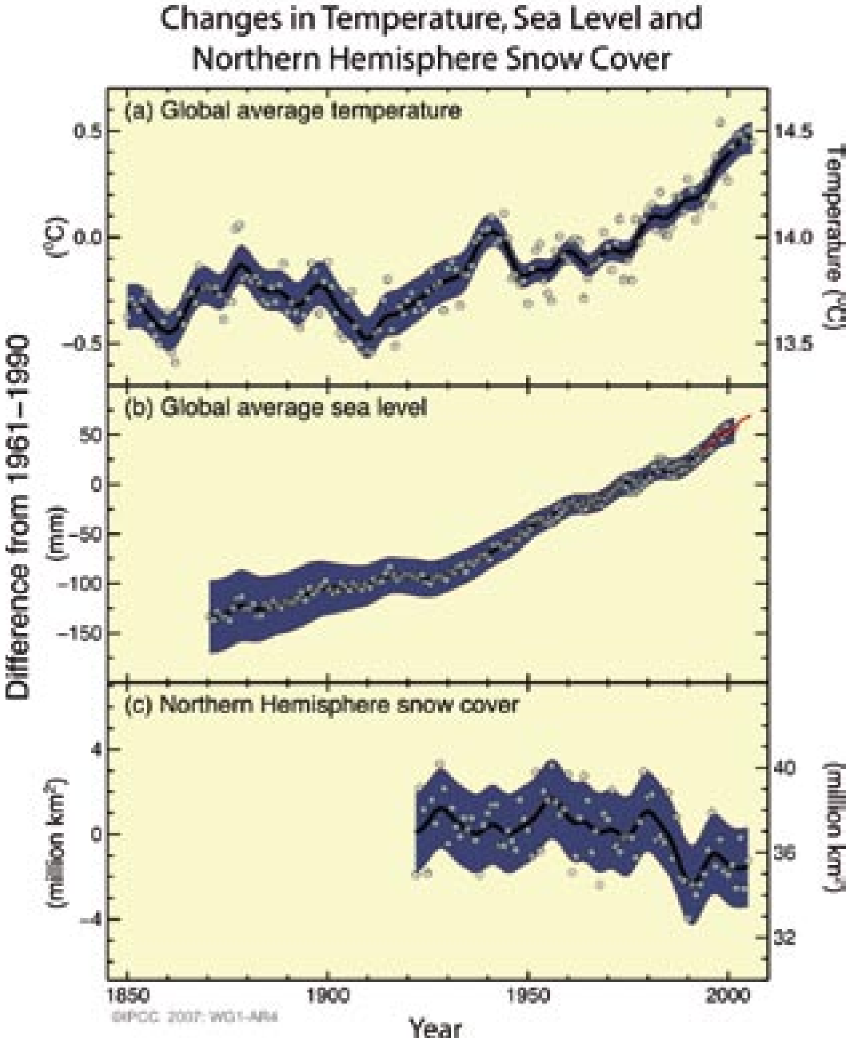
These changes have the potential to cause **serious socio-economic impacts** at both regional and local levels. Increased storminess, coastal inundation and flooding impact on maritime transport and on coastal infrastructure (urban development, road and rail networks). These impacts in turn have implications for future investments and strategies related to coastal developments and offshore construction (associated with oil and gas industry, trans-shipment and renewable ocean energy), not to mention increased insurance costs. Changes in species biogeography (i.e. the poleward movement of indigenous species and increased risk of invasions of non-indigenous species) have implications for commercial fisheries and aquaculture and on the design and implementation of effective conservation and environmental monitoring strategies.

Before the industrial age, **natural processes** such as solar variability, Milankovitch cycles and volcanic outgassing were the dominant forcing factors producing long-term climate changes over periods of decades, centuries and millennia. There is now convincing evidence that since the industrial revolution, human activities, resulting in increasing concentrations of **greenhouse gases** have become a major agent of climate change. These greenhouse gases affect the global climate by retaining heat in the troposphere, thus raising the average temperature of the planet and altering global atmospheric circulation and precipitation patterns. Climate change influences the oceans and coasts in various ways: through changes in temperature and sea level, ocean circulation, storminess and hence vertical mixing and wave regimes, all of which in turn can influence marine ecosystems and modify marine habitats. In this context one can expect changes in nutrient availability, biological productivity, phenology (the timing of biological events such as spawning), population biogeography and migratory patterns, community structure, and predator-prey relationships from the bottom to the top of the food web.

> *'The 2nd of February 2007 here in Paris will perhaps one day be remembered as the day when the question mark was removed behind the debate whether climate change had anything to do with human activities on this planet.'*
>
> *Steiner (IPCC Meeting Feb. 2007)*

Although species have responded to variations in climate throughout their evolutionary history, a primary concern for species and their ecosystems is the rapid rate of change currently observed (Root *et al.* 2003). Regional changes are often more relevant in the context of ecological responses to climate change than are global averages (Walther *et al.* 2002). Impacts of climate change should therefore not only be studied on ocean basin scales, but also at **regional and local scales.** Such regions encompass coastal areas from river basins and estuaries to the seaward boundaries of continental shelves and the outer margins of the major current systems.

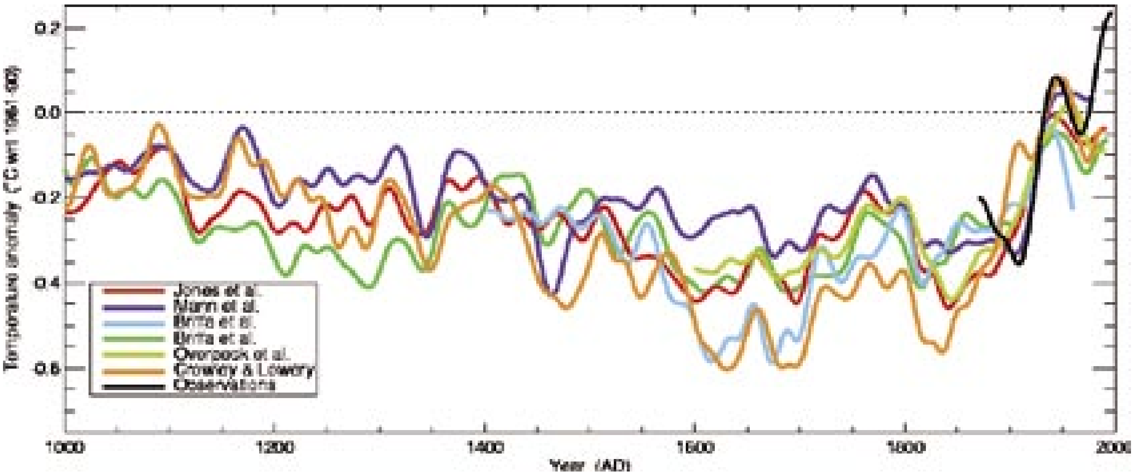
In addition to the specific characteristics of a particular region (e.g. coastal versus shelf seas), the response of marine systems to climate change will also depend on other human-induced changes in the marine environment. For example, fishing has reduced the number of large fish at higher trophic levels worldwide (Pauly *et al.* 1998; Jackson *et al.* 2001; Myers and Worm 2003), whilst increasing agricultural, industrial and household activities have resulted in nutrient enrichment of many coastal waters (Schindler 2006). These and other **global change-induced effects,** such as ocean acidification, contamination and the introduction of non-indigenous species, are likely to result in more fragile marine ecosystems, which will challenge the effectiveness of the management strategies to reduce the impacts of climate change.



Observed changes in (a) global mean temperature, (b) global average sea level rise from tide gauge (blue) and satellite (red) data, and (c) Northern Hemisphere snow cover for March-April. All changes are relative to the 1961-1990 average values. Dots represent yearly values, solid lines are 10-years running means, and shaded areas indicate the uncertainty intervals around the running means (International Panel on Climate Change 2007).

While national and international actions to curtail and reduce greenhouse gas emissions are being implemented, the levels of greenhouse gases currently in the atmosphere and their impacts are likely to persist for several decades. Accordingly, while on-going efforts to mitigate climate change through reductions in greenhouse gas emissions are crucial, a more proactive adaptive strategy is required. This could include a better understanding of potential climate change impacts at both regional and local levels **(scenarios),** the development of improved methods to quantify the **uncertainty of climate change projections,** the construction of usable **climate change indicators,** and an improvement of the **interface between science and policy** formulation in terms of risk management (American Meteorological Society 2003).

> *'Although there can be no certainty regarding the precise nature and rate of changes to the marine environment due to alterations in climate, in the absence of policies and measures to prepare for and accommodate the changes, even the more moderate of the predicted scenarios would have major social and economic impacts.'*
>
> *Boelens et al. (2005)*



The Millennial Temperature Record (© 2000, Climatic Research Unit).

1.2 Climate change and climate variability

> *'Recent research, including the examination of ice cores and growth rings of ancient trees, shows that the Northern Hemisphere has been warmer since 1980 than at any time during the last 2000 years.'*
>
> *Mann and Jones (2003)*
> *Moberg et al. (2005)*

Whilst weather conditions fluctuate daily, monthly and seasonally, **climatic regimes** vary on decadal to millennial time scales. The geological record shows that climate has changed significantly over time. For example, during the last Ice Age (which began 130 000 years ago, and ended 10 000 years ago) most of northern Europe was under snow and ice. In contrast, Europe experienced periods of significant warmth during medieval times (890-1170) and colder periods during the so-called Little Ice Age (1580-1850) (Osborn and Briffa 2006). In the last century there was a warm period (1930-1960s) followed by a cooler period (1970s) with temperatures rising again after 1980 (Johannessen *et al.* 2004). In other words, climate is always changing. However, today's concern is: are the observed changes in climate **beyond previously observed ranges**? If so, what will be the future rates of these changes and what are the **implication** for our world? The fourth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC 2007) concludes that 11 of the last 12 years rank among the 11 warmest years in the instrumental record of global surface temperature (since 1850). The total temperature increase from 1850-1899 to 2001-2005 is 0.76°C, and this increase in mainly due to the linear warming trend over the last 50 years of 0.13°C per decade. For the next two decades, a warming of about 0.2°C per decade is projected for a range of emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected mainly because of the slow response of the oceans in adapting to absorb these levels of greenhouse gases (IPCC 2007). Depending on the scenario applied, temperatures are predicted to rise by 1.8°C to 4.0°C in 2090-2099 as compared with 1980-1999 (IPCC 2007).

Because of the uncertainties outlined above, there is much speculation regarding associated changes in regional climatic conditions and the implications for aquatic and terrestrial ecosystems.

Box 1. Signals of large-scale interactions between Ocean and atmosphere

Two of the largest signals of ocean/atmosphere interaction are the El Niño-Southern Oscillation **(ENSO)** in the equatorial Pacific Ocean and the North Atlantic Oscillation **(NAO).** The latter is the Atlantic part of the Arctic Oscillation **(AO),** also called the Northern Hemisphere Annual Mode **(NAM)** (Delworth and Dixon 2000; Thompson and Wallace 1998, 2001). The atmospheric variability over the North Atlantic is predominantly determined by the NAO.

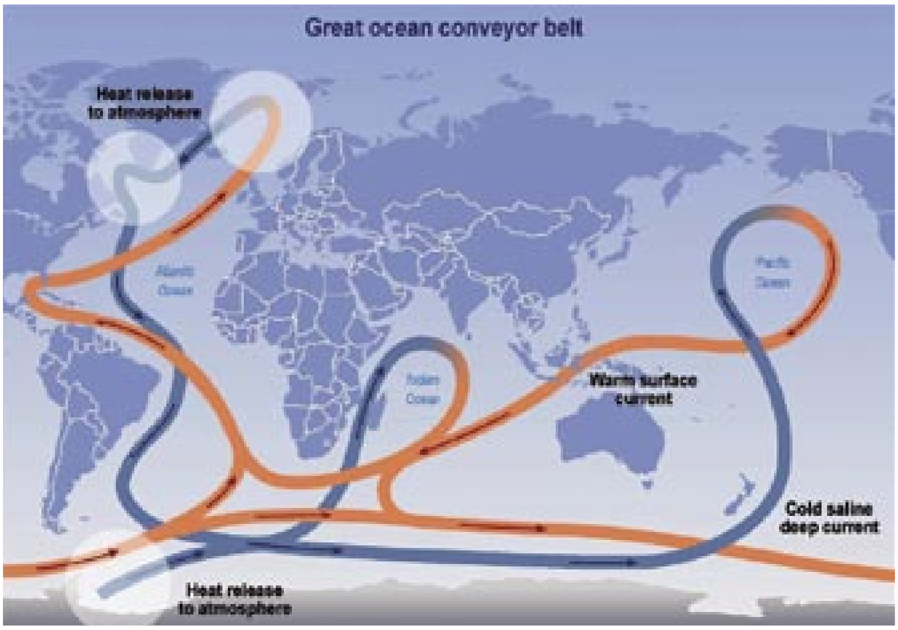
The **NAO index** is the difference in sea-level pressure anomalies between two stations representing the Azores High and the Icelandic Low pressure systems and is a measure of the strength of the westerly winds across the North Atlantic. During a positive NAO the westerly winds are stronger and conditions are colder and drier than average over the Northwest Atlantic (eastern Canada to Greenland) and the Mediterranean region, whereas conditions in northern Europe and the eastern United States are warmer and wetter than average. Winter temperature, precipitation, sea-ice distribution and movement in the Arctic, winter storminess, ocean wave heights, marine ecosystems, fisheries, sea-ice coverage in marginal seas, hurricane occurrence and tracks in the Caribbean and the severity of winters over an extensive area stretching from Siberia to central USA and Norway to Morocco have been shown to be modulated by the NAO (Marshall *et al.* 2001).

1.3 Role of the Oceans in climate regulation

The oceans play a key role in the regulation of climate. They store, distribute and dissipate energy from solar radiation and exchange with the atmosphere. In turn, the oceans are affected by the climatic conditions they help to create. Constituting more than 70% of the surface of the Earth, the oceans and shelf seas implement their role as a **regulator of climate:** as the main reservoir and distributor of heat and salt; by influencing weather patterns and storm tracks; as the primary water source on the globe and modulator of evaporation, precipitation and water vapour in the atmosphere; by contributing to the formation, distribution and melting of sea-ice; as the primary storage medium for greenhouse gases such as carbon dioxide (CO2), via an active biological system that plays a crucial role in the carbon cycle; and through rising sea levels and an increasing frequency of storm surges.

The oceans have an immense capacity to store heat (when compared with the atmosphere). They also show great variability in the concentration in salinity due to the changing balance between evaporation and precipitation. Spatial differences in temperature and salinity generate density-driven **circulation patterns** that redistribute water masses between the equator and the poles. In the Atlantic, this Thermohaline Circulation **(THC)** helps to ensure that Europe is much warmer than equivalent latitudes in North America; Europe is 6°C warmer at 44°N and 15°C at 63°N than is North America. Slowing down of the Atlantic THC could have a severe, and possibly sudden, impact on the climate of Europe.

1. Climate change



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The thermohaline circulation (THC) is a global ocean circulation pattern that distributes water and heat both vertically, through the water column, and horizontally across the globe. As cold water sinks at high latitudes, it pulls warmer water from lower latitudes to replace it.

The amount of heat in the upper ocean and how it is geographically distributed governs atmospheric pressure, **storm tracks** and the development of severe weather such as **hurricanes and cyclones;** a major reorganisation of heat patterns would have severe impacts on weather conditions. With a volume of close to 1,400 million km³, the oceans play a vital role in the water cycle of the Earth. Evaporation and precipitation patterns will change as temperatures rise, and with the distribution of atmospheric pressure. These modifications can alter the timing and intensity of monsoons, droughts and floods, and the occurrence of exceptional weather events. Variations in the extent of sea-ice cover in polar regions have a major impact on climate, as ice reflects 30% of the incoming solar radiation. A warming ocean in seasonally ice-covered seas will contribute to more rapid melting of sea-ice.

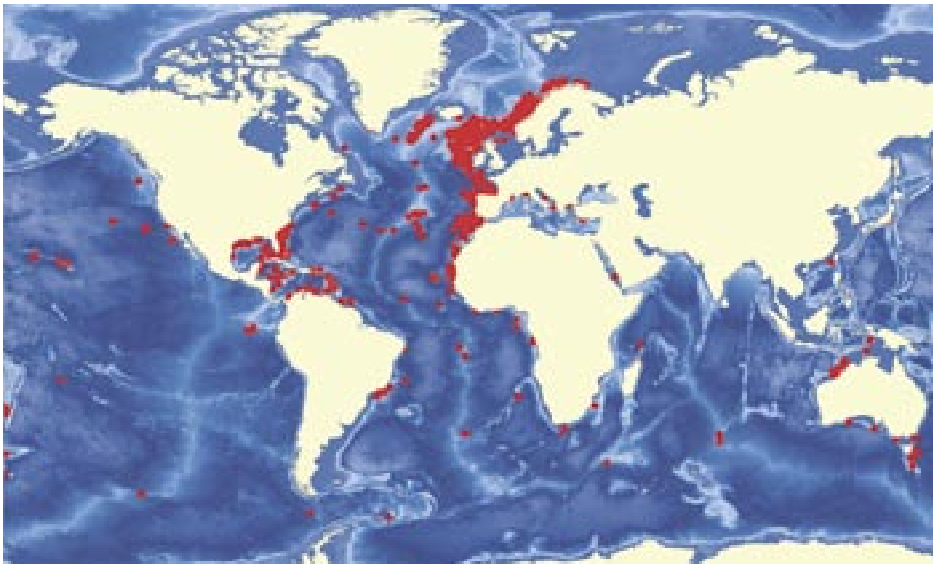
The oceans are able to absorb large quantities of the **greenhouse gas** CO_2 (37 000 gigatonnes of carbon are stored in the deep ocean). CO_2 at the surface of the ocean is in equilibrium with the air and moves freely between the two media. When chemically transformed into dissolved and particulate forms of carbon, CO_2 is transferred to the deep ocean by mixing and sinking and by a steady rain of particulate carbon sourced from the plankton and from shelf export. Without this oceanic uptake, concentrations of CO_2 in the atmosphere would be much higher. Since the beginning of the 19th century the oceans are estimated to have taken up approximately 50% of fossil fuel emissions and approximately 30% of all anthropogenic emissions (including those originating from land-use change). The North Atlantic plays a particularly key role as it has stored 23% of the total CO_2 sink in an area that covers only 15% of the global ocean. Warming of the surface of the ocean is expected to reduce its capacity to take up CO_2.

Phytoplankton accounts for approximately 50% of the total photosynthesis on Earth, and provides food for higher trophic levels. These microalgae and photosynthetic bacteria contribute to the removal of CO_2, because a proportion of their production is transferred as detritus to the deep ocean, either by sinking or via food webs. Changing composition and seasonal timing of the plankton, due to rising temperatures, may affect the efficiency of this downward transfer known as the **biological pump.** Many planktonic groups, including the larval stages of shellfish, have calcareous body parts. Their existence is threatened by the increasing acidity of the ocean caused by higher levels of CO_2 and may provide a feedback that could further reduce the ability of the oceans to take up CO_2 from the atmosphere.

Box. 2 Ocean acidification

Although not strictly climatic, acidification of the ocean is an example of a global environmental change linked to carbon dioxide emissions. According to a report, published by the UK's Royal Society (2005), atmospheric concentrations of carbon dioxide (CO_2), the main greenhouse gas, increased from 280 parts per million (ppm) in 1750 to over 375 ppm today. Absorption of CO_2 by the oceans has lowered the average pH of the oceans by about 0.1 units from pre-industrial levels. If CO_2 emissions continue according to current trends, this could lower the average pH of the surface oceans by between 0.14 and 0.35 units by 2100 (IPCC 2007). Ocean acidification decreases the ability of the ocean to absorb additional atmospheric CO_2, which implies that future emissions of CO_2 are likely to lead to more rapid global warming.

Increasing acidity of the oceans reduces the formation and speeds up the breakdown of essential shell-forming carbonates such as magnesian calcites (from coralline algae), aragonite (from corals and molluscs such as pteropods), and calcite (from certain species of phytoplankton such as coccolithophorids and foraminiferas). If present trends in anthropogenic CO_2 continue to rise for the next several hundred years, the Royal Society (2005) suggests that this may have severe implications for many species of calcium carbonate CaCO3 shell-forming organisms such as coral reefs, deep-water reef ecosystems, and calcifying phytoplankton and foraminiferas.



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Current global distribution of reef framework-forming cold-water corals (Roberts *et al.* 2006). Ocean acidification may affect these reefs before they have been fully explored (Royal Society 2005; Guinotte *et al.* 2006).

2. Projections of future climate

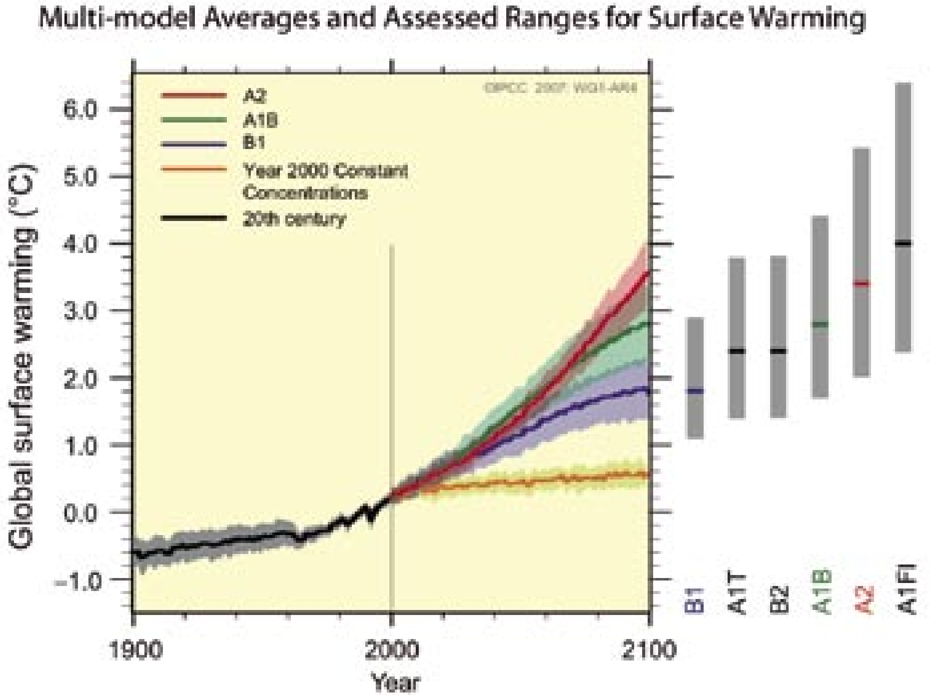
2.1 Forecasts and scenarios

Estimates of what the future climate will be like (projections) are typically made using coupled ocean/atmosphere/sea-ice/land models. Global Circulation Models (GCMs) describe the time evolution of atmospheric variables such as temperature, winds, precipitation, water vapour and atmospheric pressure throughout the globe in response to increasing atmospheric CO_2 concentrations. When a projection is categorised as *most likely* it becomes a **forecast** or prediction. A **scenario,** on the other hand, is a plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future may unfold. The baseline is the standard against which changes are measured, usually present-day conditions or the 30-year standard period from 1961 to 1990 used by meteorologists.

Because there is uncertainty as to how rapidly atmospheric concentration of CO_2 will increase, the primary body leading investigations into future climate change, namely the IPCC, has devised several possibilities (scenarios) based on the rate of population increase, economic development and technology change. Many studies (for example, the Arctic Climate Impact Assessment: ACIA 2005) use the **B_2 intermediate scenario** which describes a world with moderate population growth, economic development and technology change. This scenario predicts in a **doubling of atmospheric CO_2** after approximately **80 years.**

A set of CO_2 scenarios can be used to reflect the range of uncertainty in projections from a particular model. In addition, their results will not be identical because different GCMs can differ in their spatial resolution, representation of physical processes and boundary conditions. Since no one model can be indicated as the correct one, model results tend to be averaged to produce a **multimodel average,** as if each model is one experimental representation. The spread in the model estimates is considered to represent our uncertainty.

The horizontal spatial resolution of GCMs has generally been too coarse (with typical grid sizes of 200-400 km) to resolve local or regional topography. For regional and local impact studies, therefore, the approach has been to develop higher resolution (with typical grid sizes of 1-20 km) **regional climate models,** using the results from the GCMs as boundary conditions.



Variations of the Earth's surface temperature between 1900 and 2100 as predicted under six scenarios (B1, A1T, B2, A1B, A2, A1FI) where solid lines represent average measured (black) and predicted values and shading denotes the plus/minus one standard deviation range of individual model annual means. The grey bars at the right indicate the best estimate (solid line within each bar) and the likely range assessed for the six scenarios (© International Panel on Climate Change).

Some European countries, such as Spain, Sweden and the UK, have developed regional forecasts with a variety of different emission scenarios based on low, medium-low, medium-high, high emissions, for three 30-year time periods (centred on the 2020s, 2050s and 2080s). The basline convention for these scenarios is 1961-1990 (Hulme *et al.* 2002).

2.2 Model scenarios for Europe

It is estimated that annual air **temperatures** will rise throughout Europe relative to recent conditions, with the lowest increase (1-2°C) in the Mediterranean, Iberian, North Sea, Northeast Atlantic and south Nordic Sea regions (IPCC 2001c). Temperature increases will be higher (4-6°C) in the more northern regions such as the northern Nordic Seas and the Barents Sea, and highest (up to 7°C) in the Arctic (ACIA 2005). Because of its high capacity to store heat, the ocean will not warm quite as much as the land will. The frequency of extremely high air and ocean temperatures will increase and the frequency of extremely low temperatures will decrease throughout Europe (IPCC 2001c). There will be a decrease in the daily temperature range, with night-time lows increasing more than day-time highs.

Precipitation and **runoff** will increase in northern Europe and the Arctic, but will decrease in warmer regions such as the Mediterranean (IPCC 2001c). In the Arctic annual precipitation is projected to increase by 20%, with a 30% increase during the winter (ACIA 2005). With the increase in temperature, more precipitation will fall as rain in northern and upland regions resulting in an increase in winter runoff and a decrease in spring runoff. At higher altitudes much of the precipitation will continue to fall as snow in winter, but the spring peak in runoff will occur slightly earlier. The intensity of winter rainfall events north of 45°N is expected to increase while to the south there will be an insignificant change or a decrease in intensity (Frei *et al.* 2006). In central Europe river runoff will change by approximately 10% by the 2050s, but this is smaller than the observed natural multidecadal variability (Hulme *et al.* 1999). In Mediterranean regions, the range in river flows between winter and summer is likely to increase considerably while in maritime Western Europe there will be a smaller increase.

As temperatures rise, **sea-ice coverage** will decrease; most climate models suggest an ice-free summer in the Arctic by 2100 (IPCC 2001c; Teng 2006). In the Barents Sea, the winter ice-edge is projected to retreat at an approximate rate of 10 km per year northward; the Barents Sea is predicted to be ice-free by 2070 (Furevik *et al.* 2002). A significant loss of ice cover in the western Nordic Seas is expected, which by 2070 will be restricted to the northwestern Greenland Sea and the Baltic.

The projected melting ice and increased precipiand ation and river runoff in northern latitudes will lead to decreases in surface **salinity** in the order of 0.5-1 ppm in the Arctic Ocean, the western regions of the Nordic Seas and in the Baltic by the 2070s (Furevik *et al.* 2002).

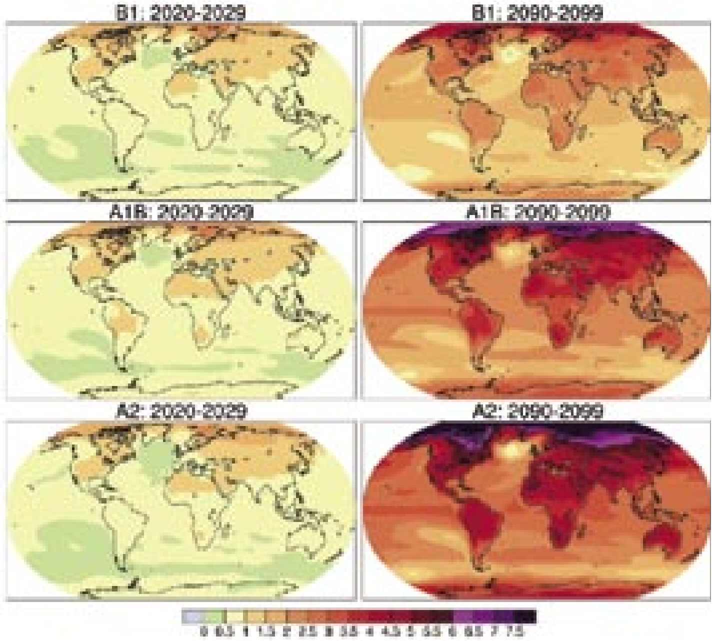
Based on current model simulations, it is very likely that the **Meridional Overturning Circulation** (MOC, see Section 3 for a description) will slow down during the 21st century (IPCC 2007). This gradual weakening of the MOC may be in the order of 20% to 25% (Hadley Centre; www.met-office.gov.uk/corporate/scitech0304/MetOfficeScience0304.pdf), depending on future emissions (IPCC 2007). However, temperatures in the Atlantic region, including Europe, will continue to warm, due to the atmospheric warming effect of the greenhouse gases (IPCC 2007).

> *'Under scenarios of faster industrial development leading to higher CO_2 levels than those assumed for the B2 scenario, temperatures in the Arctic are projected to increase up to 14°C by 2100'*
>
> *Teng et al. (2006)*

With melting ice caps and higher ocean temperatures, sea level is expected to rise by 18-59 cm at 2090-2099 relative to 1980-1999 (IPCC 2007). However, these projections do not include possible future rapid dynamical changes in ice flow. For example, if this contribution were to grow linearly with temperature change, this may add an additional 10-20 cm to the upper ranges of sea level rise (IPCC 2007).

Low-lying areas adjacent to regions with low tidal range such as along the coasts of the Mediterranean, Baltic and Black Sea are more vulnerable than most of the Atlantic Ocean and North Sea coasts (Nicholls and Mimura 1998).

2. Projections of future climate



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Projected surface temperature changes for the early and late 21st century relative to the period 1980-1999 for various emission scenarios. It is predicted that after CO_2 emissions are reduced and atmospheric concentrations stabilise, surface air temperature will continue to rise slowly for a century or more. Thermal expansion of the ocean will continue long after CO_2 emissions have been reduced, and melting of ice sheets will contribute to sea-level rise for many centuries into the future.

3. Possible responses and impacts

3.1 Physical responses and impacts

Changes in the ocean to the west of Europe will have important effects on the weather patterns of Europe. The **Atlantic Meridional Overturning Circulation (MOC)** refers to the northward flow of ocean water, its subsequent cooling and sinking in the North Atlantic and the return southward flow at intermediate and near bottom depths. This process contributes about 90% to the oceanic south–north heat fluxes in the North Atlantic and is thus most significant for European climate and its variability (Quadfasel 2005). A slowdown of the Atlantic MOC has been suggested as possibly causing a drop in temperatures over Europe of as much as 4°C (Quadfasel 2005). However, while recent observations indicate that the returned subsurface flow associated with the MOC has slowed down due to reduced convective sinking, there is no evidence that the near surface flows have decreased (Bryden *et al.* 2005).

Climate-induced changes in **Arctic sea-ice** cover and thickness represent one of the largest uncertainties in the prediction of future temperature rise (Laxon *et al.* 2003; MacDonald *et al.* 2005). The extent of the perennial Arctic sea-ice has decreased in extent by about 15% since 1980 (Francis *et al.* 2005). Furthermore, the ice became less thick and its composition shifted towards more first-year ice, which melts faster than multi-year ice (MacDonald *et al.* 2005). A continuation of the observed increase in the length of the melt season is expected to lead to further overall thinning of sea-ice (Laxon *et al.* 2003), resulting in an ice-free Arctic during summer within 100 years (Johannessen *et al.* 2004).

Elevated summer temperatures will strengthen near-surface **stratification** and decrease the ability of the winter winds to mix the water column (e.g. McClain *et al.* 2004; Llope *et al.* 2006). Several coupled ocean-atmosphere models have shown global warming to be accompanied by an increase in vertical stratification (IPCC 2001c).

> *'New evidence on the melting of ice sheets indicates that a sea level rise of seven meters could occur with in 500 rather than 1000 years.'*
>
> *Alley et al. (2005)*
> *Dowdeswell (2006)*

Increased storminess will exacerbate the effect of sea-level rise in coastal systems because of the higher frequency of storm surges and extreme wave action. Wetland losses due to sea-level rise are expected to be in the order of 17% along the Atlantic coasts, 31-100% along the Mediterranean coast and 84-98% along the Baltic coast (IPCC 2001c). Greater defence of these coastlines to prevent coastal flooding will lead to additional **loss of coastal habitats** (IPCC 1990). Offshore structures and installations for hydrocarbon extraction and renewable energy will also be at greater risk.

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Coastal communities in the Arctic have used sea walls and other human-made barriers to hold back erosion. These measures have worked to an extent, but as areas of open water become larger, wave and wind effects also increase and eat away at these temporary solutions.

3.2 Biological responses and impacts

Climate change is expected to have a range of effects on marine systems. Some effects may be related to changing water temperatures, circulation or habitat, while others occur through altered pathways within biogeochemical cycles and food webs. Climate change may influence nutrient and contaminant concentrations via ocean currents and fluctuations in the depth of the surface mixed layer and period of vertical stratification.

Climate-induced changes in microorganisms, such as bacteria and archea, will affect biogeochemical cycles, e.g. those of nitrogen, iron and sulphites. In estuaries and upwelling areas, changes in strength and seasonality of circulation patterns can affect the retention-dispersion mechanism of planktonic larvae (Gaines and Bertness 1992). An increase in precipitation-driven flooding will particularly affect estuaries through enhanced river runoff and changes in nutrients and salinity in coastal regions, including aquaculture areas. Summer droughts will lead to increased salinisation of upper reaches in northern Europe and hypersalinisation of estuaries and lagoons in the south.

Increasing temperatures and enhanced stratification could affect the amount and production of phytoplankton. Because these pelagic microalgae are responsible for removing CO_2 from the atmosphere and transferring the carbon to higher trophic levels, any change in the timing, abundance or species composition of these primary producers will have consequences on the rest of the marine food web. A meta-analysis of a number of models suggests an increase in global **primary production** of between 1% and 8% by 2050, when compared to pre-industrial times (Sarmiento *et al.* 2004).

In open marine ecosystems the population dynamics of many species of marine invertebrates and fish are driven by **recruitment** processes. Recruitment refers to the number of young that are added to the population each year. Recruitment in cold temperate species is often synchronised with seasonal production cycles of phytoplankton. If warming results in advancement of the timing of reproduction of these species, this may result in a mismatch with the presence of their main food source (phytoplankton). Any subsequent decrease in recruitment success will inevitably lead to shifts in species composition.

In general, a rapidly warming environment would be expected to result in a poleward movement of species. Such a change in **geographical distribution** occurred at the end of the last glacial maximum with the colonisation of northern seas and coasts. More recently, during the cold period of the 1970s some species shifted southwards. Since warming accelerated in the late 1980s, poleward advances of southern species and retreats of northern species have been recorded in zooplankton, fish and benthic species, including those found on rocky shores (Brander *et al.* 2003; Southward *et al.* 2005). When encountering unfavourable environmental conditions, species distribution may not always exhibit displacement northwards. For example, when the stock of the main prey of the harp seals in the Barents Sea collapsed, these seals migrated southward along the coast of Norway and into the North Sea in search of food (Harkönen *et al.* 2006).

Climate-induced decoupling of **phenological relationships** (relative timing of life cycle events) may locally affect community structure and food webs by altering the interaction between a species and its competitors, mutualists, predators, prey or pathogens. For example, in the case of sea birds, chick diet composition during development is likely to be an important mechanistic link between climate variability and the observed decline in seabird populations (Kitaysky *et al.* 2005). Also, with reference to cod population, a shift from large to smaller copepod species resulted in an enhanced prey availability and subsequent survival of cod larvae during the 1970s, the so-called 'gadoid-outburst' (Beaugrand *et al.* 2003). Further temperature rises are likely to influence entire ecosystem assemblages (Genner *et al.* 2004), as well as having profound impacts on exploitation of living marine resources (Perry *et al.* 2005).

> *'In the North Sea, nearly two-thirds of the fish species have shifted their mean latitude and/or depth over the last 25 years'*
>
> *Perry et al. (2005)*

Rapid warming can accelerate **establishment of non-indigenous species,** many of which have been shown to do better under the warmer conditions experienced in recent years (Stachowicz *et al.* 2002). When the Pacific oyster (*Crassostrea gigas*) was introduced in northwestern Europe as a potential aquaculture species, it was not expected to reproduce, because of the relatively cold water temperatures. However, the recent warming (in association with its possible adaptation to its new environment) has now removed this species' reproductive barrier, resulting in massive proliferation of *C. gigas*, especially in the Netherlands, but also in the UK (Reise *et al.* 2004). Non-indigenous species from coastlines with a strong continental influence and seasonal extremes (e.g. Asia, east coast of America) whose larvae are transported to European waters by means of ballast water, may already be very well adapted to the warmed waters of Europe.

European policies on management of marine resources (e.g. European Common Fisheries Policy, Marine Thematic Strategy) and marine conservation (e.g. the Bird and Habitat Directives and the Natura 2000 network) can never assume that the marine environment is relatively stable.

Even without human-induced climate change, natural variability and evolutionary processes continuously alter biodiversity and biogeography of species (Leslie *et al.* 2005). Climate change may cause serious problems for this type of management when marine systems become even **more dynamic and variable** than before.

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A climatic regime shift during the mid-1970s in the North Pacific resulted in decreased availability of lipid-rich fish to seabirds and was followed by a dramatic decline in number of kittiwakes. Experiments revealed that diets low in lipids induce nutritional stress and impair cognitive abilities in young red-legged kittiwakes, which is likely to result in their increased mortality and low recruitment rates (Kitaysky *et al.* 2005).

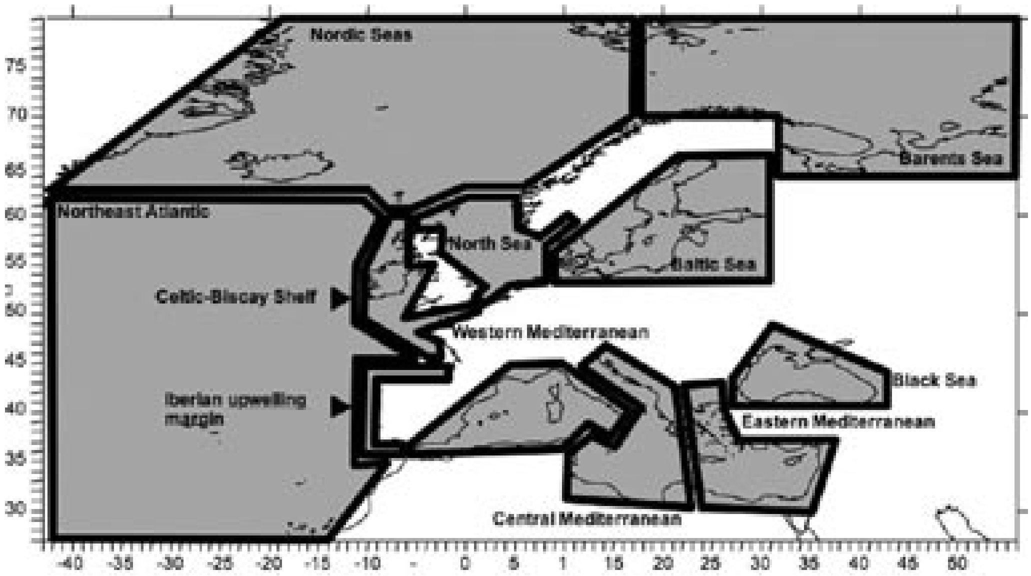
4. Regional responses and impacts

4.1 Introduction

Climate change is expected to affect different regions in different ways, including:

- Observed trends and expected changes strongly differ throughout the globe. Warming will be more pronounced at the poles than at the equator (MacDonald *et al.* 2005).
- The responses to climate change are expected to differ for different marine systems. For example, while open oceans are more affected by the influence of wind on the timing and strength of stratification, coastal areas are more vulnerable to the effects of wind via storm surges. In addition to expected warming of seawater, polar regions will experience changes in ice cover.

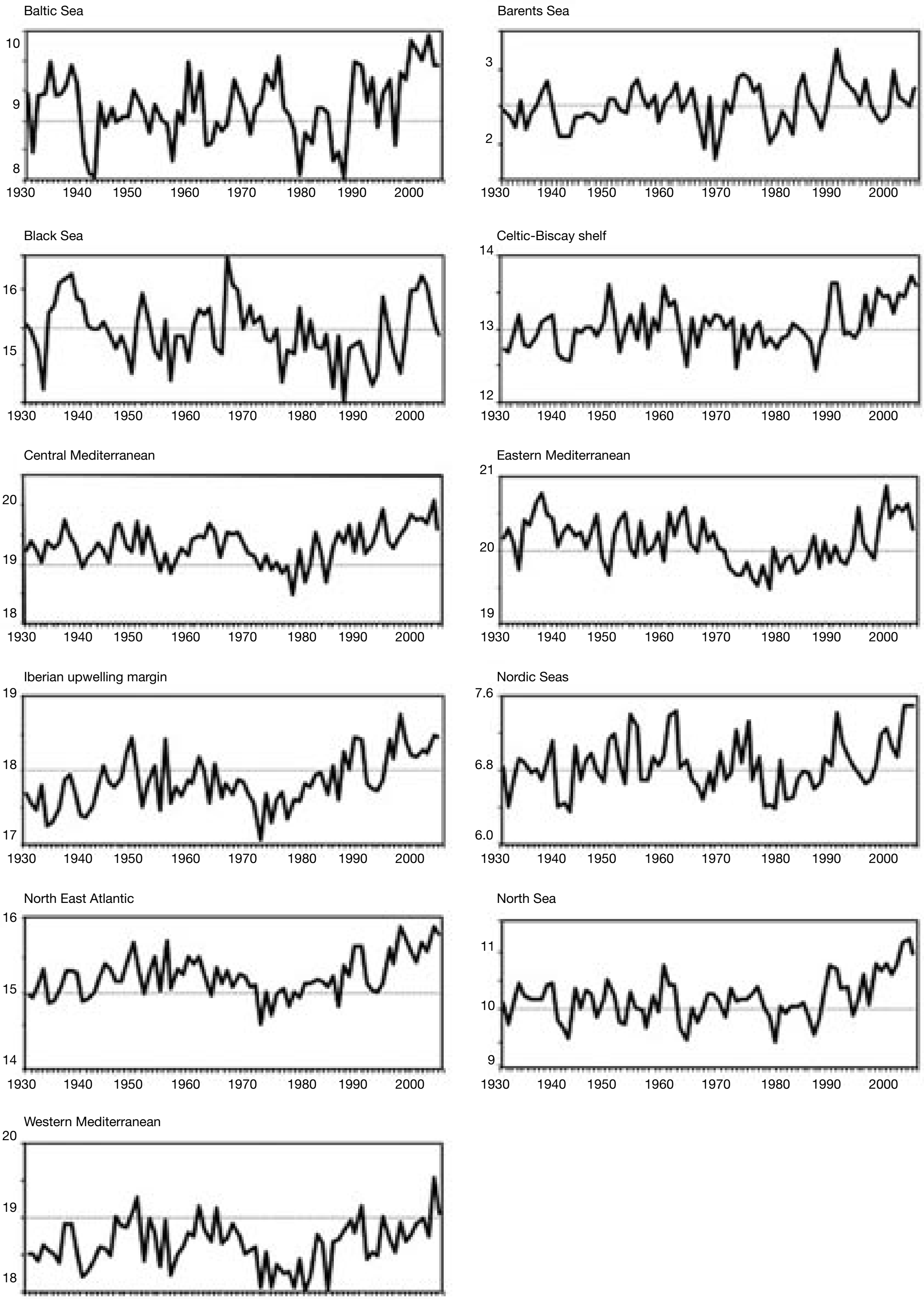
> *'Between 1993 and 2003, in Australia, sea level increased at a rate of more than 30 mm y $^{-1}$ whilst a decrease in sea level of more than 20 mm y $^{-1}$ was observed in parts of the northeastern Pacific.'*
>
> *Holgate and Woodworth (2005)*



Map compiled by Priscilla Licandro/SAHFOS and Katja Philippart/NIOZ

European marine and coastal environments for which temperature time series were compiled.

During the past 10 years, sea-surface temperatures (SST) appear to be rising and exceptionally high temperatures have occurred in all European marine waters, except for the Black Sea. During the past 75 years, area-averaged sea-surface temperatures were lowest in the Barents Sea (less than 5°C), followed by the Nordic Seas and the Baltic Sea (5°C to 10°C temperature range), and the North Sea and the Celtic-Biscay Shelf (10-15°C), and higher in the Northeast Atlantic and the Black Sea (15-17°C), whilst the warmest waters were found in the Iberian upwelling margin and Mediterranean basins (18-20°C). Because of the ice coverage, long-term observations of sea-surface temperature are not available for the Arctic. Variations in sea-ice extent, however, may be considered as an index of changes in sea-surface temperature (see Section 4.2).



Long-term variation in area-averaged sea-surface temperatures (°C) in European marine and coastal environments based on HadSST2 data from the Hadley Centre, UK (Data compiled by Priscilla Licandro/SAHFOS).

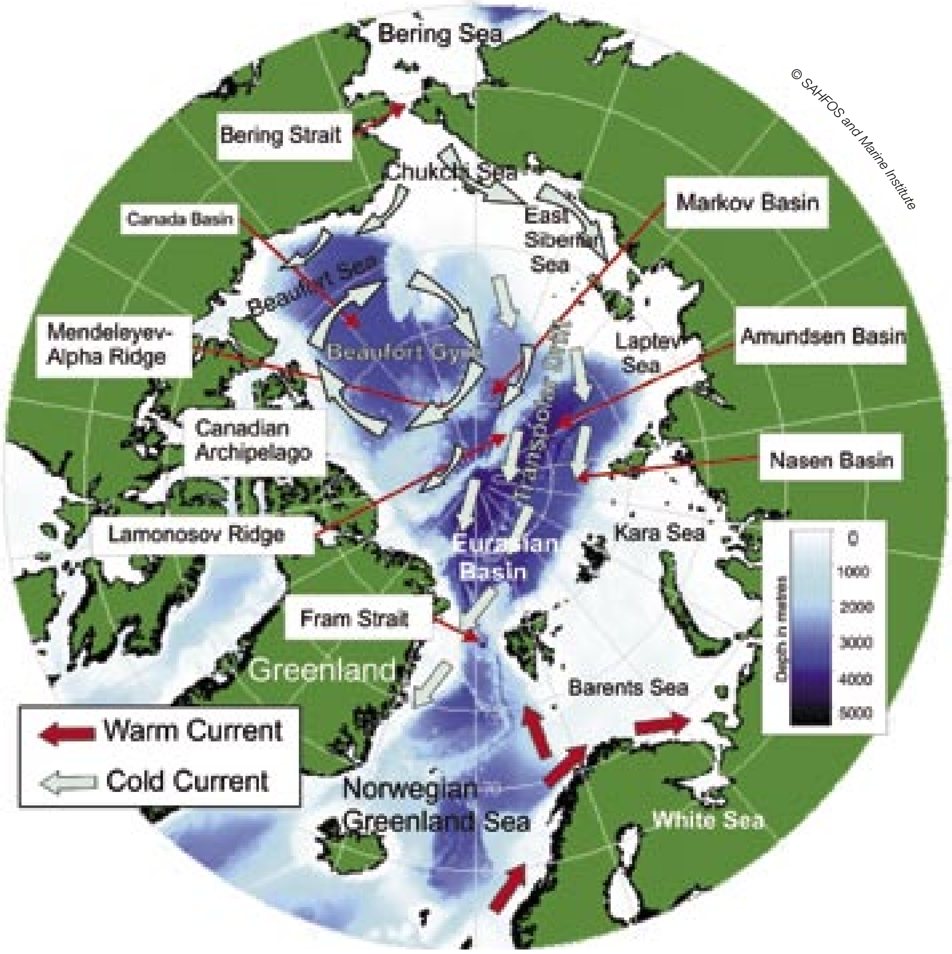
4.2 Arctic Ocean

Description of the area

The Arctic Ocean consists of the deep (>4,000 m) Eurasian, Markov and Canada Basins, the surrounding continental shelf seas (Barents, White, Kara, Laptev, East Siberian, Chucki and Beaufort Seas) and the Canadian Archipelago.

Pacific waters enter the Arctic Ocean through the Bering Strait (Woodgate and Aagaard, 2005) and, augmented by freshwater runoff and forced by the mean winds, most flow towards the Atlantic Ocean in the Trans-Arctic Drift. The clockwise Beaufort Gyre is located landward of the Trans-Arctic Drift on the Canadian side.

The majority of the water from the Arctic exits the region through the Fram Strait off northeastern Greenland, although some water also makes its way through the Canadian Archipelago. Water from the Atlantic Ocean enters the Arctic through the Barents Sea and the eastern Fram Strait.



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The Arctic Ocean.

Signals of climate change

The Arctic climate has varied on geological to interannual time scales. In the last century the climate shifted from generally cold conditions in the early 1900s to a warm period from the 1920s to the 1950s, cooled again through the 1960s and 1970s before the recent warming (Johannessen *et al.* 2004). Decreases and increases in the seasonal ice coverage and thickness have been recorded concurrent with these warm and cool periods (Johannessen *et al.* 2004; ACIA 2005).

The recent warming in the Arctic has been unprecedented, with annual mean air temperatures rising at a rate 50% greater than from Iceland to the equator (ACIA 2005) and in the advection pattern of warm air from the south (Overland *et al.* 2004). The recent warming has resulted in vast reductions in the amount of multi-year ice, a 20% decrease in the summer extent of the Arctic sea-ice during the last 30 years of the last century (Johannessen *et al.* 1999) and a thinning of the ice by up to 2 m in the central Arctic between the 1960s and the 1990s (Rothrock and Zhang 2005).

With less sea-ice, the decrease in the albedo effect led to increased absorption of the solar heating, thereby adding to the increased rate of warming (ACIA 2005). Additional warming (over 1°C) occurred at intermediate depths in the Arctic Ocean, especially in the Eurasian Basin, due to increased inflow of warm Atlantic water (Polyakov *et al.* 2005). The boundary between Atlantic and Pacific waters shifted towards the Pacific from the Lomonosov Ridge to the Mendeleyev-Alpha Ridge and the percent Atlantic waters in the Canada Basin increased (McLaughlin *et al.* 2002). Sea-ice melt, coupled with increased river runoff into the Arctic, led to freshening of the surface layers and a rise in sea level (ACIA 2005).

Because of the extensive ice cover, difficult logistics, few inhabitants, and no commercial fisheries in the high Arctic, there are few published studies on the biological consequences of past climate changes in this region (ACIA 2005). However, benthic studies in the Chukchi Sea north of the Bering Sea have shown population changes in the dominant species, which are thought to be related to changing hydrographic conditions (Grebmeier *et al.* 1995).

> *'Sea-ice coverage will further decrease with suggestions of an ice-free Arctic during summer before 2100 and thus no multi-year ice in winter.'*
>
> *ACIA (2005)*

Projections of climate change

Recent projections of future climate scenarios indicate continued warming with temperature increases in the order of 2-10°C over this century (ACIA 2005). Increased precipitation will result in higher river runoff adding to the freshwater additions through ice melt. In the absence of ice, surface waters will be exposed to wind-driven circulation (ACIA 2005). The Transpolar Drift would shift eastwards to favour flow directly toward the Fram Strait. The Beaufort Gyre may weaken and retreat into the Canada Basin with the position of Atlantic/Pacific Front tending to align permanently with the Mendeleyev-Alpha Ridge. Also, when summer ice retreats seaward of the continental slope, enhanced deep basin–shelf exchange of seawater will occur through increased wind-induced upwelling and downwelling (Carmack and Chapman 2003).

The retraction of the sea-ice and the enhanced exchange of deep-basin seawater will result in higher light levels and nutrient concentrations on the shelves, leading to increased primary production. Wind-driven vertical mixing is likely to increase the depth of the surface mixed layer. If the Arctic becomes ice-free in winter, the Nansen Basin may become a region of strong convection (sinking of cold dense water) and water mass formation. Predicted strengthening of the westerly winds in the Nordic Seas is expected to increase the transport of Atlantic water entering the Arctic via the Fram Strait and the Barents Sea (ACIA 2005).

Based upon our understanding of biological processes in the Arctic, some predictions of the impacts of climate change can be made. Where sea-ice coverage is reduced, ice algal production will significantly decrease (ACIA 2005). This loss of production will be more than made up for by increased open ocean plankton production in these ice-free regions because of higher light levels and increased nutrient concentrations through enhanced vertical mixing. This production may be limited in some areas by the negative effects of increased stratification from increased sea-ice melt and higher surface layer temperatures. Benthic production is likely to decrease, but this will depend upon the match/mismatch between phytoplankton and zooplankton, i.e. the amount of phytoplankton that sinks to the bottom before being eaten (ACIA 2005).

Higher production at the lower trophic levels is expected to lead to increased zooplankton and fish production in the Arctic, although the extent of such an increase is uncertain (ACIA 2005). In contrast, the abundance of ice-dependent species such as polar bears, as well as some seals and seabirds is likely to decrease.

4. Regional responses and impacts

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In 2006, polar bears were placed on the Red List of Threatened Species of the World Conservation Union (IUCN). Because of their slow reproduction cycle and the speed of global warming, it seems unlikely that polar bears will be able to adapt to the current warming trend in the Arctic. If climatic trends continue polar bears may diminish from most of their range within 100 years.

Already polar bears are showing some signs of being in poor condition, associated with the decrease of seal prey availability, which is linked to the decline in ice coverage.

Distributional shifts in organisms, from phytoplankton to marine mammals and seabirds, may result in the establishment of non-indigenous species in the Arctic, forcing a further geographical retraction of indigenous Arctic species and the possibility of some species disappearing altogether.

The absence of ice in summer will enhance the probability of import/transport of non-indigenous marine organisms from the Pacific. Recent studies have demonstrated that the barrier to a trans-Arctic exchange of plankton between the two oceans has already been breached (Reid *et al.* unpublished)

Current monitoring and research programmes and projects in the Arctic

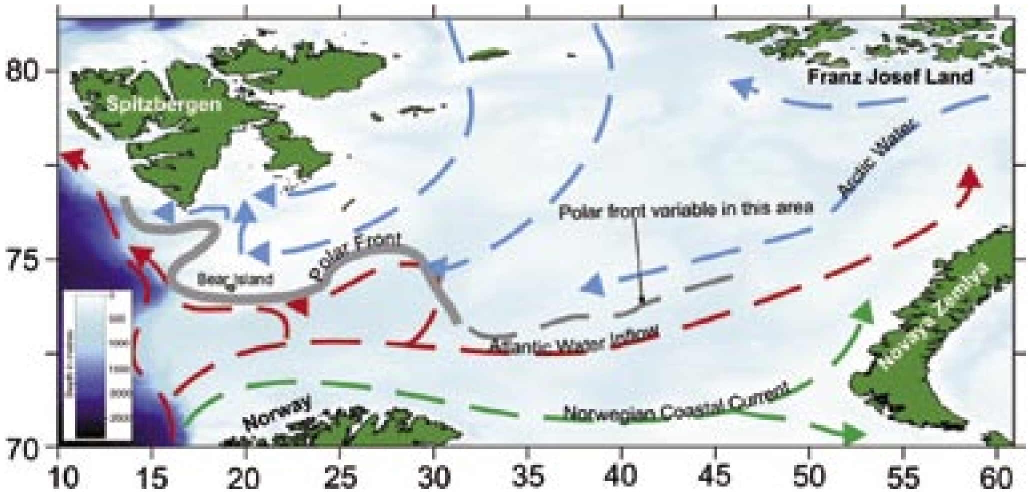
- Monitoring and research programmes and projects for the Arctic have been expanding during recent years although most regions generally remain undersampled;
- The international Arctic Climate Impact Assessment was recently completed (ACIA 2005);
- The Arctic Monitoring and Assessment Programme (AMAP) has on-going activities, especially related to contaminants;
- Transports of water, heat and freshwater to and from the Arctic are monitored and examined by the Arctic/Subarctic Ocean Fluxes (ASOF) programme;
- The Circumpolar Biodiversity Monitoring Programme (CBMP) has been initiated in the Arctic of which the first report is due out shortly;
- Activities during the International Polar Year (IPY 2007/2008) are expected to greatly increase research and understanding of the role of climate on the marine ecosystems, as well as to expand monitoring activities in the Arctic.

4.3 Barents Sea

Description of the area

The Barents Sea is one of the shallow shelf seas that collectively form the Arctic continental shelf. Its western boundary is defined by the shelf break towards the Norwegian Sea, the eastern boundary by the Novaya Zemlya archipelago, the southern boundary by Norway and Russia, and the northern boundary by the continental shelf break towards the deep Arctic Ocean. The Barents Sea covers 1.4 million km^2 with an average depth of 230 m and a maximum depth of approximately 500 m near the western entrance.

Atlantic waters enter the Barents Sea between Bear Island and northern Norway; they cool and freshen before exiting principally to the north of Novaya Zemlya. Most Arctic waters enter between Spitzbergen and Franz Josef Land and exit south of Spitzbergen (Loeng *et al.* 1995). A narrow transition zone, called the Polar Front, separates the Atlantic and Arctic water masses. Winter convection in the Barents Sea also provides cold intermediate water to the Arctic Ocean to a depth of 1,200 m through sinking and subsequent northward advection (Schauer *et al.* 1997). Sea-ice typically covers the northern and eastern regions of the Barents Sea in winter.



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The Barents Sea.

Signals of climate change

Climate variability in the Barents Sea, as elsewhere, occurs on a variety of time scales. At multidecadal periods, the waters in the Barents Sea have undergone similar changes to those in the Arctic, being relatively cold in the late 19th century and the early part of the 20th century, warm from the 1920s to the 1950s, cool through the 1960s to the 1980s and warm during the last decade or more (Drinkwater 2006). These changes are due to a combination of atmospheric heating and cooling and variability in both the volume and temperature of the incoming Atlantic waters (Ingvaldsen *et al.* 2003). In association with warm and cool periods, sea-ice coverage has contracted and expanded, respectively. Recently, sea-ice coverage has been near its lowest recorded level, although the 1930s was another period of low ice coverage.

During the warm period of the 1920s to 1950s, the distribution of fish species such as cod, haddock and herring expanded northward and eastward (Drinkwater 2006). A similar geographic expansion of Atlantic associated benthic species occurred, while Arctic species declined (Berge *et al.* 2005).

> *'During recent warming, large numbers of blue whiting have extended northward as far as the western entrance of the Barents Sea, and blue mussels have appeared in Svalbard after a 1000 year absence.'*
>
> *Berge et al. (2005)*

At interannual to decadal time scales, ocean temperature variability is correlated with the NAO with higher temperatures generally associated with the positive phase of the NAO (Ingvaldsen *et al.* 2003). The higher correlation after the early 1970s is attributed to the eastward shift in the Icelandic Low (Ottersen *et al.* 2003). Interannual variation in the position of the ice-edge in a particular month is about 3-4°C of latitude.

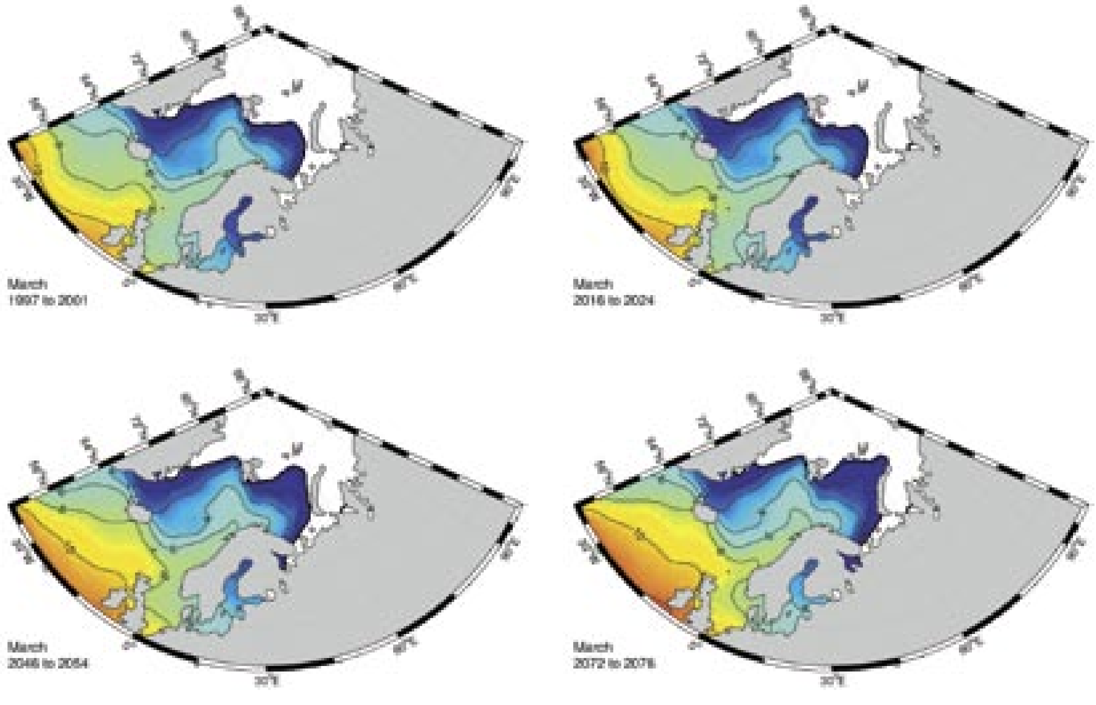
4. Regional responses and impacts

Projections of climate change

Furevik *et al.* (2002) modelled future climate scenarios for the Barents Sea. They suggest that by 2080, surface ocean temperatures will warm by 1-2°C, winter sea-ice will almost disappear, Atlantic waters will spread further eastward and northward, there will be more continental runoff but this will be partially compensated by an influx of higher salinity in Atlantic waters, and the surface mixed layer depth will increase due to stronger winds.

Under the projected warming in the Barents Sea, Atlantic water species of fish and benthos are expected to extend further east and north. Modelling studies (Slagstad and Wassmann 1996) suggest primary production levels are 400% higher in ice-free regions in a warm year compared to when these same areas are ice-covered. Relative to the entire Barents Sea region, reduced ice cover will result in between 8% (Ellingsen *et al.* 2006) and 30% (Slagstad and Wassmann 1996) increase in primary production in years free of summer ice. This is due to a combination of higher light levels in areas of decreased ice cover, higher nutrient levels in the Atlantic waters where they extended northward and eastward, and faster turnover times of the phytoplankton, associated with higher temperatures.

This higher production is expected to result in increased abundance of cod, haddock and other species (ACIA 2005). Improved growth rates together with expected increased recruitment will lead to increased yields in species such as cod, although this will depend to a large degree upon fishing intensity. More fish will spawn farther north, as observed for cod (Drinkwater 2005), and new spawning sites are likely to be established. Herring and blue whiting will spread further eastward and salmon abundance is likely to increase in Russian waters as previously observed (Lajus *et al.* 2005) and to extend to northern Spitzbergen. Capelin will follow the Polar Front further to the northeast to feed, but are expected to continue to spawn off northern Norway. The distribution shifts of fish populations will bring more of the major commercial species (such as cod and haddock) into Russian waters, this distribution shift of commercial populations may require renegotiation of present fisheries treaties between Norway and Russia.



Historical and forecast sea-surface temperatures and sea-ice during March based on the Bergen Climate Model (data compiled by T. Furevik/UIB).

Current monitoring and research programmes and projects in the Barents sea

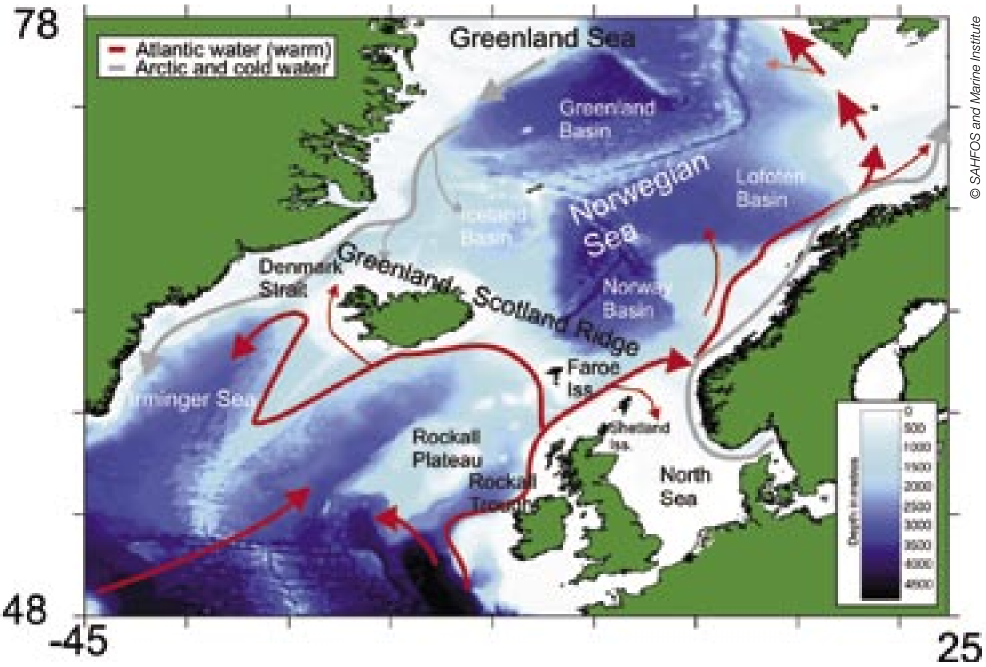
- Russia has maintained the Kola Section (a hydrographic transect north of the Murman coast) for over 100 years and has also carried out numerous benthic and fish surveys;
- Norway has undertaken annual fish surveys to assess fish stocks for over 35 years and in recent years these have been expanded to include other components of the ecosystem;
- Norway has led projects investigating the impact of climate evolution on the Barents Sea ecosystem, e.g. the earlier completed Barents Sea Impact Study (BASIS); projects completed at the end of 2006 include the Carbon Flux and Ecosystem Feed Back in the Northern Barents Sea in an era of Climate Change (CABANERA), Effects of North Atlantic Climate Variability on the Barents Sea Ecosystem (ECOBE), Co-evolution of life histories of *Calanus* and herring in the Norwegian Sea (ADAPT), the Climate and Production of Marine Resources (CliMar), and the Norwegian component of the Ecosystem Study of Sub-Arctic Ecosystems (NESSAS) will continue until 2008;
- In 2007/2008, several International Polar Year (IPY) activities are planned that focus on the effects of climate variability and change on the Barents Sea ecosystem; these include ESSAR and ARCTOS-FLUXES.

4.4 Nordic seas

Description of the area

The Nordic Seas, which include the Greenland, Norwegian and Iceland Seas, are a transition zone for warm and saline Atlantic water on its way to the Arctic, and for cold and less saline waters flowing from the Arctic to the Atlantic Ocean. The Greenland-Scotland Ridge forms a barrier between the deep waters of the Nordic Seas and the North Atlantic.

The eastern Norwegian Sea consists of relatively warm Atlantic water in the upper layers (<1,000 m) while the cold water from the Arctic dominates the western side of the Nordic Seas. The Arctic Front, a narrow region with large horizontal gradients in temperature and salinity, separates these two regions.



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The Nordic seas.

Signals of climate change

Rapid warming of the waters occurred in all three basins during the late 1900s in response to atmospheric heating and to advection of warm water into the region. In the Norwegian Sea, advection is due to warmer Atlantic waters, whereas in the Greenland Sea, advection occurs because of warmer waters flowing out of the Arctic. Convection in the Greenland Sea, caused by winter cooling, has decreased to the extent that the deep waters are not being renewed.

In the deep, south-flowing waters of the Greenland Sea there has been a 40-year trend towards decreasing salinity which has spread throughout much of the northern North Atlantic (Dickson *et al.* 2002) causing a general freshening of the whole Atlantic (Dickson *et al.* 2003; Curry *et al.* 2003).

> *'Since the mid-1980s there has been a steady increase of more than 0.05 ºC for the waters between 1,200 m and 2,000 m, and even the deepest water has shown a small temperature increase.'*
>
> *Sterhus and Gammelsrød (1999)*

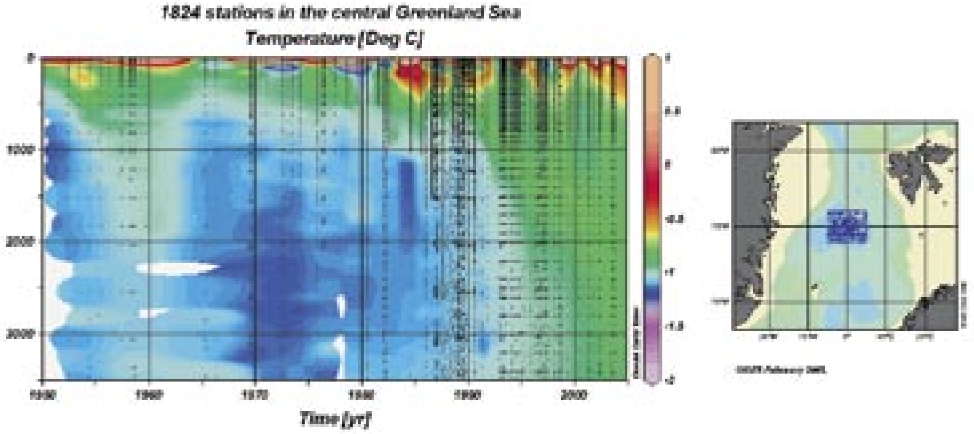
The deep-water exchanges from the Nordic Seas to the North Atlantic over the Scotland-Greenland Ridge have decreased (Hansen *et al.* 2001; Bryden *et al.* 2005). In spite of this, the northward flow in the upper layers has remained relatively constant (Bryden *et al.* 2005). To the north of Iceland, there has been an increase in the flux of Atlantic waters as indicated by higher salinities (Jónsson and Vladimarsson 2005). The Arctic Front to the east of Iceland has shifted closer to Greenland.

Large ecosystem changes have been observed in the past. For example, the abundance of Norwegian spring spawning herring increased during the warming of the 1920s, decreased during the cooling period in the 1960s but has risen again since the temperature increases in the 1990s (Toresen and Østvedt 2000). During warm periods, i.e. 1920s-1950s, herring migrated from their spawning locations on the west coast of Norway and around the Faroes, and their nursery areas in the western Barents Sea to the feeding grounds off northeastern Iceland (Vilhjálmsson 1997). The overwintering grounds were primarily to the east of Iceland; then in spring the herring migrated back to their spawning grounds.

As the Arctic Front shifted southeastward during the colder 1960s, the herring feeding grounds moved farther eastward and then to the southwest of Spitzbergen. When the herring population declined to drastically low levels, those individuals remaining no longer migrated out into the Norwegian and Greenland seas but stayed near the Norwegian coast to both feed and spawn (Vilhjálmsson 1997). In the 1990s, as temperatures warmed and the herring population increased, the population again began migrating back towards Iceland to feed (ACIA 2005).

Capelin, the major prey of adult cod off Iceland, have moved further northwest during the recent warming requiring the capelin fleet to travel further in order to obtain their catches. This distributional shift is somewhat similar to the response observed during the early 20th century warming period when the capelin population shifted northward. Cod spawn along the south and southwest coasts of Iceland and their larvae drift northwards with many developing off the north coast of the island.

In recent years, warm conditions due to the increased influx of Atlantic waters off northern Iceland have led to a higher level of cod recruitment (Jónsson and Vladimarsson 2005). This may be because of the shorter vulnerable larval stages, and increased food because of higher primary and secondary production (Astthorsson and Vilhjálmsson 2002) or a combination of both. The presence of Atlantic waters provides for an enhanced phytoplankton bloom that lasts longer because of reduced stratification and higher nutrient concentrations than are found in Arctic waters.



Time-series of temperature with depth (left panel) in the central Greenland Sea (area shown in right panel). The black dots in the left panel represent station data (© ICES Oceanographic Database and Service).

Projections of climate change

Furevik *et al.* (2002) reported on future climate scenarios for the Nordic Seas up to 2080. These included a 1-2°C increase in sea-surface temperatures, increased Atlantic flow to the Norwegian Sea and north of Iceland but a reduction in the overturning circulation, a weakening of the Nordic Sea Gyre, little if any ice on the East Greenland shelf, reduction in winter convection in the Greenland Sea, reduced outflow through the Fram Strait, and fresher waters along the Greenland and Norwegian shelves because of increased runoff and in the case of Greenland, ice melt from the Greenland ice cap and sea-ice melt from the Arctic.

The biological response to these changes are expected to include a slight increase in primary production occurring north of Iceland, because of the greater presence of Atlantic waters, and also off East Greenland, associated with increased light levels due to the absence of ice. However, production in the ice-free areas will also be affected by a limited nutrient supply due to the increased freshwater input from nutrient-poor Arctic rivers, which will increase vertical stratification. It is expected that the abundance of the Arctic zooplankton species *Calanus hyperboreus* and *C. glacialis* will decrease, while the smaller *C. finmarchicus* that inhabit the Atlantic waters should increase.

The growth and condition of cod, haddock and capelin should improve and these species will continue their movement northward, eventually occupying the waters around Jan Mayen island on a regular basis. Atlantic herring should again begin to overwinter to the east of Iceland and move northwestwards with the Arctic Front. More southern species will invade the Nordic Seas with some becoming frequent visitors. These invasions may lead to an increase of biodiversity within the fish communities of the Nordic Seas.

Current research and monitoring programmes and projects

- The longest continuous monitoring of ocean temperature and salinity in the open Nordic Seas is from the Ocean Weather Station Mike (1948 to present);
- Direct measurements of the water mass exchanges between the Nordic Seas and both the Atlantic and the Arctic Oceans by the international community have been on-going for over a decade as part of several different programmes and projects, most recently the ASOF project on Arctic and Subarctic Ocean Fluxes (Hansen *et al.* 2001);
- Annual ecosystem monitoring of the Iceland Sea and the Norwegian Sea is carried out by Iceland and Norway, respectively, as part of their fisheries assessment work;
- Much less attention has been paid to the Greenland Sea with most work conducted as part of special programmes such as the 1957 International Geophysical Year (IGY);
- The activities planned for the International Polar Year (IPY 2007/2008) include a major study of capelin undertaken by Iceland (Ecosystem of the Iceland Sea Project) and ecosystem studies in the vicinity of the Arctic Front undertaken by Norway.

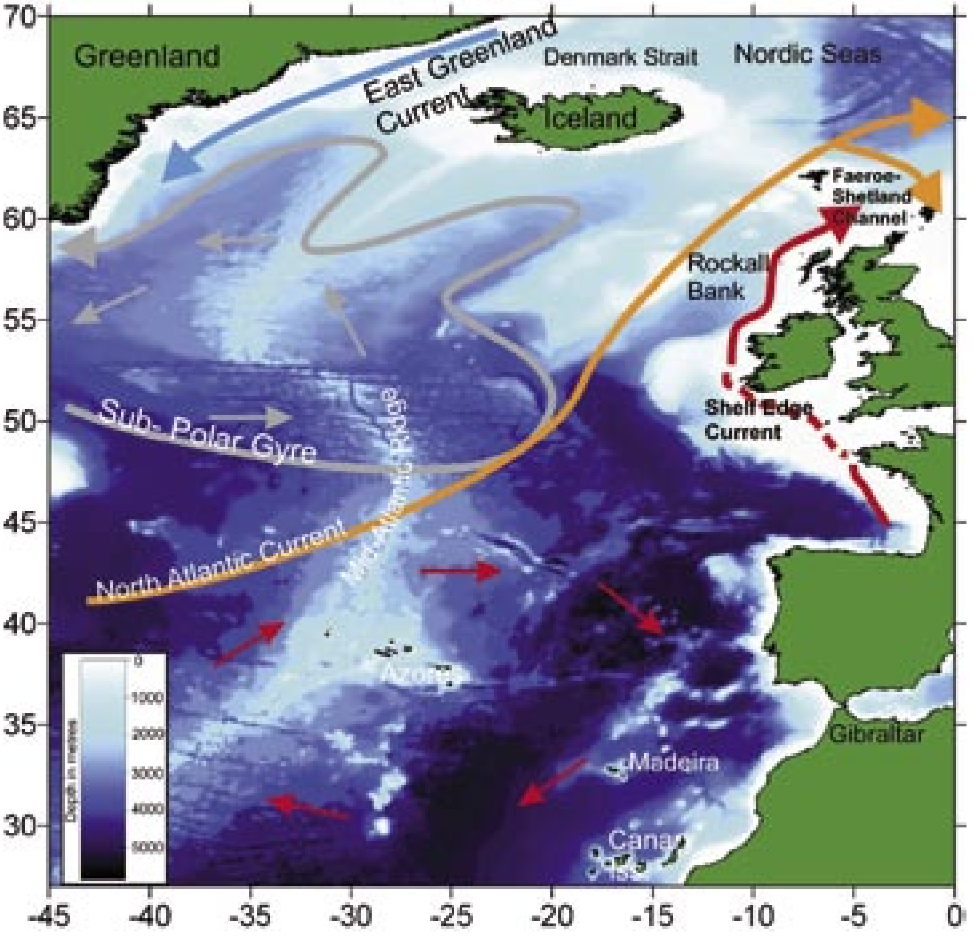
4.5 Northeast Atlantic

Description of the area

The Northeast Atlantic is referred to here as the ocean to the east of the European shelf, to the north of a line from Gibraltar eastward to a line from the southern tip of Greenland, with the Nordic Seas north of 62°N as its northern boundary. These are the oceanic waters with depths mostly over 1,000 m, which are closest to Europe. Topographically, the region includes the north-south trending Mid-Atlantic Ridge with deep abyssal plains to either side that extend down to 5,800 m in the southeast, and the Rockall Bank that lies west of Scotland. Occasional sea mounts dot this landscape with the volcanic archipelagos of the Azores, Madeira and Canary Islands to the south.

This region plays a key role in the climate of Europe as heat is transferred to the atmosphere from the warm extension of the Gulf Stream, the northeastward-directed North Atlantic Current (NAC). To the north of the NAC, the circulation is anticlockwise in the colder waters of the subpolar gyre and to the south of the NAC clockwise in the warm subtropical gyre. Water with a subtropical component is also transferred from the south in a current that roughly follows the margin of the European shelf. Saline water from the Mediterranean overflows into the Atlantic at mid-water depths (1,000 m), up to the southwest coast of France.

The heat transferred from the ocean to the atmosphere as the oceanic waters are mixed by the wind and cool down in their generally northeastward movement helps ensure, together with northeastward storm tracks, that Northwest Europe is much warmer on an annual basis than equivalent latitudes on the western side of the Atlantic (see Section 1.3). During the last Pleistocene glaciation, sea-ice extended as far south as 45°N with ice caps over the British Isles and much of continental Europe. These colder conditions are hypothesised to have been generated by a slowing down by the North Atlantic Meridional Overturning Circulation, MOC (see Section 3.1).



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The Northeast Atlantic.

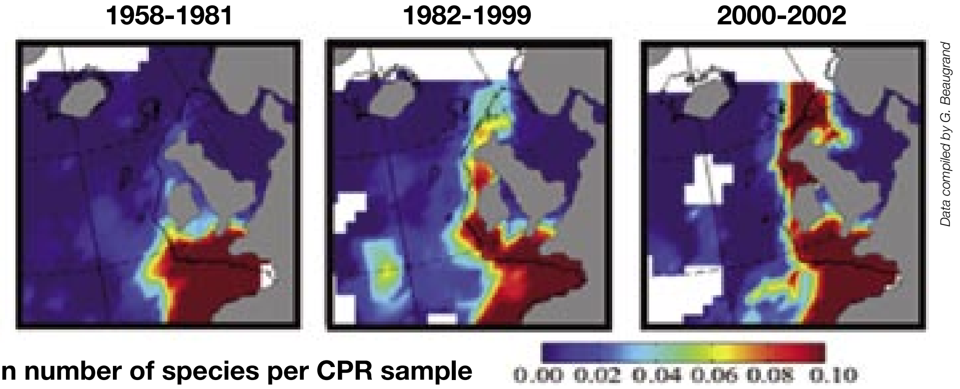
The Northeast Atlantic plays a key role in this circulation as the warmer water is pulled into the Arctic Ocean by deep convection of cold dense water. This flows out into the Atlantic through the Faeroe-Shetland Channel flowing as a deep current to join a similar outflow through the Denmark Strait between Iceland and Greenland around the western margin of the Labrador Sea and thence south along the eastern margin of North America. The balance between these surface and deep-water flows is believed to be the key to large-scale climatic variability in Northwest Europe.

Signals of climate change

It has been demonstrated that the southerly outflow through the Faeroe-Shetland Channel decreased by 20% in the last 50 years (Hansen *et al.* 2001) and there is evidence from satellite observations that the northward flow of surface waters has reduced since the 1970s (Häkkinen and Rhines 2004). While recent observations indicate that the returned subsurface flow associated with the MOC has slowed down due to reduced convective sinking, there is no evidence that the near surface flows have decreased (Bryden *et al.* 2005).

In the Northeast Atlantic to the south of the subpolar gyre, sea-surface temperatures (SSTs) are highly positively correlated with surface land and sea temperatures averaged for the whole of the Northern Hemisphere. In the subboreal gyre, SST is inversely correlated with the North Atlantic Oscillation (NAO). Reduced circulation of the North Atlantic Current (NAC) and increased northward flow in the shelf edge current are correlated with negative winter NAO. This means that the strength of the NAC and the poleward flow along the continental edge are out of phase (Pingree 2002, 2005).

> *'Over the last 40 years, warmer water groups of plankton to the west of the British Isles have moved north by 1,000 km.'*
>
> *Beaugrand et al. (2002)*



Mean number of species per CPR sample

Long-term changes from 1960 to 1999 in the mean number of warm-temperate species such as Calanus helgolandicus. In the eastern North Atlantic Ocean and European shelf seas, strong biogeographical shifts in all copepod assemblages have occurred with a northward extension of more than 10 latitude.

The increase in sea temperatures especially in winter months since the mid-1980s has had a marked effect on plankton population and higher trophic levels. Both plankton (Beaugrand *et al.* 2002) and mid-water to surface-water fish (Quero *et al.* 1998; Brander *et al.* 2003) have shown similar northward range extensions. There is clear evidence that the levels of phytoplankton concentrations as measured by chlorophyll have increased and that their season has lengthened since the mid-1980s (Edwards *et al.* 2006).

The number of Atlantic salmon returning to spawn in Northeastern Europe has greatly declined; this appears to be linked to climatic variability (Beaugrand and Reid 2003). Most other exploited fish species in the region, including deepwater species, have also undergone large reductions in stock size, an impact that is believed to be due, in large measure, to overfishing, but which may include an environmental component.

Deeper water organisms are less likely to be impacted by climate change other than through changes to their food by the settling of particulate material through the water column. Reefs of cold water corals are currently threatened by human activities such as fishing, and by ocean acidification.

Projections of climate change
There is strong evidence that changes seen in the North Atlantic are on a scale not previously recorded. The ocean is freshening both at the surface and at depth (Curry *et al.* 2003; González-Pola *et al.* 2005) and has undergone a period of rapid warming (Levitus 2000). Associated changes have taken place in the circulation and in the formation of deep water, both in the Nordic Seas and in the Labrador Sea.

Taken together, these conditions are likely to impact on the Thermohaline Circulation (see Section 1.3) which could lead to a cooling of Europe's climate. Modelling studies to date, however, suggest that this is unlikely to happen in the next 100 years and that the current trend of warming is likely to continue with increases of 2°C and more over this time frame. Changes of this scale (+ 2°C) over such a period are nonetheless likely to have significant effects on the circulation and ecosystems of the Northeast Atlantic.

Perhaps the greatest impact of climate change within the Atlantic will be on the biological pump (see Section 1.3).

Current research and monitoring programmes and projects in the Northeast Atlantic

- The International Council for the Exploration of the Sea (ICES) is the intergovernmental organisation that coordinates and promotes marine research, with particular reference to fisheries management, in the North Atlantic and the adjacent seas such as the Baltic Sea and North Sea. ICES comprises 19 member countries. The scientific advice prepared by the Advisory Committee on Fisheries Management (ACFM) of ICES is examined by the Scientific, Technical and Economic Committee for Fisheries, who consults with industry and other parties before formulating proposals for quotas, for discussion at the annual December meetings of the Council of Fisheries Ministers and for advice to the Common Fisheries Policy (CFP);
- ICCAT (International Commission for the Conservation of Atlantic Tuna), NASCO (North Atlantic Salmon Conservation Organisation) and NEAFC (North East Atlantic Fisheries Commission) also provides inputs to the CFP;
- As an open ocean region, monitoring is largely restricted to periodic cruises by research vessels. An exception is the monthly sampling by the 75 year-old Continuous Plankton Recorder (CPR, coordinated by SAHFOS) surveying along standard tracks of ships of opportunity;
- A number of strategic hydrographical sections are operated, e.g. across the Faeroe-Shetland Channel and the Rockall Trough (Ellett Line) and an ocean-wide section is being monitored just to the south along 26°N (Bryden *et al.* 2005);
- A wide range of studies have been carried out at the Station Papa site in the Porcupine Sea Bight, formerly at Ocean Weather Ship stations India and Juliet;
- Long-term current meter studies are being undertaken in the Denmark Strait and in the Faeroe-Shetland Channel to measure overflow waters;
- Surveys of seabirds and cetaceans at sea from ships and aircraft have been obtained since 1979 as part of the European Seabird at Sea (ESAS) programme, and are managed by the UK Joint Nature Conservation Council (JNCC).

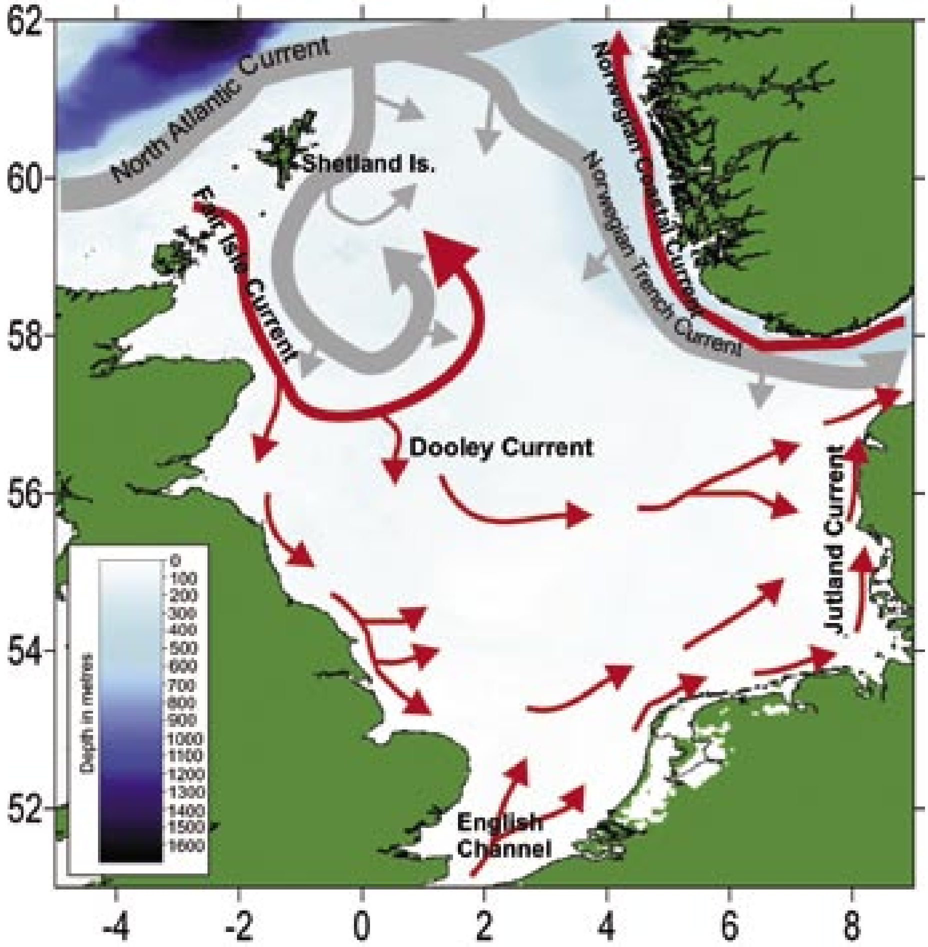
4.6 North Sea

Description of the area

The topography of the North Sea can broadly be described as a gradual slope from shallow (<50 m) in the south to deeper (100-150 m) in the north. Including estuaries and fjords, the total surface area of the North Sea is approximately 750,000 km^2 and the total volume 94,000 km^3. Atlantic water enters mainly via the Norwegian Trench and around the Shetlands in the north, and to a lesser degree via the English Channel in the south.

Signals of climate change

In the North Sea two climatic periods stand out as exceptional within the past 50 years. During the most recent change in the late 1980s, a pronounced modification occurred in large-scale hydro-meteorological forcing and ecosystem parameters, including a marked increase in oceanic inflow and sea-surface temperature (Beaugrand 2004). This warm temperate period has continued to the present day. The previous change occurred in the late 1970s and was characterised by low temperatures and salinities, a reduced inflow of Atlantic water, and cold boreal conditions (Reid *et al.* 2003). Both periods were characterised by wide-scale and rather sudden changes in plankton, benthos and fish populations (e.g. Weijerman *et al.* 2005).



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The North Sea.

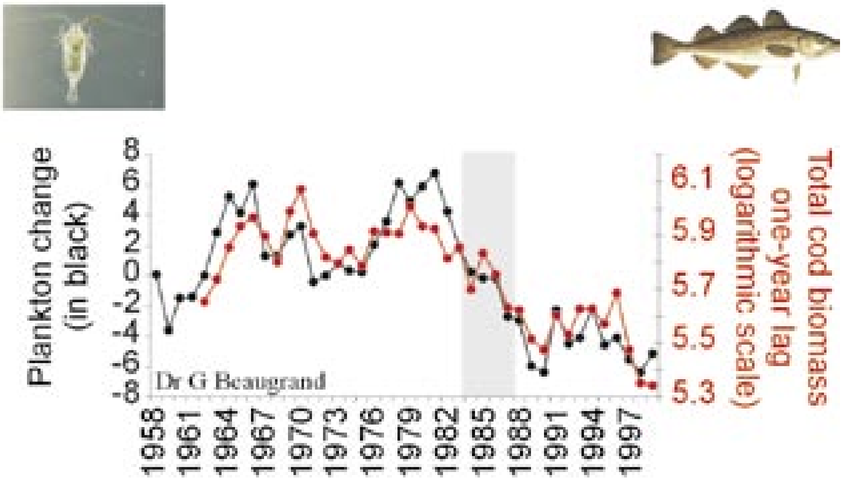
The response to these events was at times regionally different. For example, a delay in the timing of the spring phytoplankton bloom occurred in the Wadden Sea after the mid-1980s, while over much of the open North Sea the bloom occurred earlier. At the same time the first appearance of juvenile shrimp in the Wadden Sea advanced, as did the first appearance of fish larvae in the German Bight.

Patterns of change in sea-surface temperature that distinguish these two periods are strongly correlated with two indices of climatic variability: The Northern Hemisphere Temperature (NHT) and the North Atlantic Oscillation (NAO). Ecological responses to these signals in the North Sea are wide ranging and encompass changes in the timing of reproduction, the length of the growing season of phytoplankton, the timing of the spring migration of birds, as well as the population dynamics, abundance, competition and predator-prey relationships, and the geographical distribution and abundance of populations of many fish species (e.g. Beaugrand and Reid 2003; Brander *et al.* 2003; Drinkwater *et al.* 2003; Perry *et al.* 2005). While these indices only partly explain observed climatic variability, they strongly impact on the North Sea and, at least in the case of the NHT, are linked to global warming and the increase in atmospheric level of greenhouse gases (IPCC 2001c).

In terms of phenology, seasonal changes in response to warming in the timing of biological events for different planktonic functional groups are leading to a mismatch in the timing between phytoplankton and zooplankton, between zooplankton and fish, between bivalve larvae and shrimp, and between fish and seabirds (e.g. Beaugrand and Reid 2003; Philippart *et al.* 2003; Edwards and Richardson 2004; Wiltshire and 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).

> *'Many warm-water rocky shore snails and barnacles formerly absent or just extending into the North Sea have spread south along the North Sea coast of the UK from the tip of Scotland.'*
>
> *Mieszkowska et al. (2005)*
> *Hawkins and Burrows (personal communication)*

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). Warmer water species of plankton, for example, have extended their range northward by 1,000 km in only 40 years and colder species have retreated out of the North Sea (Beaugrand *et al.* 2003). Sardines and anchovies have moved northward in the North Sea and red mullet and bass have extended their ranges north to western Norway (e.g. Brander *et al.* 2003).



Beaugrand, unpublished

Relationship between food supply (indexed as plankton change, Beaugrand *et al.* 2003) and total biomass of cod for the North Sea for the period 1958-1999. Note that changes in food supply had an effect on cod biomass with one- to two-year lags.

4. Regional responses and impacts

Projections of climate change

Regional climate change scenarios predict an increase in air temperature of 2-3.5°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). Water temperatures will also increase, but not as rapidly as temperature over land. Sea-level is expected to rise by 35-84 cm at 2100 compared to 1990 (van den Hurk *et al.* 2006).

Observed correlations strongly suggest 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 rely on temperature as a trigger, and further increases in temperature may disrupt the connectedness between species potentially leading to changes in community structures and possibly local extinctions. For many marine species, including commercially caught fish, the number of recruits mainly determines 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) have the potential to significantly impact fisheries and have strong effects on the local ecosystem.

Because of the strong tidal regime and the effects of storm surges many of the coastal regions of the North Sea, especially in the south, are particularly susceptible to rising sea levels and to an increase in the frequency and severity of storms. If existing natural and human-made sea defences are breached, flooding could be extensive since parts of the southern UK and the Netherlands are slowly sinking due to gradual settling. Greater defence by artificial coastal defences in order to minimise the risk of future flooding of these coastlines will lead to loss of coastal habitats (IPCC 1990), and may become far more difficult in the future, threatening major coastal cities such as London and Amsterdam.

Current research and monitoring programmes and projects in the North sea

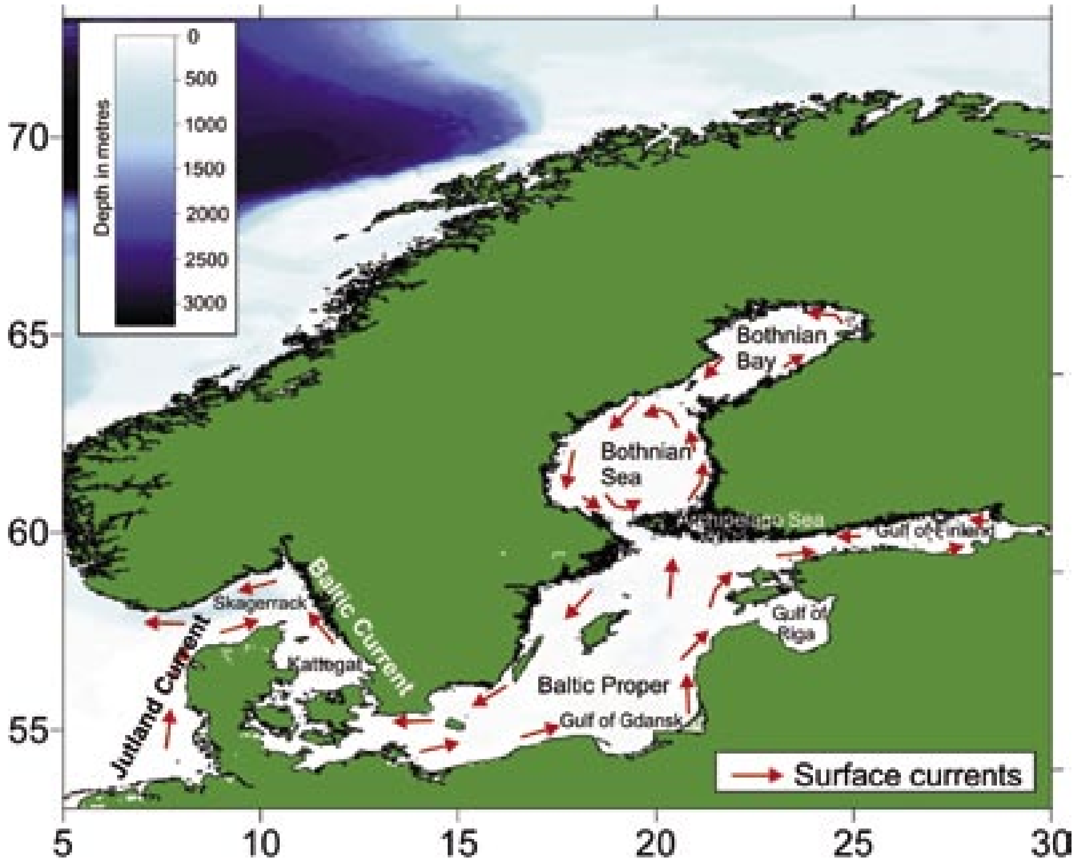
- Most countries around the North Sea undertake meteorological and hydrodynamic monitoring for national purposes, which in a number of cases is linked to the Global Ocean Observing System (GOOS) and EuroGOOS;
- The German Federal Maritime and Hydrographic Agency produces weekly maps of sea-surface temperature;
- The International Council for the Exploration of the Sea (ICES) maintains a bank of oceanographic data, dating back to the early 1900s and coordinates a suite of annual and triennial fish surveys;
- North Sea plankton has been monitored by the Continuous Plankton Recorder (CPR) coordinated by SAHFOS since 1931;
- Several marine institutes (e.g. Alfred Wegener Institute (AWI), Centre for Environment, Fisheries and Aquaculture Science (CEFAS), Fisheries Research Services (FRS), Royal Netherlands Institute for Sea Research (NIOZ), Universities of Lille and Newcastle) undertake local long-term (>30 yrs) field observations on environmental parameters and marine organisms. The UK observations are coordinated via the Marine Environmental Change Network (MECN);
- Some European initiative network monitoring and research efforts on effects of climate change on the North Sea. These networks include implementation and networking of large-scale long-term Marine Biodiversity research in Europe (BIOMARE), Marine Genomics Europe (MGE), and Marine Biodiversity and Ecosystem Functioning (MarBEF). MarBEF has developed a European database of biogeographic information on ocean environmental parameters and marine organisms (EurOBIS) and hosts the European Register of Marine Species (ERMS).

4.7 Baltic Sea

Description of the area

The Baltic Sea is a semi-enclosed basin with a total area of 415,000 km^2 that includes its narrow entrance, the Kattegat. The catchment area is four times larger than the sea itself and is populated by approximately 85 million inhabitants. Because of its location with respect to the expansions and contractions of the Scandinavian ice sheet, the Baltic Sea has never been in a steady state since its formation. Postglacial processes have shaped the Baltic's coastline, topography, basic chemistry and sedimentary environment on millennium scales.

Climate variability acts on centennial and decadal scales and, particularly in the last 150 years, overlaps with human activity in the drainage basin and the coastal zone have led to considerable change in the biogeochemistry of the Baltic Sea basin. The Baltic Sea is characterised by a closed circulation in the central basin, low salinities, and by strong horizontal gradients both in salinity and in ecosystem variables resulting in low biodiversity.



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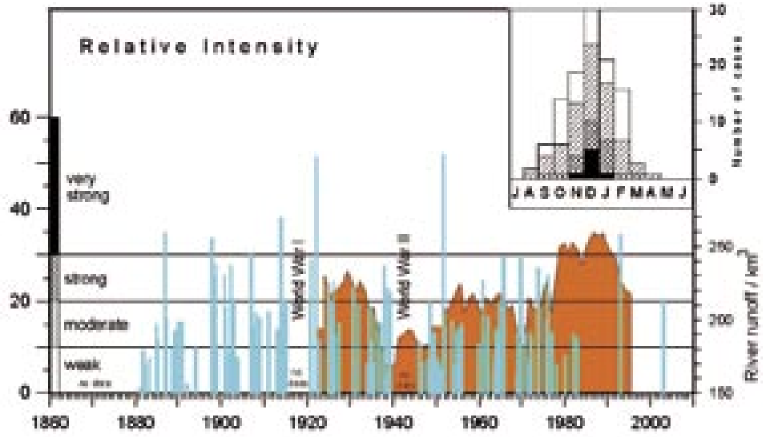
The Baltic Sea.

The interannual variability of the Baltic Sea is modulated by the North Atlantic Oscillation (NAO) and by the inflow of Atlantic water from the North Sea into this area, referred to as major Baltic inflows. These inflows represent the only mechanism by which the Baltic deep water is displaced and renewed to a significant degree with relatively high salinity (17-25 ppm) and oxygenated water. In the longer lasting stagnation periods between inflow events, all of the oxygen in the deep waters is used up, resulting in anoxic conditions.



Major Baltic inflows (blue bars) between 1880 and 2005 and their seasonal distribution (upper right), shown in terms of their relative intensity after Matthäus and Frank (1992) and the total amount of river runoff (red) after Bergström and Carlsson (1994). The time series have been supplemented and updated by Matthäus (2006).

Signals of climate changes

Analysis of a cumulative Baltic winter index indicates that during the last 350 years, six regime shifts have occurred (Hagen and Feistel 2005). The Baltic Sea ecosystem appeared to be strongly influenced by the interplay of non-periodic shifts from lake to sea and back during the late quaternary period (Dippner *et al.* 2006). This in turn resulted in changes between marine and limnic (freshwater) species composition, shifts from cold water to warm water species and back, changes between oxygen-rich and oxygen-poor conditions in the deep basins, and the occasional intrusion of non-indigenous species.

> *'In the Baltic Sea, the anthropogenic influence of eutrophication in near coastal areas is overwhelming the signal of climate variability.'*
>
> *Dippner and Ikauniece (2001)*

Projections of climate change

Climate change simulations with different regional climate models, hydrological models and circulation models for a number of greenhouse gas emission scenarios give variable results for changes in Baltic climate variables. Nonetheless, some general trends are projected (Graham *et al.* 2006). All scenarios and all climate models predict temperature increases during all seasons with a mean warming of 3-5ºC in the atmosphere and 2-4°C in the sea-surface temperature in the Baltic by the end of the 21st century. One consequence is a decrease in sea-ice extent by 50-80% over the same period. Projected changes in precipitation are variable. Winters will probably be wetter and in southern parts of the region, summers are predicted to be drier under many climate scenarios. As a consequence, river runoff during winter is expected to increase by as much as 50%, with the opposite pattern occurring in summer.

Each of the predicted changes has a different consequence for the ecosystem. Uncertainty is created by the fact that while much is know about the consequences of change in salinity or temperature, little is known about the consequences of their interactions or of combined changes. An increase in temperature prevents late winter convection, which is essential for nutrient supply in the upper layer. Higher temperatures during winter may result in increased metabolic rates for bacteria and a shift in species composition from cold to warm water species, whereas higher temperatures in summer may enhance blooms of cyanobacteria blooms (that is bacteria that obtain their energy via photosynthesis). An increase in precipitation will result in higher river runoff, reduced salinity, higher nutrient input by rivers and enhanced eutrophication in near coastal areas with higher phytoplankton and benthic biomass (Dippner and Ikauniece 2001).

Projections of climate change do not indicate a robust signal with respect to windiness. Nevertheless, possible increasing windiness during late winter would lead to stronger vertical mixing with the consequence that nutrients would be mixed into the euphotic zone and would be directly available for primary production. This process would provide higher than normal phosphate concentrations in early spring which would be used by cyanobacteria later in summer (Janssen *et al.* 2004). An increase in windiness might also cause remobilisation of contaminants from bottom sediment. Lower salinities would cause osmotic stress for phyto- and zooplankton and may result in a shift in species composition from marine to limnic species. Such a shift would influence the food quality and therefore the growth rate and fat content of fish.

Decreasing salinity in combination with oxygen-poor and oxygen-depleted conditions due to cyanobacteria blooms would result in benthic deserts in the deep basins and poor survival conditions for cod eggs. In contrast, higher temperatures would lead to an increase in the carrying capacity for sprat stocks and likely alter food web structure (Möllmann *et al.* 2005). Reducing salinities would result in distributional changes and favour the invasion of non-indigenous species.

Current research and monitoring programmes and projects

- National Baltic Sea monitoring programmes and projects of physical, chemical or biological properties are co-ordinated by HELCOM;

- Data collection on fish and fisheries is co-ordinated by ICES;

- hIn the framework of the BONUS ERA-NET project (networking of funding agencies – funded by the European Union Sixth Framework Programme), the BONUS-169 Baltic Sea Science Plan has been developed to create prudent, long-term, holistic multidisciplinary solutions involving sustainable use of the sea by: i) understanding and quantifying the role of climate change and variability and its implications for the dynamics of the region's ecosystem; ii) understanding the physical, chemical and biological functioning of marine ecosystem and understanding and quantifying human impacts; and iii) developing the scientific basis for sustainable use and protection of the marine environment and its associated biodiversity.

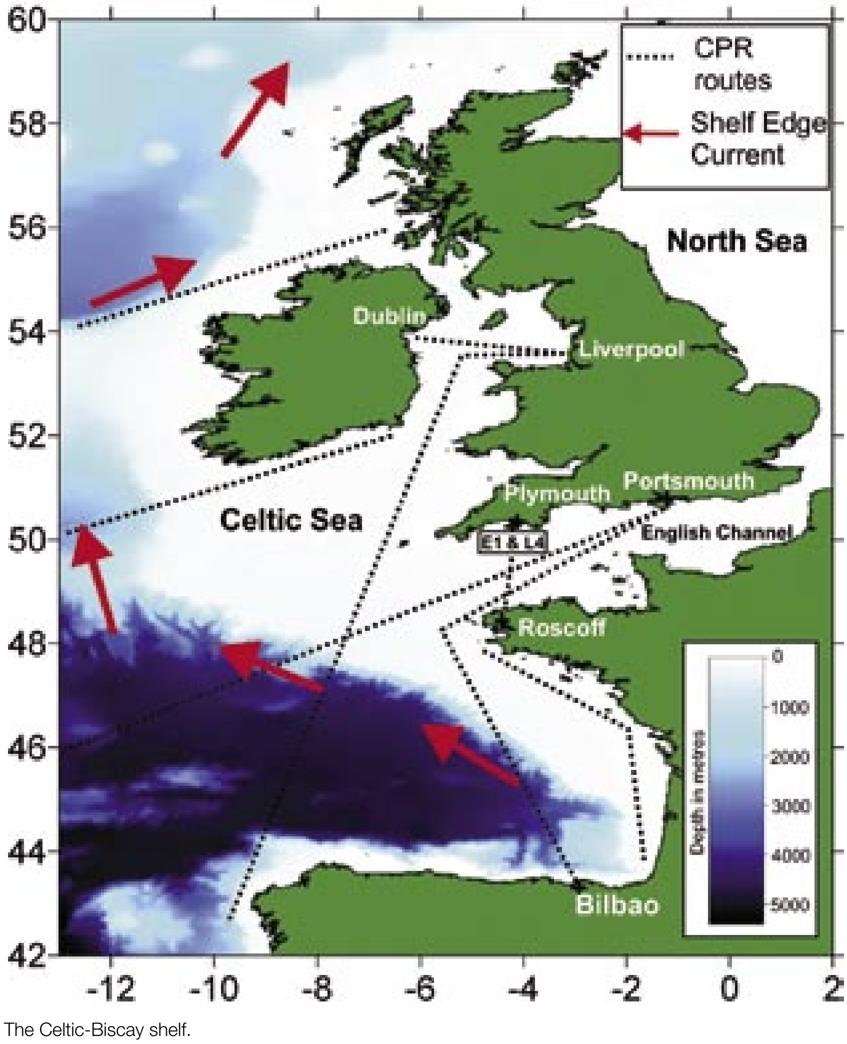
4.8 Celtic-Biscay shelf

Description of the area
The region considered as the Celtic-Biscay Shelf includes the coastal and shelf seas of the northern Bay of Biscay, the Celtic Sea, English Channel and the Irish Sea, plus the coastal seas to the west of Scotland and Ireland. This region has a complex topography, with patterns of water movement primarily from the south and west penetrating into the English Channel and the Irish Sea. Water also leaves the region to enter the North Sea from the south and west via the English Channel and from the north and west around Scotland. The deeper water of the Bay of Biscay is best considered as part of the wider Northeast Atlantic.

The water masses in these coast and shelf regions are primarily of North Atlantic origin but with some influence from Mediterranean water in the Bay of Biscay. In NAO negative years (Navidad years), warm water enters the Bay of Biscay and can propagate northwards west of Ireland (Pingree and Le Cann 1989; Pingree 2002).

The Celtic Sea and western English Channel stratifies strongly, leading to pronounced surface fronts. Much of the Irish Sea is tidally mixed except for a stratified patch west of the Isle of Man bound to the north and south by fronts. The English Channel becomes less stratified from west to east; the eastern basin is tidally mixed (Pingree and Griffiths 1978).

The Celtic-Biscay Sea region including the English Channel and Irish Sea is known to sit astride a biogeographic boundary zone (Forbes 1958). Many boreal and cold temperature species reach their southern limits in this area (e.g. kelp, herring, cod), while warm-temperate lusitanean species exist at their northern limit (e.g. sardines, breams, red mullet, *Cystoceira*). Thus, this region is particularly sensitive to climate change in both offshore and inshore waters.



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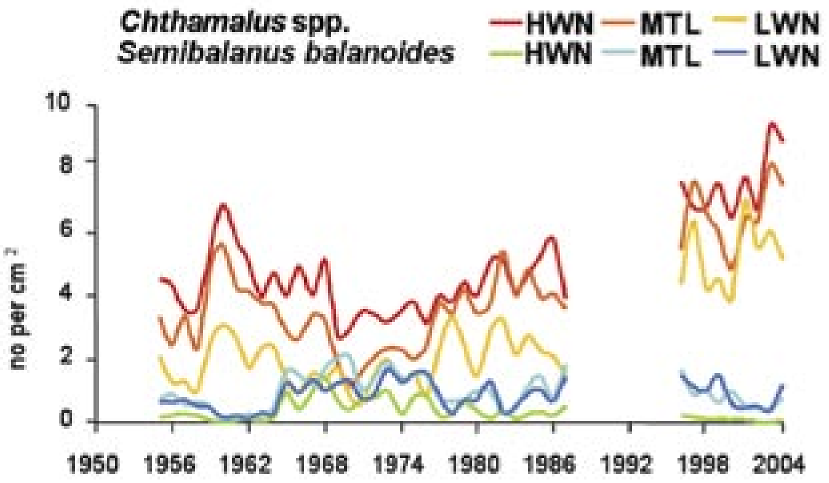
The Celtic-Biscay shelf.

Signals of climate change

Observations of sea-surface temperatures have been made in the Celtic-Biscay region since the middle of the 19th century. Sea-surface temperatures show that, following a warm period in the 1880s, temperatures cooled until the early 20th century before increasing from around 1920, and remained warm until the 1960s. A cooler period followed the extremely cold winter of 1962/1963 and continued well into the 1980s. Since then, accelerated warming has been apparent (see Southward *et al.* 2005 for further details). Similar changes have been seen in the Bay of Biscay (Planque *et al.* 2003; Blanchard and Vandermeirsch 2005), the Irish Sea (Evans *et al.* 2003) and the eastern English Channel (Woehrling *et al.* 2005).

The CPR survey clearly shows that in the 1960s warm temperate zooplankton species just reached the region. Since the late 1980s these species have spread northwards encompassing much of the west coast of France, Britain and Ireland (Beaugrand *et al.* 2002). A longer term picture of changes in this region can be derived from the time-series collected by the CPR. Rapid warming occurring from the late 1980s onwards can be put into the context of past changes including warming up to around 1960.



Long-term changes in northern (*Semibalanus balanoides*) and southern (*Chthamalus spp*) barnacles averaged for several shores at different submersion levels (HWN: High Water Neap; MTL: Mean Tidal Low; LWN: Low Water Neap) on the south coast of Devon and Cornwall (© Southward 1991; Southward *et al.* 1995; Southward and Hawkins, unpublished).

During the warming in the 1930s the herring fishery in the English Channel collapsed, associated with much change in the rest of the ecosystem, indicating that overfishing was probably not the main underlying cause of the decline of the herring population. Cold temperate herring were replaced by warmer water pilchards (sardines). These ecosystem-wide changes were subsequently ascribed to climate change (Southward 1980). Historical research has since shown that such switches in species populations were commonplace and have occurred at least since the 13th century during alternating cold or warm periods (Southward *et al.* 1988).

In the 1960s there was a switch back to colder conditions and the planktonic communities returned to their previous colder water characteristics. Populations of pilchards declined again. Herring populations did not recover – perhaps because at that time in the 1970s stocks were at historically low levels in the eastern English Channel and North Sea and recolonisation was not possible (Hawkins *et al.* 2003). Sardines are now abundant again and the warmer water chaetognath *Sagitta setosa* with other southern species predominates in the plankton.

In addition to changes in the plankton and in pelagic and demersal fish assemblages, parallel changes were described on rocky shores, using barnacles as a sensitive indicator of wider changes in marine life (Southward *et al.* 1995, 2005). These showed switches between warm water barnacles in the 1950s to greater dominance by the cold water barnacle *Semibalanus balanoides* in the 1960s and 1970s. On rocky shores warm water barnacles now exceed the levels found in the 1950s and southern species of gastropods and limpets have increased in abundance and recovered ground lost during the cold winter of 1962/1963. In some cases range extensions have occurred beyond the limits of the 1950s. This is particularly the case in the eastern English Channel and off the northwest of Scotland where several species have penetrated far beyond their previous limits (Mieszkowska *et al.* 2005).

Projections of climate change

Rapid responses are likely with accelerating climate change in this biogeographic boundary region. Previous changes involving major fluctuations in dominant species of pelagic and demersal fish, zooplankton and benthos were in response to changes of less than 1°C in average annual temperatures (Southward 1980). Predicted changes are in the order of 1.5-5°C over the next 100 years.

> *'By extrapolation of trends from catches of southern fish off Plymouth over the last 80 years it is possible to forecast that by 2025, even under low emission scenarios, the fish assemblage off Plymouth will resemble that currently found far to the south in the Iberian Peninsula.'*
>
> *Genner et al. (2004)*
> *Sims et al. (unpublished)*

Forecast models of intertidal assemblages suggest that northern species (such as the barnacle *Semibalanus balanoides*) will become extinct in much of the southwest of England and probably also in northwest France in the next 20-30 years. Some species, such as the kelp *Alaria esculenta*, were badly impacted by the last warm period of the 1950s and seem to have retracted further in recent years (Mieszkowska *et al.* 2005).

Many commercial fishery species now found more commonly further north in the English Channel command high market prices in France, Spain and Portugal. With good transport links from the UK there are now high-value markets for species such as cuttlefish (*Sepia*), spider crabs (*Maja*) and various bream and red mullet, encouraging exports from southwest Britain and Ireland. The possibility still remains of cooling at some stage, should thermohaline circulation be slowed down, leading to a weakened Gulf Stream. Should this occur, then re-adjustment to northern assemblages is likely, as occurred after the last extremely cold winter of 1962/1963 (Genner *et al.* 2004; Sims *et al.* unpublished).

Current research and monitoring programmes and projects in the Celtic-Biscay Shelf

- Considerable effort has been made via the MarCLIM project to resurvey existing baseline studies of rocky shores in Britain and Ireland;
- Many of the long-term time-series records collected by the Marine Biological Association at Plymouth have been reactivated in recent years, e.g. observations of hydrography and plankton at station E1, benthos and fish at station L4, and broadscale surveys of the English Channel benthos (see Southward *et al.* 2005 for details). The Plymouth Marine Laboratory has collected information on zooplankton and much of the pelagic ecosystem at station L4 since 1988;
- The SAHFOS-CPR surveys provide good coverage of the pelagic species of the English Channel and the Bay of Biscay. The resumption of the Plymouth-Roscoff and the Portsmouth-Bilbao CPR tows are particularly valuable and together these observations will form the core of the proposed western English Channel observatory based in Plymouth. Similar approaches are underway via the observatory at Roscoff;
- There are also long-term time-series records for the benthos of the eastern Channel collected by the Wimereaux Laboratory in Flanders.

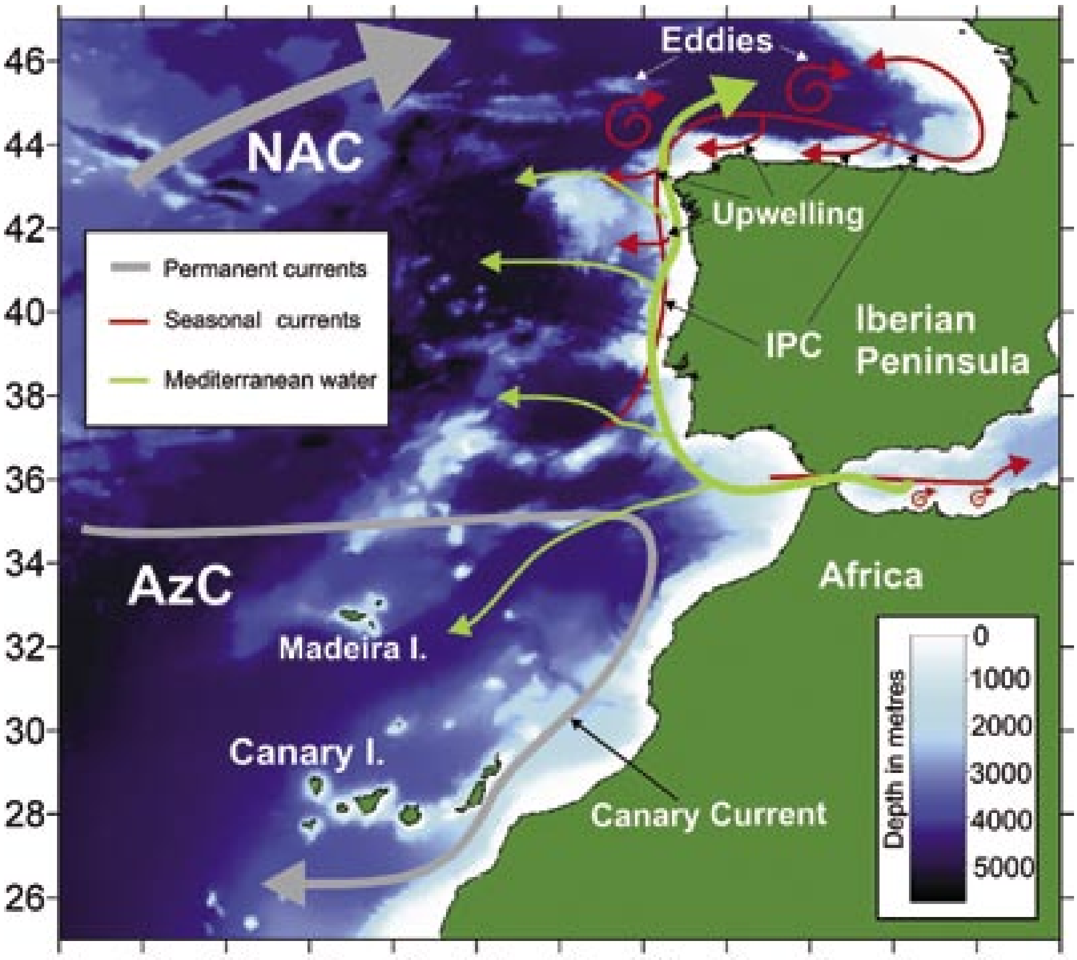
4.9 Iberian upwelling margin

Description of the area

The Iberian coastal area includes the continental shelf region and the oceanic part of the Eastern Atlantic Ocean, lying between 35ºN and 44ºN. The deep ocean floor is around 4,000 m deep. The west and north Iberian Peninsula present a narrow shelf when compared with the North Bay of Biscay and Celtic Sea. This shelf is crossed by several submarine canyons in the Bay of Biscay and on the Portuguese coast; several rivers enter along the Galician coast. The east-west orientation of the coast in the northern part breaks the normal north-south orientation of the European Atlantic coast.

The Iberian coastal area has a weak circulation pattern, with seasonal variability (Valdés and Lavín 2002). The main oceanographic features are: the Iberian Poleward Current, coastal upwelling (more intense and extended in the west Iberian coast) and the seasonal stratification in oceanic waters. The exchange of waters between the Atlantic and the Mediterranean is also relevant. As a result of the Iberian Poleward Current, several anticyclonic eddies are shed into oceanic waters, off the northeast corner of the Iberian Peninsula, and in the Central Bay of Biscay.

As a result of the summer upwelling, two parallel biogeographical gradients can be distinguished in Atlantic waters of the Iberian Peninsula (that is North-South in the west and West-East in the north). Many northern species are much more common in the northwest Iberian Peninsula and some southern species are recorded as absent or less abundant before reappearing in the inner Bay of Biscay and south Portugal (Fischer-Piette 1963; Ardré 1970; Anadón and Niell 1980). A similar biogeographical anomaly appears off North Africa, associated with upwelling (Lüning 1990).



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The Iberian upwelling margin.

4. Regional responses and impacts

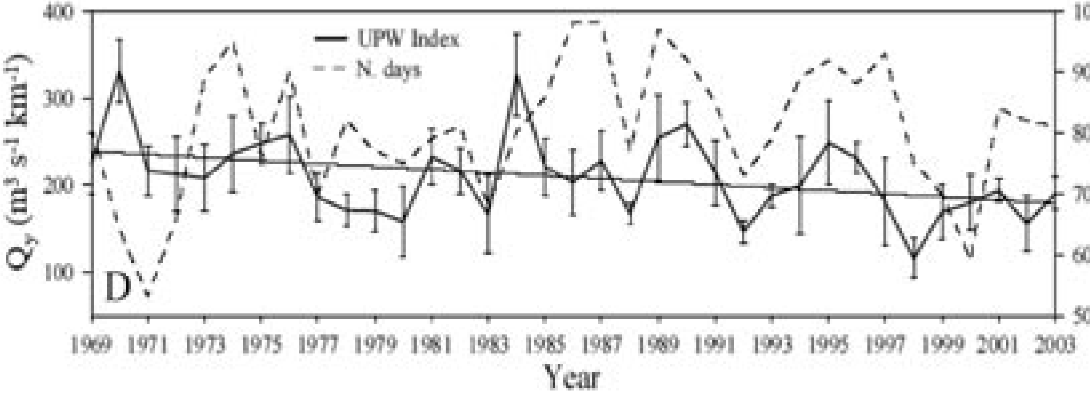
Signals of climate change
Changes in the sea-surface temperatures (SST) derived from the 1860-2000 Comprehensive Ocean-Atmosphere Data Set (COADS) for the Bay of Biscay (Planque *et al.* 2003) show two cold temperature periods, around 1910 and 1970, and warm temperate periods in 1870 and 1960. Rapid warming in surface temperatures (0.055 ºC y $^{-1}$ over 30 years) has occurred in the last few decades (Koutsikopoulos *et al.* 1998; Llope *et al.* 2006) in all the oceanic areas of the bay. Due to high variability, the increase was not significant in coastal areas. In very near coast locations along northern Spain, the long-term trend in changes in SST could be negative (Borja *et al.* 2002). A decreasing salinity trend in the surface and subsurface waters towards the southern Bay of Biscay was observed in the past 15 years (González-Pola *et al.* 2005).

An averaged sea-level rise of 2.12-2.91 mm y $^{-1}$ in the last 50 years was detected in the northwest Iberian Peninsula (Marcos *et al.* 2005), with a 6.5 mm y $^{-1}$ rise between 1991 and 2001. A decreasing trend in the upwelling index and the seasonality of upwelling off northern Spain has also been detected (Llope *et al.* 2006).

Biological responses to climate change have been detected for various organisms and ecosystems. Both primary productivity and species composition of the phytoplankton are affected by long-term changes in chemically different water masses. A rapid increase (1993/1994) in abundance of the rare warm temperate copepod *Temora stylifera* occured in the Bay of Biscay, which correlated with the decreasing abundance of the coastal *Temora longicornis*.

Several other organisms of subtropical origin have been detected during recent years (Guerra *et al.* 2002). There have been changes in species abundance and diversity of intertidal communities (Sánchez *et al.* 2005), and northward displacement of southern origin species (i.e. *Patella rustica*, Lima *et al.* 2006). Decreases of biomass of some seaweeds were observed over the past 15 years (Fernández, unpublished).

There have been changes in exploited fish populations such as pilchard sardine, anchovy, mackerel and horse mackerel, but it is quite difficult to differentiate between the impact of climate and fishing effects. Many changes in migratory routes and spawning areas, however, are associated with fluctuations in the NAO index, indicating a climate effect (Borja *et al.* 2002).



Intensity (Mean and S.E.) and number of days with upwelling per year averaged from April-September values. The straight line is the linear fit for intensity (Llope *et al.* 2006) (© 2006 American Geophysical Union - Reproduced by permission of American Geophysical Union).

Projections of climate change

The Iberian coast supports intense fisheries and aquaculture, involving traditional mussel rafts and modern intensive fish and mollusc farming. Several impacts related to climate change could have socio-economic impacts. The observed increase in harmful algal blooms could affect these commercial activities. The changes in primary productivity related with upwelling intensity and seasonality affecting growth will impact upon the quality of the mussels (Blanton *et al.* 1987).

> *'The increase in parasites of subtropical origin (such as Perkinsus) endangers the extensive mollusc farming along the Spanish coasts'*
>
> *Labarta (personal observation)*

The predicted changes in SST as well the observed and predicted changes in circulation and stratification could influence the retention-dispersion mechanism of larval stages of fish and shellfish with unknown consequences for species recruitment. Changes in the distribution of seaweed and invertebrate fauna along northwest Iberian and Atlantic French coasts will be evident in the first half of the 21st century, based upon the actual temperature limits of their distribution and predictions of global circulation models on future SST (Alcock 2003). Beaches, infrastructures and urban facilities could be seriously impacted by the sea-level rise (Cendrero *et al.* 2005).

Current research and monitoring programmes and projects

- The main programme devoted to oceanographic research in the global change context in Spain is a part of the National Programme on Environmental Science and Technology. The plan identifies, as a special task, the functional role of the oceans in global change and the impacts of global change on the regional and local seas in which Spain has an interest. The programme also financed cooperative research in the international arena;
- The Spanish Institute of Oceanography (IEO) RADIALES project monitors physical, chemical and biological conditions in coastal waters of Spain. This project was initiated in 1991 and covers five localities sampled monthly;
- The IEO has supported the deployment of three tide gauges for more than 50 years;
- Moored buoys that take continuous physical data including currents and wave height are maintained by Puertos del Estado (State Ports);
- The HIPOCAS project (Funded by the European Union's Fifth Framework Programme, FP5) carried out retrospective analysis of climatic and oceanographic parameters of the Iberian coast. Some Spanish regional institutions have recently implemented automatic near-coast observation platforms (e.g. AZTI, in the Basque Country);
- Some Portuguese universities carry out research on the impacts of climate change on intertidal species (e.g. Porto University, see Lima *et al.* 2006), including competition between species at their southern limits with warmer water species (Boaventura *et al.* 2002);
- Oceanographic and fisheries monitoring and research is also conduct by IPIMAR in northern Portugal.

4.10 Mediterranean Sea

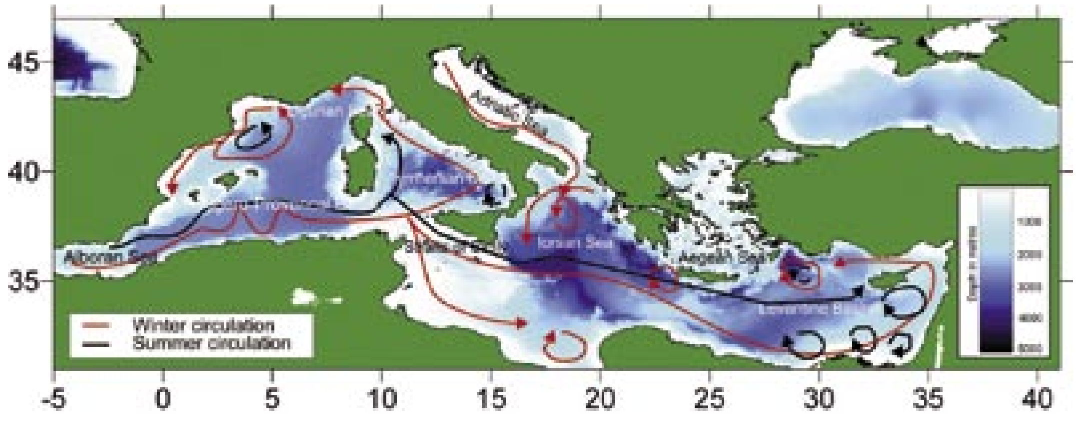
Description of the area

The Mediterranean basin is approximately 3,680 km long with an average width of 700 km and is divided into the Western and Eastern Mediterranean, separated by the straits of Sicily, and the Central Mediterranean. The Western Mediterranean (mean depth approximately 1,600 m) consists of two deep basins: the Algero Provençal basin and the Tyrrhenian Sea. The Central Mediterranean includes the Adriatic and Ionian seas, while the Eastern Mediterranean includes the Aegean Sea and the Levantine Basin.

The principal traits of this semi-enclosed miniature ocean are:

- Limited freshwater input (the Mediterranean basin is characterised by a freshwater deficit of 0.9 m y $^{-1}$ as evaporation exceeds precipitation and runoff). The major water exchanges are through the Straits of Gibraltar with surface inflow of Atlantic (top 300 m), and deep outflow of the deep, high-salinity, Mediterranean waters (Béthoux *et al.* 2002);
- Small amplitude tides (microtidal regime);
- High oxygen concentrations;
- High deep-sea temperatures (>12.8°C);
- Oligotrophic conditions, with low nutrient concentrations that typically decrease eastward.

As a result of these characteristics, the Western and Eastern Mediterranean are characterised by different primary productivity. In the Western Mediterranean, primary production is about 350-450 mgC m $^{-2}$ d $^{-1}$, whereas in the Eastern Mediterranean primary production is much lower (about 150 mgC m $^{-2}$ d $^{-1}$; Turley *et al.* 2000). The low productivity in the Eastern Mediterranean region, 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 seabed (Turley *et al.* 2000).



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The Mediterranean Sea.

Although it occupies only 0.82% of the world's ocean surface and 0.32% of its volume, the Mediterranean is a hot spot for biodiversity. Species richness (approximately 8500 species of metazoa) 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 Mediterranean, 38% in the Adriatic Sea, 35% in the Central Mediterranean, 44% in the Aegean Sea and 28% in the Levantine Sea.

This trend in species richness indicates a west-east impoverishment of species, reflecting climatic and trophic gradients. Mediterranean marine assemblages are different from their Atlantic counterparts, and Mediterranean organisms are typically characterised by smaller individual sizes.

The Mediterranean Sea is biologically diverse as 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 five million years, the Mediterranean has formed 10 distinct biogeographic regions (Bianchi and Morri 2000). According to Bianchi (1997), the present marine biota of the Mediterranean is composed of species characterised as originating from:

- A temperate Atlantic - Mediterranean background;

- Cosmopolitan/panoceanic species;
- Endemic elements, comprising both paleoendemic and neoendemic species;
- Subtropical Atlantic species (interglacial remnants);
- Boreal Atlantic species (ice-age remnants);
- Red Sea migrants (especially into the Levant Sea);
- Eastern Atlantic migrants (especially into the Alboran Sea).

Signals of climate change

Western mediterranean

> *'In the Western Mediterranean, climate changes during the 1980s altered plankton assemblages and food webs with high positive temperature anomalies favouring jellyfish outbreaks, which resulted in a strong decrease in the copepod abundance.'*
>
> *Molinero et al. (2005)*

In the Western Mediterranean, climate change influences the boundaries of biogeographic regions, with some warm water species extending their ranges and colonising new regions where they were previously absent. The northward migration of species with a warmer affinity has been demonstrated in several regions (Bianchi and Morri 1994; Morri and Bianchi 2001). The Ligurian Sea, one of the coldest areas in the Mediterranean Sea, has a lower number of subtropical species and a higher abundance of species characteristic of cold-temperate waters. The warming of Ligurian Sea waters (Béthoux *et al.* 1990; Astraldi *et al.* 1995) has favoured the penetration of warm-water species including, for example, the ornate wrasse *Thalassoma pavo*, which from 1985 onward established large and stable populations (Bianchi and Morri 1994).

However, the increase in numbers of tropical Atlantic species found in the northern Mediterranean may result from a combination of anthropogenic and climate factors. Recent studies have identified a correlation between the NAO and the climate variability of the northwestern Mediterranean (Molinero *et al.* 2005).

A large mass-mortality event was observed in 1999 (Cerrano *et al.* 2000; Perez *et al.* 2000), when a positive thermal anomaly during summer combined with an increase in the warm mixed layer down to a depth of 40 m (Romano *et al.* 2000) resulted in an extensive mortality of 28 invertebrate species (Perez *et al.* 2000). The area impacted by this climate anomaly extended from the French to the Italian coast and, to a lesser extent, impacted the island of 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). It is evident that temperature anomalies, even of short duration, can dramatically change Mediterranean faunal diversity. Once a species disappears, other species, pre-adapted to the new conditions, can replace them, thus hampering the ecosystem resilience to pre-impact conditions. High thermal anomalies can also impact the fauna inhabiting marine caves, replacing endemic species by warm water species (Chevaldonne and Lejeusne 2003).

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The colourful warm-water fish Thalassoma pavo was favoured by rising temperatures in the Western Mediterranean, establishing large and stable populations from 1985 onwards (Bianchi and Morri 1994)).

Climate change in the Mediterranean also favours epidemiological outbreaks, as most pathogens are temperature sensitive. Studies performed on the coral *Oculina patagonica* identified the coral-bleaching bacteria *Vibrio shiloi*, as an agent involved in the Mediterranean mass mortalities of coral (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). Furthermore, viral life strategies may be promoted by rising temperatures. Although data are limited, morbilliviruses that cause disease epidemics in seals have been identified in Mediterranean monk seals (van de Bildt *et al.* 1999), potentially impacting the survival of this rare and endangered species.

> *'In the northern Adriatic, the frequency of appearance of mucilaginous aggregates (associated with a malfunctioning of the microbial loop) has doubled in the last 25 years, concomitantly with a significant increase in sea-surface temperature of circa 1.5°C'.*
>
> *Russo et al. (2002)*

Adriatic sea

Most information dealing with climate change impacts on marine ecosystems in the central part of the Mediterranean has been collected in the Adriatic Sea. During the past 30 years in the Adriatic Sea, the thermophilic species of ichthyofauna have increased (Dulcic and Grbec 2000). Fish and zooplankton species that were previously rare are becoming more abundant, and other new species are being recorded (Dulcic and Grbec 2000; Kamburska and Fonda-Umani 2006). These observations are related to warming temperatures and salinity variations in the Adriatic Sea, which intensified after 1988 (Russo *et al.* 2002).

Other climate changes (increases in storm frequency and rainfall, and changes in wind speed and direction) also had an impact on water properties (e.g. salinity, mixing, altered turbidity), which in turn affect the whole Adriatic Sea ecosystem (Russo *et al.* 2002). A number of phenomena such as blooms of jellyfish (*Pelagia noctiluca*) and thaliacea (Boero 1996), harmful algal blooms (by several species of dinoflagellates) and red tides, were triggered by these meteorological and oceanographic changes (Boero 2001). Increased surface temperatures, altered circulation, and precipitation changes causing increased stratification have been invoked to explain the increased frequency of bottom water hypoxia (low oxygen) 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 may have important cascade effects on biodiversity.

The Adriatic Sea, furthermore, has undergone dramatic changes related to low temperatures. In the winter of 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 (northern to north-eastern winds passing through the valleys of the Dinaric Alps) associated with decreased temperatures, although recent studies have reported a lack of open-sea convection related to higher temperatures (and mild winter conditions). This phenomenon alters deep-water and strongly reduces spring phytoplankton blooms and export production to the deep layers.

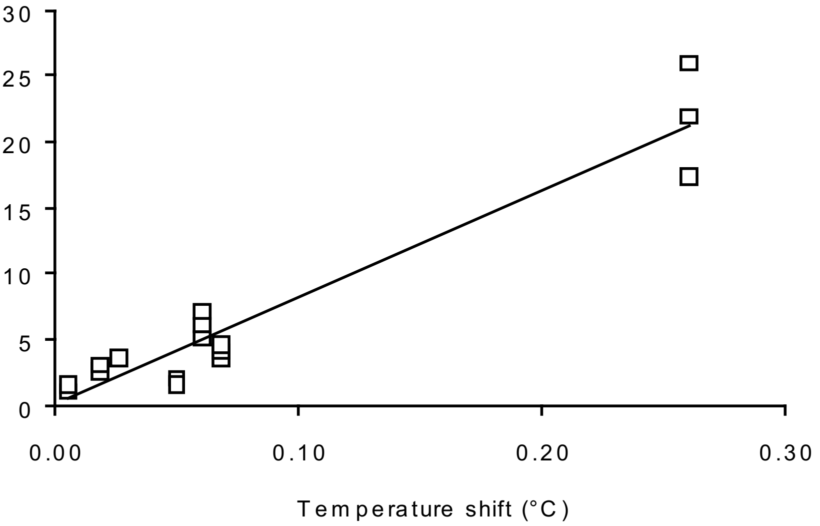
Eastern mediterranean

Most of the non-indigenous species in the Mediterranean are thermophilic originating in the tropical Indo-Pacific (Lessepsian migrations, Galil 1993). The list of exotic animals and plants that have invaded the Mediterranean, and particularly the Eastern Mediterranean, is continuously increasing. The rise of sea water temperatures may be partly responsible for changes in the range of some species creating maritime corridors linking this region to other seas and regions. The invasion of non-indigenous species has resulted in the dislocation of other species and possibly cascade effects on food webs (CIESM 2002).

Despite an overall tendency towards sea-surface warming, the Eastern Mediterranean has also experienced a temperature decrease. This major climatic event, defined as the Eastern Mediterranean transient, with a decline in temperature of about 0.4°C, 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 approximately 50% of nematode diversity (and possibly the diversity of other groups). Moreover, the extent of the impact on nematode diversity was directly related to the extent of the temperature shift. Temperature declines also caused a decrease in functional diversity and species evenness, resulting in increased similarity between the nematode fauna of the warm deep-Eastern Mediterranean and the colder deep-Atlantic. After 1994, when the temperatures gradually recovered to pre-transient values, the biodiversity began to revert towards more evenness. However, the community composition in 1998 still differed from that observed in 1989 (Danovaro *et al.* 2004).

Projections of climate change (Adriatic Sea, Eastern and Western Mediterranean)

Due to its depth (on average about 1,450 m), rapid deep-water turnover time (40-50 years), and the presence of many endemic species (about 25% of the species are restricted to the Mediterranean), it is expected that the impacts of climate change may be amplified with earlier changes in biodiversity than witnessed in other seas.



Relationship between temperature changes and species richness (nematodes) in the continental margins of the Eastern Mediterran (data compiled by R. Danovaro).

Recent evidence points to large-scale warming of the Mediterranean basin (Béthoux *et al.* 1990; Astraldi *et al.* 1995; Walther *et al.* 2002) and changing biodiversity in response (Francour *et al.* 1994). However, the richness of microclimates in the Mediterranean (ranging from climate conditions similar to those of the Northern Sea in the Adriatic to almost tropical conditions in the Eastern Mediterranean) makes any prediction on large spatial scales difficult. Indeed, most effects of climate change (or climate anomalies) on marine biodiversity have so far been identified only on regional scales.

These results indicate that: i) 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 irreversible. Moreover, these events indicate that not only coastal ecosystems but also continental-margin ecosystems may experience abrupt climate-driven temperature shifts, which reflect changes in the prevailing climate conditions occurring on a regional scale (Bethoux *et al.* 1990). Since there are close interactions between deep-sea and coastal ecosystems, the vulnerability of deep-sea ecosystems to climatic changes may have important implication on the biodiversity and functioning of continental shelf ecosystems.

Current research and monitoring programmes and projects

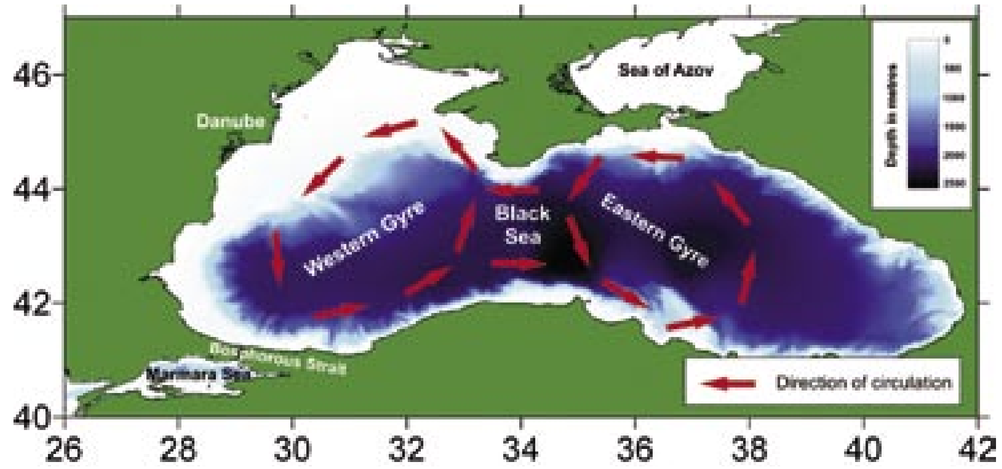
- The European Union’s Framework Programmes – funded projects investigating aspects of the impacts of climate change – (including seawater-atmosphere interaction) in the Mediterranean Sea include ADIOS (Atmospheric deposition and impact of pollutants, key elements and nutrients on the open Mediterranean), INTERPOL (Impact of natural and trawling events on resuspension, dispersion and fate of pollutants), HERMES (Hotspot Ecosystem Research on Europe’s Deep-Ocean Margin), ORFOIS (Origin and fate of biogenic particle fluxes in the ocean and their interaction with the atmospheric CO_2 concentration as well as the marine sediment) and SESAME (Southern European Seas: Assessing and Modelling Ecosystem changes);
- The CIESM financially supported the programme CIESM-SUB (sur-un-bateau) aimed at investigating the effect of recent climate change in the deep-Mediterranean;
- The projects CoMarge and Nagisa promoted by the Census of Marine Life and sustained by EuroCOML allow the gathering of information on long-term changes of marine biodiversity to improve understanding of the impacts of climate change on coastal and deep-sea ecosystems;
- Programmes and projects implemented at national level include SINAPSI and VECTOR, financially supported by the Italian government.

4.11 Black Sea

Description of the area

The Black Sea is a deep (about 2,000 m) oval-shaped basin with the zonal and meridional dimensions of ~1,000 km and ~400 km, respectively, located approximately between 28° and 42°E, 41° and 46°N. The Black Sea has only a narrow opening to the shallow (<75 m deep) Bosphorus Strait; otherwise it is a completely enclosed marginal sea. Examination of physical records superimposed on oscillations in the order of 15-30 years, constructed by combining all the available hydro-meteorological and biogeochemical data from 1960 onwards, indicates robust decadal oscillations and demonstrates a concurrent response to large-scale atmospheric systems (Oguz 2006).

The North Atlantic Oscillation (NAO) predominantly regulates these variations. The NAO teleconnection to the Black Sea is opposite to that taking place in the eastern North Atlantic. The relatively cold and dry winters occur during the positive phase of the NAO, and vice versa for the milder and wetter winters (Oguz *et al.* 2006). The NAO teleconnection is further modulated by the East Atlantic-West Russia (EAWR) atmospheric pattern which consists of the low and high surface pressure anomaly centres over the North Atlantic and Eurasia.



The Black Sea.

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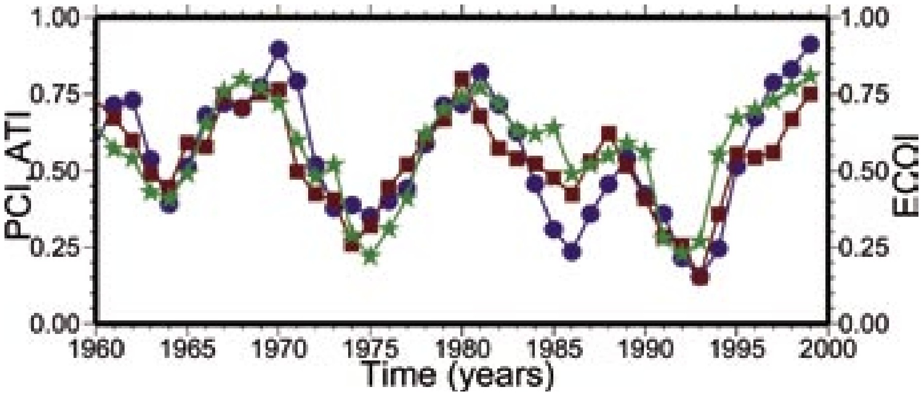
Signals of climate change

During the 1980s, the Black Sea experienced the most dramatic changes ever encountered throughout the last century. The upper layer water column cooled significantly in response to large increases in the NAO index. The strength of winter cooling is marked by a more than 1.5°C drop in the winter mean sea-surface temperature during the first half of the 1980s. A three-fold increase in the subsurface peak nitrate concentration due to excessive nutrient input from the River Danube, when combined with strong winter cooling and preconditioning, led to very high phytoplankton biomass. The impact of nitrate concentration then propagated to higher trophic levels and contributed to considerable increase in herbivorous and carnivorous zooplankton abundance (bottom-up control). At the same time, the intense eutrophication together with overexploitation of pelagic fish stocks caused diversion of the classical phytoplankton-zooplankton fish food chain to an alternative pathway dominated by gelatinous and opportunistic species.

Overfishing is responsible for the sharp reduction and/or disappearance of medium and large pelagic fish in the Black Sea (Prodanov *et al.* 1997). Removal of large fish from the system made the smaller and less valuable planktivorous fish (mainly anchovy and sprat) the dominant predators in the ecosystem. This change doubled the exploited stocks of anchovy and sprat, and subsequently their total catch at the end of 1970s. As a result, a new and different type of top-down cascade started operating on the lower levels of the food web, resulting in a two-fold decline in mesozooplankton biomass and a comparable increase in phytoplankton biomass during the 1970s (Prodanov *et al.* 1997). The increase encountered in total phytoplankton biomass, therefore, was not a result of eutrophication alone, but a process that also included overfishing (top-down effect).

Once the small pelagic fish became the main target of industrial fisheries, their catches began to decrease and gradually shifted towards newly recruited, small-sized fish species during the 1980s. The catches finally exceeded a sustainable level in 1987 and 1988 (Shiganova 1998; Gucu 2002; Daskalov 2002) and collapsed in 1989 and 1990. The niche vacated by these fish was gradually replaced by gelatinous zooplankton (in particular the jellyfish *Aurelia aurita*) and other opportunistic species (e.g. *Noctiluca scintillans*).



Temporal variations of the atmospheric index (ATI) (squares), marine physical climate index (PCI) (dots), and ecological index (ECOI) (stars) from 1960 to 1999. All three indices possess remarkable synchronous oscillations with a period of 10-12 years (Oguz *et al.* 2006).

The increase in *Aurelia aurita* biomass in the 1970s may have been associated with overfishing and removal of mackerel, which was a main predator of this jellyfish in the Black Sea. Because of their competitive advantage for food, when compared with small pelagic fish species, and their predation on eggs and larvae of these fish species, the total gelatinous biomass, mostly of the jellyfish *Aurelia aurita*, reached 1.5 kg m $^{-2}$ during the mid-1980s, and finally attained the peak value of about 2.5 kg m-2 in 1989 when the population of the ctenophore *Mnemiopsis leidyi* exploded. Relaxation of the fishing pressure during the second half of the 1980s may be responsible for a gradual increase in the mesozooplankton biomass up to its maximum value of 15 g m $^{-2}$ in 1990, when the small pelagic fish stock collapsed and the *Mnemiopsis* population exploded. Predation of *Mnemiopsis* on fish larvae further accelerated depletion of small pelagic stock at the expense of an additional increase in *Mnemiopsis* biomass.

Strong changes continued to prevail in 1991-1993. As phytoplankton biomass continued to retain its maximum level and the entire pelagic stocks were depleted, herbivorous zooplankton and gelatinous carnivore standing stocks collapsed abruptly within a year. Complete collapse of standing stocks at all trophic levels above the first level, reflects a unique catastrophic event experienced by any large marine ecosystem over the world to date.

The Black Sea has been impacted by the adverse effect of climatic warming after the mid-1990s, which led to poor nutrient enrichment of the surface layer and subsequent decrease in phytoplankton abundance. Poor productivity of all higher trophic levels occurred because of limited food availability. However, the decline of *Mnemiopsis* helped small pelagic fish to recover, to take over the control of the food web, and to gradually establish the classical food chain. The introduction in 1998 of another gelatinous carnivore *Beroe ovata* into the Black Sea (via ballast waters), which preyed mainly on *Mnemiopsis*, also contributed to the recovery of the ecosystem at the end of 1990s. *Beroe ovata* adapted quickly and easily to the Black Sea conditions, and spread a year later over most parts of the sea. Predation of *Mnemiopsis* by *Beroe* was immediately reflected by a two- to three-fold increase in mesozooplankton biomass, ichtyoplankton biomass, and fish stocks (Kideys 2002; Shiganova *et al.* 2003).

The impact of climate change on the rise and fall of small pelagic standing stocks emerges very clearly in the temporal distributions of sprat and anchovy abundance (Oguz *et al.* 2006). Sprat and anchovy are the two most dominant small pelagic fish species in the Black Sea and acted as the top predators in the ecosystem following the depletion of higher predators due to overfishing during the 1960s and the early 1970s. Sprat is a cold-water species spawning in autumn and winter months. Sprat stocks therefore increased up to 500-600 ktons during the cold years (during the mid-1970s and mid-1980s) and dropped to a minimum level of about 100-200 ktons during the warm years (early 1970s and 1980s). On the other hand, anchovy is a warm water species, spawns preferentially during summer and autumn months, and therefore follows an opposite trend in variations to those of sprat stocks between the extreme values of 300 and 700 ktons. The cyclic variations in both sprat and anchovy stocks were however disrupted byan abrupt drop in their stocks to about 100 ktons at the end of the 1980s as they had exceeded a sustainable level in 1987 because of strong overfishing (Prodanov *et al.* 1997; Gucu 2002). In addition, excessive feeding pressure introduced by high *Mnemiopsis leidyi* populations may have contributed to depletion of the sprat stocks (e.g. Shulman *et al.* 1994; Shiganova 1998; Kideys *et al.* 2000).

Projections of climate change

At present, no projection on how climate change may affect this region is available. The data show well-defined oscillations during the past 100 years and there is no reason to expect that these oscillations will not continue into the future. However, these oscillations may be superimposed on a more well-defined general trend of warming. The Black Sea region is influenced by several teleconnection patterns, making future predictions more challenging than for areas that are mainly modulated by, for example, the NAO alone. In addition, this region was strongly influenced by external factors other than climate change alone, such as eutrophication and overfishing. Both eutrophication and overfishing have had tremendous impacts on the ecosystem and still have a strong influence.

Current research and monitoring programmes and projects in the Black Sea

The various research and monitoring programmes and projects which are currently carried out from national funding in different countries bordering the Black Sea are mostly decoupled, except for a few small-scale collaborative efforts funded by various international bodies including the European Union;

Truly interdisciplinary, international collaborative research efforts are needed to detect and monitor the evolution of the present post-eutrophication phase of the ecosystem.

4.12 General trends and regional specific expectations

Recent research, including the examination of ice cores and growth rings of ancient trees, shows that the Northern Hemisphere has been warmer since 1980 than at any other time during the last 2000 years (Mann and Jones 2003; Moberg *et al.* 2005). The observed and predicted increase in temperature under climate change is generally higher in northern than in southern European seas. For the most northern seas, such as the Arctic and the Barents Sea, the most obvious temperature-related change is the decline in sea-ice cover. Both the Arctic and the Barents Sea are predicted to be ice-free during summer within the next 100 years. The reduction of the formerly ice-covered area is expected to result in a decline, and possible extinction, of the species that depend on this habitat, such as ringed seals and polar bears. The disappearance of the ice may increase local productivity levels in the sea. On a larger scale, the reduction of the ice-covered areas may lead to an increase in heat absorption and changes in convection and water mass formation, possibly affecting temperature and ocean currents globally.

Although all ecosystems have been influenced by many other factors, such as eutrophication and overfishing, every region examined has shown at least some changes which are most likely a direct or indirect result of recent climate change. Although there can be 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. For future planning and development of adaptation strategies to climate change, improved understanding and prediction of the ultimate consequences of climate change in relation to concurrent effects of other stressors such as changes in nutrient loads, invasion of non-indigenous species and exploitation of marine living resources is needed.

The population of many marine species are exhibiting a displacement northward. The rate and direction of this movement, however, differs amongst the various seas and species. Enclosed seas, such as the Baltic Sea, the Mediterranean and the Black Sea, have only small and primarily east-west orientated movement corridors, which may restrict northward displacement in these areas. Further warming will presumably drive the marine species with a preference for cooler waters up to the northern coastlines of these areas, followed by extinction if they are not able to adapt to the new circumstances. Invasion of warm-water species into the North Sea and English Channel could occur by species originating from the south or the east, and by species originating from the more oceanic waters off the western coasts of Britain, Ireland and France, which have relatively high winter temperatures. Noticeably, the enclosed seas appear to have undergone far more dramatic changes than the more open seas during the past decades. Relatively small changes in the frequency of inflow (as in the Baltic Sea) or in temperature (as in the Eastern Mediterranean and Black Sea) have had strong effects on large parts of the ecosystem. This implies that although the temperature increase is predicted to be relatively small in the more southern waters, the effects of climate change are still likely to be quite large in these waters.

For most open seas, there is evidence of species moving northwards and/or northern species being replaced by more southern ones. Such changes not only affect the local ecosystems, but also the international fishing industry when commercial species are affected. It must be noted, however, that a climate-induced decline in species abundance and biodiversity may trigger overfishing if one tries to gain the same yield from a (locally) reduced stock. Under such circumstances, it is impossible to distinguish between the effects of climate change and overfishing. Even in the more open seas, however, species do not always move northwards if their prey is not available. Both in the Barents Sea and in the North Sea, marine mammals were observed to move southwards when their prey stocks collapsed. Such changes indicate that detailed knowledge of species' physiology, bioenergetics and behaviour is needed to adequately predict the impact of climate change on the distribution of marine organisms and marine food webs.

It is expected that within open systems there will generally be northward movement of species, for example Arctic species will be replaced by Atlantic species in the more northern seas such as the Arctic, Barents Sea and the Nordic Seas, while temperate species will be replaced by more subtropical species in the southern seas such as the Iberian upwelling margin. For seas that are highly influenced by river runoff, such as the Baltic Sea, an increase in freshwater due to enhanced rainfall will lead to a shift from marine to more brackish and even freshwater species. If enclosed systems such as the Mediterranean and the Black Sea lose their endemic species, their associated niches will probably be filled by species originating from adjacent waters and, possibly, from other sources such as ballast water.

European seas consist of more than 68,000 km of coastline, harbouring internationally important wetlands and major cities and ports. The combination of accelerating sea-level rise (and a possible increase in the frequency andintensity of storms), as predicted for most European seas, will severely increase the risk of flooding and subsequent loss of these areas. Further extension, raising and reinforcement of artificial coastal defences may protect populated areas, but result in loss of sedimentary nourishment of coastal marine habitats, with consequences for living marine resources, including aquaculture. Many marine organisms such as fish spend part of their life cycle in the relatively sheltered areas along the coast. Loss of these areas may impact on these animals during that specific part of their life cycle. In addition, changes in the strength and seasonality of upwelling in areas along the coast could influence the retention-dispersal mechanisms of (juvenile) fish and shellfish between coastal waters and open sea, with unknown consequences for species' recruitment.

5. Future needs for monitoring and indicators

5.1 Introduction

Although marine waters are relatively well monitored throughout Europe, most of these monitoring programmes and projects are limited to regional seas (or parts thereof) and/or to a few parameters selected as indicators of a particular state (e.g. temperature, concentrations of a particular contaminant, size of a commercial fish stock). At present, pan-European monitoring programmes and projects are being developed in the context of the EU Water Framework Directive and the EU Marine Thematic Strategy (see Box 3). A concerted effort is needed to ensure that previously and currently collected marine environmental data and those that are planned as part of future pan-European initiatives contribute to a better evaluation of climate change and its impacts.

To predict the consequences of climate change for our marine environment, it is necessary to measure parameters that are indicative of underlying mechanisms of climate-induced changes. Since the indicative value of the parameters may change in time, the application of such mechanistic indicators should go hand in hand with in-depth research on these mechanisms. New technologies should be

Box 3: Towards pan-european monitoring activities

On 23 October 2000, the Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy; known as the **EU Water Framework Directive** (WFD) was adopted (http://ec.europa.eu/environment/water/water-framework). The key objectives at European level are general protection of the aquatic ecology, specific protection of unique and valuable habitats, protection of drinking water resources, and protection of bathing water. All these objectives must be integrated for each **River Basin District,** defined by natural geographical and hydrological boundaries and including coastal waters, up to one nautical mile beyond the shoreline. The general objective of the WFD is to achieve 'good ecological status' (for ecological protection) and good chemical status (minimum chemical standard) for all surface waters by 2015. The first deadline in the Directive relating to monitoring is at the end of 2007, when Member States should have their **monitoring programmes** defined and ready for commencement.

Meanwhile, a **Marine Thematic Strategy Directive** will establish **European Marine Regions** on the basis of geographical and environmental criteria. Each Member State, in close cooperation with the relevant other Member States and third countries within a Marine Region, will be required to develop **Marine Strategies** for its marine waters. The Marine Strategies will contain a detailed assessment of the state of the environment, a definition of good environmental status at regional level and the establishment of clear environmental targets and monitoring programmes. The key aim is to achieve good status of the EU's marine environment by 2021.

On 7 June 2006, the European Commission adopted a **Green Paper on a Future Maritime Policy for the European Union** (http://ec.europa.eu/maritimeaffairs). One of the motivations for the EU to be involved in such a policy is that it recognises that the protection of marine ecosystems and fisheries resources in European waters cannot be tackled by Member States individually. One proposal of the Green Paper is to establish a **European Marine Observation and Data Network** which would provide a sustainable focus for improving systematic observation (in situ and from space), interoperability and increasing access to data, based on robust, open and generic information and communication technology solutions. In this context, the **Global Monitoring for Environment and Security (GMES)** initiative will implement a number of public information services in support of European policies, derived from in situ and space observations (http://www.gmes.info). It is proposed that GMES should constitute a major component for the Data Network of the Maritime Policy.

employed to measure these types of indicators (e.g. fluxes) and to reach the appropriate temporal and spatial resolution (e.g. using automatic sampling equipment and satellite images).

5.2 Indicators

An **indicator** (e.g. temperature or length of growing season) is defined as a variable or measure that reveals some key element of a system. Its value and long-term trend indicates the present state relative to a reference point and thus measures dynamics of the system. Specific indicators can be used to monitor trends and detect sudden changes in environmental conditions which are considered to be the result of climate variability.

Indicators should be simple, reliable and affordable; simplicity implies being easy to understand and to measure. To be reliable, indicators should be conceptually and methodologically well founded. Indicators based on **on-going long-term monitoring programmes and projects** can take advantage of tested protocols for routine collection of data, historical data for estimation of reference values (for example, an average temperature for the period 1961-1990) and build up confidence in interpretation. If long-term monitoring protocols have to be adapted for new indicators, however, some conflict may arise between consistency and improvement.

Application of indicators on a pan-European scale requires that the indicators are consistently measured over time and over a broad range of ecosystems. Intercalibration of similar indicators (e.g. primary production) is desirable, but not essential if the rate of change, and not the actual value is desired. None of the individual indicators is likely to be influenced by climate change alone. **Groups of indicators** will therefore be needed to conclusively demonstrate if and how climate change affects marine systems.

5.3 Abiotic indicators

Abiotic indicators of potential climate change consist of **ocean forcing functions** (atmospheric and hydrological) as well as **sea-ice and oceanographic properties.** These represent a minimum suite of indicators needed to address climate change issues and determine possible causes of ecosystem changes. Many of these indicators are already being measured or estimated, but such measurements must be maintained. Others need to be expanded. Year-to-year variations of the indicators should be considered, and also the seasonal variation (e.g. onset of stratification and upwelling). Abiotic indicators include:

Atmospheric indicators

- **Large-scale atmospheric pressure indices** (e.g. NAO, AO, etc.);
- **Atmospheric temperatures** at standard meteorological sites;
- **Winds,** directly measured as well as modelled values that provide broad spatial coverage throughout European waters;
- **Precipitation** directly measured at standard meteorological sites plus modelled values over marine areas.

Hydrological indicators

- **River runoff** in all of the major rivers in Europe and flowing into the Arctic;
- **Estimated total river runoff** into each of the major European marine regions (including human activities in catchment areas such as agriculture irrigation and canalisation of rivers).

Sea-ice indicators

- **Sea-ice area coverage** in the Baltic, Barents and Nordic Seas and the Arctic;
- **Sea-ice concentrations, thickness and ice type,** including amount of multi-year ice.

Oceanographic indicators

- **Temperature and salinity:** This should include continuation of long-term monitoring such as the Kola Section in the Barents Sea and the Weather Station Mike in the Norwegian Sea, as well as numerous coastal sites, standard ocean transects, etc; monitoring of sea-surface temperatures by satellite; and use of new technology such as gliders for undersampled regions (e.g. the Arctic) and seasons (winter);
- **Mixed Layer Depth:** The depth of the surface mixed layer;
- **Stratification:** The strength of vertical change in density between the mixed layer and subsurface waters;
- **Heat content:** The amount of heat in the upper 200 m of the ocean;
- **Ocean fronts:** The position of the large-scale ocean fronts separating water masses with different temperature and salinity characteristics, e.g. the Arctic Front between Arctic and Atlantic water masses in the Nordic and Barents Seas;
- **Sea-level elevations:** direct measurements at long-term coastal sea-level monitoring sites and estimates from satellite information;
- **Frequency, intensity and location of storm surges;**
- **Volume transports:** Current measurements should focus on water exchanges in channels and straits such as the Fram Strait, Denmark Strait, the entrances to the Barents Sea and North Sea as well as the Baltic (Kattegat), the Mediterranean (Straits of Gibraltar) and the Black Sea (Bosphorus and Dardenelles);
- **North Atlantic currents:** Detected from satellite altimetry and annual hydrological data along 26°N and along 22°W;
- **Regional currents:** e.g. the Iberian Poleward Current (IPC);
- **Upwelling indices** (based on measure of upwelling frequency and intensity): obtained from wind data, satellite thermal imagery and in situ observations for regions off the Iberian Peninsula and off the Bay of Biscay.

Coastline indicators

- **Number of stormy days** (above a fixed wind speed);
- **Rise in sea level relative to land;**
- Frequency and intensity of flooding events;
- **Coastal erosion and accretion:** length of protected and defended coastline; area and volume of sand nourishment;
- **Status and trend of specified coastal habitats;** salt marsh, tidal flats, sand dunes, sandy beaches.

5.4 Biotic indicators

Biotic indicators of potential climate change can be categorised into four groups, as **indicators related to: i) community composition; ii) species abundance; iii) phenology of biological events; and iv) distribution of marine organisms.** Some aspects of these indicators are already being measured or estimated, but they must be recalculated to be used as an indicator for climate change; other aspects still need to be developed. Biotic indicators include:

Community composition indicators

- **The ratio of species with colder affinities to those with warmer affinities** within phytoplankton, zooplankton, macrozoobenthos, fish, bird and mammal communities;
- **The ratio between diatoms and dinoflagellates** within phytoplankton communities;
- **The biomass ratio between populations of** demersal and pelagic fish; biomass ratio in catch and landing statistics may also be used.
- **The (functional) biodiversity of microbes and changes thereof** in space and time, as detected via new rapid sequence techniques.

Abundance indicators

- **Phytoplankton:** CPR colour index (chlorophyll) and satellite-derived measures of chlorophyll concentrations;
- **Standing stocks of fish** as a measure of production at this higher trophic level (they are strongly influenced by fishing effort, but will still to some extent reflect climate variability).

Phenology indicators

- **Onset of the phytoplankton spring bloom and timing of flowering of seagrass;**
- **Timing of reproduction and seasonal migration of selected species of zooplankton, macrozoobenthos, fish, birds and mammals.**

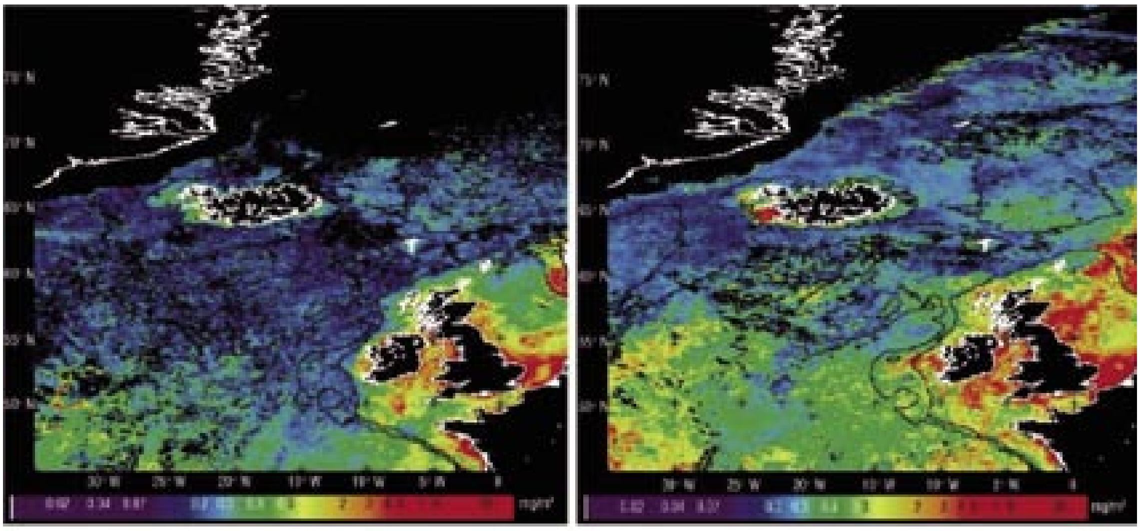
Reproduction indicators

- **Recruitment indices** (indices for year class strength) for macrozoobenthos and fish;
- **Recruitment-spawning stock relationships** for macrozoobenthos and fish;
- **Reproductive parameters:** age and size at maturity, size of reproductive output, development time, and condition of juveniles;
- **Reproductive volume:** the water mass suitable for reproduction (e.g. for cod in the Baltic Sea the reproductive volume is estimated from information on salinity, as cod eggs float at salinity >11 ppm, and from information on oxygen content, as the minimum oxygen concentration for cod eggs to survive is 2 ml l^{-1}). Cod recruitment is poor if the reproductive volume is small.

Distribution indicators

- **Range extension of existing species** (presence/absence);
- **Annual and seasonal connectivity between subpopulations of species with pelagic larvae;**
- **Records of non-indigenous species;**
- **Abundance-weighted centres of distribution.**

5. Future needs for monitoring and indicators



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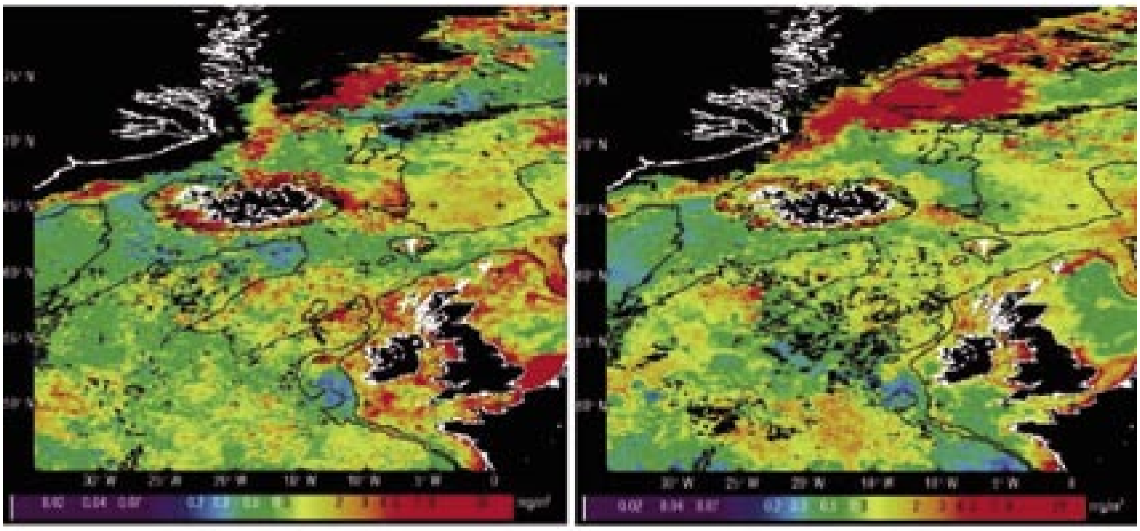


May 1999

June 1999

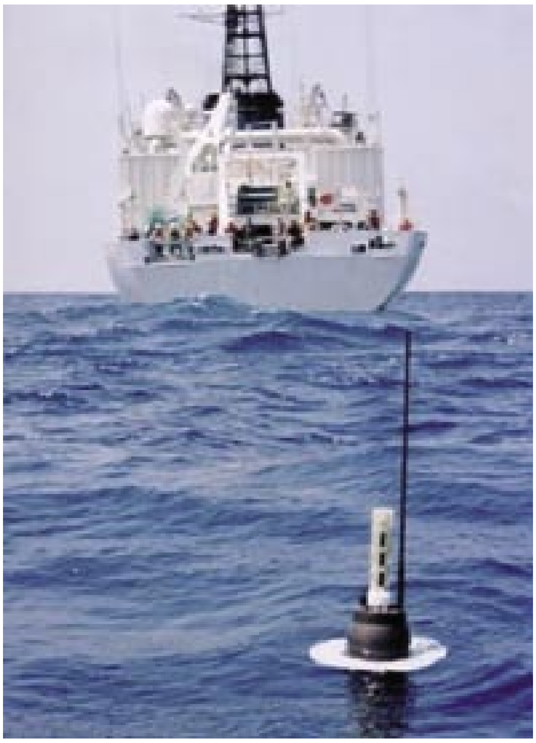
SeaWiFS satellite images of chlorophyll concentrations in the Northeast Atlantic.

Data collection: NASA's SeaWiFS Project GeoEye/Data analysis: Plymouth Marine Laboratory for analysis/

5.5 Recommendations

With regard to future monitoring and the use of indicators, the authors recommend the following actions:

- Maintenance of sustained monitoring efforts (large-scale and long-term programmes and projects and local efforts);
- Use of new technologies to increase spatial and temporal resolution of measurements, for example ARGO floats, ferry boxes, gliders, satellite images, genomics;
- New or increased monitoring at key locations, e.g. encouragement of monitoring efforts by Russia (in the Bering Strait) and Canada (in the Canadian Archipelago);
- Development of new indicators to fill in gaps in knowledge on particular state variables and processes. There is a real need to develop a benthic habitat indicator at the scale of the European shelf. This could be achieved by using new technology based on multibeam side-scan sonar (in combination with in situ measurements);
- Development of both general large-scale and specific regional indicators;
- Establishment of a pan-European (or preferably global) database with open access;
- Pan-European annual reporting based on national contributions .



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ARGO is a global array of 3,000 free-drifting profiling floats that measures the temperature and salinity of the upper 2,000 m of the ocean. This allows continuous monitoring of the temperature, salinity, and velocity of the upper ocean, with all data being relayed and made publicly available within hours after collection (Provor float waiting to be recovered by the Japanese coastguard boat, the Takuro).

6. Future research needs

Arising from the preceding analysis of climate change impacts on European marine and coastal waters, a number of research needs can be identified. Future research needs include: i) the identification and further analysis of historical data to describe past ocean climate and ecosystem development; and ii) a better understanding of biogeochemical fluxes, food web dynamics and ecosystem functioning, including feedback mechanisms, under current predictions of climate change. Increased understanding will enable the development of improved regional climate models and predictive ecosystem models. As part of the global ecosystem, European research programmes and projects on the marine environment must be integral to international research initiatives with a climate component, for example, IMBER, SOLAS, GLOBEC and CLIVAR.

Historical data and sustained observations

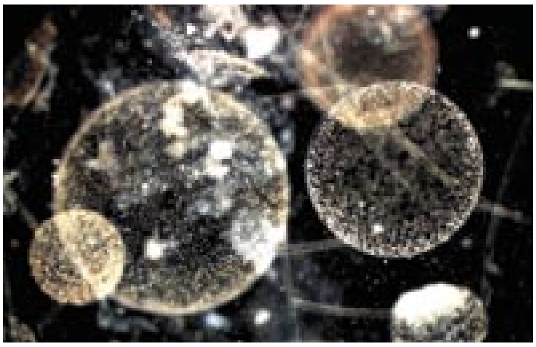
1. **Reconstructing past climates** (Palaeoceanography): Further research is needed to identify and analyse proxy data sets (ice and sediment cores, growth rings, etc.) of climate change to recreate past ocean climate scenarios with the finest possible spatial and temporal resolution to better understand geographic variations and their causes under natural conditions.
2. **Harnessing existing environmental data:** Increased effort is needed to identify, quality control, assess, and make available the wealth of existing environmental data collected as part of regional seas monitoring programmes and projects and annual fish stock assessment surveys, to better detect and quantify climate-induced ecosystem changes.
3. Support for the **continuation and linking of existing monitoring and time-series programmes and projects** and improvement in the spatial and temporal resolution of the variables. This would include, for example, the extension of the CPR (Continuous Plankton Recorder) surveys to all European seas and the establishment of new sustained observations in important regions (e.g. Iberian upwelling margin, Alboran Sea, Inner Bay of Biscay) by means of both traditional and new techniques (e.g. moorings and cabled networks). Oceanographic observations need to be integrated with observations on biodiversity and ecological processes in both the pelagic and offshore benthos, as well as the littoral zones (intertidal and subtidal).
4. **Synthesis and overview of climate change in European marine waters:** The compilation of Regional European Reports using a similar approach to ACIA (Arctic Climate Impact Assessment) and the Baltic BACC (Baltex Assessment of Climate Change).

Drivers and ecosystem responses

5. **Large-scale climate forcing:** European seas are strongly influenced by large-scale atmospheric variability as reflected in different air pressure patterns through indices such as the North Atlantic Oscillation and the Arctic Oscillation. Research is needed to address the relationships between the different pressure patterns and their interactions, the temporal variability in the strength of the patterns, the mechanisms responsible for their generation and variability, including far-field effects and teleconnection (e.g. the effects of the Aleutian low pressure variability on the NAO) and the relative importance of these far-field effects compared to local processes.
6. **Ocean circulation and hydrodynamics:** Research is needed to enhance understanding of how ocean circulation and hydrodynamic conditions (temperature, salinity and stratification) will respond to predicted climate change, with particular emphasis on regional responses, time lapse to measurable response, variability and possible feedback mechanisms.
7. **Sea-ice and albedo effect:** Sea-ice plays an important role in climate change through feedback mechanisms, e.g. as the result of the high reflectivity of ice-covered compared to open ocean surfaces. Research is needed on the relationships between air-sea heat fluxes and sea-ice concentrations, leads and melt ponds.
8. **Biogeochemical fluxes:** Research is needed on the influence of climate change on microbially driven biogeochemical fluxes between ocean and atmosphere in coastal and in open waters, the influences of changes in the carbon and other cycles on sedimentation, and subsequent benthic-pelagic coupling. There is a need to define the importance of the nitrogen cycle (including nitrogen fixation) and atmospheric

iron fertilisation for element cycling in the ocean under the aspects of climate change, and to know how these changes affect the ratios between elements such as carbon, nitrogen and phosphorus in the water. Much is still unknown on the impact of climate change on oxygen levels and on anoxic areas (in particular in enclosed seas such as the Baltic Sea and the Black Sea).

9. **Ecosystem structure and functioning:** To understand and predict the effects of climate change on marine ecosystem structure and functioning, there is a requirement to examine how climate change will affect structural and functional biodiversity, how the structure (e.g. species composition, food web lengths, size distribution) and functioning (e.g. biomass, production and decomposition processes, predator-prey interactions) of marine ecosystems will change under current predictions of climate change, and how changes in the chemical composition of elements in the ocean will influence food web dynamics. Research is needed on the possible consequences of climate change on the nature and strength of the interactions between the various trophic levels of the system. Further research is needed to predict when and under what conditions climate-induced regime shifts of marine ecosystems will occur, if such changes will be reversible, and if so, what the recovery dynamics would be.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Colonies of *Phaeocystis globosa* in the Wadden Sea. How well a model will predict the extent to which marine ecosystems are affected by climate change will depend on the detailed understanding of the response of species toward changes in temperature. For example, climate-driven changes in blooms of the highly abundant and harmful alga *Phaeocystis globosa* may have feedback effects on the ocean's temperature via its production of the cloud-forming gas dimethylsulphide.

10. **Adaptation and evolution:** Climate change will result in a change in the physical and biological environment for many marine organisms. It is as yet unknown, however, to what extent individuals are able to change their physical or biochemical (phenotypic) characteristics in order to adapt to these changes (e.g. faster growth at higher temperatures), how populations will respond genetically to the changes in selection pressure (e.g. shifts in timing of spawning), or how climate change will modify the reproductive potential of marine organisms. Part of the required information may be derived from using latitudinal differences in life-history patterns.

11. **Coastal habitats:** Current models of climate change predict sea-level rise and increased frequency and intensity of storminess that will impact on the coastal zone. There is a need to examine if more accurate regional predictions of sea-level rise in Europe can be derived, taking into account ice-cap and glacial melting, alteration in the strength of ocean circulation, heating and freshening of the water column and the rising or sinking of coastlines. This will facilitate research on the socio-economic and ecological implications for coastal protection and the development of adaptive strategies.

Predictive models

12. **Improvement of regional climate models:** In particular with respect to the hydrological cycle, e.g. river runoff and the role of clouds in evaporation.

13. **Development and validation of (regional) biophysical models:** Biophysical models are being developed to investigate the effects of physical forcing on primary production, zooplankton distribution and advection, fish and invertebrate larval drift, and fish migration. Improvements in and validation of such models need to be encouraged.

14. **Species loss:** Modelling the effects of climate change on species distribution, abundance and competition and mapping potential local and larger scale extinction.

6. Future research needs

15. **Triggers of biological events:** Little is known about the mechanisms triggering events such as spawning, diapause, migration, and temperature tolerance for most species. Some biological events are temperature dependent while others are light dependent. Since temperature will rise under climate change, while light will more or less stay the same (except for changes in cloud cover), there is a large potential for a future mismatch in timing of lifecycles between some species and their prey or predators. In order to make reliable ecosystem predictions, knowledge of the triggering mechanisms of biological events is absolutely essential.
16. **Food webs and species connectance in ecosystems:** Research is needed on predator-prey relationships and functional groups. This information is necessary to determine the energy flows in the ecosystem (i.e. balancing production, consumption and mortality of species or species groups), and the influence of hydrology. To accurately assess impacts of climate change on ecosystem, will require enhanced understanding of the interactions among different species.
17. **The roles of fishing, eutrophication and climate change:** Climate change is occurring in combination with fishing and eutrophication. Research is needed on what can be assigned to each cause, including potential synergistic effects (e.g. fishing can cause fish stocks to become more vulnerable to climate change).

Enabling technologies and supporting initiatives

18. **Development of new technologies:** Research is needed to design new observational and measurement systems (e.g. sensors for air-sea interactions of specific substances for identifying long-term changes in hydrodynamic regimes and changes in deep-water temperatures) to support climate change research.
19. Participation in and contribution to **international climate change research programmes and projects should be suppported.**
20. **Good** and **fast data access,** including pictures of changes in plankton assemblage composition and ocean colour data (data centres, real time data, basic processing and computer programs) is essential.

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Appendix 1. Glossary of terms

Albedo effect
Increased reflectivity of the ground surface following a change of its characteristics or cover thereby changing the heat balance of the surface-atmosphere system.

Beaufort Gyre
The Beaufort Gyre is a circulation system swirling the waters of the Arctic Basin and turning the ice-cap with it.

Greenhouse gases
Greenhouse gases are components of the atmosphere that contribute to the greenhouse effect, they include water vapour, carbon dioxide, methane, nitrous oxide and ozone

Milankovitch cycles
The variation of the Earth's exposure to the sun's rays, or insolation, that results from variations in the orbit of the Earth and the tilt of its axis, and that might affect climate, sea level and sedimentation (with a time period in the order of thousands of years).

Transpolar Drift (or Trans-Arctic Drift)
Transpolar Drift is a circulation system carrying water and ice from Siberia across the North pole and down to the east coast of Greenland.

Appendix 2. List of acronyms

ACIA	Arctic Climate Impact Assessment
AO	Arctic Oscillation
ASOF	Arctic/Subarctic Ocean Fluxes)
CPR	Continuous Plankton Recorder
EAWR	East Atlantic-West Russia
ENSO	El Niño-Southern Oscillation
EU	European Union
GCM	Global Circulation Model
GMES	Global Monitoring for Environment and Security
IGY	International Physical Year (1957/1958)
IPCC	Intergovernmental Panel on Climate Change
IPC	Iberian Polward Current
IPY	International Polar Year (2007/2008)
IUCN	International Union for the Conservation of Nature and Natural Resources
JNCC	Joint Nature Conservation Council
MOC	Meridional Overturning Circulation
NAC	North Atlantic Current
NAM	Northern Hemisphere Annual Mode
NAO	North Atlantic Oscillation
NHT	Northern Hemisphere Temperature
SAHFOS	Sir Alister Hardy Foundation for Ocean Science
SST	Sea-Surface Temperature
THC	Thermohaline Circulation
WFD	Water Framework Directive

Appendix 3. Glossary

Glossary of large-scale monitoring programmes and research activities related to climate change impacts on the European marine and coastal environment

CIESM: The Mediterranean Science Commission integrates a broad spectrum of marine disciplines, encompassing geo-physical, chemical and biological processes, along with high-resolution mapping of the sea-bottom. Today, changes are occurring at a fast, unprecedented pace in the Mediterranean Sea. CIESM tracks and analyses these changes at the scale of the whole Basin, from the impact of global warming on sea level and water masses to changes in marine biodiversity; from morphological changes in coastlines to the accumulation of trace metals in marine food chains (www.ciesm.org).

CIRCLE: Climate change is increasingly seen as one of the greatest issues facing the world in the 21st century, and Europe is taking a leading role in responding to its challenges. Whatever the success of mitigating climate change may be, certain impacts are unavoidable and European countries will need to adapt to those impacts driven by certain vulnerabilities and exposures in the regions of Europe. Their adaptation response must be informed by a coherent body of research and it is the prime objective of Climate Impact Research Coordination for a Larger Europe to contribute to such efforts by aligning national research programmes. This process will be a strong support for the overall goal: Implementing a European Research Area (ERA) for the field of climate change (www.circle-era.net).

CLIVAR: The specific objectives of the Climate Variability and Predictability research programme are: i) to describe and understand the physical processes responsible for climate variability and predictability at different time-scales, through the collection and analysis of observations and the development and application of models of the coupled climate system; ii) to extend the record of climate variability over the time scales of interest through the assembly of quality-controlled paleoclimatic and instrumental data sets; iii) to extend the range and accuracy of seasonal to interannual climate prediction through the development of global coupled predictive models; and iv) to understand and predict the response of the climate system to increases of radiatively active gases and aerosols (www.clivar.org).

DEDUCE: Spatial analysis of particular habitats project using GIS (e.g. Corine Coastal Erosion) that may lead to the development of other indicators. This work contributed to an assessment of the state of European Coasts published by the EEA in 2006 and will be taken forward on a European scale (www.eurosion.org).

DIVERSITAS: An international programme of biodiversity science to promote an integrative biodiversity science, linking biological, ecological and social disciplines in an effort to produce socially relevant new knowledge; and provide the scientific basis for the conservation and sustainable use of biodiversity. DIVERSITAS achieves these goals by synthesizing existing scientific knowledge, identifying gaps and emerging issues, and promoting new research initiatives, while also building bridges across countries and disciplines. The Programme also investigates policy implications of biodiversity science, and communicates these to policy fora, including international conventions (www.diversitas-international.org).

EEA: The European Environment Agency aims to support sustainable development and to help achieve significant and measurable improvement in Europe’s environment through the provision of timely, targeted, relevant and reliable information to policy-making agents and the public. The EEA has developed a set of indicators with regard to climate change (greenhouse gasses and temperature), and for the marine environment (nutrients and chlorophyll) (www.eea.europa.eu).

ERA-NET: The objective of the ERA-NET scheme (funded by the European Union Sixth Framework Programme, FP6) is to step up the cooperation and coordination of research activities carried out at national or regional level in the Member States and Associated States through the networking of research activities conducted at national or regional level, and the mutual opening of national and regional research programmes (cordis.europa.eu/coordination/era-net.htm).

EuroBIS: Within the MarBEF network, the European Ocean Biogeographic Information System is the European regional node of the Ocean Biogeographic Information System. This distributed system of biogeographic information will integrate individual data sets on marine organisms into one large consolidated database, that can provide a better understanding of long-term, large-scale patterns in European marine waters (www.marbef.org/data/eurobis.php).

EuroCoML: The European Census of Marine Life is a regional implementation committee of the Census of Marine Life, a growing global network of researchers in more than 70 nations engaged in a 10-year initiative to assess and explain the diversity, distribution, and abundance of marine life in the oceans – past, present, and future (www.eurocoml.org).

GCOS: the Global Climate Observing System aims to ensure that the observations and information needed to address climate-related issues are obtained and made available to all potential users. GCOS stimulates, encourages, coordinates and otherwise facilitates the taking of the needed observations by national or international organisations in support of their own requirements as well as of common goals. It provides an operational framework for integrating, and enhancing as needed, observational systems of participating countries and organisations into a comprehensive system focused on the requirements for climate issues (www.wmo.ch/web/gcos).

GLOBEC: Global Ocean Ecosystem Dynamics was initiated by SCOR and the IOC of UNESCO in 1991, to understand how global change will affect the abundance, diversity and productivity of marine populations constituting a major component of oceanic ecosystems. The aim of GLOBEC is to advance our understanding of the structure and functioning of the global ocean ecosystem, its major subsystems, and its response to physical forcing so that a capability can be developed to forecast the responses of the marine ecosystem to global change (www.globec.org).

GMES: The Global Monitoring for Environment and Security represents a concerted effort to bring data and information providers together with users, so they can better understand each other and agree on how to make environmental and security-related information available to the people who need it (www.gmes.info).

GODAE: Global Ocean Data Assimilation Experiment is an international programme that aims to advance ocean data assimilation by synthesising satellite and in situ observations (e.g. from satellite altimeters and ARGO floats) with state-of-the-art models of global ocean circulation. In the past few years, a suite of GODAE systems have been developed to produce global and basin-scale ocean analysis and short-term forecasts. GODAE products are also being used for ecosystem applications and to provide lateral open boundary conditions for regional and coastal systems (www.bom.gov.au/bmrc/ocean/GODAE).

GOOS: The Global Ocean Observing System is global system for sustained observations, modelling and analysis of marine and ocean variables to support operational ocean services worldwide observations of the ocean, comprising the oceanographic component of the Global Earth Observing System of Systems (GEOSS). GOOS provides descriptions of the present state of the oceans, including living resources; continuous forecasts of the future conditions of the

Appendix 3. Glossary

sea, and basic information for forecasts of climate change (www.ioc-goos.org).

HELCOM: The Helsinki Commission works to protect the marine environment of the Baltic Sea from all sources of pollution through intergovernmental cooperation between Denmark, Estonia, the European Community, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. They provide information about: i) the state of trends in the marine environment; ii) the efficiency of measures to protect it; and iii) common initiatives and positions which can form the basis for decision-making in other international fora (www.helcom.fi).

HERMES: Funded by the European Union Sixth Framework Programme, FP6, Hotspot Ecosystem Research on the Margins of the European Seas brings together expertise in biodiversity, geology, sedimentology, physical oceanography, microbiology and biogeochemistry so that the generic relationship between biodiversity and ecosystem functioning can be understood. Study sites extend from the Arctic to the Black Sea and include biodiversity hotspots such as cold seeps, cold-water coral mounds and reefs, canyons and anoxic environments, and communities found on open slopes. These important systems require urgent study because of their possible biological fragility, unique genetic resources, global relevance to carbon cycling and susceptibility to global change and human impact (www.eu-hermes.net).

ICES: The International Council for Exploration of the Sea is an intergovernmental organisation that deals with fishing and fishing assessments in the North Atlantic. This includes adjacent seas such as the Baltic Sea and North Sea. Scientists working through ICES gather information about the marine ecosystem. As well as filling gaps in existing knowledge, this information is also developed into unbiased, non-political advice, and then used by the 19 member countries, which fund and support ICES, to help them manage the North Atlantic Ocean and adjacent seas (www.ices.dk).

IGBP: International Geosphere-Biosphere Programme provides scientific knowledge to improve the sustainability of the living Earth. IGBP studies the interactions between biological, chemical and physical processes and human systems IGBP collaborates with other programmes to develop and impart the understanding necessary to respond to global change (www.igbp.kva.se).

IHDP: The International Human Dimensions Programme on Global Environmental Change is an international, interdisciplinary, non-governmental science programme dedicated to promoting, catalysing and coordinating research on the human dimensions of global environmental change. IHDP takes a social science perspective on global change and it works at the interface between science and practical applications (www.ihdp.uni-bonn.de).

IMBER: The Integrated Marine Biogeochemistry and Ecosystem Research project was initiated by the IGBP/SCOR Ocean Futures Planning Committee in 2001 to identify the most important science issues related to biological and chemical aspects of the ocean's role in global change and the effects of global change on the ocean, with emphasis on important issues that are not major components of existing international projects (www.imber.info).

MedCLIVAR: A programme which aims to coordinate and promote research on the Mediterranean climate. The main goals include reconstruction of past evolution, description of patterns and mechanisms characterising space-time variability, and identification of the forcing responsible for the observed changes. Emphasis is on identification of trends in observational records as well as on climate predictions under future emission scenarios. The study of the occurrence of extreme events and of climate change impacts is also included in MedCLIVAR (clima.casaccia.enea.it/medclivar).

MERSEA: The strategic objective of Marine Environment and Security for the European Area project (funded by the European Union Suxth Framework Programme, FP6) is to provide an integrated service of global and regional ocean monitoring and forecasting to intermediate users and policy makers in support of safe and efficient offshore activities, environmental management, security, and sustainable use of marine resources. The system to be developed will be a key component of the Ocean and Marine services element of GMES (www.mersea.eu.org).

MGE: Marine Genomics Europe is a Network of Excellence project funded by the European Union Sixth Framework Programme, FP6, devoted to the development, utilisation and spreading of high-throughput approaches for the investigation of the biology of marine organisms. Moreover, MGE will establish databases of marine resources through large-scale biodiversity studies (www.marine-genomics-europe.org).

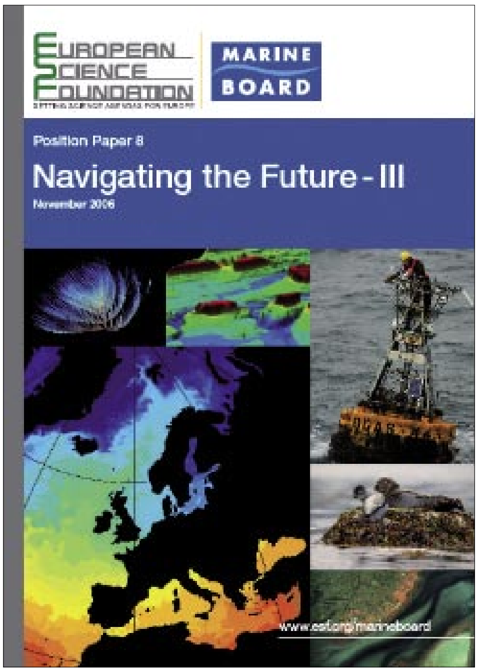
OSPAR: The Convention for the Protection of the Marine Environment of the Northeast Atlantic. In 2000, the OSPAR Commission published the first comprehensive Quality Status Report on the quality of the marine environment of the Northeast Atlantic. This was supported by five reports on the different parts of the OSPAR maritime area. In 2003, the Ministerial Meeting of the Commission adopted a new Strategy for the Joint Assessment and Monitoring Programme (JAMP). This provides for the work to support and produce a series of thematic assessments, leading to a further comprehensive assessment in 2010 (www.ospar.org).

SCOPE: Scientific Committee on Problems of the Environment is an interdisciplinary body of natural and social science expertise focused on global environmental issues, operating at the interface between scientific and decision making instances, and a worldwide network of scientists and scientific institutions developing syntheses and reviews of scientific knowledge on current or potential environmental issues (www.icsu-scope.org).

SCOR: Scientific Committee on Oceanic Research is the leading non-governmental organisation for the promotion and coordination of international oceanographic activities. SCOR science activities focus on promoting international cooperation in planning and conducting oceanographic research, and solving methodological and conceptual problems that hinder research (www.jhu.edu/~scor).

WCRP: The World Climate Research Programme objectives are to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate. The programme encompasses studies of the global atmosphere, oceans, sea- and land-ice, and the land surface, which together constitute the Earth's physical climate system. WCRP studies are specifically directed to provide scientifically founded quantitative answers to the questions being raised on climate and the range of natural climate variability, as well as to establish the basis for predictions of global and regional climatic variations and of changes in the frequency and severity of extreme events (www.wmo.ch/web/wcrp).

Appendix 4. Extract from Navigating the Future III on climate change



The following text is extracted from **Navigating the Future III,** Position Paper no. 8 (November 2006) from the Marine Board of the European Science Foundation (MB-ESF). It outlines the most important marine thematic research priorities for Europe, taking into account the priorities not only for FP7, but also the objectives of national research programmes, the European Marine Environment Strategy and the Galway Declaration 2004.

For general background information, the section of **Navigating the Future III** dealing with ocean-climate interactions and feedback has been extracted and added to this report.

Navigating the Future III can be downloaded on the Marine Board website (www.esf.org/marineboard), paper copies are available upon request to the Marine Board secretariat.

Climate change

4.1 The ocean is a crucial component of the Earth's climate system. It is the driver of many important climate processes on a range of time scales. Although there can be no certainty regarding the precise nature and rates of change in the marine environment due to alterations in climate, in the absence of policies and measures to prepare for these changes, even the more moderate of the predicted scenarios indicate major social and economic impacts. The 2001 Report of the Intergovernmental Panel on Climate Change states that 'global climate change will affect the physical, biological and biogeochemical characteristics of the oceans and coasts, modifying their ecological structure, their functions and the goods and services that the oceans provide'. The Stern Review on the Economics of Climate Change (2006 Report to the UK Government) further reiterates this prediction, stating that climate change will have serious impacts on economic growth and development, and that the failure to address global warming will cost the global economy 3.68 trillion pounds sterling (5 500 billion euros) by 2050, triggering a catastrophic recession, unless it is tackled within a decade. Thus, it is estimated that the effects of climate change would cost the world between 5% and 20% of GDP. Increasing dialogue between scientists and policy makers is necessary to allow assessment of whether there is sufficient sound scientific evidence on which to base new policies. Specialist workshops are required to address not only the environmental challenges that the scientists and policy makers face, but also the inevitable socio-economic repercussions associated with rising temperatures. To support the development of knowledge-based policies, there is a requirement for validated methods to turn data into information, in the form of integrated assessments and indicators, and for improved methods to assimilate data into climate models. This would improve reanalysis of climate variability in climate evolution over past decades. **The global nature and scale of the environmental and economic impacts of climate change emphasise the need for European research programmes to coordinate and integrate with the climate component of international research programmes, including CLIVAR, GLOBEC and IMBER.**

4.2 Palaeoclimate records provide an important tool for analysing the response of the climate system to internal and external forcing (e.g. greenhouse gases, volcanic activity and solar energy), and for understanding the physical, chemical and biological processes responsible for the changes. **Gathering the vast amount of palaeoclimate records into databases and their spatial and temporal analysis is necessary.** In order to place the present status of the Earth's climate within an historic perspective of climate variability, the ability to develop numerical models of past climatic events requires further improvement and refinement. The combined use of palaeoclimate data and palaeoclimate models with fine spatial and temporal resolution will facilitate the recreation of past ocean climate scenarios, which will advance the understanding of the mechanisms of climate change. **Research is required to improve the temporal resolution in the reconstruction of climate history of the ocean in scales from tens to hundreds of years. Continuous development of geochemical proxies is required for reconstruction of past surface CO_2 content, temperature, salinity, pH values and nutrients.**

4.3 One of the potential effects of climate change is the change in intensity, frequency and location of extreme events, such as storms, tidal surges and extreme wave heights. **Improved definition of extreme events, their statistical analysis, definition of proxies for past events, identification of processes at play in their generation, and the identification of their variability and trends, all need to be developed. Observation networks provide crucial contributions to monitoring and forecasting extreme events, and require further development.**

4.4 As well as the development of improved simulation models of climate variability and its effects, there is a requirement for the development of long-term capabilities for climate observation. **Detecting the actual phenomena, understanding in more detail the processes at play, such as the Pacific El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) and their potential change in frequency and intensity, is critical. To support climate change research, new observational and measurement sensors and systems need to be designed, including sensors for air-sea interactions of specific substances.** With observation networks in place, there will be a requirement for new methods to assimilate data into Atlantic and Mediterranean circulation and climate impact models.

Appendix 4. Extract from Navigating the Future III on climate change

4.5 There is a need to improve the use of existing data on physical, chemical and biological status in the field of operational oceanography modelling tools. **To support development of climate change models, an open data policy is needed, facilitating timely and improved access to data.** Data access should include near real-time, high frequency sea level data from tide gauges, satellite missions, and in situ observation systems, including pictures of changes in plankton assemblage compositions and ocean colour data. Efforts in data archaeology, to retrieve and make accessible historical sea level records, should also be supported.

4.6 The impacts of climate change on functional biodiversity are unknown. Developing the capability to predict the response and feedbacks of marine biota to climate change is required. Research is needed to assess how marine ecosystems' structure (e.g. food webs, population size and distribution) and functioning (e.g. biomass, production, decomposition) will change under current predictions of climate change. **Experimental and numerical studies using climate-simulating mesocosms are required to unravel the basic biogeochemical links and responses of climate-critical plankton species (e.g. diatoms, coccolithophorids, N2 fixers, DMS producers, bacteria, viruses, archaea) to physical and chemical drivers of climate change (e.g. temperature, pH, CO_2, solar radiation) and the associated biogeographic consequences.**

Ocean-atmosphere coupling and the Ocean thermohaline circulation

4.7 The ocean circulation in the North Atlantic plays a fundamental role in the coupled ocean-atmosphere system which results in the present temperate climate of Western Europe. The Atlantic Thermohaline Circulation (THC), or North Atlantic Current (one of the strongest ocean currents in the world), refers to a key regional heat engine mechanism partly responsible for allowing some areas of Europe to experience a climate 10°C higher than areas at similar latitudes. There are indications that this system can change dramatically on a time scale of one to two decades, with far-reaching consequences. Observations of decadal changes in the THC, and of the subsurface heat fluxes in the North Atlantic, have been described. Models and recent observations suggest that the THC may be weakening in response to greenhouse forcing. It has already been shown that the circulation of the North Atlantic Current has slowed by 30% over the last 12 years, and that part of this current came to a 10-day halt during November 2004, the most abrupt change on record. **Prototype observational experiments should be transformed into multidisciplinary long-term observational networks to monitor the evolving dynamics of the system. Research effort is required to focus on key Arctic and sub-Arctic deep water formations, gateways and pathways for the out-flows of cold dense water, and return flows of warm surface currents in the world ocean.**

4.8 Over the last two decades climate models have predicted that the impact of global warming caused by elevated atmospheric CO_2 would be stronger and faster in the Arctic. Climate simulation models currently show that with a doubling of atmospheric CO_2 (predicted to happen by 2080) Arctic sea-ice could disappear in the summer months. During the winter months, the reduction in sea-ice may be up to 20%, resulting in the opening of the now seasonally ice-covered Barents Sea to shipping. Climate change will thus induce dramatic changes to the economy of the areas bordering on regional seas, impacting on local communities, fishing practices, maritime transport and oil exploitation. **Efforts should be directed towards research on impacts of climate change on regional seas (e.g. the Artic, Nordic, Baltic and the Mediterranean Seas) as these are areas where the effects of climate change would impact most immediately on Europe. Global models of ocean-climate coupling and the THC should be downscaled to incorporate: i) flux-critical processes of subduction, convection, overflows and boundary currents; ii) teleconnections between the Pacific El Niño and the NAO, and between the NAO-IO (North Atlantic Oscillation - Indian Ocean) dipole and Mediterranean climate; and iii) greenhouse forcing: the responses of European seas, and its local and regional impacts.** As the Mediterranean Sea is a region in between the Atlantic and the Indian climate regions, capturing the specific modes of climate variability in this region is necessary. The impact of outflow of Mediterranean waters into the Atlanti and their behaviour in the Atlantic Iberian region requires particular attention.

4.9 The ARGO experiment, with its in situ global array of profiling floats recording oceanographic data, demonstrates the feasibility of providing a world-scale near real-time tri-dimensional observation of ocean hydrographic parameters. **Through EURO-ARGO Europe should actively contribute to the global ARGO experiment to provide hydrographic observations in the long term, both for operational oceanography and for monitoring climate change.** The development of more cost-effective profilers would help to extend the ARGO array of profiling floats and to implement the ARGO system.

Ocean biogeochemical impacts and feedbacks in a greenhouse Ocean

4.10 Estimates of current absorption of anthropogenic CO_2 into the ocean are still uncertain and have recently been re-evaluated; the ocean is the dominant sink for anthropogenic CO_2, as it has taken up 50% of anthropogenic CO_2. Greenhouse scenarios predict a globally warmer, more stratified and more acidic upper-ocean that could significantly reduce both convective and biogeochemical export sinks of atmospheric CO_2 into the deep ocean. This would accelerate accumulation of CO_2 in the atmosphere, with an associated risk of accelerated greenhouse warming. Increasing CO_2 levels are leading to a decline in seawater pH to levels that have not existed in at least 20 million years, so the oceans are becoming increasingly acidic. Ocean acidification not only changes the distribution of dissolved carbon species but also impacts on plankton, which could affect carbon uptake by primary production. Plankton absorb CO_2 from the atmosphere, and in so doing help to counter global warming. With a decrease in plankton diversity and population density, the oceans will absorb less CO_2 from the Earth's atmosphere. Research to profile status of phytoplankton assemblages is required. **To reliably predict future CO_2 levels, research is necessary to further elucidate these mechanisms, and to estimate absorption limits and oceanic budgets for anthropogenic CO_2 under greenhouse scenarios.**

4.11 The United States Japan, UK and Norway are developing experiments to assess whether deep ocean disposal of liquefied CO_2 (carbon sequestration) and iron fertilisation, can be used for large scale removal of CO_2 into the deep ocean. **Europe should conduct independent studies and evaluations, so that there can be an objective debate on the environmental feasibility, usefulness, ethics and impacts of ocean carbon sequestration.** Interactions between decision makers, scientists, environmental NGOs and the public should be promoted to facilitate the development of the most appropriate approaches towards such sensitive issues.

Ventilation of marine biogases and fertilisation feedbacks

4.12 Research is needed on current air-sea fluxes of climatically critical biogases (CO_2, DMS, N_2O, CH_4), particularly on their regional and seasonal variability, to enable a global assessment of their role in climate change. **The biogenic sources, distributions and pathways responsible for production, transformation and flux of climatically reactive marine biogas compounds should be investigated and modelled under present and future climate conditions.** This effort should be developed as a contribution to the SOLAS international programme.

4.13 **There is a requirement to further develop coupled physical biogeochemical ocean climate models that incorporate carbon speciation and nutrient dynamics.** This would allow prediction of changes and feedbacks in global and regional ocean productivity under various greenhouse scenarios. In particular, in view of the importance of medium- and small-scale phenomena for primary productivity, it is necessary to assess how their inclusion in climate models could be made.

4.14 Single-celled marine organisms (archaea, bacteria, phytoplankton, etc.) are abundant, diverse and productive and are the principal drivers of marine and global biogeochemistry. **Support should be directed towards adapting biogeochemical gene probes, coupled with phylogenetic probes, to enable the application of high-throughput bioanalytic technologies (e.g. analytical flow cytometry, microarrays) for use onboard shipduring large-scale oceanographic expeditions for exploration of microbial biodiversity, and assessment of food web dynamics and biogeochemical feedbacks in diverse oceanic environments.**

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