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ICES COOPERATIVE RESEARCH REPORT
RAPPORT DES RECHERCHES COLLECTIVES

NO. 293 SPECIAL ISSUE
NOVEMBER 2008

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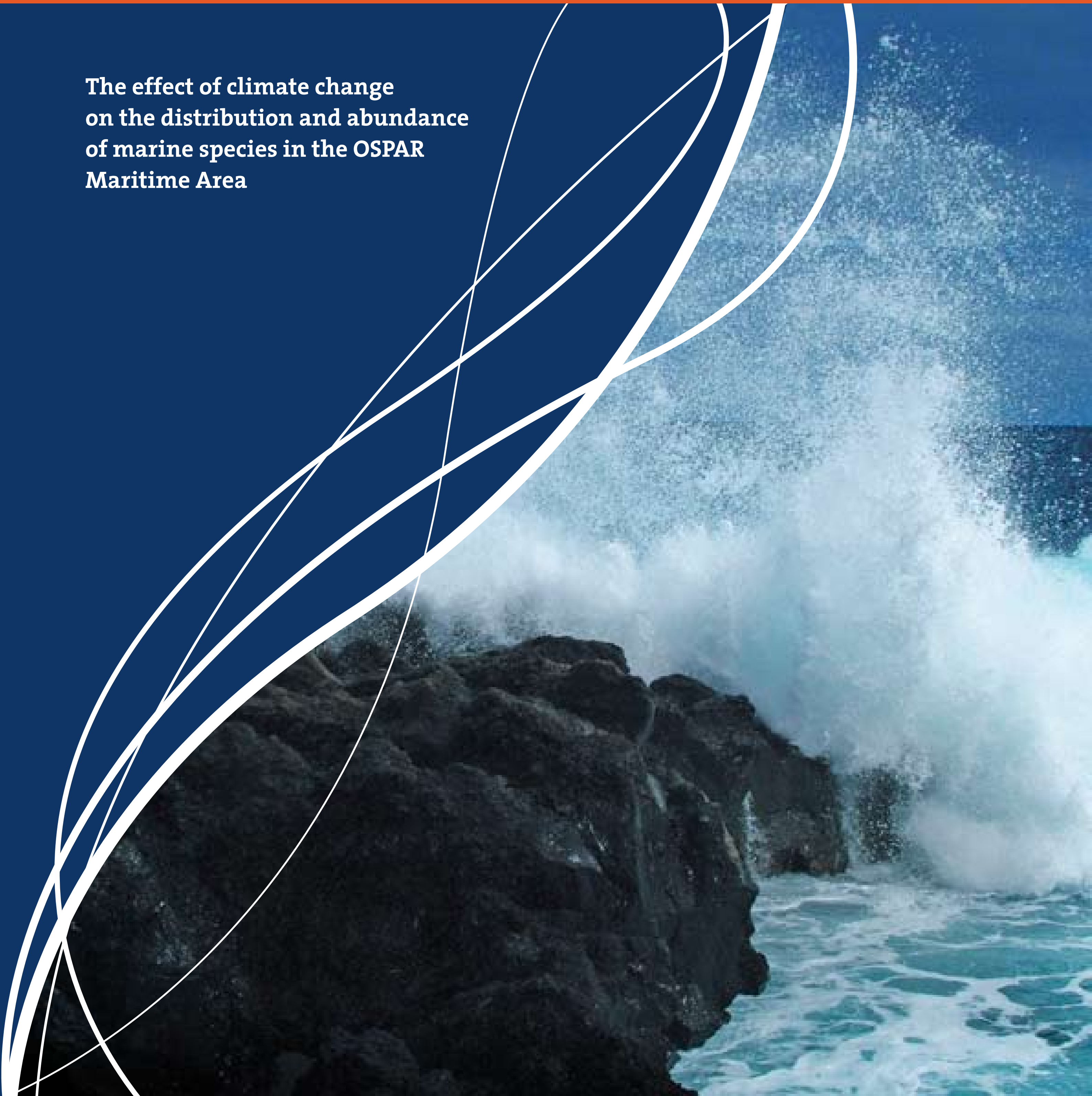

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November 2008

The effect of climate change on the distribution and abundance of marine species in the OSPAR Maritime Area

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Recommended format for purposes of citation:
Tasker, M. L. (Ed.) 2008. The effect of climate change on the distribution and abundance of marine species in the OSPAR Maritime Area. ICES Cooperative Research Report No. 293. 45 pp.

This report is a product of the advisory process of the International Council for the Exploration of the Sea. As such, it is based on the work of many scientists working within ICES Expert Groups. This work has been synthesized, edited, and agreed by scientific representatives of the 20 ICES Member Countries.

ISBN 978-87-7482-039-0
ISSN 1017–6195

SUMMARY

This report examines the evidence of the effect of climate change on the distribution and abundance of marine species in the OSPAR Commission Maritime Area (OSPAR Maritime Area). It focuses primarily on effects that may be linked to changes in sea surface temperature (SST).

It is the product of many scientists working within the ICES framework, who examined long-term datasets, often developed and formed from the work of other scientists. The main conclusions are that oceanographic conditions do influence the marine biota in the OSPAR Maritime Area, and that oceanographic conditions are changing. There was evidence to support this in both the narrative and the analytical information examined by ICES throughout the OSPAR Maritime Area. Effects of climate change varied from weak to very strong, particularly when environmental conditions were exceptionally cold or warm.

ICES scientists undertook a meta-analysis, which demonstrates that the changes in distribution, abundance, and other characteristics (particularly seasonality) of marine biota in the OSPAR Maritime Area are consistent with expected climate effects. This does not mean that all changes are consistent with a climate-change effect, nor that climate is the only cause, but it is undoubtedly a recognizably important factor in around three-quarters of the 288 cases examined here. These cases include zooplankton (83 cases), benthos (85 cases), fish (100 cases), and seabirds (20 cases). For seabirds, only 12 of the 20 changes were consistent with a climate effect, but for the other taxa, the proportion of consistent cases was much higher. The overall results for each OSPAR region were also consistent with a climate-change effect. Available information on phytoplankton and other lower trophic organisms did not allow a similar analysis. The majority of the cases examined here were from OSPAR Region II; there were none from OSPAR Region V. This is primarily ascribable to the relative availability of suitable datasets in the regions.

There is no doubt about the existence of a global climate change, driven by anthropogenic factors. However, climate-change effects are difficult to detect at a regional scale, given the high degree of both spatial and temporal variability at this finer scale. This is true even for a relatively easily (and routinely) observed variable, such as sea temperature. Other key climate variables include advection, vertical mixing, convection, turbulence, light, rainfall, fresh-water run-off, evaporation, oxygen concentration, pH, salinity, and nutrient supply. These variables are often interlinked and far less commonly observed, and their effect on biota is less widely investigated and considerably more complex. This is why our analysis is generally confined to temperature effects. Despite the occurrence of climate changes, current regional SSTs are only a few tenths of a degree above the averages recorded in the middle of the 20th century.

In addition to natural spatial and temporal variability in the direct and indirect effects of climate change, a number of other factors affect the abundance and distribution of individual species, population, and communities in the OSPAR Maritime Area:

- **Fishing.** This is the major non-climate anthropogenic factor. Biota removal and habitat disturbance are, respectively, two of the most prominent pressures for fish and benthos, which have also demonstrated increasing trends over the past few decades. Population sizes and geographic distributions of many marine species reflect responses to these pressures.

- **Oceanographic factors.** These may be direct (increased or decreased mortality because of temperature, transport to new areas, or arrival at different times, etc.) or indirect (mediated, e.g. by a climate-related change in the food available to predators).

The difficulty in identifying the cause of any of these effects may be confounded by:

- **Buffering.** Many fish, marine mammals, seabirds, and some benthos are long-lived. Therefore, the effects of oceanographic conditions may be buffered at the population scale and integrated over time, even at an individual scale.

- **Complex life histories.** Most marine invertebrates and fish have complex life histories, with eggs, larvae, juveniles, and adults often found in different places, both geographically and in the water column. The effects of oceanographic conditions on the different life-history stages of even a single species may differ by an order of magnitude, and possibly even in sign (either positive or negative direction of change).

Other factors, such as eutrophication, pollution, diseases, and introduced species, affect the abundance and distribution of species, populations, and communities, particularly at a local scale, and they can interact with climate change and fisheries as drivers of change.

In conducting these analyses, ICES scientists were searching for observed changes beyond what might have been expected from natural variability. As noted above, this type of analysis is very difficult to carry out at a local or regional level for individual species, populations, or even ecosystems. For this reason, ICES scientists chose to undertake a meta-analysis (an analysis that combines the results of several studies, each addressing a common hypothesis). This allowed a combination of various types of information to be used, which, despite being individually inconclusive, enable the better detection of any collective response of the ecosystem.

The meta-analysis methods employed by ICES scientists were based on those used by the International Panel on Climate Change (IPCC; see the Annex: Methods). This assessment suffered from a number of shortcomings, mainly as a result of unavoidable limitations in the data and resources available for analysis. However, objective data-extraction methods were used, and cases were screened to minimize bias in selection. The analytical approaches adopted were simple and not based on strong assumptions about the data or the relationships between the indicators of population state and oceanographic conditions. The results are considered reliable.

Implications

Although ICES has already made a considerable contribution to the extensive scientific literature on the species–environment relationships of marine ecosystems, it is still unable to partition causality between oceanographic conditions and other agents for change at the level of the individual taxon. This will probably remain the case, even with better data and more in-depth analyses. Therefore, the precautionary approach dictates the need to consider the possibility that species and populations will respond as climate changes occur. These responses may be partly or wholly hidden by other factors, such as changes in fishing pressure, habitat alteration, etc. Consequently, this should be taken into account in planning, risk assessment, and precautionary management in industries, such as fishing, that exploit marine ecosystems. The individual analyses in this report and ancillary documentation are sufficiently comprehensive to provide some specific guidance into the types of species and communities most likely to be affected and the direction of such change.

An additional issue implicit in the concern about change "beyond natural variability" is the potential for the existence of a "tipping point", that is, a threshold of change that, when exceeded by even a small incremental amount, would result in species, and even communities, undergoing dramatic changes in abundance and distribution. This problem is unlikely to be readily answerable for marine ecosystems, even those as comparatively data-rich and well studied as the OSPAR Maritime Area. Modelling can explore scenarios, but results will be highly uncertain and dependent on model assumptions that cannot be ground-truthed for conditions not yet observed.

The difficult task of partitioning causality between oceanographic conditions and other agents for change, together with the complex, potentially non-linear interactions between climate and non-climate (natural or otherwise) factors, advocate the need for a precautionary approach in the management of human activities in the marine environment. Several actions can contribute to the incorporation of necessary precautions into policy and management, and to the provision of the required scientific support. Scientists need to monitor and analyse results in ways that take advantage of spatial and temporal patterns in both hydrographic and species occurrences, build consistent time-series, and design research programmes aimed at reducing uncertainty about relationships between oceanography and climate, and between species and populations. This will reduce uncertainty about the potential responses of marine ecosystems to climate change.

There is ample evidence for changes in fish distribution and abundance that are consistent with those expected, namely:

(i) a northward shift or deepening of their distribution;

(ii) an increase in abundance in the northern part and a decrease in the southern part of their range.

Changes were most prominent in the northern OSPAR regions (I and II) and were observed in bottom-dwelling and pelagic species as well as in exploited and unexploited species. The observed changes cannot be interpreted unequivocally as a response to climate because other factors may also be significant, particularly fishing, although it is highly likely that climate effects are involved. Heavily exploited species will have a diminished gene pool and reduced resilience to environmental change. Consequently, they may be affected more strongly by climate change than less exploited or unexploited species. Measures that reduce large-scale habitat impacts, such as a reduction in fishing pressure, could be a key adaptation strategy in reducing the threat of climate change in marine ecosystems in the OSPAR Maritime Area.

Changes in the distribution of fish in response to climate change may have important effects for the design of marine-protected areas (MPAs) or the effectiveness of existing MPAs. For example, the "Plaice Box", a partially enclosed area in the coastal waters of the southern North Sea, established in 1989 to reduce the bycatch of undersized plaice in the flatfish fisheries, may have become less effective in terms of its original objective because undersized plaice have moved to deeper water outside the protected area (van Keeken *et al.*, 2007).

1 INTRODUCTION

This report is based on an answer to a request to ICES from the OSPAR Commission to provide "an assessment of changes in the distribution and abundance of marine species in the OSPAR maritime area in relation to changes in hydrodynamics and sea temperature". Specifically, ICES was asked to consider:

- ecologically indicative species, including the threatened and declining species identified by OSPAR, for which adequate time-series data exist;
- changes in their distribution, population, and condition;
- changes beyond what might have been expected from natural variability.

There is ample circumstantial evidence that global climate change is affecting many aspects of life on this planet. However, as scientific effort becomes directed at questions about the evidence of changes to the Earth's climate, and the effects of those changes on the Earth's ecosystems, the evidence is ceasing to be simply circumstantial. Major scientific syntheses, particularly the recent Nobel Prize-winning report of the International Panel on Climate Change (IPCC, 2007a; Rosenzweig *et al.*, 2008), have provided compelling evidence for both a warming of the Earth's climate over the past century and the effects of that warming on the Earth's ecosystems at a global scale.

The evidence for effects on ecosystems was strongly dominated by information from terrestrial rather than marine ecosystems. The present request from OSPAR is for information about the likelihood and nature of the effects to be expected in marine ecosystems in the OSPAR Maritime Area should the forecasts for continued warming of the planet prove true. This information will be included in its next Quality Status Report (QSR) and will make a more specific contribution to the policy and social debate that has followed the release of the IPCC report. It should be noted that the translation of global change to regional scales is complex, as pointed out by IPCC (2007a), and this present report concerns regional, not global, scales.

The basic premise underlying the OSPAR request was the existence of changes in hydrodynamics and sea temperature beyond what might have been expected from natural variability. A number of changes in hydrographic features over the past few decades, and their possible attribution to anthropogenic and natural causes, have already been documented. Key changes relative to the OSPAR request are summarized in Section 3 of this report and provide the background against which any changes in the distribution, population, and condition of ecologically indicative species should be interpreted.

The process conducted by ICES involved experts in ocean hydrography and in the ecology of zooplankton, benthos, fish, seabirds, marine mammals, and invasive species in the assembly of relevant information from the OSPAR Maritime Area. The evidence is generally scattered; most data were collected for other purposes and often not ideal for answering specific questions about the role of ocean conditions and climate on long-term trends in distribution, abundance, and biology of marine species. However, it has been possible to assemble a variety of types of information that, although individually inconclusive, collectively allow the request from OSPAR to be addressed by means of a meta-analysis (an analysis that combines the results of several studies, each addressing a common hypothesis), following a methodology consistent with that used in the IPCC analysis, which it is intended to complement. ICES stresses that, in trying to bring the required consistency to the analyses, it had to balance standardization, so that "best practice" was used throughout the process, but set against sufficient flexibility to allow for the accommodation of real differences among taxa and regions.

In the analysis of distribution and abundance of marine species, we need to distinguish between climate and non-climate causes of observed changes, and between natural and anthropogenic factors. In the case of non-climate causes, the division between natural and anthropogenic factors is fairly clear, but, relative to climate, most factors are the same in both cases, and the requirement is to partition them in order to attribute a proportion of the observed changes in marine species in the OSPAR Maritime Area to anthropogenic climate change.

The size and direction of a particular climate impact depends on the size of the climate change, the sensitivity of the species or biological system to this change, and where the change is observed within the full biogeographical range of the species or biological system. Also, there are interactions between causes within and among the four categories in the chart below that should not be ignored. A large number of studies demonstrate that populations and systems become more sensitive to climate impacts when they are heavily exploited (Brander, 2005; Hsieh *et al.*, 2006; Ottersen *et al.*, 2006; Perry *et al.*, 2008; Planque *et al.*, 2008). The increased sensitivity may be the result of reduced age structure, constriction of geographic distributions, or other kinds of loss of diversity.

This report does not include observations on whole ecosystem changes (e.g. Beaugrand, 2004). Nor does it attempt to explain all of the changes in terms of the underlying processes and mechanisms. However, ICES is confident that the following assessment provides a good description of our best knowledge of the changes in the distribution and abundance of marine species in the OSPAR Maritime Area in relation to hydrographic changes, even if the completion of the final step, that of partitioning causality between oceanographic conditions and other agents for change, is likely to remain very difficult for the foreseeable future.

Causes of change	Natural	Anthropogenic
Non-climate	Competition, predation, disease, internal dynamics, etc.	Fishing, eutrophication, pollution, habitat alterations, species introductions, etc.
Climate	Temperature, vertical mixing, circulation, etc.	Temperature, vertical mixing, circulation, pH, etc.

1.1 Geographic terminology

The OSPAR regions described in this document are shown in Figure 1.1.1. Figure 1.1.2 shows the biogeographical provinces of the OSPAR Maritime Area used in this document (after Dinter, 2001).

Figure 1.1.1.
The OSPAR regions of the Northeast Atlantic: I = Arctic; II = greater North Sea; III = Celtic Sea; IV = Bay of Biscay and western Iberian coast; V = wider Atlantic.

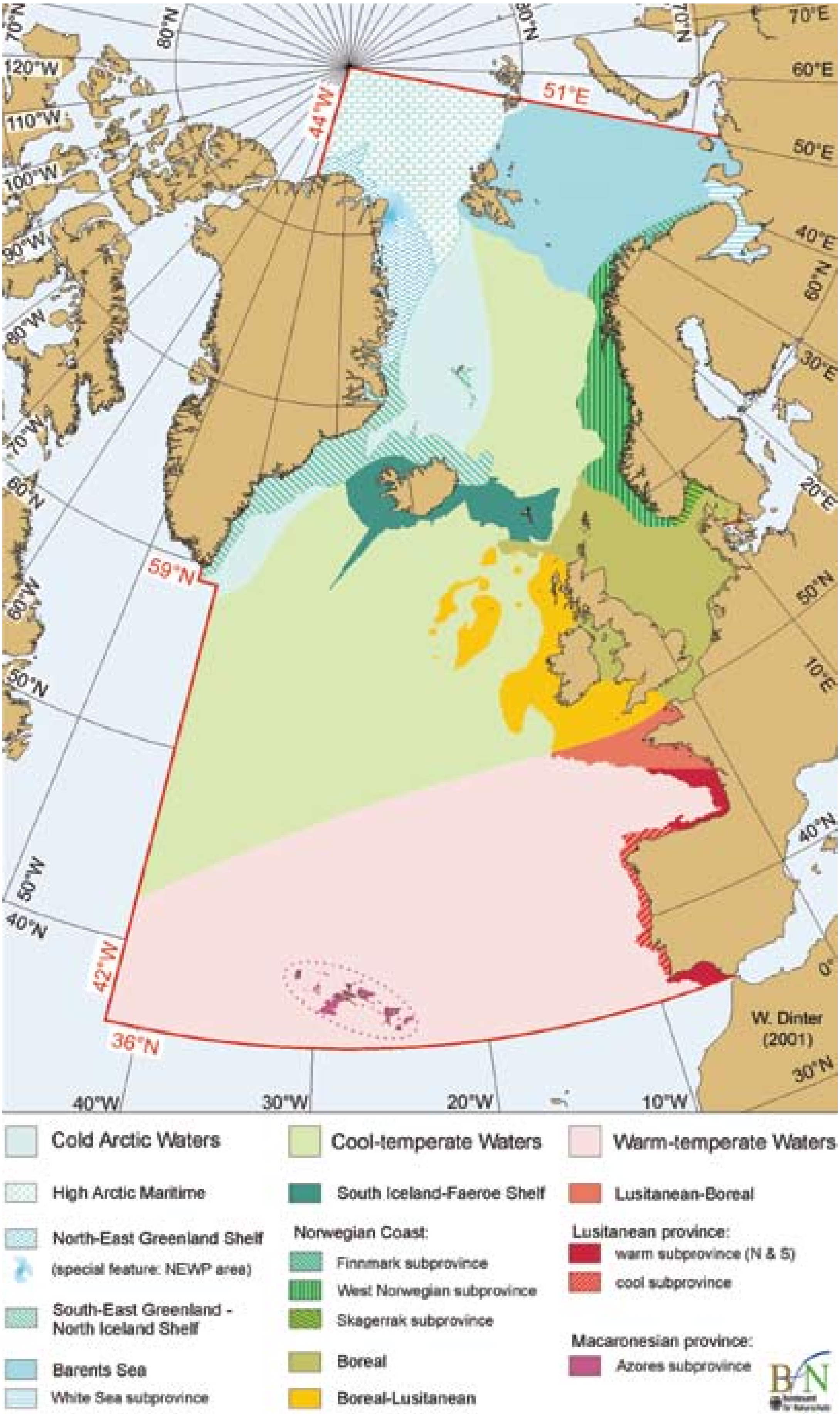

Figure 1.1.2.
Biogeographical classification of the benthal and neritopelagial areas of the shelf and upper continental slope (<1000 m depth), and of ice-cover biomes combined with the superordinate holopelagic provinces (<1000 m depth) of the OSPAR Maritime Area (reproduced from Dinter (2001) and based on Forbes and Godwin-Austen (1977)).

2 OCEANOGRAPHIC BACKGROUND

2.1 Present situation

Model simulations that compare 20th-century global-scale land and ocean surface temperatures, with and without anthropogenic greenhouse gases, reveal a significant divergence from the 1970s onwards (IPCC, 2007a; Figure 2.1.1). The simulations, including anthropogenic forcing, agree well with observations. These results led the IPCC (2007a) to state that "Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the result of the observed increase in anthropogenic greenhouse gas concentrations". This statement represented a greater degree of certainty than in previous assessments of the role of human activity on global climate.

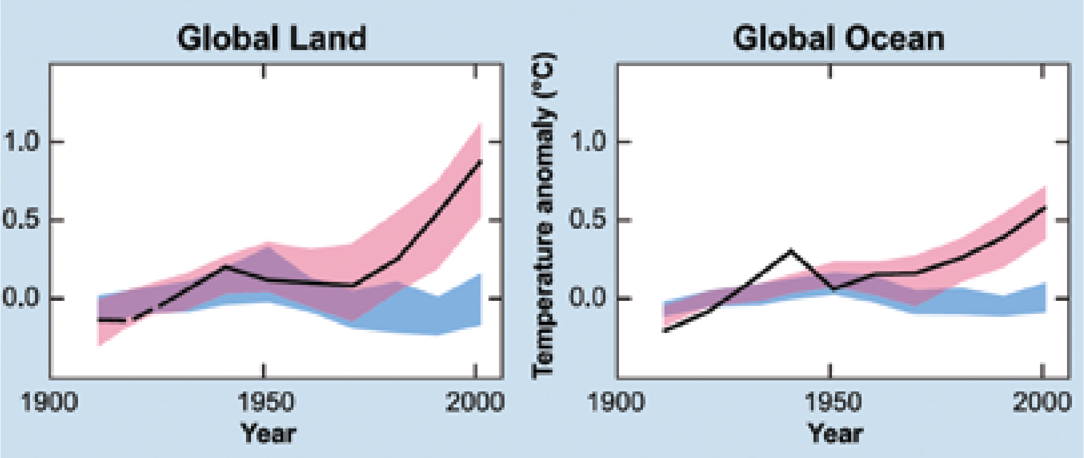

Figure 2.1.1.
Global land (left) and global ocean (right) decadal average temperatures during the 20th century (black lines) compared with a climate model simulation, including anthropogenic forcing (pink shading) and natural-only forcing (blue shading). From IPCC (2007b).

Although the impact of greenhouse gases on surface temperature is clear at the global scale, the signal at regional scales is complicated. Processes working on regional and local scales, such as surface advection patterns, convection, evaporation, and precipitation, indicate that the temperature increase has not been uniform over the planet. Some areas have warmed more rapidly than the global mean, while others have experienced cooling (Figure 2.1.2). Moreover, the temperature increase in the ocean has been considerably less than over land (Figure 2.1.1), which is consistent with the large heat capacity of the deep oceans. IPCC (2007a) noted that natural temperature variability is larger at the regional scale than at the global scale and, with the smaller temperature increase in the ocean, it is apparent that natural variability is still (during the 20th century) a more dominant factor of temperature change in the European oceans than over the continent of Europe. Nevertheless, from 1995 to 2004, both sea and land surface temperatures in the OSPAR Maritime Area have increased at a rate well above the global mean.

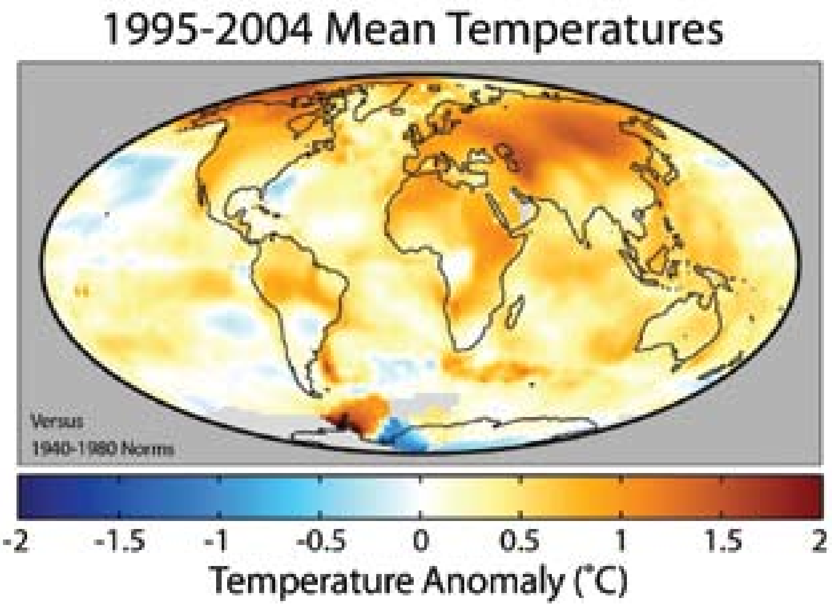

Figure 2.1.2.
Regional variation in global temperature change. This plot is based on the NASA GISS Surface Temperature Analysis (GISTEMP), which combines the 2001 GISS land-station analysis dataset (Hansen et al., 2001) with the Rayner–Reynolds oceanic sea surface temperature dataset (Rayner, 2000; Reynolds et al., 2002). The data themselves were prepared through the GISTEMP online mapping tool, and the specific dataset used is available at http://data.giss.nasa.gov/cgi-bin/gistemp/do_nmap.py?year_last=2007&month_last=10&sat=4&sst=1&type=anoms&mean_gen=0112&year1=1995&year2=2004&base1=1940&base2=1980&radius=1200&pol=reg. These data were replotted in a Mollweide projection with a continuous and symmetric colour scale. The smoothing radius is 1200 km, meaning that the reported temperature may depend on measurement stations located up to 1200 km away, if necessary. Image prepared by Robert A. Rohde from public domain data for Global Warming Art (http://www.globalwarmingart.com/wiki/Image:Global_Warming_Map_jpg).

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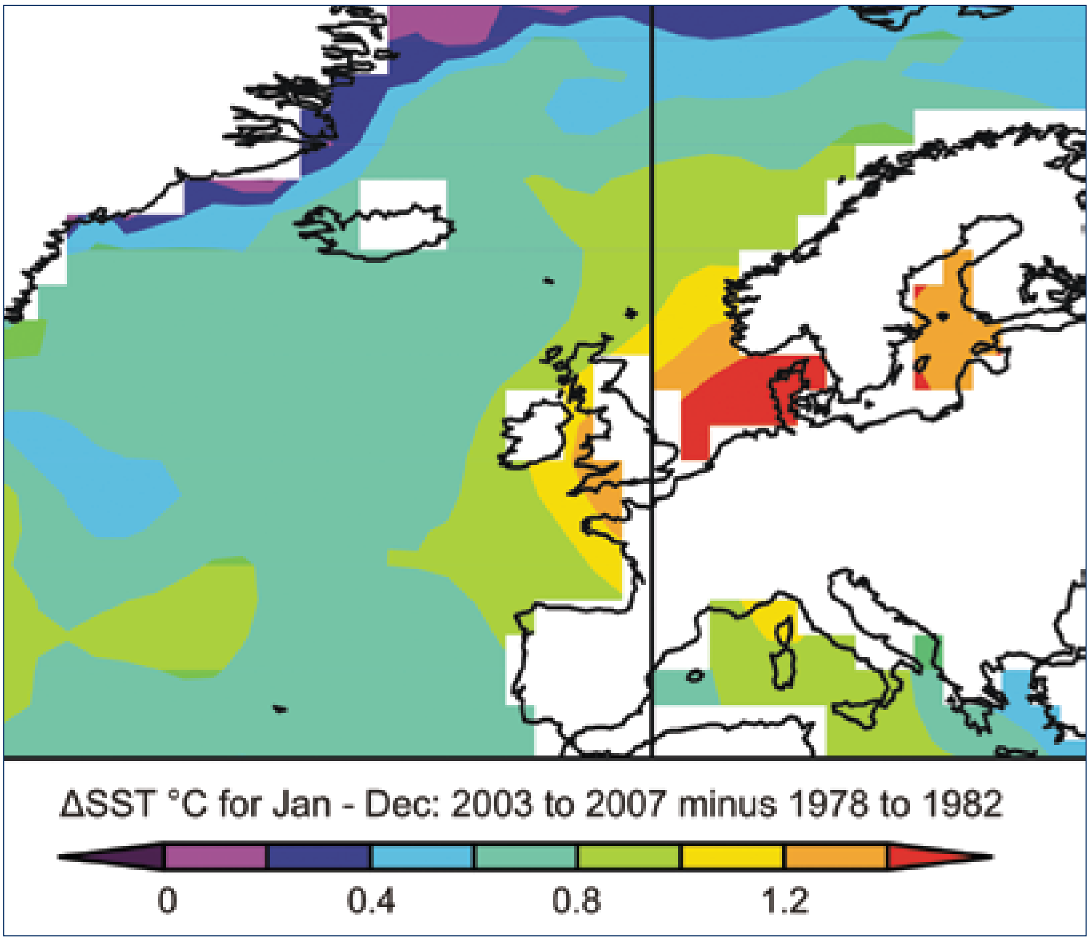


Figure 2.1.3.
Sea surface temperature (SST), showing the mean for 2003–2007 minus the 1978–1982 mean. The plots are based on NOAA NCDC ERSST version 2, which is an extended reconstruction of global SST data based on ICOADS (Worley et al., 2005) monthly summary trimmed group data (http://www.cdc.noaa.gov/).

Temporal patterns of temperature change also reveal a systematic spatial structure at the subregional level (Figure 2.1.3). The two longest instrumentally recorded time-series of temperature data in the Northeast Atlantic (Kola section and Faroe–Shetland Channel) reveal strong coherence at time-scales and periodicities greater than the decadal scale (Figures 2.1.4 and 2.1.5). The Kola and Faroe–Shetland data reflect ocean-water mass conditions and are closely related to the Atlantic Multidecadal Oscillation (AMO) index (Sutton and Hodson, 2005; Figure 2.1.6). The North Atlantic is currently in a positive phase of the AMO.

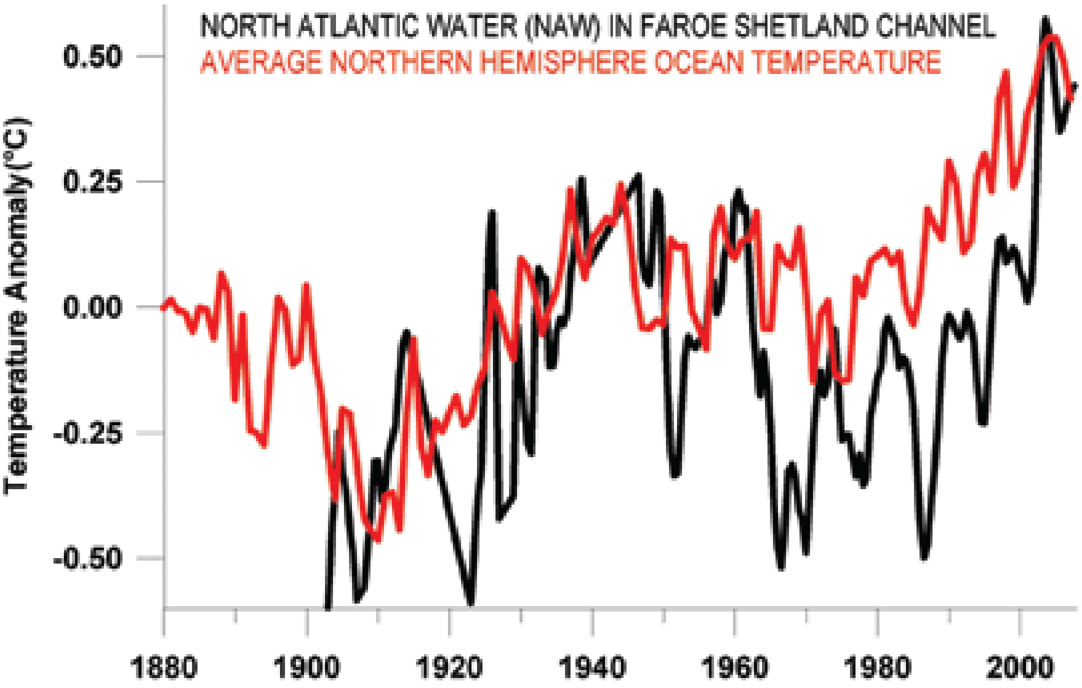


Figure 2.1.4.
Temperature anomalies of the Atlantic Water masses in the Faroe–Shetland Channel compared with the ocean temperature anomalies of the northern hemisphere. Data sources: FRS, Marine Laboratory Aberdeen, Scotland, and http://lwf.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html.

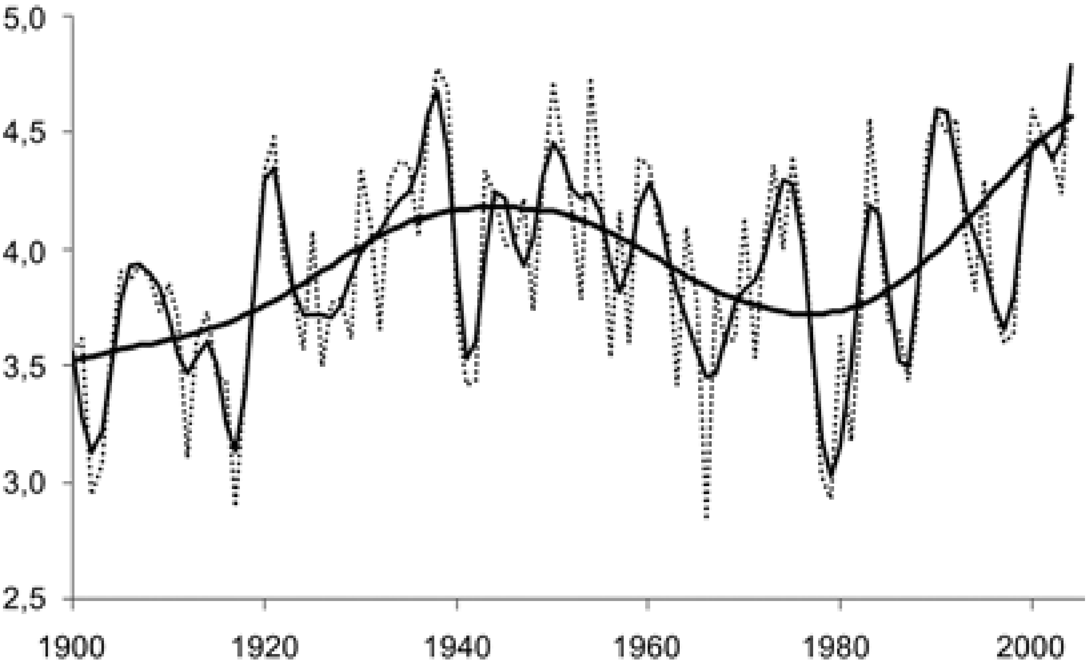


Figure 2.1.5.
Temperature (°C) of the Atlantic Water masses at the Kola section in the Barents Sea (Source: PINRO, Murmansk). Dotted line: annual mean. Thick lines: three-year moving average and a 30-year low-pass filter. From Sundby and Nakken (2008).

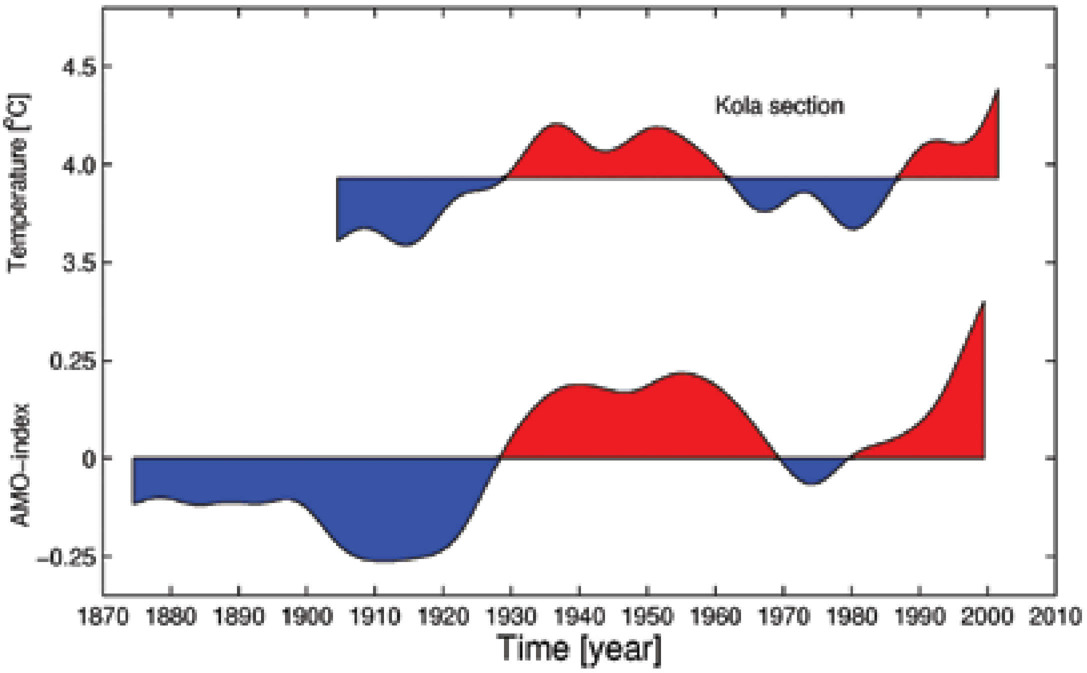


Figure 2.1.6.
Time-series of the Kola section long-term average temperature with the shorter term filtered out (upper graph) and the Atlantic Multidecadal Oscillation (AMO) index (lower graph). The AMO index is based on the sea surface temperature in the region 0–60°N and 7.5–75°W, as presented by Sutton and Hodson (2005), but with the long-term detrending removed. The Kola section data were obtained from PINRO. From Skagseth et al. *(2008).*

In addition to the century-long time-series of the Kola section and Faroe–Shetland Channel, ocean variability in the OSPAR regions as a whole has been observed with high-quality measurements over the last 50–60 years (Hughes and Holliday, 2007). Such *in situ* observations are relatively sparse or unavailable in many places, which restrict our ability to compare changes in marine ecosystem properties with changes in ocean climate. To address this problem, we also used the gridded HadISST sea surface temperature dataset (Rayner *et al.*, 2003). The long-term variability and trends derived from this dataset have been compared with long time-series of *in situ* measurements from ICES standard sections in the North Atlantic and Nordic Sea (Hughes *et al.*, 2008).

The *in situ* measurements demonstrate an interdecadal Atlantic Water temperature increase of about 1°C from the 1970s to the present, consistent along the shelf break from Ireland to the Barents Sea and the Fram Strait (Figure 2.1.7; Holliday *et al.*, 2008). In OSPAR Region II (North Sea), the rate of warming is even greater (1–2°C), whereas the warming in the western OSPAR regions is less (0.4–0.8°C; illustrated for the surface layer in Figure 2.1.3). The increase in temperature in OSPAR Region IV (Bay of Biscay and western Iberia) is lower in the south and also strongly influenced by upwelling. Superimposed on this general warming over the past 30 years are interannual to decadal-scale variations, with amplitudes two to three times greater than the size of the long-term change in the past century. Average temperatures in some parts of the North Atlantic during the previous warm period, from the 1930s to the 1950s, were slightly colder than today (Figures 2.1.4 and 2.1.5).

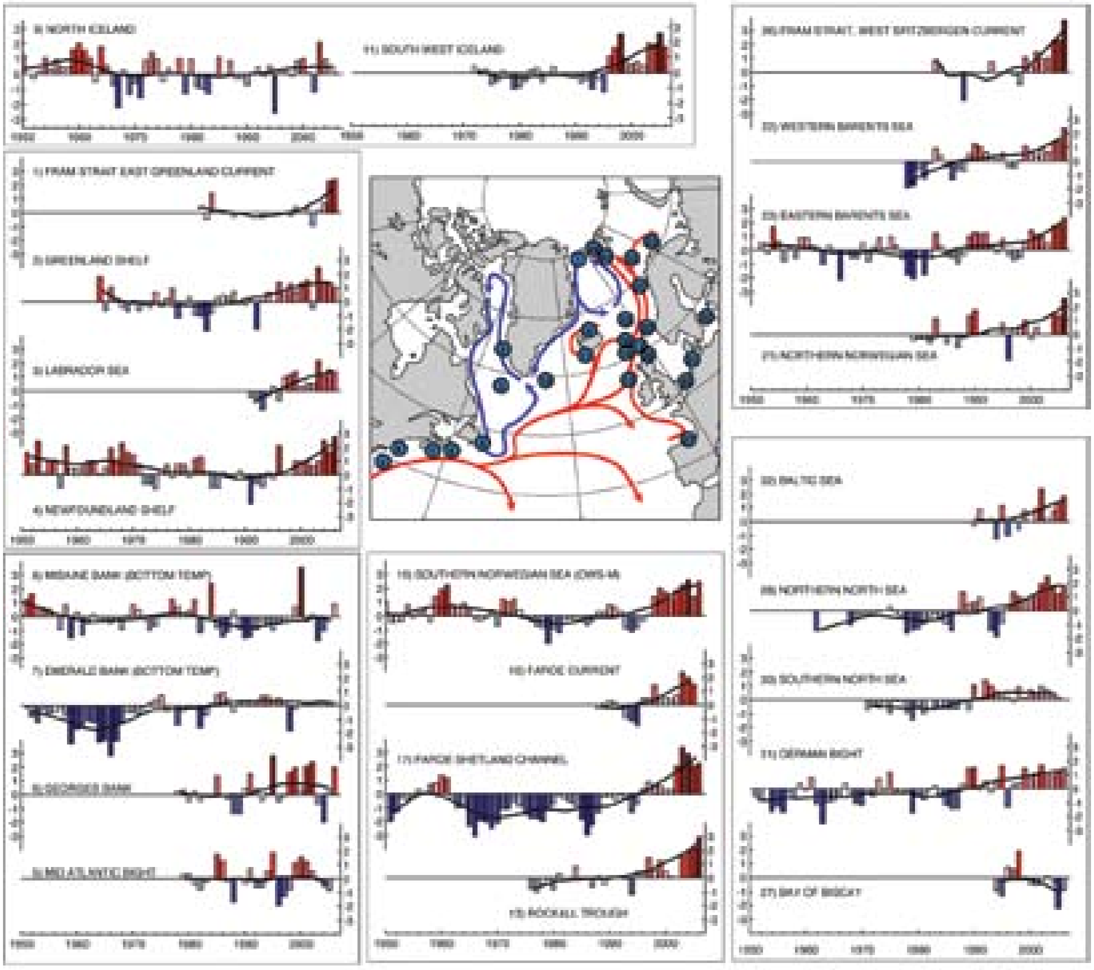


Figure 2.1.7.
Overview of upper ocean temperature anomalies from the long-term mean across the North Atlantic. The anomalies are normalized with respect to the standard deviation (e.g. a value of +2 indicates 2 standard deviations above normal). The maps show conditions in 2006 (colour intervals 0.5; reds are positive/warm and blues are negative/cool). From Hughes and Holliday (2007).

A regional scale of natural variability in the North Atlantic is connected to changes in the Subpolar Gyre (Häkkinen and Rhines, 2004). The weakening of the Subpolar Gyre after 1995 has been demonstrated to have a large effect on hydrographic conditions in the eastern part of the OSPAR area as a result of the presence of a larger fraction of warmer and more saline water from the eastern Atlantic (Hatun *et al*., 2005; Figure 2.1.4). Since the 1960s, changes in the large-scale wind pattern, principally the North Atlantic Oscillation (NAO), have resulted in a gradual change in the water mass distribution in the Nordic Seas. In particular, this is manifested by the development of a layer of Arctic intermediate waters, deriving from the Greenland and Iceland seas and spreading over the entire Norwegian Sea (Blindheim *et al*., 2000). In the Norwegian Basin, this has resulted in an eastward shift of the Arctic front and, accordingly, an upper-layer cooling over wide areas as a result of increased Arctic influence. The extent of sea ice in the Barents Sea has reduced since the 1970s (ICES, 2008a), coinciding with increased temperature of the Atlantic inflow (Skagseth *et al*., 2008).

Superimposed on the AMO signal are the interannual to decadal-scale temperature variations that are largely linked to the NAO. Although the AMO is a thermal signal, the NAO causes changes in circulation and volume fluxes (Sundby and Drinkwater, 2007), as well as in the thermal regime. The NAO signal also has a smaller spatial scale, resulting in different development and signature in the southern and northern OSPAR regions.

2.2 Effects of oceanography on the OSPAR marine ecosystem

Estimates of the degree of influence of marine climate on marine ecosystems probably depend on the rate of change of the marine climate and on the choice of variable used to describe climate. In addition to temperature, several interlinked climate variables influence marine ecosystems, including advection, vertical mixing conditions, convection, turbulence, light, rainfall, run-off, evaporation, oxygen, pH, salinity, and nutrient supply (including wind-blown nutrients from the land). The NAO, which is an atmospheric pressure phenomenon primarily of a decadal time-scale, has specific characteristics with respect to influence on ocean circulation, mixing, and precipitation (Hurrell *et al*., 2003), and also to spatial extent. Climate phenomena of longer term periodicity, such as multidecadal-scale oscillations and anthropogenic climate change, are interlinked across the range of climate variables and with respect to spatial scales.

The general link between spatial and temporal scales in nature makes it more difficult to reveal the effects of short-term (e.g. interannual variability) climate changes on species distributions simply because such changes are not correlated across larger spatial scales. Analysis of changes, even within an explicit spatial context such as the Northeast Atlantic, requires observations at decadal time-scales and longer.

The present report focuses primarily on the effects of longer term, and hence larger scale, climate change, as manifested by the change in the thermal regime of the Northeast Atlantic during the second half of the 20th century. It should be emphasized, however, that the ecosystem effects recently observed are not unique to the past century. In 1948, ICES sponsored a symposium focusing on what happened in the North Atlantic during the warming after a relatively cool period at the beginning of the 20th century, which lasted until the 1930s and 1940s (ICES, 1949). At this time, similar changes, with northward shifts of fish species, occurred in both the Northwest Atlantic and the Northeast Atlantic (Drinkwater, 2006). The subsequent cooling, which reached its lowest temperatures in the 1960s and 1970s, resulted in new distributions and changes in abundance. The "gadoid outburst" in the North Sea (Cushing, 1980) was one result of this new cooling. Hence, in a century-long time-scale, the recent warming and its effects on marine ecosystems is part of a dynamic change in which species are observed to move northwards in warm periods and southwards in cool periods. In the present century, with anthropogenic climate change becoming increasingly dominant compared with long-term natural variability, past oscillations in species distributions may be replaced by a more permanent northward change.

3 EVIDENCE ANALYSIS

3.1 Plankton

3.1.1 Data sources and related information

Information on zooplankton biomass abundance, distribution, or condition in the OSPAR Maritime Area was extracted from peer-reviewed material reported by the ICES Working Group on Zooplankton Ecology (ICES, 2007a, 2008b) and additional peer-reviewed material. Much of this information results from the Continuous Plankton Recorder (CPR) time-series. The work of ICES (2006a) was used to identify changes in phenology, such as the start of the zooplankton production season and the duration of the zooplankton season. Unlike some of the documented changes in abundance and distribution linked to increase in temperature, changes in phenology (ICES, 2006a) tend to be reported at the functional group or genus level.

Beaugrand *et al*. (2002) reported on the distribution of organisms, which can be linked to their relative biogeographical affinities and northern hemisphere temperature (NHT) anomalies and the NAO index. This allowed an understanding of regional modifications in the marine ecosystem caused by changes in the hydrographic regime. Strong biogeographical shifts in all calanoid copepod assemblages were identified with a northward extension of more than 10° in latitude of warm-water species, associated with a decrease in the number of colder water species. These changes have been attributed to regional SST warming. Identifying the biogeographical affinities allows inferences to be made regarding distribution with respect to changes in temperature through marine systems.

Thus, there is an expectation of a demonstrable shift/expansion of distribution northwards with increasing temperature relating to species' biological associations and ecological characteristics for pseudo-oceanic temperate species such as *Centropages typicus, Candacia armata,* and *Calanus helgolandicus* (Bonnet *et al*., 2005). Similarly, changes in abundance can be correlated with these biogeographical affinities (Lynam *et al*., 2004). Additionally, the appearance of species in areas where they were previously unknown (Faasse and Bayha, 2006; Boersma *et al.*, 2007; Valdés *et al.*, 2007) can be linked in the same manner.

Temperature changes over time are also thought to alter the timing of annual recurring events, such as the phenophases (e.g. timing for seasonal migrations).

3.1.2 Results

Analysis of the CPR time-series has provided evidence of significant changes in the abundance, distribution, community structure, and population dynamics of zooplankton and phytoplankton in the OSPAR Maritime Area. These events are mainly responses to changes in regional climate, caused predominantly by the warming of air and sea surface temperatures, as well as by associated changes in hydrodynamics. Some changes and examples of their effects are outlined below.

- **Change in biomass.** This has been observed in both zooplankton and phytoplankton. For example, the population of the previously dominant zooplankton species in the North Sea (*Calanus finmarchicus*) decreased in biomass by 70% between the 1960s and the 2000s. Species that prefer warmer waters have moved northwards, but their total biomass is not as great as the decrease in *Calanus* biomass (Edwards *et al.*, 2006). There are reported increases in phytoplankton biomass (as determined by the Phytoplankton Colour Index, or PCI, i.e. the degree to which the CPR silk is stained green) since the mid-1980s (Edwards *et al.*, 2008). This is mainly reported in OSPAR Regions II, III, and V in relation to increasing SST.

- **Change in distribution.** A shift in the distribution of many plankton species by more than 10° latitude northwards has been recorded in the OSPAR Maritime Area over the past 30 years. (Depending on the temperature affinity of organisms, this can be an increase in the range, e.g. in temperate pseudo-oceanic species, or a shift of the centre of distribution, e.g. in Subarctic species; Figure 3.1.1). This shift is particularly associated with the current running northwards along the shelf edge of the European continental margin (Beaugrand *et al.*, 2002; Edwards *et al.*, 2006). In addition, an extension of the seasonal PCI has been recorded in OSPAR Regions II, III, and V.

Hydroclimatic changes have been related recently to increases in the abundance of jellyfish, as recorded in several OSPAR regions (Lynam *et al.*, 2004; Attrill *et al.*, 2007). Temperature appears to be one of the main triggering mechanisms for exceptional outbreaks of these gelatinous carnivores (CIESM, 2001; Purcell, 2005). Furthermore, warm temperatures may be related to a prolonged period of persistence and increased abundance of the ctenophore *Mnemiopsis leidyi* (Purcell, 2005). This gelatinous predator was accidentally introduced into the Black Sea and has contributed to a reduction in the fisheries (see references in Purcell, 2005).

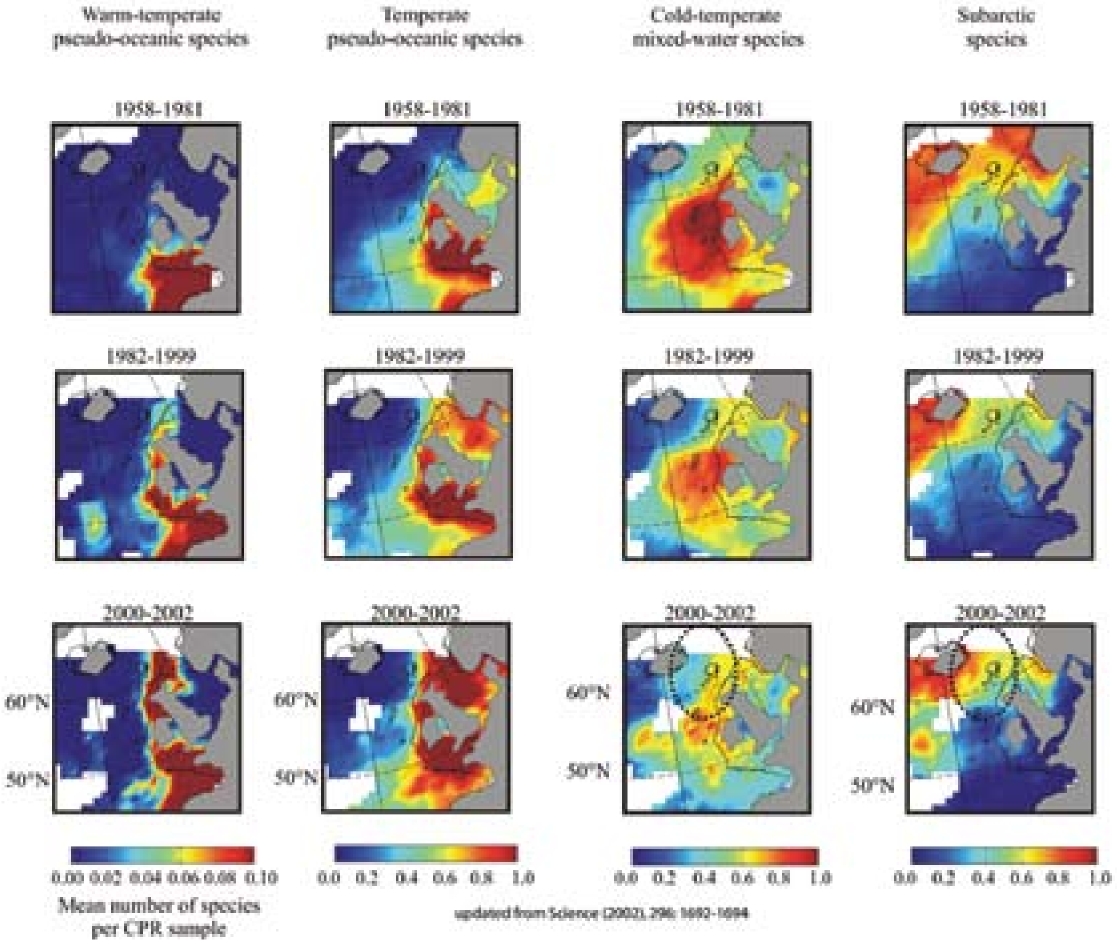
3.1.3 Conclusions

Based on the long-standing CPR survey, Beaugrand *et al.* (2002) and Edwards *et al.* (2008) provide strong evidence of observed changes in zooplankton distribution and abundance, specifically biogeographical shifts of calanoid copepod communities in recent decades, with warm-water species shifting northwards and cold-water species likewise retracting northwards (Figure 3.1.1).

The information presented here also offers articulate and credible evidence of change in the OSPAR regions. In our analyses, changes in distribution are by far the most obvious response to climate change displayed by zooplankton. Although these changes in distribution have been linked with warming trends, these are unlikely to have been the sole driver; stronger north-flowing currents on the European shelf edge may also play a role (Appenzeller *et al.*, 2004). Phenology appears to be very sensitive to temperature variation; however, the response appears to vary substantially across functional groups. This may reflect the hierarchical level of analyses, as breaking down the information to species level may elucidate specific trends characteristic of individual species in response to temperature variation.

Jellyfish are very often population-bloom species, known to be co-responsive with climate indices (Attrill *et al.*, 2007; Lynam *et al.*, 2004). In warmer waters associated with climate-change scenarios, the frequency of jellyfish is expected to increase (Attrill *et al.*, 2007).

Changes in zooplankton and phytoplankton communities at the base of the marine pelagic foodweb can affect organisms at higher trophic levels (e.g. fish, seabirds, mammals) through loss of synchrony between predator and prey (match–mismatch) abundance–demand. This synchrony



updated from Science (2002), 296: 1692-1694

Figure 3.1.1.
Maps showing biogeographical shifts of calanoid copepod communities in recent decades, with the warm-water species shifting northwards and the cold-water species likewise retracting north, by more than 10° of latitude (From Edwards et al.*, 2008).*

can play an important role (bottom–up control of the marine pelagic environment) in the successful recruitment of top predators, such as fish and seabirds (Beaugrand and Reid, 2003; Beaugrand, 2003; Edwards and Richardson, 2004; Richardson and Schoeman, 2004; ICES, 2006b; Frederiksen *et al.*, 2006a).

Kirby *et al*. (2007) demonstrated that warmer conditions earlier in the year in the North Sea, combined with increased phytoplankton abundance, have occurred since the late 1980s, which has determined the significant increase of meroplankton (i.e. temporary plankton species), particularly the larvae of echinoderms (*Echinocardium cordatum*).

In order to assess climate-change effects on the marine community and fisheries resources, it is important to maintain the few time-series that exist at single sites and along transects and to expand the CPR survey with the aim of increasing the geographical coverage of zooplankton monitoring in the OSPAR Maritime Area.

3.2 Benthos

3.2.1 Data sources and related information

ICES extracted information from a variety of sources regarding benthos in the OSPAR Maritime Area. This provides the evidence of the effects of responses in abundance and range, relative to oceanographic conditions.

3.2.2 Main conclusions

The majority of benthic species and communities examined revealed changes in distribution and abundance over time. Most of these patterns were consistent with the expected changes if the species were responding to oceanographic conditions.

Many of the strongest signals in the benthic data were large changes in abundance associated with anomalously cold winter conditions (Kröncke *et al.*, 2001, 2007). However, similar large effects were evident in response to, for example, seabed disturbance and changes in water quality. This strong effect of extreme temperature conditions on benthic abundance and/or distribution indicates that, if climate change results in temperature conditions outside the recent historical range of natural variation, major effects on at least some species and communities would be likely.

3.2.3 Highlights of published knowledge

The distribution of many benthic species in the Bay of Biscay, including macroalgae, molluscs, and arthropods, has been studied since the end of the 19th century. Some latitudinal shifts in distribution, both northwards and southwards, have been documented and are related to the occurrence of warm and cool periods during the 20th century (Alcock, 2003). Similarly, changes in the benthic community off La Coruña (Spain) could be partly explained in terms of the expansion and contraction of warm- and cold-water species in response to changing environmental conditions linked to the NAO (Lopez-Jamar *et al*., 1995; S. Parra, pers. comm.).

The sand-burrowing brittlestar *Amphiura* had a long period of absence or rarity in the southern North Sea, but has been recorded in low to moderate abundance since 1975. Temperature is reported as a limiting factor for the distribution of this species, with its apparent range extension to the inner German Bight area linked to higher winter temperatures compared with previous decades. The species is reportedly absent from areas where temperatures are higher than 10°C in summer and not less than 3°C in winter (Boos and Franke, 2006).

3.2.4 Interpretation and synthesis

Benthic species and communities may well be sensitive to anomalous oceanographic conditions, especially extremes of temperature, but also other factors. Most long-term benthic monitoring programmes were implemented either to study how other factors affect benthos or to use benthic indicators to provide information about trends in other factors (Beukema, 1990, 1992).

The strongest evidence of responses in benthic taxa that would be expected as a result of climate change is supplied in reports of:

- anomalously cold winter conditions leading to die-offs of species commonly associated with relatively warmer waters, or outbreaks of species commonly associated with relatively colder water (Beukema, 1990; Reiss *et al*., 2006);

- benthic species expanding outside their historical ranges into more northerly or less coastal areas.

Both of these observations are consistent with climate sensitivity in the benthos, but may possibly be a non-linear response. This situation could make the benthic biota a particularly high-risk community for impacts of climate change because such changes are likely to occur abruptly rather than incrementally over time.

Climate-related changes in oceanographic conditions can be expected to affect benthic populations and communities by a number of pathways (Bhaud *et al*., 1995). These pathways include:

- **temperature** (the only effect looked at in this report) – influencing the distribution of "northern" and "southern" species;

- **hydrodynamics** (e.g. current velocities, stratification of water layers, wave climate) – determining the transport of larvae and influencing sediment composition, which, in turn, determines habitat suitability for species and reflects food availability to the benthos;

- **precipitation** (pattern and amount) – affecting the distribution of suspended particulate matter, salinity, and nutrient run-off; these changes affect nutrient availability to the benthos and increase the risk of hypoxia events in estuaries rich in organic matter;

- **acidification** (increasing acidification of the ocean, caused by increasing atmospheric carbon dioxide, is becoming well documented) – posing a threat to corals and other benthos, particularly species requiring calcium or carbonate for shells.

Thus, climate-related changes in a range of physical and chemical conditions in the sea will, in turn, affect species composition directly or indirectly and, therefore, the trophic structure of benthic communities. These effects are compounded in situations where the benthic species that are affected create distinct habitats, for example, coral reefs or mussel beds.

3.3 Fish

3.3.1 Introduction (fish-specific approach)

To interpret the changes for different species, we have followed the classification of fish species by Ellis *et al.* (2008), who distinguished between Arctic, Boreal, Lusitanian, African, and Atlantic species, as follows:

- Arctic species are restricted to the northernmost parts of the ICES/OSPAR areas, with southern limits off northern Norway and Iceland (Figure 1.1.2).
- Boreal species extend northwards to the Norwegian Sea and Icelandic waters, with the southern limits of their distribution around the British Isles or west of Brittany.
- Lusitanian species are southerly species that tend to be abundant from the Iberian Peninsula (including the Mediterranean Sea) to as far north as the British Isles, and may have northerly limits in the southern or central North Sea (although many of these species extend to more northerly latitudes on the western seaboards of the British Isles, and so can also occur in the northwestern North Sea). Many of these species have distributions extending into the Mediterranean Sea and off northwest Africa.
- African fish species are considered to be those that have a northerly distribution in the southern or western Mediterranean, but are more typically encountered off northwest Africa.
- Atlantic species (often pelagic or deep-water) are widespread in the North Atlantic and include many of the deeper water species widely distributed along the continental slope.

Changes in the distribution of fish within their respective regions could only be assessed for OSPAR Regions II and III. Here, the expectation was that, for Boreal species, a decrease in the southern area could be expected, whereas no change or an increase should be observed in the northern area. For Lusitanian species, two outcomes were anticipated: either an increase in the southern area together with no change in the northern area, or an increase in the northern area combined with no change in the southern area. Any of the above was considered to be in accordance with expectations of a climate change-driven effect.

For OSPAR Regions II, III, and IV, the expectation was that the abundance of Boreal species should decrease, whereas that of Lusitanian species should increase. However, for the Barents Sea (OSPAR Region I), many of the Atlantic, Boreal, and certainly Lusitanian species are on their northern boundary and could therefore be expected to increase with increasing water temperature. Therefore, it was assumed that any increase of an Atlantic, Boreal, or Lusitanian (but not Arctic) species in OSPAR Region I could be interpreted as being a result of climate change.

3.3.2 Data sources and related information

The sources of information for the fish component were ICES (2007b, 2008c) and a selection of peer-reviewed publications. ICES (2007b, 2008c) provided the results of analyses of groundfish survey data on the changes in abundance and/or distribution for four OSPAR regions (I, II, III, and IV). For OSPAR Regions II and III, a distinction was made between a northerly (N) and a southerly (S) area (respectively, the northern vs. the southern North Sea, and west of Scotland vs. the Celtic Sea). OSPAR Region I was represented by the Barents Sea and Region IV by the Bay of Biscay.

3.3.3 Main conclusions

There is ample evidence for changes in the distribution and abundance of fish, consistent with those expected, namely:

(i) a northward shift or deepening of distribution;

(ii) an increase in abundance in the northern part of the range and a decrease in the southern part of the range.

Changes were most prominent in the northern OSPAR Area (Regions I and II) and were observed in bottom-dwelling and pelagic species, as well as in exploited and unexploited species. The observed changes cannot be interpreted unequivocally as a response to climate effects because other factors may be important as well, particularly fishing, although it is highly likely that climate effects are involved.

3.3.4 Tabulation

The criteria described in the Annex were used to select records to include in the analysis. For the meta-analysis of the fish data, two periods were compared: 1990–1999 and 2000–2005. Some comparisons were made with the period 1977–1989 but, to ensure that changes in fishing activity during the 1970s and 1980s did not mask the climate-change signal, only data from 1990 onwards were included in the analysis.

In order to interpret the observed changes in abundance and/or distribution based on the work of ICES, the same approach was applied across all species and regions. For each period, we assessed whether or not there had been an overall change (a decrease or increase) in abundance (as indicated in Table 3.3.1). Where a northern and a southern area were distinguished, both areas needed to demonstrate the same direction of change. If this was not the case, it was interpreted in the table as a change in distribution.

3.3.5 Interpretation and synthesis

In more than 70% of the cases where changes were observed, abundance and distribution changed in line with the expected change in response to the recent warming (Table 3.3.1). In a minority of the studies, no change was observed or the change was opposite to that expected. Changes in the expected directions are seen in species that are demersal and pelagic, Lusitanian, Boreal, and Atlantic, exploited and unexploited. From this database, we determined how many records demonstrated a change and what percentage of these changes was in accordance with expectations from climate change. We assessed this by OSPAR region for two properties: abundance and distribution. Data were mainly available on changes in distribution and abundance. Data were insufficient and no analyses were conducted to assess change in fish condition.

Although the general outcome is consistent with the expected change attributable to an increase in temperature, the results cannot be interpreted as evidence for climate change because other explanations cannot be ruled out. In particular, the observed changes may be influenced by fishing. For example, because fishing mortality rates have been higher in the southern North Sea than in the northern North Sea (Heath *et al.*, 2003; Heath, 2007), the apparent changes in distribution in this part of the region could be a consequence of local patterns of fishing pressure (Hutchinson *et al.*, 2001; Daan *et al.*, 2005; Daan, 2006; Wright *et al.*, 2006). The effects of fishing thus interact with the effect of climate. The disentanglement of the effects of hydrographic attributes and other drivers is difficult and must be considered as a work in progress.

Table 3.3.1.
Frequency by which fish species responded to an increase in water temperature by a change in their (A) distribution or (B) abundance. If a species showed a response, the response was classified as either expected or opposite to expectation.

	Observed change in relation to climate			
OSPAR region	No change	Change as expected	Change opposite to expectation	Grand total
(A) Change in distribution				
I	0	2	0	2
II	1	33	9	43
III	9	8	1	18
IV	1	2	0	3
I–IV	11	46	10	67
(B) Change in abundance				
I	1	8	5	14
II	0	10	5	15
III	1	11	1	13
IV	17	3	2	22
I–IV	19	32	13	64

The results of these analyses demonstrate that, in most cases, for the four OSPAR regions considered, both abundance and distribution of fish species have changed. Substantially more than half of these changes are in accordance with expectations regarding climate change, and changes in the expected directions are seen in species that are demersal and pelagic, Lusitanian and Arctic, exploited and unexploited. However, there are questions about the suitability of many of the individual cases as valid sources of information about the effects of climate and oceanographic conditions on fish, because other effects may predominate in individual situations.

3.3.6 Highlights of observations, by OSPAR region

Many demersal and pelagic species changed abundance and distribution in all OSPAR regions. Many, but not all, of these changes are in accordance with what can be expected from climate change. The changes in abundance were observed for large areas and over relatively long periods (one or more decades). The changes observed over the last decade quite often appear to agree with the expected climate effect, possibly because other effects, such as fishing, may have had a larger effect over the longer periods. Two changes in distribution were apparent: a shift along the depth gradient and a latitudinal shift. The whole North Sea demersal fish assemblage has deepened by ~3.6 m per decade (Dulvy *et al.*, 2008) in response to climate change, and the deepening is coherent for most assemblages. The latitudinal response to warming seas is more heterogeneous and is a composite of at least two patterns:

- a northward shift in the average latitude of abundant, widespread thermal specialists (e.g. grey gurnard and poor cod);

- a southward shift of relatively small, abundant southerly species with limited occupancy and a northern range boundary in the North Sea (e.g. scaldfish, solenette, bib, sole, and lesser spotted dogfish).

The southward shift of warm-tolerant species in the North Sea is consistent with climate change acting through:

- the warming and increasing availability of shallow habitats in the southern North Sea;

- the NAO-linked inflows of warm water into the northeastern North Sea.

The species demonstrating an expected response in distribution or abundance are summarized in Table 3.3.2.

In some cases, it is apparent that warming has meant that species once considered strays have become much more common. In other cases, warming has improved recruitment for some species, thus creating a shift in the apparent range of the species, although not necessarily a change in individual movement.

The warming in the 1980s also ended the period of high recruitment of several gadoids in the North Sea, such as cod and haddock. This "gadoid outburst" coincided with the cool period in the 1960s and 1970s.

3.3.7 Highlights of observations by species: case studies

Six species were selected to illustrate a variety of patterns in spatial distribution in the North Sea between two periods: 1977–1989 and 2000–2005. The distribution of each species was mapped using data from the International Bottom Trawl Survey (IBTS) and the Norwegian survey. Data from Quarter 1 (January–March) were used for this analysis, because it was the most consistently surveyed period. The survey coverage was standardized by removing any areas not surveyed in either of the two periods (the overall area covering 524 400 km^2). The maps from the two periods for Quarter 1 were overlaid, and density at all locations was compared. Differences in density were classified to 12 levels (12 equal areas on the map) in a matrix model (spatial modelling in SPANS, Geomatica). These consisted of six areas of varying degree of change in density, where density in the first period was higher, and six areas where density was lower. The resulting reclassified map illustrated where and to what degree the density of fish had changed between the two periods.

3.3.7.1 Atlantic cod (*Gadus morhua*)

A Boreal species of prime commercial significance, the cod is among the top predators inhabiting the northern temperate and cold waters of the Atlantic. This species has decreased significantly in the North Sea between 1977–1989 and 2000–2005 (Figure 3.3.1). The reduction in density was highest in the southeast, along the Dutch coast, where density decreased by a factor of approximately 100, whereas a limited increase was observed along the northeastern fringe. An increase in density was observed over 11% of the survey area and a decrease over 87% of the survey area. Within the North Sea, a northward shift in the mean latitudinal distribution of cod has occurred, but there is much controversy as to the causes. Causes could include: active migration (now considered unlikely), higher fishing mortality in the south, local differences in recruitment, or a mixture of this and other causes (Engelhard *et al.*, 2008a). Hedger *et al.* (2004) demonstrated that the Atlantic cod in the North Sea was found in deeper water during 1990–1999, compared with 1980–1989, but its distribution with respect to temperature was unchanged.

Table 3.3.2.
List of species that showed an expected response to increases in water temperature in OSPAR Regions I–IV.

Common name	Scientific name	Association	OSPAR region			
			I	II	III	IV
Twaite shad	*Alosa fallax*	Lusitanian	+			
Wolffish	*Anarhichas lupus*	Boreal		+		
Scaldfish	*Arnoglossus laterna*	Lusitanian		+		
Garfish	*Belone belone*	Lusitanian	+			
Solenette	*Buglossidium luteum*	Lusitanian		+		
Dragonet	*Callionymus* spp.	Lusitanian		+		
Boarfish	*Capros aper*	Lusitanian		+	+	
European herring	*Clupea harengus*	Boreal	+		+	
Anchovy	*Engraulis encrasicolus*	Lusitanian		+	+	
Snake pipefish	*Entelurus aequoreus*	Lusitanian	+			
Grey gurnard	*Eutrigla gurnardus*	Lusitanian		+		
Cod	*Gadus morhua*	Boreal		+		
Lesser African threadfin	*Galeoides decadactylus*	African				+
Witch	*Glyptocephalus cynoglossus*	Boreal		+		
Long-rough dab	*Hippoglossoides platessoides*	Boreal		+		
Megrim	*Lepidorhombus whiffiagonis*	Lusitanian		+		
Dab	*Limanda limanda*	Boreal		+		
Anglerfish	*Lophius piscatorius*	Lusitanian		+		
Haddock	*Melanogrammus aeglefinus*	Boreal	+	+		
Whiting	*Merlangius merlangus*	Lusitanian		+		
Hake	*Merluccius merluccius*	Lusitanian		+	+	
Blue whiting	*Micromesistius potassou*	Atlantic		+		
Lemon sole	*Microstomus kitt*	Boreal		+		
Common ling	*Molva molva*	Boreal		+		
Red mullet	*Mullus surmulletus*	Lusitanian		+	+	+
Sea lamprey	*Petromyson marinus*	Boreal	+			
Greater forkbeard	*Phycis blennoides*	Lusitanian	+			
Plaice	*Pleuronectes platessa*	Boreal		+		
Saithe	*Pollachius virens*	Boreal	+	+	+	
Thornback ray	*Raja clavata*	Lusitanian			+	
Cuckoo ray	*Raja naevus*	Lusitanian		+		
Four-bearded rockling	*Rhinonemus cimbrius*	Boreal		+		
Pilchard	*Sardina pilchardus*	Lusitanian			+	
Mackerel	*Scomber scombrus*	Atlantic	+			
Lesser spotted dogfish	*Scyliorhinus canicula*	Lusitanian		+	+	+
Common sole	*Solea vulgaris*	Lusitanian		+	+	
Sprat	*Sprattus sprattus*	Lusitanian		+	+	+
Spurdog	*Squalus acanthias*	Boreal	+	+		
Horse mackerel	*Trachurus trachurus*	Lusitanian			+	
Norway pout	*Trisopterus esmarki*	Boreal		+		
Bib	*Trisopterus luscus*	Lusitanian		+	+	
Poor cod	*Trisopterus minutus*	Lusitanian		+		
John Dory	*Zeus faber*	Lusitanian		+	+	+

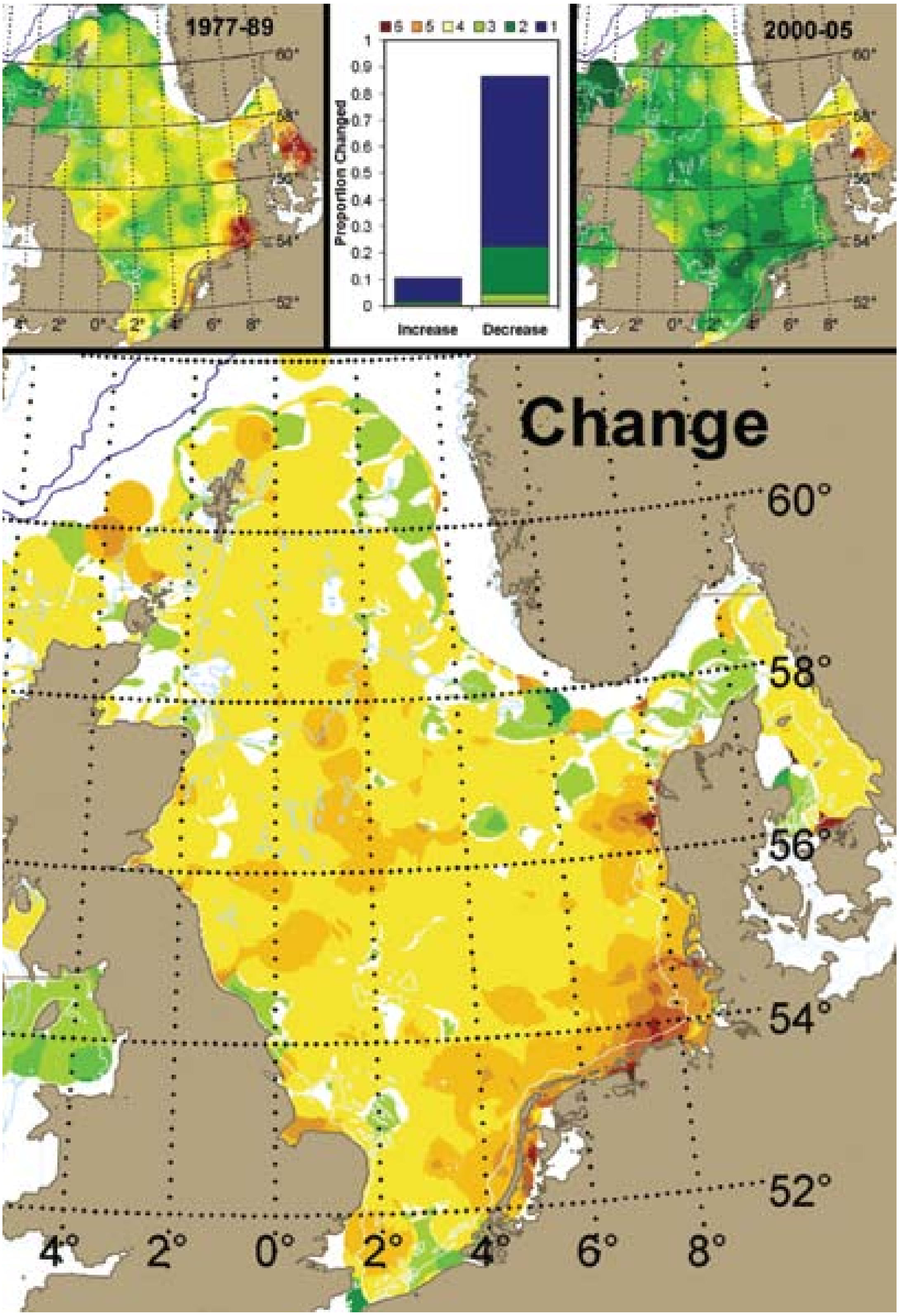


Figure 3.3.1.
Changes in the distribution of Atlantic cod (Gadus morhua) between 1977–1989 and 2000–2005 in the North Sea, Quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and the upper right panel shows distribution in 2000–2005. The lower panel shows the change in distribution between the two periods; blue–green colours indicate an increase in density, with dark colours indicating the largest change, and yellow–red colours indicate a decrease in density between the two periods, with red indicating the largest changes. The graph (upper centre panel) shows the proportion of the total survey area where an increase and decrease occurred, broken down by degree of increase or decrease (categories 1–6).

3.3.7.2 Anglerfish (*Lophius piscatorius*)

The monkfish, or anglerfish, is a Lusitanian species that increased in density in the northern North Sea, whereas densities remained largely unchanged in the southern North Sea (Figure 3.3.2). Over the past two decades, an increase in density was observed over 45% of the survey area and a decrease over 18% of the survey area.

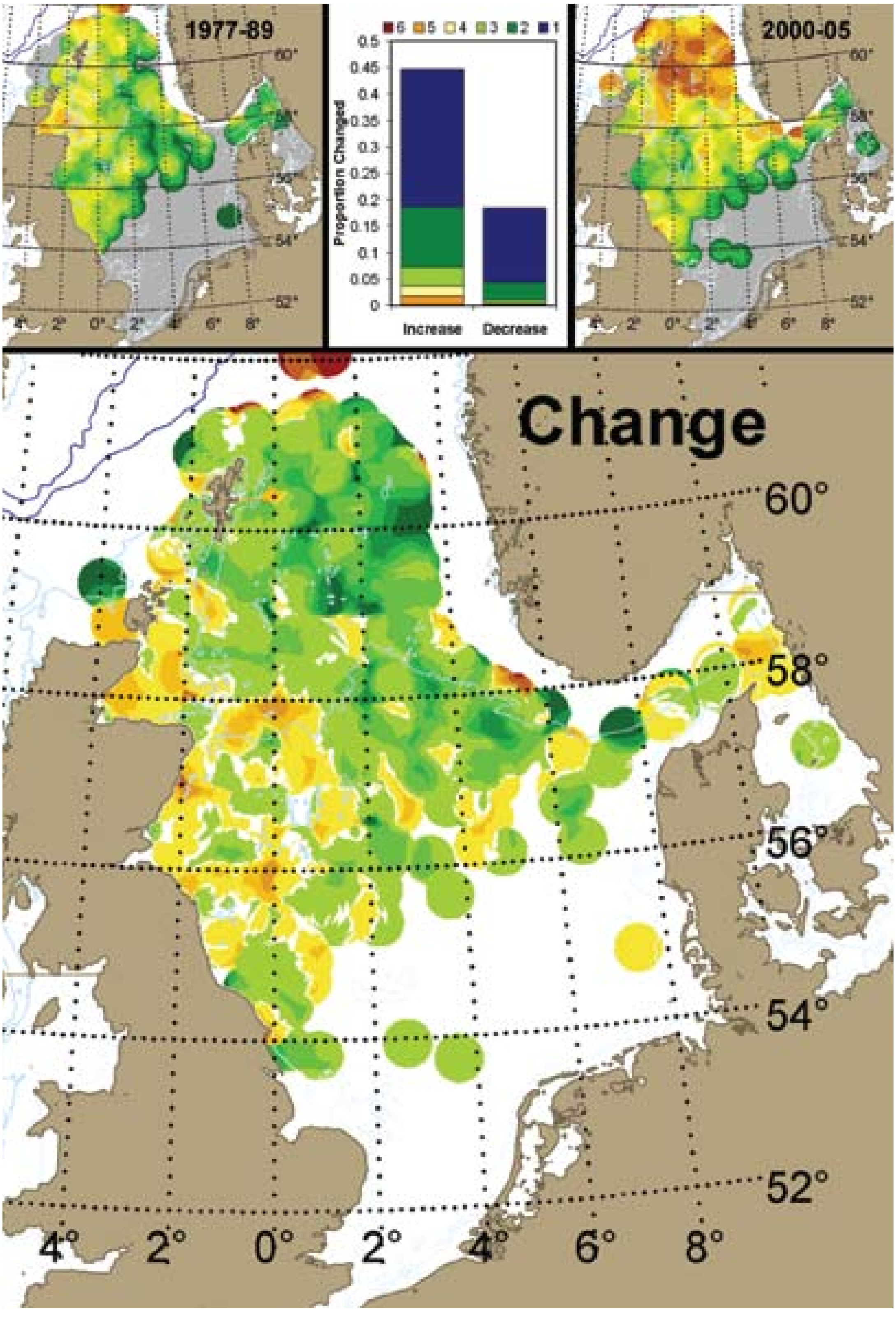


Figure 3.3.2.
Changes in distribution of anglerfish (Lophius piscatorius) *between 1977–1989 and 2000–2005 in the North Sea, Quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and the upper right panel shows distribution in 2000–2005. The lower panel shows the change in distribution between the two periods; blue–green colours indicate an increase in density, with dark colours indicating the largest change, and yellow–red colours indicate a decrease in density between the two periods, with red indicating the largest changes. The graph (upper centre panel) shows the proportion of the total survey area where an increase and decrease occurred, broken down by degree of increase or decrease (categories 1–6).*

3.3.7.3 Haddock (*Melanogrammus aeglefinus*)

The haddock is a Boreal species that decreased in density in the southern half of the North Sea, while slightly increasing in the Skagerrak and central North Sea (Figure 3.3.3). In the northern half of the North Sea, where haddock concentrate, density remained largely unchanged. Haddock densities have increased more strongly in Arctic waters. A decrease in density was observed over 39% of the survey area and an increase over 25% of the survey area. In general, the spatial change for haddock occurred only where density was low and thus had little impact on the overall abundance of this species.

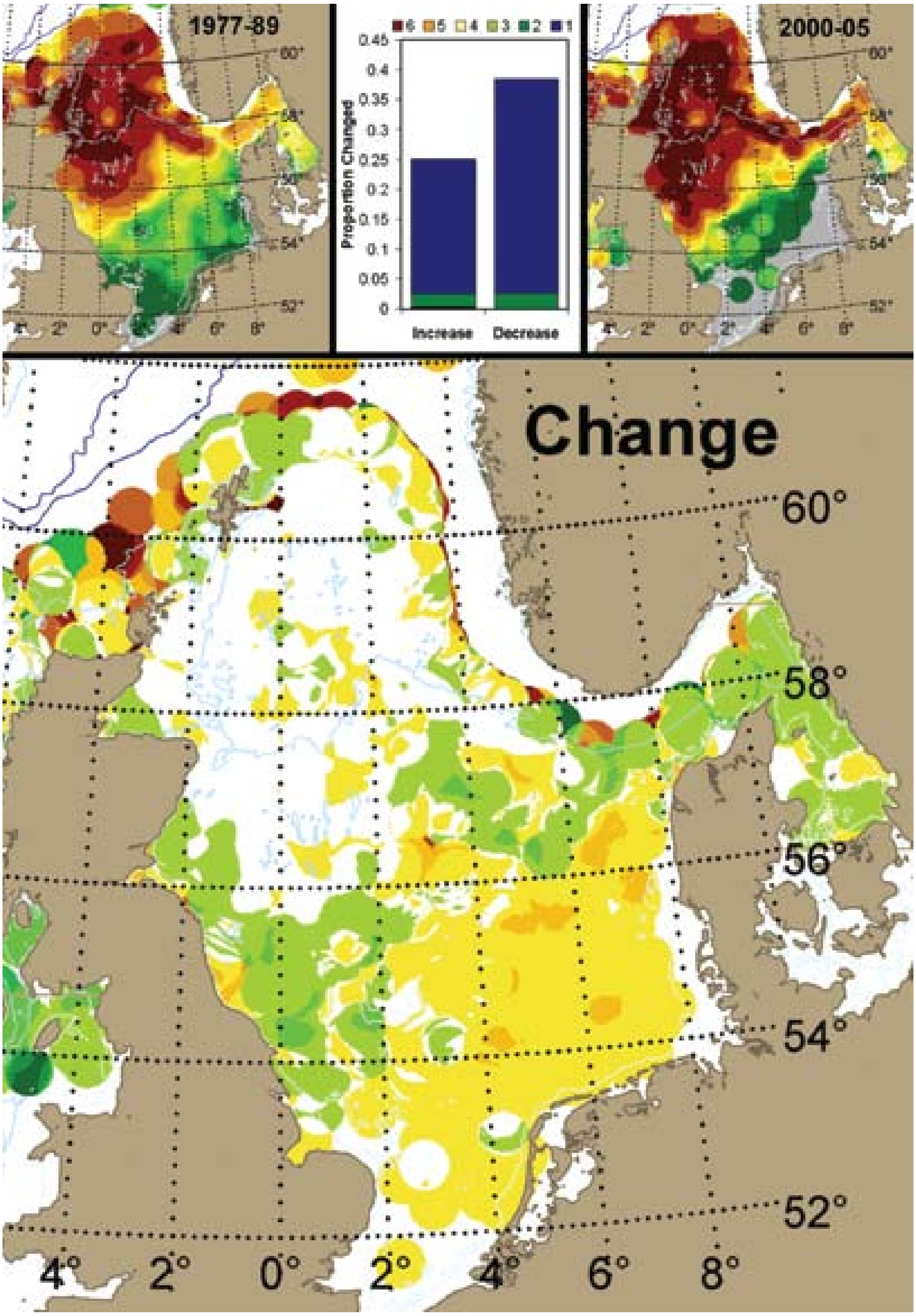
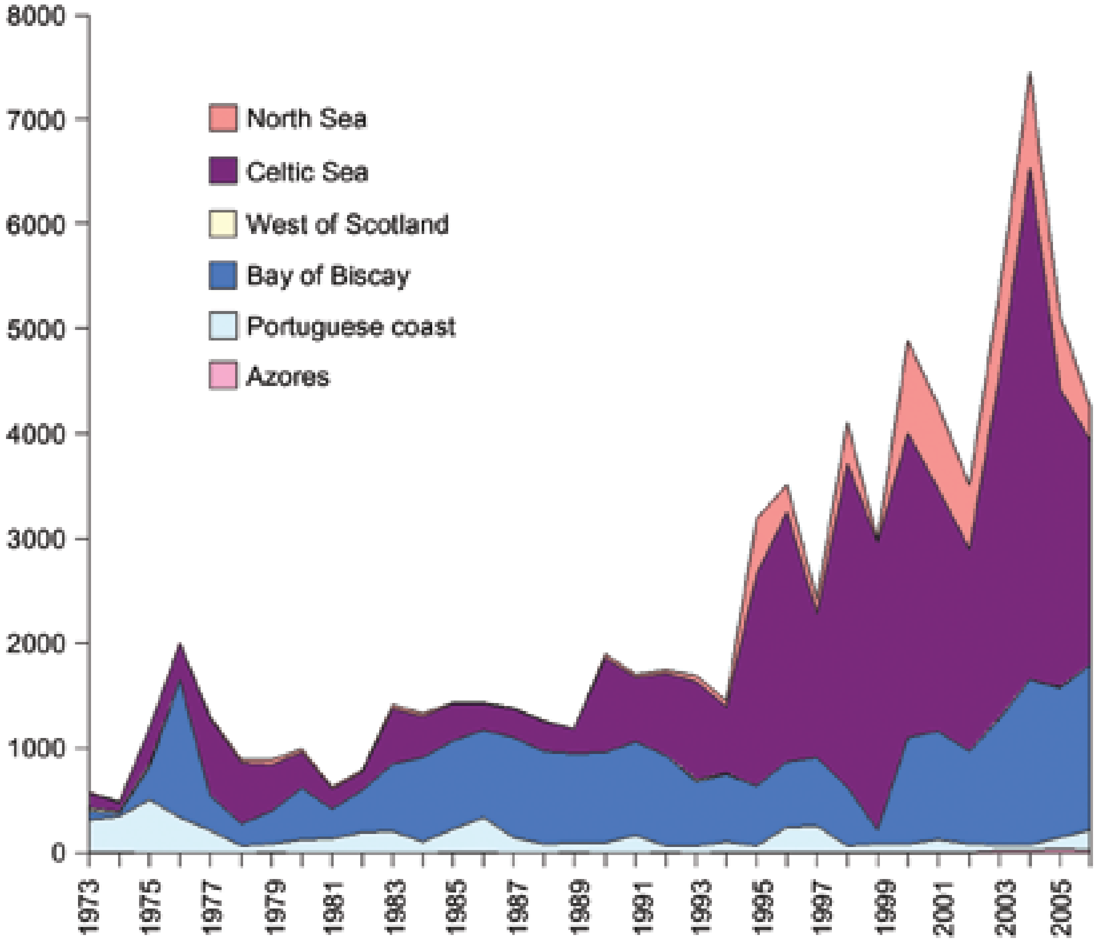


Figure 3.3.3.
*Changes in distribution of haddock (*Melanogrammus aeglefinus*) between 1977–1989 and 2000–2005 in the North Sea, Quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and the upper right panel shows distribution in 2000–2005. The lower panel shows change in distribution between the two periods; blue–green colours indicate an increase in density, with dark colours indicating the largest change, and yellow–red colours indicate a decrease in density between the two periods, with red indicating the largest changes. The graph (upper centre panel) shows the proportion of the total survey area where an increase and decrease occurred, broken down by degree of increase or decrease (categories 1–6).*

3.3.7.4 Red mullet (*Mullus surmuletus*)

The red mullet is a Lusitanian species. Its distribution extends northwards into coastal waters off Norway, northern Scotland, and to the Faroe Islands, southwards to the Strait of Gibraltar and into the Mediterranean and Black seas, and also along the coast of northwest Africa to Senegal and the Canary Islands. Most global red mullet landings are taken from the Mediterranean and Black seas, with a comparatively smaller fraction being taken from the Atlantic Ocean. In the Atlantic, landings before 1975 were mainly from the Spanish coasts and in the Bay of Biscay. Since the 1990s, landings have increased, particularly from the Celtic Sea (Figure 3.3.4).

Figure 3.3.4.
Northeast Atlantic red mullet: trends in total landings (t) by fishing region. Data from ICES Fisheries Statistics.



The very marked increases in landings of red mullet in recent years may be partly explained by a northward shift in distribution, or by increased abundance in northerly parts of the distribution range. However, more targeted fishing in recent years is likely to have contributed significantly to the increased landings.

Changes between surveys revealed that red mullet increased (48% of area surveyed) or remained as abundant as previously in the North Sea. It did not appear in surveys before 1989 (Figure 3.3.5). It has been suggested that the North Sea population migrates northwards in winter when water temperatures there are higher than in the southern North Sea (Beare *et al.*, 2005).

The combination of the high market value of the species, its potentially increasing presence in northern parts of its distribution range in response to warming climate (Engelhard *et al.*, 2008b), and the likelihood of a more targeted fishery for the species in the future, make red mullet a relevant case study in the context of climate change and fishery management. The species has a relatively high growth rate and a planktonic egg/larvae stage, which could enhance its ability to respond rapidly to climate warming by colonizing new habitats. Close monitoring of the population dynamics of this species may facilitate the improvement of recruitment models, including temperature effects in relation to habitat connectivity.

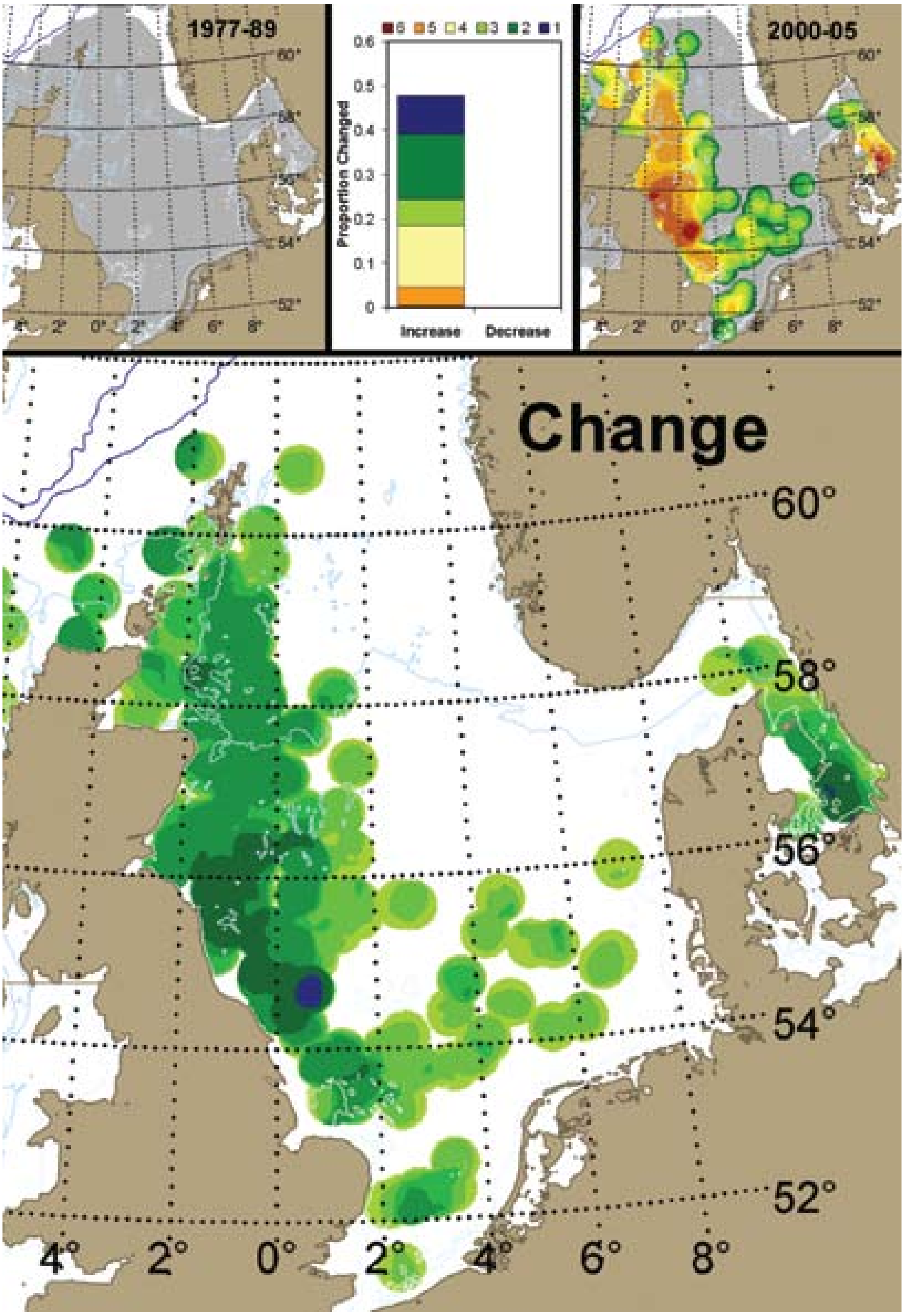


Figure 3.3.5.
Changes in distribution of red mullet (Mullus surmuletus) between 1977–1989 and 2000–2005 in the North Sea, Quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and the upper right panel shows distribution in 2000–2005. The lower panel shows the change in distribution between the two periods; blue–green colours indicate an increase in density, with dark colours indicating the largest change, and yellow–red colours indicate a decrease in density between the two periods, with red indicating the largest changes. The graph (upper centre panel) shows the proportion of the total survey area where an increase and decrease occurred, broken down by degree of increase or decrease (categories 1–6).

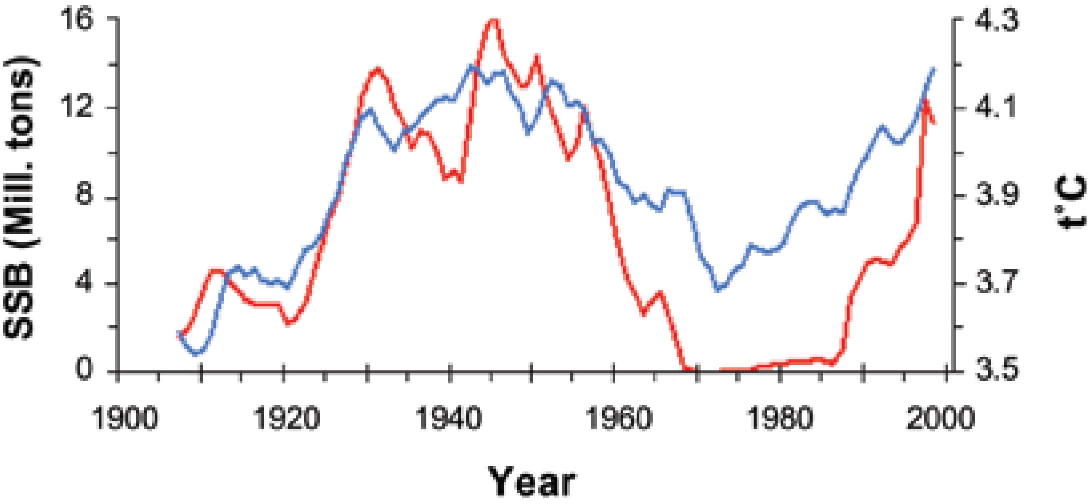
3.3.7.5 Herring (*Clupea harengus*)

The Atlantic herring is a pelagic, ocean- and coastal-dwelling species, covering a depth range of 0–200 m and occupying the temperate zones in the Eastern Atlantic, Baltic Sea, and the Western Atlantic. In recent years, herring has been between the third and the fifth largest fishery in the world (FAO statistics).

The distribution of feeding shoals of herring is correlated with zooplankton abundance and is influenced by the Atlantic inflow. In years when the peak *Calanus* abundance is farther north, herring catches are also farther north. Variations in the distribution of North Sea herring are driven by changes in stock size, zooplankton production, and variability in the Atlantic inflow by the Fair Isle Current, but the interaction of year-class strength and environmental signals is difficult to interpret. The variability in productivity and distribution of Norwegian spring-spawning herring appears to exhibit patterns that may be associated with climatic cycles such as the AMO (Toresen and Østvedt, 2000). The collapse of the herring stock in the 1960s (Figure 3.3.6) can be ascribed to a combined effect of overfishing and deterioration of environmental conditions (temperature). It is unclear to what degree and by which mechanism temperature is associated with recruitment.

Herring showed little change in distribution between 1977–1989 and 2000–2005 (Figure 3.3.7). Although change in the form of increase and decrease occurred over a substantial proportion of the area surveyed, the degree of change in density was minor over most (98%) of the area. Thus, there was no significant shift in the distribution of herring between periods.

Figure 3.3.6.
Variations in the spawning-stock biomass of Norwegian spring-spawning herring (red line) and sea temperature (blue line). The stock collapse in the 1960s was a combined effect of the decrease in sea temperature and high fishing pressure (from Toresen and Østvedt, 2000).



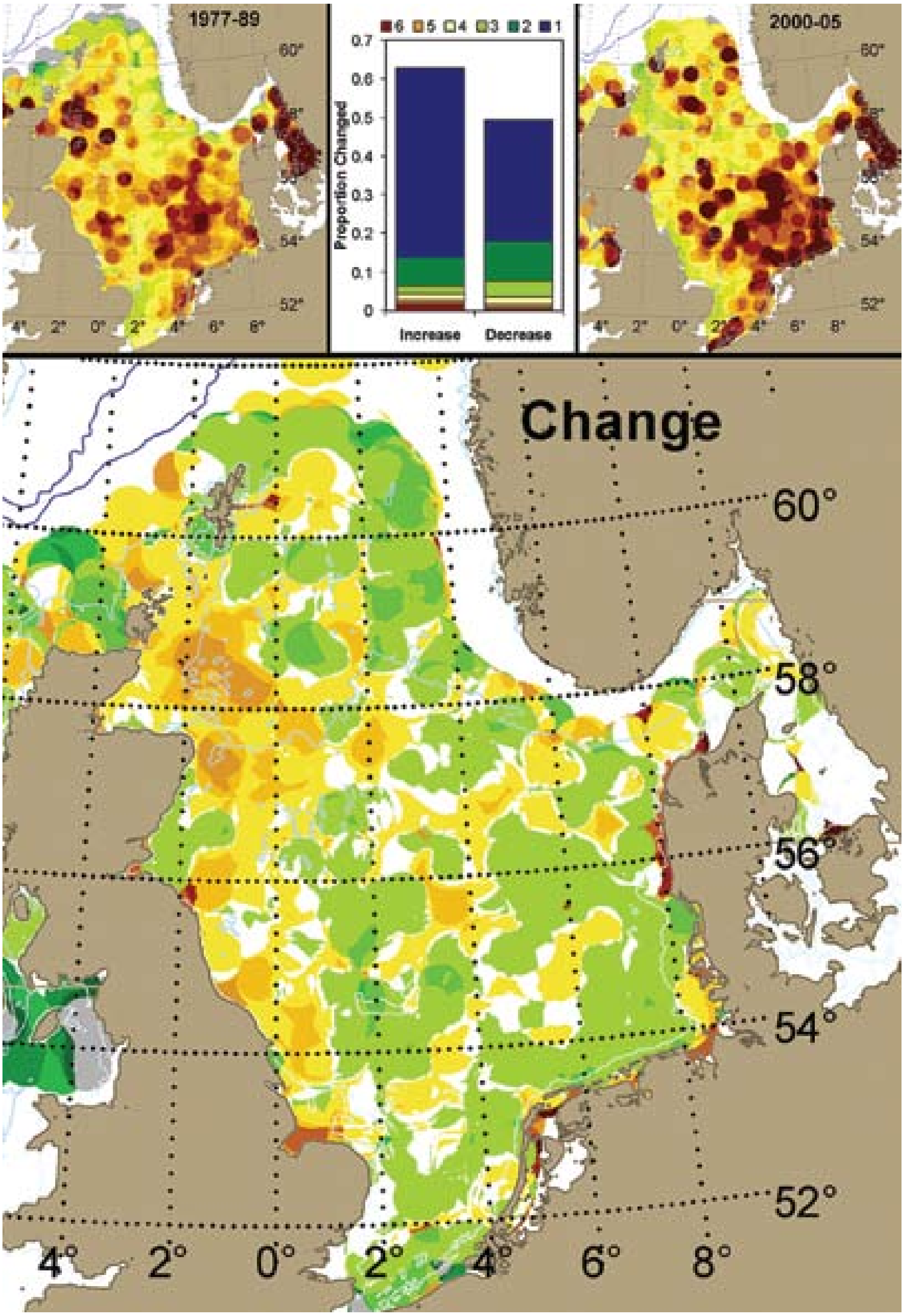


Figure 3.3.7.
Changes in distribution of herring (Clupea harengus) between 1977–1989 and 2000–2005 in the North Sea, Quarter 1. The upper left panel shows distribution in the initial period (1977–1989) and the upper right panel shows distribution in 2000–2005. The lower panel shows the change in distribution between the two periods; blue–green colours indicate an increase in density, with dark colours indicating the largest change, and yellow–red colours indicate a decrease in density between the two periods, with red indicating the largest changes. The graph (upper centre panel) shows the proportion of the total survey area where an increase and decrease occurred, broken down by degree of increase or decrease (categories 1–6). Map courtesy of D. Kulka.

3.3.7.6 Anchovy (*Engraulis encrasicolus*) in the North Sea

Typically, the anchovy is a species with subtropical affinity (Petitgas, 2008). Survey dataseries confirmed greatly increased densities of anchovy in the North Sea in recent years. In the period 1977–1989, only occasional records of anchovy were made off Britain and in the Skagerrak. The species is currently widely distributed (over almost 80% of the survey area) and fairly densely concentrated over much of the North Sea, except at the most northerly and westerly extents. An increase in density was observed over 75% of the survey area and a decrease over only 1% of the survey area (Figure 3.3.8).

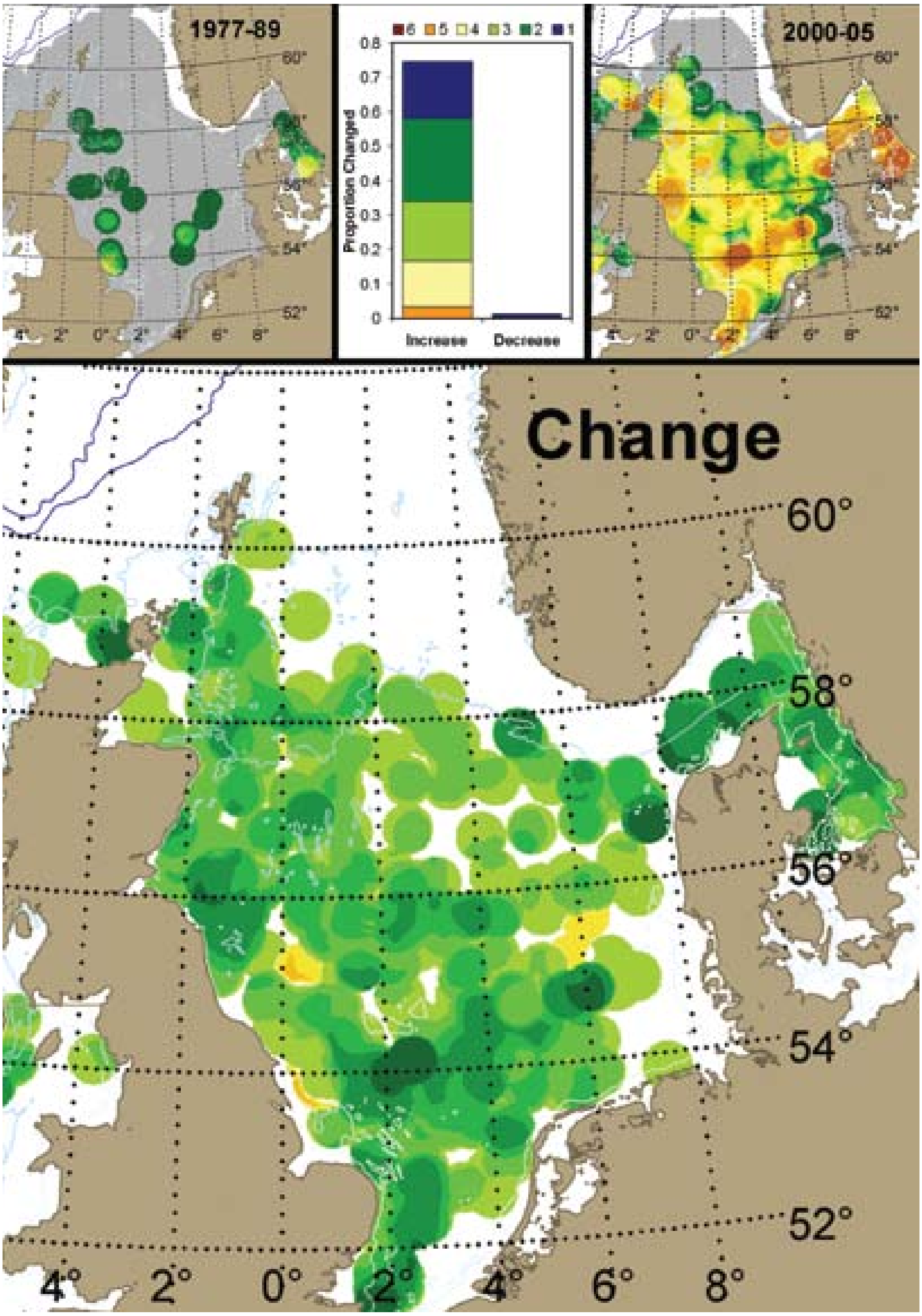


Figure 3.3.8.
*Changes in distribution of anchovy (*Engraulis encrasicolus*) between 1977–1989 and 2000–2005 in the North Sea, Quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and the upper right panel shows distribution in 2000–2005. The lower panel shows the change in distribution between the two periods; blue–green colours indicate an increase in density, with dark colours indicating the largest change, and yellow–red colours indicate a decrease in density between the two periods, with red indicating the largest changes. The graph (upper centre panel) shows the proportion of the total survey area where an increase and decrease occurred, broken down by degree of increase or decrease (categories 1–6).*

3.4 Seabirds

3.4.1 Data sources and related information

Data and conclusions were extracted from peer-reviewed publications and from summaries produced for reports of the ICES Working Group on Seabird Ecology (ICES, 2007c, 2008d).

3.4.2 Main conclusions

The response of seabirds to climate change is generally mediated through trophic effects. Most scientific data refer to analyses of variation in condition factors, such as breeding success and annual survival. Although these factors are expected to be reflected in the population dynamics of the various seabird species, there is little supporting quantitative evidence owing to the scarcity of long-term demographic data. Hence, the evidence base for impacts of climate change on the abundance and distribution of seabird species is lacking, although some conclusions can be inferred.

3.4.3 Highlights of published knowledge

3.4.3.1 Atlantic puffin (*Fratercula arctica*)

At the northern fringe of the latitudinal range, the fledging success of Atlantic puffins at Røst, northern Norway, is principally governed by the availability and size-at-age of young-of-the-year herring, which is the main food source of the chicks (Durant *et al*., 2003). Interannual variation in the growth rate of larval and juvenile herring, and recruitment to the herring stock, are positively correlated with the sea temperature of the Norwegian Coastal Current (Toresen and Østvedt, 2000; Sætre *et al*., 2002). A succession of warm years and repeated breeding failures has coincided with a decrease in population size over several decades (Anker-Nilssen, 1992). However, fledging success does not in itself explain the rate of change in population numbers from year to year (Figure 3.4.1), which must reflect the cumulative effect of a number of factors, including, for example, variation in immature survival of different cohorts (Anker-Nilssen and Aarvak, 2006).

In contrast, Atlantic puffins in the North Sea, at the southern fringe of their distribution, feed their chicks mainly on sandeels. Arnott and Ruxton (2002) found a negative correlation between recruitment of 0-group (first-year) sandeels in the North Sea and sea surface temperature during the sandeel larval period (January–May). Hence, warming would be expected to have a deleterious effect on fledging success of puffins in the North Sea. In this case, however, the relationship between fledging success and temperature may be obscured by the potentially confounding effect of fisheries on sandeel abundance. Overall, there is evidence that the response of the Atlantic puffin to warming is probably in opposite directions at the northern and southern limits of the latitudinal range (Harris *et al*., 2005).

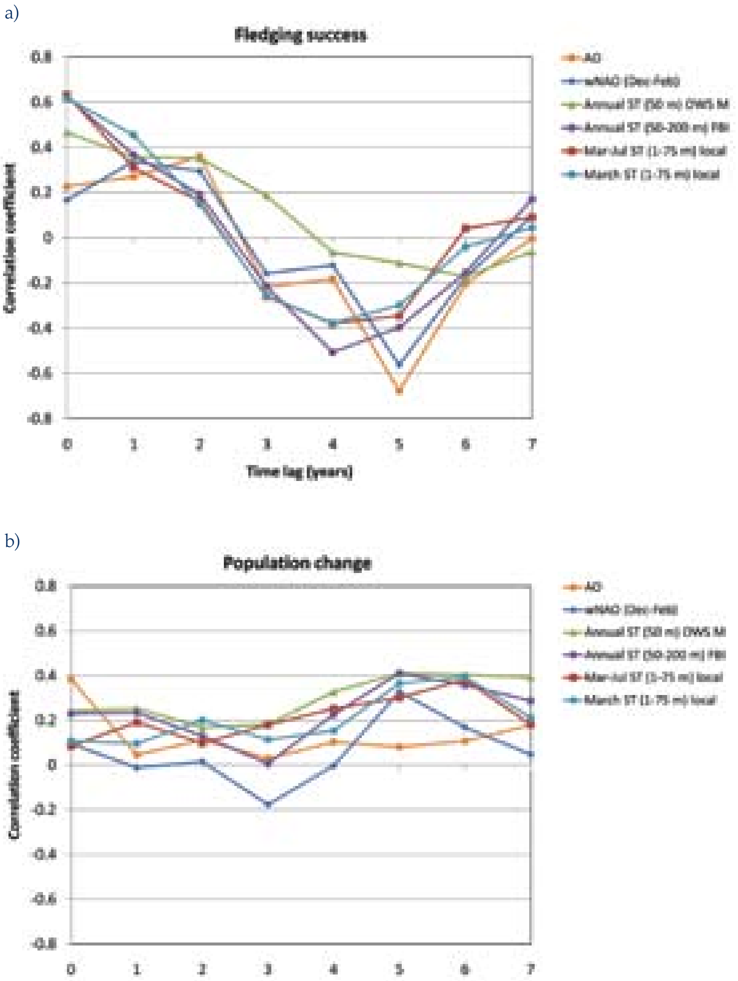


Figure 3.4.1.
Degree of correlation between a selection of climatic variables and (a) the fledging success and (b) the $\log_{normal}$ *-transformed change in annual breeding numbers of Atlantic puffins at Røst, northern Norway in the period 1979–2007. To test for indirect effects of trophic relationships and demographic processes, the data for puffin performance were also lagged by 1–7 years. Data provided by ICES WGOH, Svein Østerhus (for Ocean Weather Station Mike, OWS M), Harald Loeng (for Fugløya–Bear Island, FBI), and Anker-Nilssen and Aarvak (2006, and unpublished data).*

3.4.3.2 Black-legged kittiwake (*Rissa tridactyla*)

Frederiksen *et al*. (2004a) examined changes and correlations over time between black-legged kittiwake population parameters in the North Sea, the local sandeel fishery, and environmental factors, and incorporated the results in a deterministic and a stochastic matrix population model. Breeding success was used as an indicator of condition, and condition was a factor of temperature mediated through prey availability.

In a further study, Frederiksen *et al*. (2007) correlated black-legged kittiwake breeding productivity in six areas around the UK and Ireland with sea temperature during the winter prior to breeding. In this case, sea temperature was assumed to be a surrogate for the abundance of young-of-the-year sandeels, which form part of the kittiwake diet. Breeding productivity tended to be higher following cold winters in the Orkney and Shetland areas, but not in other areas. In an across-region comparison, breeding success was higher in regions with colder average winter sea temperatures.

3.4.3.3 Northern fulmar (*Fulmarus glacialis*)

The survival of northern fulmars breeding on Eynhallow, Orkney, UK, was negatively correlated with the winter North Atlantic Oscillation index one year earlier (Grosbois and Thompson, 2005). Thompson and Ollason (2001) investigated the survival/increased population breeding performance over time in fulmar populations, and proposed that warmer conditions favoured increased abundance.

3.4.3.4 Arctic tern (*Sterna paradisaea*)

Møller *et al*. (2006) found that natal and breeding dispersal of the Arctic tern was responsive to temperature conditions.

3.4.3.5 Balearic shearwater (*Puffinus mauretanicus*)

Wynn *et al*. (2007) investigated the distribution of the Balearic shearwater in Northeast Atlantic waters at several sites in OSPAR Regions II and III and concluded that northward range expansion was correlated with rising sea surface temperature (SST). Votier *et al*. (2008) pointed out that other factors unrelated to SST could be involved.

3.4.3.6 Seabird communities in OSPAR Region I

Sandvik *et al*. (2005) investigated the effect of climate on adult survival in five species of North Atlantic seabirds in OSPAR Region I: the common guillemot (*Uria aalge*), Brunnich's guillemot (*Uria lomvia*), razorbill (*Alca torda*), Atlantic puffin (*F. arctica*), and black-legged kittiwake (*R. tridactyla*). Annual survival was related to temperature change mediated through prey availability.

3.4.4 Interpretation and synthesis

Seabirds appear to react to climate change and variability in a variety of ways.

- In some circumstances, a warming trend advances the timing of breeding, whereas in others, it retards it.
- Seabirds demonstrate some flexibility in dealing with climate change in regard to breeding, but they are ultimately constrained because of the finite (and often lengthy) time required to complete the breeding cycle.
- Because they are long-lived, seabirds are often able to "buffer" short-term (<10 years) environmental variability, especially at the population level.
- Seabirds are vulnerable to both spatial and temporal mismatches in prey availability, especially when breeding at fixed colony sites, where there are foraging constraints.

Birds possess strategies to survive short-term variability in the environment (e.g. body fat reserves). Sustained changes in the environment, which result in suboptimal conditions for a seabird species over a prolonged period, result in changes in population dynamics, for example, through a decrease in fecundity and/or survivorship (Ashmole, 1971; Jouventin and Mougin, 1981).

Many factors influence range expansion. Although some changes in distribution have been identified, e.g. changes in breeding distribution in a few species such as the lesser black-backed gull (*Larus fuscus*), it is unclear how changes in hydrodynamics and sea temperature are involved, but they are presumed to be contributing factors (Mitchell *et al*., 2004; Wernham *et al*., 2002).

There is a substantial body of evidence for changes in seabird demography and population dynamics (Table 3.4.1). Theoretical considerations suggest that many of these changes may be caused by climate fluctuations acting through the availability and distribution of food, but it is rarely possible to identify the exact causal mechanisms.

Seabird parameter	Species	Region	Climate variable	Sign of correlation with warming	Sources
Breeding range	Lesser black-backed gull	UK	Sea temperature	Positive	Mitchell *et al.* (2004)
	Northern gannet	UK	Sea temperature	Positive	Mitchell *et al.* (2004)
Non-breeding range	Lesser black-backed gull	UK		Positive	Wernham *et al.* (2002), Mitchell *et al.* (2004)
	Common guillemot	Shetland	Sea temperature, sandeels		Heubeck *et al.* (1991)
Reproductive success	Northern fulmar	Orkney (North Sea)	NAO index	Negative (hatching) Positive (fledging)	Thompson and Ollason (2001)
	Atlantic puffin	Røst (Norwegian Sea)	Sea temperature	Positive	Durant *et al.* (2003)
	Atlantic puffin	Røst (Norwegian Sea)	Salinity	Negative	Durant *et al.* (2006)
	Greater black-backed gull	Newfoundland	Sea temperature	Positive	Regehr and Rodway (1999)
	Herring gull	Newfoundland	Sea temperature	Positive	Regehr and Rodway (1999)
	Black-legged kittiwake	Newfoundland	Sea temperature	Positive	Regehr and Rodway (1999)
	Leach's storm petrel	Newfoundland	Sea temperature	Positive	Regehr and Rodway (1999)
	Black-legged kittiwake	Isle of May (North Sea)	Sea temperature	Negative	Frederiksen *et al.* (2004a)
	Black-legged kittiwake	Six coastal sections of OSPAR Regions II and III	Sea temperature	Negative within two sections. Negative in across -section comparison	Frederiksen *et al.* (2007)
Annual survival	Northern fulmar	Orkney (North Sea)	NAO index	Negative	Grosbois and Thompson (2005)
	Black-legged kittiwake	Isle of May (North Sea)	Sea temperature	Negative	Frederiksen *et al.* (2004a, 2006b)
	Atlantic puffin	North Sea, Irish Sea	Sea temperature	Negative	Harris *et al.* (2005)
	Atlantic puffin	Røst (Norwegian Sea)	Sea temperature	Positive	Harris *et al.* (2005)
	Atlantic puffin	Norway (Barents Sea)	Sea temperature	Negative	Sandvik *et al.*(2005)
	Common guillemot	Norway (Barents Sea)	Sea temperature	Negative	Sandvik *et al.* (2005)
	Black-legged kittiwake	Norway (Barents Sea)	Sea temperature	Positive	Sandvik *et al.* (2005)

Table 3.4.1.
Links between climate change and aspects of seabird condition and behaviour. (Continued on following page)

Seabird parameter	Species	Region	Climate variable	Sign of correlation with warming	Sources
Population change	Common guillemot	Circumpolar	Sea temperature	Increase with moderate cooling of SST	Irons *et al.* (2008)
	Brünnich's guillemot	Circumpolar	Sea temperature	Increase with moderate warming of SST	Irons *et al.* (2008)
	Black-legged kittiwake	Isle of May (North Sea)	Sea temperature	Negative	Frederiksen *et al.* (2004a)
Nesting (laying or hatching) date	Black-legged kittiwake	Isle of May (North Sea)	NAO index	Positive	Frederiksen *et al.* (2004b)
	Common guillemot	Isle of May (North Sea)	NAO index	Positive	Frederiksen *et al.* (2004b)
	Atlantic puffin	St Kilda	Sea temperature	Positive	Harris *et al.* (1998)
	Atlantic puffin	Røst (Norwegian Sea)	NAO winter Index	Negative	Durant *et al.* (2004)
	Common guillemot	Isle of May (North Sea)	Sea temperature	Negative	Harris and Wanless (1988)
	Razorbill	Isle of May (North Sea)	Sea temperature	Negative	Harris and Wanless (1989)
	European shag	Isle of May (North Sea)	Wind	Negative	Aebischer and Wanless (1992)
Fledging date	Common guillemot	Baltic Sea	Air temperature	Negative	Hedgren (1979)
Foraging cost	Common guillemot	Isle of May (North Sea)	Stormy weather	Positive	Finney *et al.* (1999)
	Northern fulmar	Shetland (North Sea)	Wind speed	Negative	Furness and Bryant (1996)

Table 3.4.1.
Links between climate change and aspects of seabird condition and behaviour.

3.5 Marine mammals

3.5.1 Data sources and related information

There is a general lack of reliable baseline information and long-term datasets on the distribution, abundance, and condition of marine mammals within the OSPAR Maritime Area with which to perform formal analyses of the possible effects of climate change (ICES, 2007d, 2008e). The problems are further compounded by the difficulty in studying and censusing small populations. Many of the published reports on trends in abundance and distribution are inconclusive with regard to the causal role of climate change.

3.5.2 Theoretical considerations

Mammals differ from other marine biota in that their mortality rates are governed less by natural predation and more by human activity (hunting and bycatch in commercial fisheries). On the other hand, their low annual reproductive output makes them vulnerable to fluctuations in prey and environmental conditions, which affect breeding success. However, these are buffered by their longevity, so that even sequences of a few years of breeding failure are of lesser consequence for mammals than, for example, in short-lived fish species. This presents problems for statistical analyses that aim at distinguishing between climate dependence and the chronic effects of human-induced habitat loss, prey depletion, or mortality. In particular, there is a heightened requirement for long time-series of observations, and the relevant space–time-scales for integration of environmental data are unclear.

For migratory species, the geographic range may be a response to the distribution of optimal prey and environmental conditions, leading to highly non-linear responses of population size to regional climate. For example, the diminishing extent and duration of sea ice is considered to be an important factor for both resident and seasonal Arctic species, as based on an understanding of their biology, but demonstrating statistical significance from time-series data is difficult (Härkönen *et al*., 1998; Heide-Jørgensen and Lydersen, 1998; Stirling *et al*., 1999).

3.5.3 Case histories

Species whose habitat depends on the extent and duration of ice may demonstrate a disruption in breeding/reproductive output. This is evident in the polar bear (*Ursus maritimus*) and in seal species that depend on fjord or drift ice, namely the ringed seal (*Phoca hispida*), harp seal (*P. groenlandica*), hooded seal (*Cystophora cristata*), and bearded seal (*Erignathus barbatus*; Ferguson *et al*., 2005; Fischbach *et al*., 2007; Regehr *et al*., 2007). Because adult body condition, litter production, and subadult survival all depend on the availability of ice, the long-term effects on population dynamics of diminishing ice coverage are presumed to be considerable.

Other main marine mammal species identified as possible ecological indicators are those more loosely associated with Arctic sea ice and cold temperate to polar seas, such as the beluga (*Delphinapterus leucas*), the narwhal (*Monodon monoceros*), and the bowhead whale (*Balaena mysticetus*).

Species which undertake large-scale migrations, such as the sperm whale (*Physeter macrocephalus*) and baleen whales (Mysticeti), may also be possible indicator species (Learmonth *et al*., 2006; Simmonds and Isaac, 2007), together with those species identified in conservation legislation, for example, the harbour porpoise (*Phocoena phocoena*) and common bottlenose dolphin (*Tursiops truncatus*).

Specific issues identified with the possible indicator species are as follows:

- A decline in reproductive output and body mass of the polar bear (*U. maritimus*) in Svalbard, Norway, between 1988 and 2002, is linked to both large-scale climatic variation (Arctic Oscillation index) and upper trophic level changes in the Arctic marine ecosystem. However, changes could also be the result of an increase in population abundance in the area.

- Within the OSPAR Maritime Area, long-term changes in large-scale distribution in the bottlenose dolphin (*T. truncatus*), common dolphin (*Delphinus delphis*), and white-beaked dolphin (*Lagenorhychus albirostris*) populations over the past 100 years seem to have occurred. These may be a result of changes in SST (and linked with changes in the NAO index).

- Changes have occurred since 1995 in the distribution of the harbour porpoise (*P. phocoena*) in the North Sea and English Channel, although the reasons for the southward shift in its distribution have not been fully investigated (Camphuysen, 2004; Kiszka *et al*., 2004).

Apart from these, no other published studies have found any relationship between climate change and changes in distribution, abundance, or condition within the OSPAR Maritime Area.

Other species in more temperate regimes should demonstrate fairly plastic responses, because they are long-lived and are likely to demonstrate some degree of adaptation to slowly developing change.

In summary:

- Marine mammals that live in close association with Arctic ice and/or in cold temperate to polar seas influenced by Arctic ice will be the most affected by climate change.

- The establishment of Natura 2000 protected sites is required under the EU Habitats Directive (subject to certain conditions), with the aim of conserving both the harbour porpoise (*P. phocoena*) and bottlenose dolphin (*T. truncatus*). Possible changes in distribution of the animals caused by climate change could change the importance of such protected sites for these two species.

- As relative population sizes of many marine mammals are at low levels because of earlier exploitation, they may be more susceptible to climate change (Caswell *et al*., 1999; Green and Pershing, 2004).

- Apart from ice-dependent species, where climate change may demonstrate a disruption to breeding, feeding habitat, and food availability, most other species should demonstrate fairly plastic responses because they are long-lived and likely to demonstrate some degree of adaptation to slowly developing change.

3.6 Invasive species

3.6.1 Data sources and related information

Establishing the absence of a species from an area is, in principle, more difficult than demonstrating its presence, and initial observations of a previously rare or supposedly absent species are usually fragmentary and serendipitous. For this review, data and conclusions were extracted from peer-reviewed publications and from data in the country reports (not all countries reported each year) of the ICES Working Group on Introductions and Transfers of Marine Organisms (ICES, 2007e).

3.6.2 Theoretical considerations

Invasive species are those that have become a nuisance, whereas introduced species are those that are found outside their natural geographic range. Vagrant species are those which are indigenous to a region as a whole, but which spread into previously uncolonized areas as a result of, for example, geographical shifts in temperature conditions corresponding to the tolerance range of the species. These are distinct from introduced species, that is, those which have been transplanted either intentionally or unintentionally (e.g. from ballast water discharges or aquaculture escapes), and which subsequently reproduce and spread in their new location. This section deals only with the introduced species that have been able to establish reproducing populations as a result of warming. The spread of species that are indigenous to the OSPAR Maritime Area is covered in other sections.

The physiological tolerance of species in their native range is often greater than that implied by the range of conditions under which they are normally encountered. Native ranges are often also limited by physical and biological interactions. However, when a species is introduced into a new area, it may face fewer constraints from predators, disease, and competition than in its native region, and is thus free to exploit its full physiological tolerance.

3.6.3 Main conclusions

The list of non-indigenous species in the OSPAR Maritime Area that have now become established (i.e. reproducing in the new location) includes algae (*Codium fragile*, a green alga, and *Sargassum muticum*, a brown alga), molluscs (*Crepidula fornicata*, or slipper limpet, and *Crassostrea gigas*, the Pacific oyster), barnacles (*Megabalanus tintinnalulum, Balanus amphitrite, Solidobalanus fallax, Elminius modestus*), and a bryozoan (*Bugula neritina*).

Two non-indigenous species in the OSPAR Maritime Area seem to be examples of introduced species that have become established as a direct result of increasing temperatures:

- the Pacific oyster (*C. gigas*), which is an escaped aquaculture species;

- a barnacle species (*E. modestus*).

Natural recruitment of *C. gigas* occurs in all areas of Europe, where the species has been introduced for aquaculture purposes. This was unexpected because, at the time of the introduction, temperatures in European waters were lower than in its native areas. Extended reproductive periods are occurring along the Belgian and British coasts, in Dutch and German waters, and along the Swedish west coast, where *C. gigas* appeared after a series of mild winters in the 1990s and early 2000s (Spencer *et al.*, 1994; Reise *et al.*, 2005; Gollasch *et al.*, 2007; Kerckhof *et al.*, 2007). In recent decades, settlements of small numbers of Pacific oysters have been found on the southern and western coasts of Ireland (Boelens *et al.*, 2005).

In the Wadden Sea, *C. gigas* increased considerably in abundance after 2000, causing the partial disappearance of intertidal beds of the blue mussel (*Mytilus edulis*), and at the same time creating new oyster reefs with an approximately equally biodiverse accompanying fauna. This increase in the Pacific oyster correlates strongly with the occurrence of higher than average water temperatures during July–August in these years, which has improved the settlement success of spat (Nehls and Büttger, 2007).

The barnacle *E. modestus* has experienced extended reproductive periods as a result of warmer sea temperatures. Warm winter temperatures appear to favour *E. modestus*, whereas severe weather favours the native *Semibalanus balanoides* (Kerckhof and Cattrijsse, 2001; Kerckhof, 2002; JNCC, 2008; Kerckhof *et al.*, 2007).

4 META-ANALYSIS AND SYNTHESIS

4.1 Interpretation of the meta-analysis

Full details of the meta-analysis are provided in the Annex, including the rationale for the choice of this form of analysis, description of the method, assembly, screening and tabulation of data, setting expected *a priori* changes, and testing these. The Annex also includes a more complete presentation of the data and results than that given in the tables in this section (see Table A3).

The red and yellow cells in Table 4.1.1 show area/taxon groups in which more than half of the changes were in the expected direction. Overall, 223 of the 288 changes in distribution, abundance, or other characteristics (e.g. seasonality) were in the direction expected as a result of effects of climate change (77%). The null hypothesis that changes are equally likely in either direction is rejected (P <0.0001).

OSPAR region	Zooplankton			Benthos		Fish		Seabirds Distribution and abundance	Total	Change in expected direction (%)
	Distribution	Abundance	Other	Distribution	Abundance	Distribution	Abundance			
I	4	1				2	13	7	27	74%
II	3	9	61	40	32	42	15	10	212	77%
III						9	12	3	24	83%
IV	1	4		13		2	5		25	76%
Total	8	14	61	53	32	55	45	20	288	
Change in expected direction (%)	100%	64%	100%	66%	66%	82%	71%	60%	77%	

Table 4.1.1.
Number of cases in which there was a change in distribution, abundance, or other characteristics (e.g. phenology, seasonality). Colour coding represents the percentages of changes that were in the direction expected as a result of effects of climate (red = >75%; yellow = 50–75%, blue = <50%).

OSPAR region	Zooplankton			Benthos		Fish		Seabirds
	Distribution	Abundance	Other	Distribution	Abundance	Distribution	Abundance	Distribution and abundance
I	0	0	0	0	0	0	1	0
II	1	0	7	9	4	1	0	0
III	0	0	0	0	0	9	1	0
IV	1	0	0	6	0	2	17	0

Table 4.1.2.
Number of cases in which there was no change in either direction.

Comparison of the number of cases in Tables 4.1.1 and 4.1.2 shows that cases in which there was a change (in either direction) greatly outnumber cases in which there was no change in either direction. The only instance where the number of cases with no change outnumbered the cases where some change occurred was in fish, in Region IV.

The only area/taxon cells in which less than 50% of the changes were in the expected direction were the zooplankton distribution changes in Region II and the seabird distribution and abundance changes in Region III (the two blue cells in Table 4.1.1).

In the case of fish, the group with the most available information, markedly more than 50% of the changes that were considered informative are in accordance with expectations from climate change. For the records that passed the selection criteria, which can therefore be considered the least biased, between 60% (OSPAR Region IV) and 92% (OSPAR Region III) of the changes in abundance were in agreement with what was expected as a consequence of climate change. For changes in distribution, these percentages varied from 79% (OSPAR Region II) to 100% (OSPAR Regions I and IV). These observations are potentially confounded by fishing effects. On the other hand, a large part of the changes in abundance described are linked directly to species expanding their range and increasing in abundance at their new limit of distribution. The meta-analysis reinforced the evidence that the observed changes are at least partly caused by the changing climate.

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ANNEX: METHODS

Assembly of information

Nine ICES expert groups assembled a large body of information for most of the marine biota in the OSPAR Maritime Area in order to address the request. The subjects covered by the groups and the Uniform Resource Locators (URLs) used to obtain their reports are given in Table A1. The reports represent a major scientific effort by the ICES community and provide a valuable source of information and detail for particular species and the processes affecting their distribution, abundance, and condition in relation to climate change. Consult the expert group reports for further detail.

Expert Group	URL
Working Group on Introductions and Transfers of Marine Organisms (WGITMO)	http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=WGITMO
ICES/GLOBEC Working Group on Life Cycle and Ecology of Small Pelagic Fish (WGLESP)	http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=WGLESP
Working Group on Zooplankton Ecology (WGZE)	http://www.ices.dk/iceswork/wgdetail.asp?wg=WGZE
Benthos Ecology Working Group (BEWG)	http://www.ices.dk/iceswork/wgdetail.asp?wg=BEWG
Working Group on Fish Ecology (WGFE)	http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=WGFE
Working Group on Marine Mammal Ecology (WGMME)	http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=WGMME
Working Group on Oceanic Hydrography (WGOH)	http://www.ices.dk/iceswork/wgdetail.asp?wg=WGOH
Working Group on Seabird Ecology (WGSE)	http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=WGSE
Working Group on Ecosystem Effects of Fishing Activities (WGECO)	http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=WGECO
Study Group on Working Hypotheses Regarding Effects of Climate Change (SGWRECC)	http://www.ices.dk/iceswork/wgdetailacfm.asp?wg=SGWRECC

Table A1.
ICES expert groups and the location of their reports.

Integration by ICES Working Group on Ecosystem Effects of Fishing Activities (WGECO)

WGECO (ICES, 2007f, 2008f) reviewed and integrated the contributions of the expert groups in order to address the request. They adopted a three-step process:

1. assemble and tabulate cases presented by the expert groups;
2. select suitable cases for meta-analysis;
3. carry out meta-analysis.

The criteria for selecting suitable cases for meta-analysis are set out below.

Method

To detect the effects of climate change, the WGECO decided to adopt a method based on that used by the IPCC (2007a). A similar paper, which extends the IPCC analysis, was published in *Nature* (Rosenzweig *et al.*, 2008). The following are the advantages of adopting this form of meta-analysis. It uses a recognized methodology to address the question "How strong is the evidence that changes in distribution, abundance, and condition go beyond normal?":

- It provides a means of summarizing and adding value to the material provided by the expert groups.
- It provides a direct comparison with the IPCC meta-analysis (and greatly increases the amount of marine information beyond what was available to the IPCC).
- It is straightforward and involves little additional computation or statistics.

Further information about the method can be found in ICES (2008f), Rosenzweig *et al.* (2008), and in Chapter 1 of the IPCC report (2007), including the supplementary material available at:

http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter1.pdf

http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter1sm.pdf.

It is necessary to be aware of two potential biases when carrying out meta-analysis:

- "Positive publication or reporting bias" in which results that show a particular type of change are more likely to be transmitted than those that do not.
- Confirmatory bias. which can develop in advice that relies partly on expert judgement, where the expected outcome (e.g. decline in abundance) is based more or less consciously on observed change.

To minimize this risk as far as possible, care was taken to develop expectations of patterns that would be present if oceanographic conditions were a cause of population trends, and to infer the presence and nature of trends from independent information sources provided by different experts. (Note that the scientific literature is actually a web of cross references, so information in one source may have been partly determined by information in an apparently independent source.)

Assembly and tabulation of data for meta-analysis

The information on zooplankton, benthos, fish, and seabirds provided by the expert groups was examined and tabulated. Experts provided information from literature sources that were considered to report scientifically sound studies and from databases that had been subjected to suitable quality control in the collection and handling of data. Long-term studies were particularly sought after and were included where the abundance, distribution, and/or condition of a number of species were monitored in a consistent manner. Long-term studies of individual species were also included. Common patterns of change across a number of species can be particularly informative regarding the role of oceanographic conditions as a driver of ecological change. The information available for most taxa, particularly benthos, was strongly biased towards OSPAR Regions II and IV.

Information tabulated included:

- taxon (usually species, but occasionally a higher group, particularly for plankton and benthos);
- OSPAR region;
- property monitored (abundance, distribution, factor related to condition);

- pattern or nature of the variation observed;
- justification for expected trend;
- correspondence between observed and expected trend or pattern.

In the cases of zooplankton and birds, detailed information on the location (latitude and longitude) was presented. For some fish examples, the start and end dates of the studies were noted. In specific cases, not all of the columns in the tabulation were informative, and only the informative rows are presented in the tables in this Annex. Full tables and additional references are available electronically at:

http://www.ices.dk/committe/acom/comwork/report/2008/Special%20Requests/1.5.5.1b%20Tables.xls

http://www.ices.dk/committe/acom/comwork/report/2008/Special%20Requests/1.5.5.1a%20Additional%20references.pdf.

Each tabulation was purposely as comprehensive as possible in order to provide as large a starting basis as possible for evaluating the evidence of the effects of climate change. However, the tabulations may include cases where the selection of species to report could have been biased and where there could have been reason to suspect that the data would not be informative about the effects of oceanographic and climatic conditions. Therefore, following a review and interpretation of the full tabulation, each dataset was screened to exclude studies where there was likely to be a confirmatory bias, or where the case was otherwise considered likely to be uninformative or misleading.

Selection of cases for meta-analysis

Some of the specific cases assembled from the expert group reports were inappropriate for rigorous evaluation of the strength of evidence of the effects of oceanographic conditions on species and ecosystems in the OSPAR Maritime Area. This does not mean that these cases were not credible or of good quality, but they may have been based on time-series that were too short or lacked some other required feature, such as a clear *a priori* expectation of change. Similarly, it was not possible to include in the synthesis all the information concerning the processes by which climate affects individual species. Hence, all the tabulated cases were subjected to a screening process, and those meeting the following criteria were removed:

- Positive reporting bias – papers or reports that stated that they had only reported species that showed responses to oceanographic conditions. Without knowing the number of species examined and not reported, it is impossible to know how many misses, false alarms, and true negatives might correspond to the number of positive matches that were reported.
- **Confirmatory bias** – cases in which it was clear that the expectation of change arose from the observed changes and was therefore not *a priori.*
- ***A priori* expectation of pattern of change** – cases in which this was not given and could not be decided upon. In some cases, a time-series of a species abundance or range was reported, but there was insufficient independent information to make a biologically justifiable prediction of even first-order effects of climate.
- **Non-climate pressures** – cases in which it was specifically reported that some pressure other than climate was strongly affecting the species or population. These cases risked missing a true effect of climate, because some other pressure was aliasing its potential effects.
- **Duplication** – where different studies reported the same response of a species in the same area, only one record was retained. However, if these studies reported different responses, both were kept in the analysis. Some duplication may have remained through trophic links. Thus, any change in the range of an important forage fish change would be expected to have parallel effects on the range of dependent predators (e.g. large fish, seabirds). As outlined earlier, ICES did not attempt to establish the mechanisms behind the changes observed.

Methods used for meta-analysis

Cases that passed the screening criteria were combined in an integrated meta-analysis, which included all species groups. The null hypothesis was that, for cases that demonstrated a change, the probability that this change was in the direction expected *a priori* (i.e. as a result of change in ocean climate) was the same as the probability that it was in the opposite direction (i.e. 50:50). The cases were divided into those that revealed no change, those that changed in the expected direction, and those that changed in the opposite direction. An example of the resultant numbers and frequencies is shown in Table A2. Thus, for benthos in OSPAR

Region II, nine cases showed no change and 40 showed a change. Of the 40 cases that showed a change, 65% (i.e. 26 cases) were in the expected direction and 14 were in the opposite direction. The null hypothesis was that 50% would be in each direction. The analysis depended on the assumption that the expected change was correct. Changes in the "unexpected" direction could arise because the *a priori* expectation was wrong or incomplete.

OSPAR region	Screened records		
	No change (#)	Change (#)	Expected (%)
II	9	40	65
IV	6	13	69

Table A2.
Occurrences of changes in benthos distribution that were in accordance with what is expected from climate change.

Choice of expected *a priori* change

The selection of expected *a priori* changes attributable to climate was based on information about species range in relation to temperature and other variables. Warming is expected to cause northward shifts in the distribution of species in the OSPAR Maritime Area. The expected change in abundance depends on whether a species is close to the warm or the cold end of its range. At the warm end, an increase in temperature is expected to cause a decline in abundance, whereas at the cold end, an increase in temperature is expected to cause an increase in abundance.

In the case of benthic species, variation in bottom temperatures meant that many of the expected trends were more complex than just "'warm' species increase; 'cold' species decrease". Factors other than temperature were only considered in a few cases when choosing expected *a priori* changes. Residual water currents moving in a particular direction may result in higher immigration rates in that direction. This may confound the expected temperature effects and alter the 50% expectation.

The effects of climate on seabirds are also complex, acting directly and indirectly on different life-history stages. This makes it difficult to give *a priori* expectations of change for use in hypothesis testing, even when the component processes are well known (e.g. the effect of sea surface temperature on abundance of pelagic fish, such as herring and sandeel, which are important in the diet of the Atlantic puffin).

In the case of ice-dependent species of marine mammals, climate change may disrupt breeding and feeding (i.e. negative effect of warming), but increase the productivity of their food supply (i.e. positive effect of warming).

Statistical testing of the null hypothesis

Significance testing for the simple binary categorical analysis was carried out by calculating binomial probabilities.

Data and results

Table A3 includes a complete presentation of the data and results from the meta-analysis.

Numbers that changed

OSPAR region	Zooplankton			Benthos		Fish		Seabirds Distribution and abundance	Total	Change in expected direction (%)
	Distribution	Abundance	Other	Distribution	Abundance	Distribution	Abundance			
I	4	1				2	13	7	27	74%
II	3	9	61	40	32	42	15	10	212	77%
III						9	12	3	24	83%
IV	1	4		13		2	5		25	76%
Total	8	14	61	53	32	55	45	20	288	
Expected change(%)	100%	64%	100%	66%	66%	82%	71%	60%	77%	

Numbers that changed with the expected direction

OSPAR region	Zooplankton			Benthos		Fish		Seabirds	Total	Expected change (%)
	Distribution	Abundance	Other	Distribution	Abundance	Distribution	Abundance	Both		
I	4	1		0	0	2	8	5	20	74%
II	3	4	61	26	21	33	10	6	164	77%
III						8	11	1	20	83%
IV	1	4		9		2	3		19	76%
Total	8	9	61	35	21	45	32	12	223	
Expected change (%)	100%	64%	100%	66%	66%	82%	71%	60%	77%	

Percentage with expected change

OSPAR region	Zooplankton			Benthos		Fish		Seabirds
	Distribution	Abundance	Other	Distribution	Abundance	Distribution	Abundance	Both
I	100	100				100	162	71
II	100	44	100	65	66	79	67	60
III						89	92	33
IV	100	100		69		100	60	
Weighted sum of %	100%	64%	100%	66%	66%	82%	71%	60%

Binomial probability

OSPAR region	Zooplankton			Benthos		Fish		Seabirds
	Distribution	Abundance	Other	Distribution	Abundance	Distribution	Abundance	Both
I	0.06250	0.50000				0.25000	0.15710	0.6406
II	0.12500	0.24609	0.0000	0.02111	0.03004	0.00010	0.09164	0.20508
III						0.01758	0.00293	0.37500
IV	0.50000	0.06250		0.08728		0.25000	0.31250	

Table A3.
Tables of data and results for meta-analysis. Colour coding represents the percentages of changes that were in the direction expected as a result of effects of climate (red = >75%; yellow = 50–75%; blue = <50%).