1.5.5.1 An assessment of the changes in the distribution and abundance of marine species in the OSPAR maritime area in relation to changes in hydrodynamics and sea temperature.

1.   Summary and conclusions

This is a report examining the evidence for the effect of climate change on the distribution and abundance of marine species in the OSPAR Maritime Area. It focuses primarily on effects that may be linked to changes in sea surface temperature.

ICES examined long-term datasets available to scientists working in its expert groups. 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 for all OSPAR Regions. Effects of climate change varied from weak to very strong, particularly when environmental conditions were exceptionally cold or warm.

ICES undertook a meta-analysis that shows 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 or that climate is the only cause, but it is undoubtedly a recognisably important factor in around ¾ 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 and there were none from OSPAR Region V. This could be influenced by the relative availability of suitable datasets in the Regions.

There is no doubt 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, freshwater runoff, evaporation, oxygen concentration, pH, salinity, and nutrient supply. These variables are often interlinked, 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 climate change occurring, current regional sea surface temperatures 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 marine area:

- Fishing: this is the major non-climate anthropogenic factor. Removal of biota and habitat disturbance are two of the most prominent pressures, for fish and benthos, respectively, which have also shown increasing trends over the past few decades. Population sizes and geographic distributions of many marine species reflect responses to those pressures.

- Oceanographic factors: these may be direct (increased or decreased mortality due to temperature, transport to new areas or arrival at different times, etc.) or indirect, mediated, for example, 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 and therefore the effects of oceanographic conditions may be buffered at the population scale and integrated over time even at the scale of the individual.

- Complex life histories: most marine invertebrates and fish have complex life histories, with eggs, larvae, juveniles, and adults often 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 could be different by an order of magnitude, and possibly even in sign.

ICES acknowledges that other factors, such as eutrophication, pollution, diseases, and introduced species, affect the abundance and distribution of species, population, and communities, particularly at the local scale, and that they can interact with climate change and fisheries as drivers of change.

ICES was asked to advise if any observed changes were "beyond what might have been expected from natural variability." As noted above, this type of analysis is very difficult to carry out at the local or regional level for individual species, populations, or even ecosystems. For this reason, ICES chose to undertake a meta-analysis (an analysis that combines the results of several studies that address a common hypothesis). This allowed a combination of a variety of types of information to be used which, despite being individually inconclusive, collectively allowed the request from OSPAR to be more thoroughly addressed.

The meta-analysis methods employed by ICES were based on those used by the International Panel on Climate Change (IPCC, see Technical Annex on methods). It is acknowledged that our assessment suffered from a number of shortcomings. These were mostly the result of unavoidable limitations in the data and resources available to ICES. However, we used objective data extraction methods and cases were screened to minimize bias in selection. The analytical approaches that were adopted were simple and were not based on strong assumptions about the data or the relationships between the indicators of population state and the oceanographic conditions, and ICES considers the results to be reliable.

1.1   Implications

Although ICES has already made a considerable contribution to the extensive scientific literature on species–environment relationships of marine ecosystems, we are still unable to partition causality between oceanographic conditions and other agents for change at the level of the individual taxon. It is likely this will remain the case even with better data and more in-depth analyses. Therefore, the precautionary approach dictates that it is necessary to consider the possibility that species and populations will respond as the climate changes. These responses may be partially or wholly hidden by other factors causing change such as fishing pressure, habitat alteration, etc. Consequently, this should be taken into account as part of planning, risk assessment, and precautionary management. The individual analyses in this report and ancillary documentation are comprehensive enough 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", i.e. a threshold of change that, when it is exceeded by even a small incremental amount, would result in species and even communities undergoing dramatic changes in abundance and distribution. This problem is not likely to be readily answerable for marine ecosystems, even ones 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 that have not yet been 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 to be precautionary in the way we manage human activities in the marine environment. Several actions can contribute to building the necessary precaution into policy and management, and to provide the required scientific support. Science needs to monitor and analyse results in ways that take advantage of spatial and temporal patterns in both hydrographic and species occurrences, and to build consistent time-series and design research programmes aimed at reducing our uncertainty about relationships between oceanography and climate and species and populations, thereby reducing 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 the expected (i) northward shift or deepening of the distribution and (ii) increase in abundance in the northern part and decrease in the southern part of the range. Changes were most prominent in 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 since other factors may be important as well, in particular 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, and consequently they may be perturbed more strongly by climate 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 to reduce the threat of climate change in marine ecosystems in the OSPAR Maritime Area.

Changes in 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 closed 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 became less effective, in terms of this original objective, since undersized plaice have moved to deeper water outside the protected area (van Keeken *et al.*, 2007).

2   Introduction

ICES was asked by OSPAR 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*

This report is a contribution towards OSPAR JAMP Product BA-3 and includes material that can be included in the Quality Status Report in 2010.

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 regarding the evidence for changes to the earth's climate and effects of those changes on the earth's ecosystem, 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, 2007; Rosenzweig *et al*., 2008), have provided compelling evidence for both a warming of the earth's climate over the past century, and effects of that warming on the earth's ecosystem 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 for information to include in the next QSR will inform the policy and social debate that has followed release of the IPCC Report more specifically with regard to the likelihood and nature of effects to be expected in marine ecosystems in the OSPAR Maritime Area, should the forecasts for continued warming of the planet prove true. It should be noted that the translation of global change to regional scales is complex, as pointed out by IPCC (2007), and the OSPAR request 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 ones 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, ecology of zooplankton, of benthos, of fish, of seabirds, of marine mammals, and of invasive species in assembling relevant information from the OSPAR Maritime Area. The evidence is generally scattered, with most data collected for other purposes, and often not ideal for asking 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, if 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 that address 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, against sufficient flexibility to accommodate 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, in the case of 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:

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

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

This document does not include observations on whole ecosystem changes (e.g. Beaugrand, 2004) as the OSPAR request stresses a species-based approach.

ICES has not tried 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 final step of partitioning causality between oceanographic conditions and other agents for change is likely to remain very hard to complete rigorously for the foreseeable future.

2.1 Geographic terminology

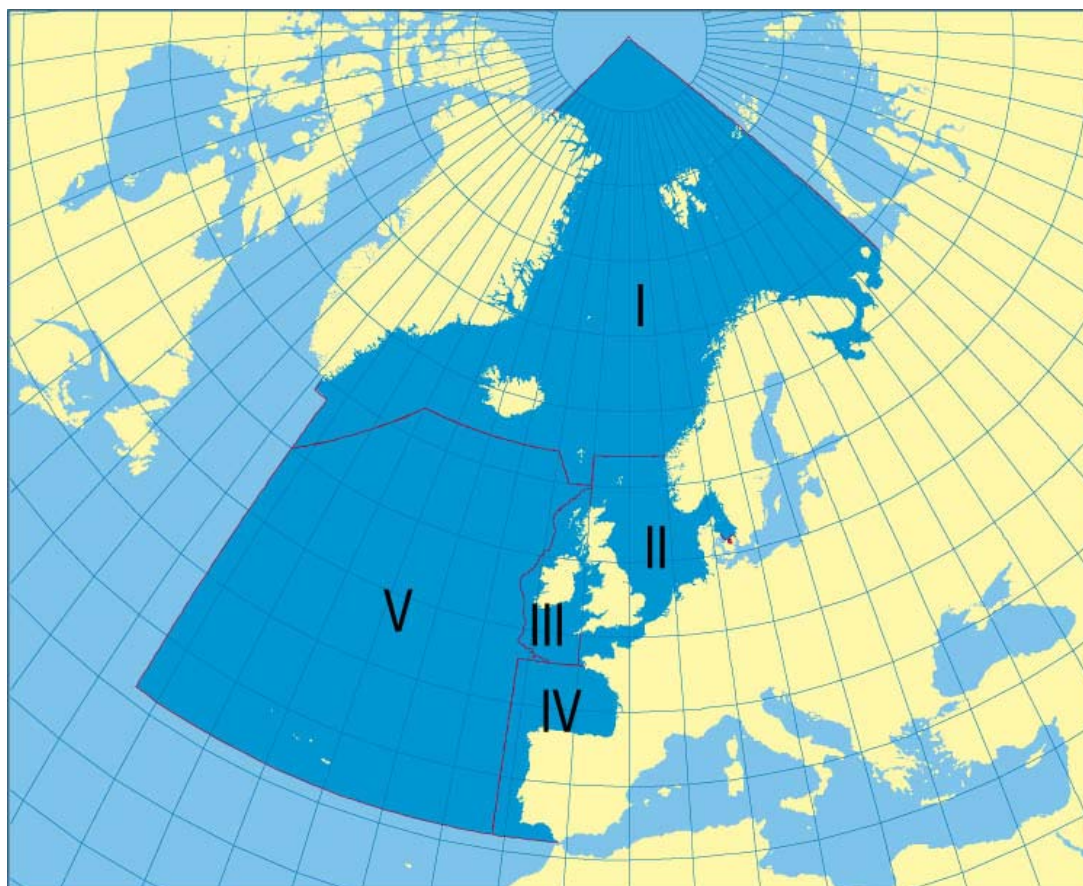In order to aid reading of this document, Figure 2.1.1 shows the OSPAR Regions.

Figure 2.1.1   The OSPAR Regions. I = Arctic; II = Greater North Sea; III = Celtic Seas; IV = Bay of Biscay and western Iberia; V = wider Atlantic.

Figure 2.1.2 shows the biogeographical provinces used in this document for the OSPAR Maritime Area (after Dinter, 2001).
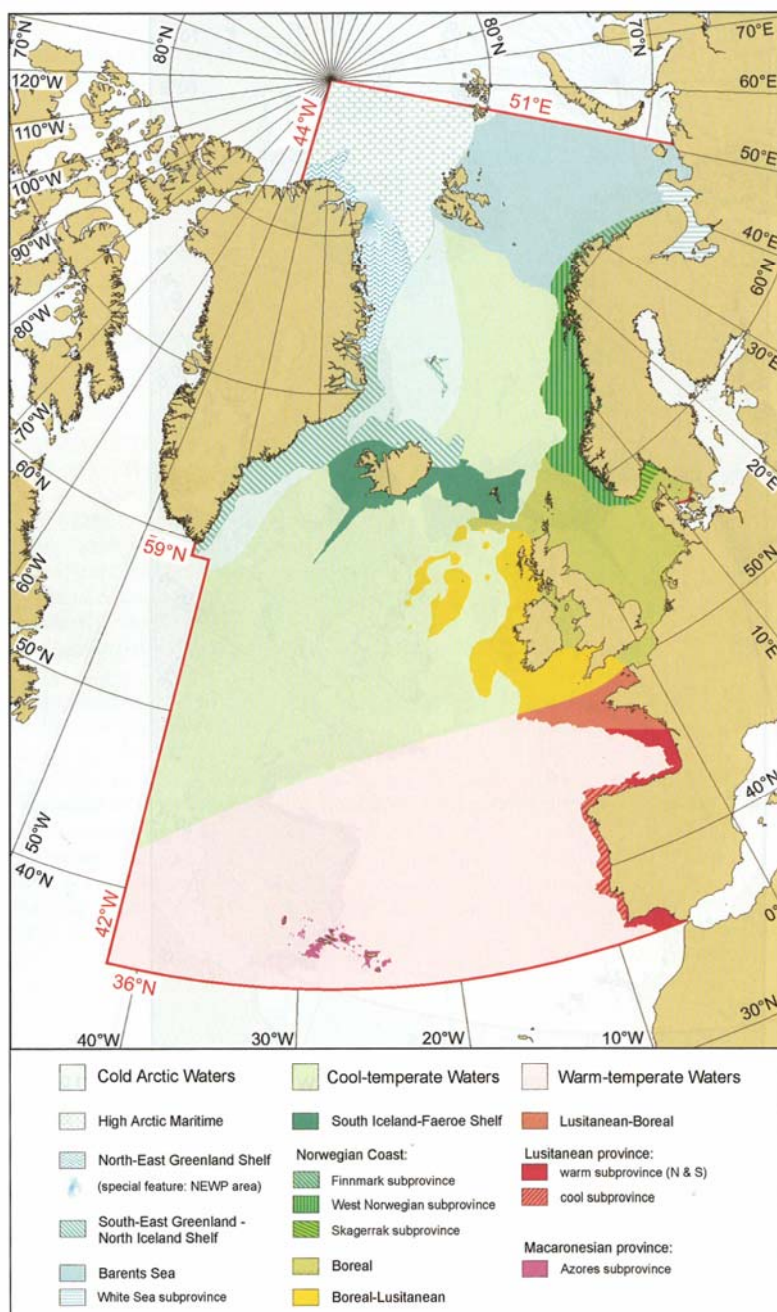
Figure 2.1.2   Biogeographical classification of the benthal and neritopelagial of the shelf and upper continental slope (<1000 m depth), and ice-cover biomes combined with the superordinate holopelagic provinces (<1000 m depth) of the OSPAR Maritime Area (reproduced from Dinter (2001) based on Forbes and Godwin-Austen (1859)).

3   Oceanographic background

3.1   Present situation

Global-scale model simulations to compare 20th century land and ocean surface temperatures with and without anthropogenic greenhouse gasses show a significant divergence from the 1970s onwards (IPCC, 2007; Figure 3.1.1). The simulations including anthropogenic forcing agree well with observations. These results led the IPCC (2007) to state that "most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to 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.
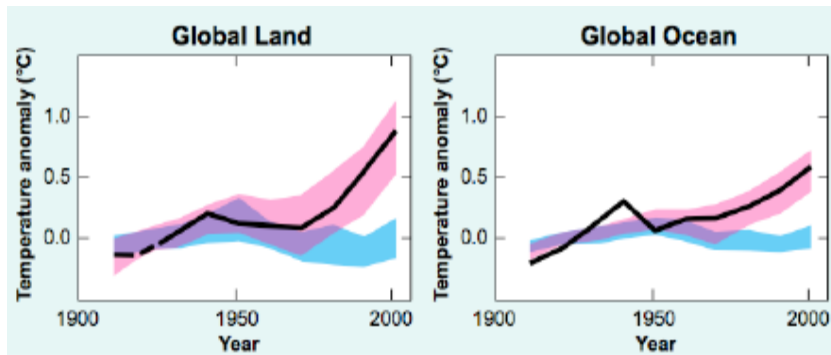
*"MOST OF THE OBSERVED INCREASE IN GLOBALLY AVERAGED TEMPERATURES
SINCE THE MID_20TH CENTURY IS VERY LIKELY DUE TO THE OBSERVED INCREASE
IN ANTHROPOGENIC GREENHOUSE GAS CONCENTRATIONS". IPCC 2007*

Figure 3.1.1   Global land (left) and global ocean (right) decadal average temperatures during the 20th century (black lines) compared to climate model simulation, including anthropogenic forcing (pink shading) and only natural forcing (blue shading) (from Solomon *et al.*, 2007).

Whilst the impact of greenhouse gases on surface temperature is clear at the global scale, the signal at regional scales is complicated. Processes working on the regional and local scale like surface advection patterns, convection, evaporation and precipitation mean that the temperature increase has not been uniform over the planet. Some areas have shown more rapid warming than the global mean, whilst others have experienced cooling (Figure 3.1.2). Moreover, the temperature increase in the ocean has been considerably less than over land (Figure 3.1.1), indicating the large heat capacity of the deep oceans. IPCC (2007) noted that natural temperature variability is larger at the regional 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, both sea and land surface temperatures in the OSPAR Maritime Area have increased from 1995 to 2004 at a rate which is well above the global mean.
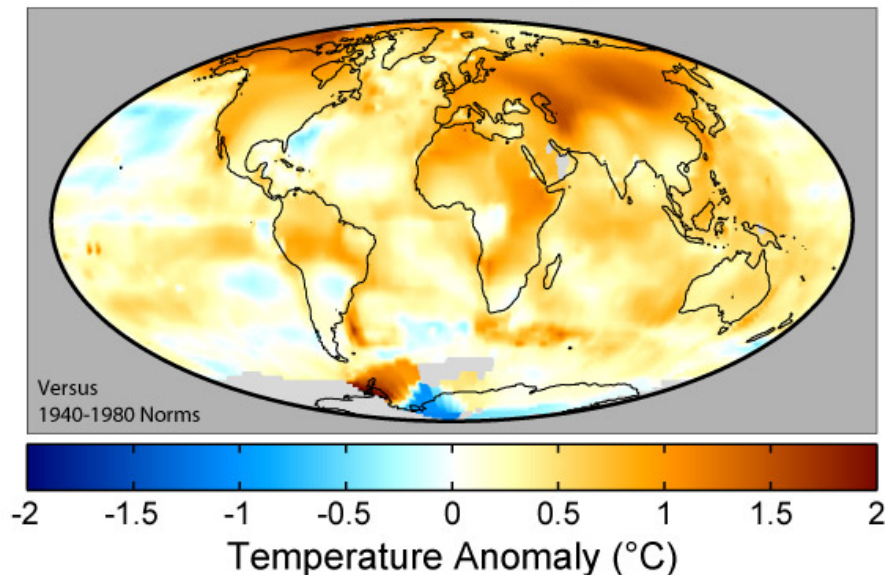

Figure 3.1.2   Regional variation in global temperature change. This plot is based on the NASA GISS Surface Temperature Analysis (GISTEMP), which combines the 2001 GISS land station analysis data set (Hansen *et al.*, 2001) with the Rayner/Reynolds oceanic sea surface temperature data set (Rayner, 2000; Reynolds *et al.*, 2002). The data itself was prepared through the GISTEMP online mapping tool, and the specific dataset used is available here. This data was replotted in a Mollweide projection with a continuous and symmetric colour scale. The smoothing radius is 1200 kilometre, 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).
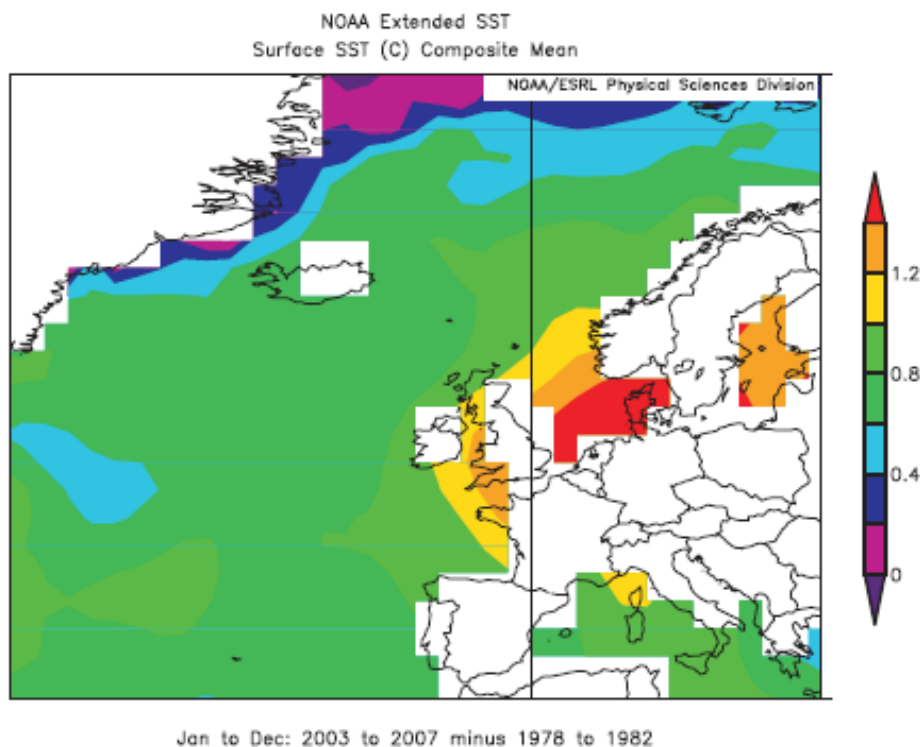
NOAA Extended SST
Surface SST (C) Composite Mean

Jan to Dec: 2003 to 2007 minus 1978 to 1982

Figure 3.1.3   Sea surface temperature (SST), showing the mean of the period 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 show systematic spatial structure at the sub-regional level (Figure 3.1.3). The two longest instrumented time-series of temperature data in the northeast Atlantic (Kola and Faroe–Shetland sections) show strong coherence at time scales and periodicities larger than the decadal scale (Figures 3.1.4 and 3.1.5). 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 3.1.6). The North Atlantic is presently in a positive phase of the AMO.
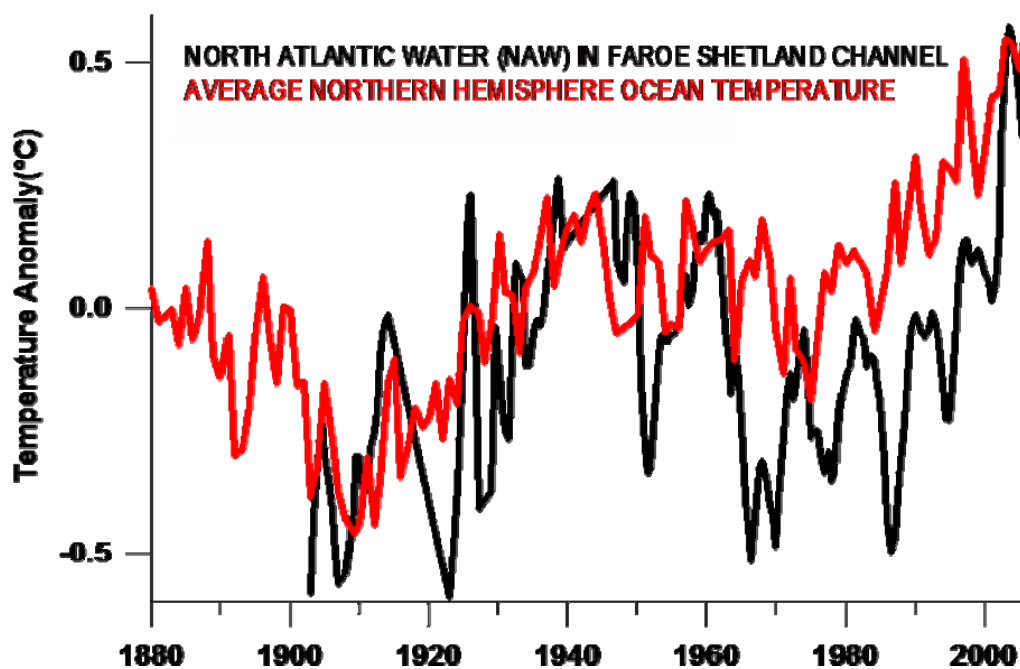

Figure 3.1.4   Temperature anomaly of the Atlantic water masses in the Faroe–Shetland Channel (data source: Fisheries Research Services, Marine Laboratory Aberdeen, Scotland) compared to the ocean temper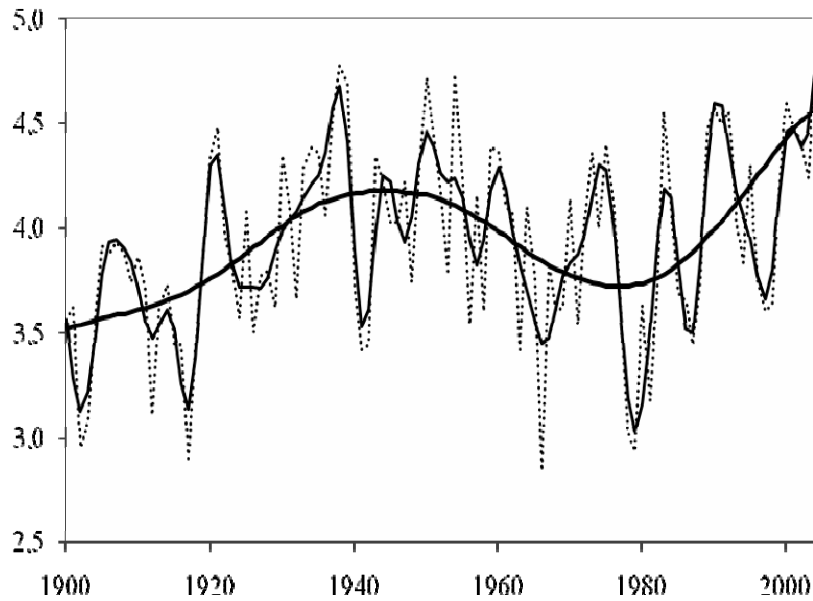ature anomalies of the Northern Hemisphere (data source: http://lwf.ncdc.noaa.gov/oa/climate/research/anomalies/anomalies.html)

Figure 3.1.5   Temperature (°C) of the Atlantic water masses at the Kola Section in the Barents Sea (Source: PINRO, Murmansk). Dotted line: Annual mean. Thick lines: 3-year moving average and a 30-year low-pass filter (from Sundby and Nakken, 2008).
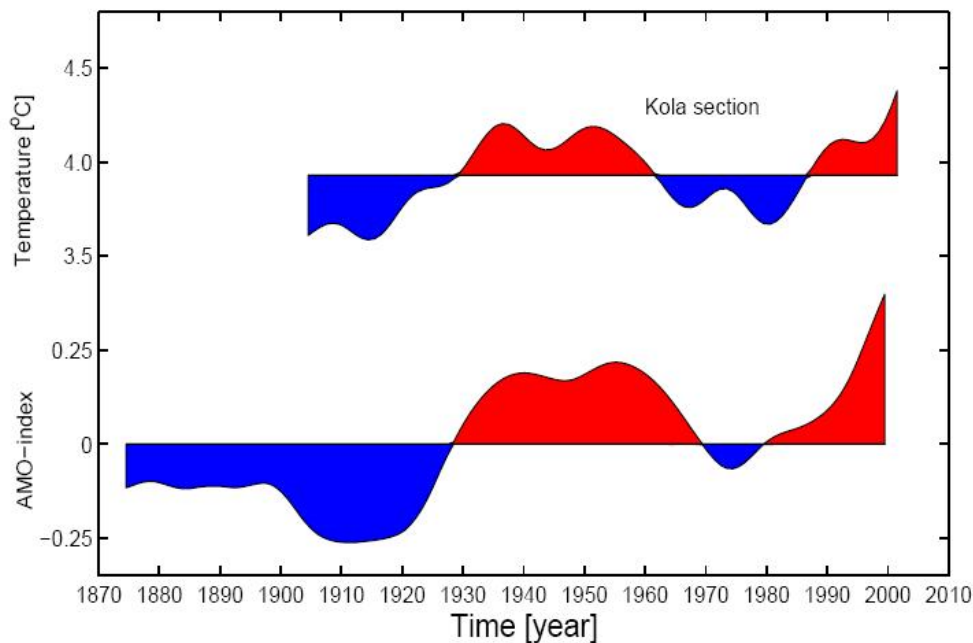

Figure 3.1.6   Time-series of the Kola section long-term average temperature with the shorter term filtered out (upper graph) and the Atlantic Multidecadal Oscillation (AMO) index (lower graph). The AMO index is based on the sea surface temperature in the region 0°–60°N and 7.5°–75°W as presented by 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 Faroe–Shetland and the Kola sections, the ocean variability in the OSPAR Regions as a whole has been observed with high quality measurements over the last 50 to 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 data set (Rayner *et al*., 2003). The long-term variability and trends derived from this data set have been compared with long time-series of in situ measurements from ICES standard sections in the North Atlantic and Nordic Seas (Hughes *et al*., 2008). The in situ measurements show an interdecadal Atlantic Water temperature increase of about 1°C from the 1970s to date, consistent along the shelf break from Ireland to the Barents Sea and Fram Strait (Figure 3.1.7) (Holliday *et al*., 2008). In the OSPAR Region II (North Sea) the rate

of warming is even greater (1–2°C) whereas in the western OSPAR Regions the warming is less (0.4–0.8°C) (illustrated for the surface layer in Figure 3.1.3). The increase in temperature in OSPAR Region IV (Biscay and western Iberia) is lower in the south and is also strongly influenced by upwelling. Superimposed on this general warming over the last 30 years are interannual to decadal-scale variations, with amplitudes 2–3 times larger than the size of the long-term change in the past century. The 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 3.1.4 and 3.1.5).
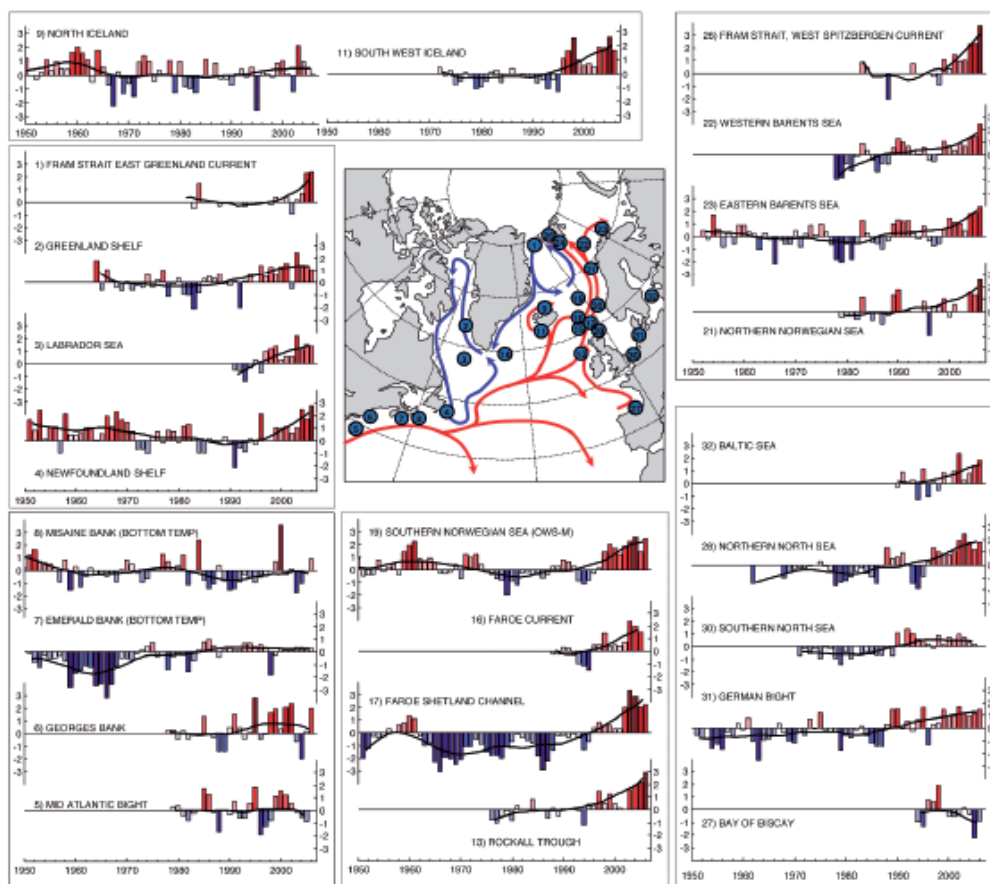

Figure 3.1.7   Overview of upper ocean temperature anomalies from the long-term mean across the North Atlantic. The anomalies are normalized with respect to the standard deviation (e.g., a value of +2 indicates 2 standard deviations above normal). The maps show conditions in 2006 (colour intervals 0.5, 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 shown to have a large effect on hydrographic conditions in the eastern part of the OSPAR region due to the presence of a larger fraction of warmer and more saline water from the eastern Atlantic (Hatun *et al*., 2005; Figure 3.1.4). Since the 1960s, changes in the large-scale wind pattern, principally the North Atlantic Oscillation (NAO), have resulted in a gradual change of 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 it has resulted in an eastward shift of the Arctic front and, accordingly, an upper layer cooling over wide areas due to 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 multidecadal temperature (AMO) signal is the interannual to decadal-scale temperature variations that are largely linked to the NAO. While 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.

3.2   Effects of oceanography on the OSPAR marine ecosystem

Estimates of the degree of influence of marine climate on marine ecosystems are likely to depend on the rate of change of the marine climate and on the choice of variable used to describe climate. In addition to the temperature, several interlinked climate variables influence marine ecosystems including advection, vertical mixing conditions, convection, turbulence, light, rainfall, runoff, evaporation, oxygen, pH, salinity, and nutrient supply (including aeolian). NAO,

which is an atmospheric pressure phenomenon primarily of decadal time scale, has specific characteristics with respect to influence on ocean circulation, mixing and precipitation (Hurrell *et al.*, 2003) and with respect 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 is primarily focusing on the effects of the 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, however, be emphasized that such ecosystem effects recently observed are not unique to the past century. In 1948 ICES arranged a symposium with the focus on what happened in the North Atlantic during the warming of a relatively cool period at the beginning of the 20th century onto the 1930s and 1940s (ICES, 1949). Similar changes with northward shifts of fish species occurred then both in 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 abundances. 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 dynamical change where species are observed to move northward in warm periods and southward in cool periods. With the anthropogenic climate change becoming increasingly dominant compared to long-term natural variability during the present century it could be expected that the past oscillations in species distributions will be replaced by a more permanent northward change.

4 Evidence analysis

4.1 Plankton

4.1.1 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 Working Group on Zooplankton Ecology (ICES, 2007a, 2008b) and additional peer-reviewed material. Much of this information is a result of 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) report on the distribution of organisms which can be linked to their relative biogeographical affinities and Northern Hemisphere (NHT) anomalies and the NAO index. This allowed understanding of regional modifications in the marine ecosystem modified 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 sea surface temperature 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 that there will be a demonstrable shift/expansion of distribution northward with increasing temperature relating to species' biological associations and ecological characteristics for pseudo-oceanic temperate species such as *Centropages typicus*, *Candacia armata*, *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 (Boersma *et al*., 2007; Faasse and Bayha, 2006; Valdés *et al*., 2007) can be linked in the same manner.

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

4.1.2 Results

The analysis of the CPR time-series has provided evidence that significant changes have occurred 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, and 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 (i.e. determined by the Phytoplankton Colour Index–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 sea surface temperature.

Change in distribution: A shift in the distribution of many plankton species by more than 10° latitude northward has been recorded in the OSPAR Maritime Area over the past thirty 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. Subartic species) (Figure 4.1.2). This shift is particularly associated with the current running north 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 the OSPAR Regions II, III, and V.
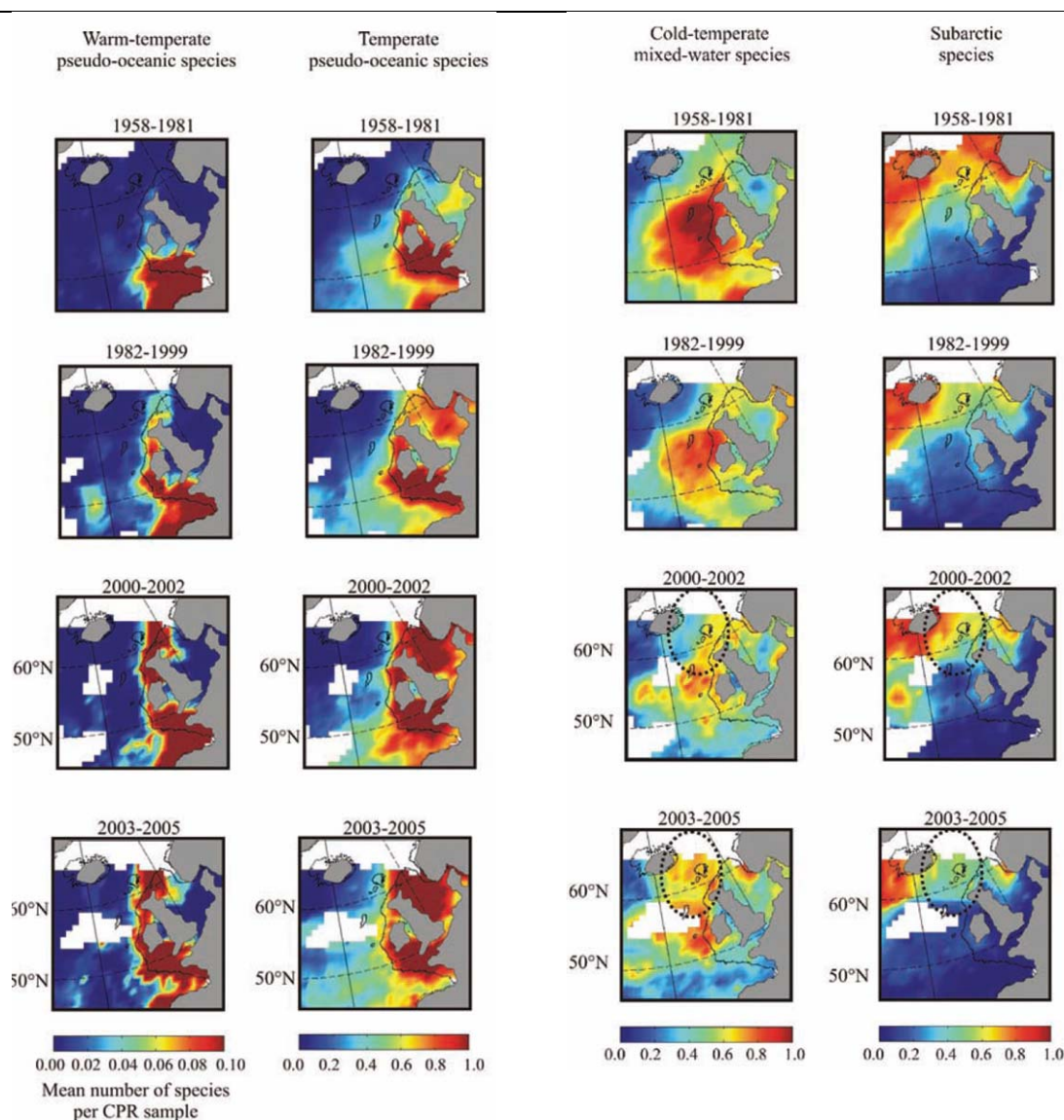

Figure 4.1.2 Maps showing biogeographical shifts of calanoid copepod communities in recent decades, with the warm-water species shifting northwards and the cold-water species likewise retracting north, by over 10° of latitude (from Edwards *et al*., 2008).

Hydroclimatic changes have been recently related to jellyfish increases 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 occurrence and increased abundance of the ctenophore *Mnemiopsis leidyi* (Purcell, 2005). This gelatinous predator has been accidentally introduced into the Black Sea, and has contributed to the reduction in the fisheries there (see references in Purcell, 2005).

4.1.3 Conclusions

Beaugrand *et al*. (2002) and Edwards *et al*. (2008) provide strong evidence based on the long-standing CPR survey on observed changes in zooplankton distribution and abundance, specifically biogeographical shifts of calanoid copepod communities in recent decades, with the warm-water species shifting northwards and the cold-water species likewise retracting northwards (Figure 4.1.2).

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. While these changes in distribution have been linked with warming trends, this is not likely to be 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 hierarchal level of analyses, as breaking down the information to the species level may elucidate specific characteristic species trends to temperature variation.

Jellyfish are very often population bloom species, known as 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 (Atrill *et al*., 2007).

The changes in the zooplankton and phytoplankton communities that are at the base of the marine pelagic food-web can affect higher trophic levels (fish, seabirds, mammals), for instance through loss of synchrony between predator and prey (match-mismatch) abundance/demand. This synchrony 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 in the North Sea warmer conditions earlier in the year combined with increased phytoplankton abundance have occurred since the late 1980s, which has determined the significant increase of meroplankton (i.e. temporary plankton species), in particular echinoderm larvae of *Echinocardium cordatum*.

In order to assess climate change effects on the marine community and fishery 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.

4.2 Benthos

4.2.1 Data sources and related information

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

4.2.2 Main conclusions

The majority of benthic species and communities examined showed changes in distribution and abundance over time, and the 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, similarly 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 historic range of natural variation, then major effects on at least some species and communities would be likely.

4.2.3 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 19th century. Some latitudinal shifts in distribution, both northward and southward, have been documented and are related to the occurrence of warm and cool periods during the 20th century (Alcock, 2003). Similarly, off La Coruña (Spain) changes in the benthic community 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 brittle star Amphiura had a long period of absence or rarity in the southern North Sea, but has been recorded in low to moderate abundances since 1975. Temperature is reported as a limiting factor for the distribution of this species, with the apparent range extension of this species to the inner German Bight area linked to the higher winter temperatures as compared to 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).

4.2.4 Interpretation and synthesis

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

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

> a) cases where anomalously cold winter conditions led 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).

> b) cases of benthic species being reported as expanding in areas outside their historical ranges that are characteristic of areas to the south or more coastal than the areas into which they are spreading.

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

A number of pathways can be identified by which climate-related changes in oceanographic conditions could be expected to affect benthic populations and communities (Bhaud *et al.*, 1995). Although this report has looked only at temperature effects, these pathways include:

- Temperature (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 the sediment composition, which determines habitat suitability for species and reflects food availability to the benthos);
- Precipitation (changes can affect the distribution of suspended particulate matter, changes in the salinity variability, and changes in nutrient run-off. These changes affect nutrient availability to benthos and increase the risk of hypoxia events in estuaries rich in organic matter);
- Acidification (increasing acidification of the ocean caused by increasing atmospheric CO_2 is becoming well documented, and poses 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 cases where the benthic species affected create distinct habitats, e.g. coral reefs, mussel beds.

4.3 Fish

4.3.1 Main conclusions

There is ample evidence for changes in distribution and abundance of fish that are consistent with the expected (i) northward shift or deepening of the distribution and (ii) increase in abundance in the northern part and decrease in the southern part of the range. Changes were most prominent in 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 effects since other factors may be important as well, in particular fishing, although it is highly likely that climate effects are involved.

4.3.2 Introduction (Fish-specific approach)

To interpret the changes for different species, we have followed the classification of fish species according to Ellis *et al*. (2008) who distinguished between Arctic, Boreal, Lusitanian, African, and Atlantic species. Arctic fishes are those species restricted to the most northern parts of the ICES/OSPAR areas, with southern limits off northern Norway and Iceland (Figure 2.1.2). Boreal fishes extend northwards to the Norwegian Sea and Icelandic waters and have the southern limits of their distribution around the British Isles or west of Brittany. Lusitanian fishes are those 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. Atlantic fishes are those (often pelagic or deep-water) species that are widespread in the North Atlantic, and includes many of the deeper-water species that may be widely distributed along the continental slope.

Changes in distribution of fish within the 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, while in the northern area no change or an increase should be observed. For Lusitanian species, two outcomes were anticipated: either an increase in the southern area together with no change in the northern area, or increase in the northern area combined with no change in the southern area. Any of the above we 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 we assumed that any increase of an Atlantic, Boreal, or Lusitanian (but not Arctic) species in OSPAR Region I could be interpreted as a result of climate change.

4.3.3 Data sources and related information

The sources of information for the fish component were ICES (2008c) and a selection of peer-reviewed publications. ICES (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 versus southern North Sea and West of Scotland versus Celtic Sea). OSPAR Region I was represented by the Barents Sea and Region IV by the Bay of Biscay.

4.3.4 Tabulation

The criteria described in the Technical 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 versus 2000–2005). Some comparisons were made with the period 1977–1989, but to ensure that changes in fishing activity during the 1970s and 1980s do not mask the climate change signal, only data from 1990 onwards were included in the analysis.

In order to interpret observed changes in abundance and/or distribution based on the work of ICES, we applied the same approach across all species and Regions. For each period we assessed whether there had been an overall change (decrease or increase) and, if so, this was put in the summary Table 4.3.1 as a change in abundance. For those areas where a northern and southern area was distinguished, both areas needed to show the same direction of change. If this was not the case, then this was interpreted in the table as a change in distribution.

4.3.5 Interpretation and synthesis

4.3.5.1 Observations from the tabulation

Of the cases where changes were observed, abundance and distribution changed in line with expected change in response to the recent warming in more than 70% of these cases (Table 4.3.1). In a minority of the studies no change was observed or the change was opposite to the expected change. Changes of 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 showed a change and which percentage of these changes was in accordance with expectations from climate change. We assessed this per 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 due to an increase in temperature, the results may not be interpreted as evidence for climate change as other explanations cannot be ruled out. In particular the observed changes may be influenced by fishing. For example, fishing mortality rates have been higher in the southern North Sea than in the north (Heath et al., 2003, 2007), and so 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; Wright et al., 2006; Daan et al., 2005; Daan, 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 4.3.1   Frequency by which fish species responded to an increase in water temperature by changing their distribution (A) or abundance (B). If a species showed a response, the response was classified as either conforming to or opposite to the 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 show 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 of 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.

4.3.6   Highlights of observations by OSPAR region

Many demersal and pelagic species changed abundance and distribution in all OSPAR Regions and while many of these changes are in accordance with what can be expected from climate change, others are not. The changes in abundance were observed for large areas and over relatively long time periods of one or more decades. The changes observed over the last decade appear to agree more often with the expected climate effect, possibly because over the longer time periods other effects such as fishing may have had a larger effect. 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., in press) 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: (i) a northward shift in the average latitude of abundant, widespread thermal specialists (e.g. grey gurnard and poor cod), and (ii) the 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: i) the warming and increasing availability of shallow habitats in the southern North Sea and ii) the North Atlantic Oscillation-linked inflows of warm water into the NE North Sea. The species showing an expected response in distribution or abundance are summarized in Table 4.3.2.

Table 4.3.2 List of species that showed an expected response to increases in water temperature in OSPAR Regions I–IV.

Common name	Scientific name	Association	OSPAR Regions 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		+		
Striped 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		+	+	+

It is apparent that warming in some cases has meant that species once considered strays have become much more common. In other cases the warming has improved recruitment for some species, thus creating a shift in the apparent range of the species though 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.

4.3.7 Highlights of observations by species; case studies

Five species were selected to illustrate a variety of patterns in spatial distribution, in the North Sea between two periods, 1977–1989 vs. 2000–2005. Distribution of each species was mapped using the International Bottom Trawl survey (IBTS) and the Norwegian survey data. Survey data from quarter one 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 (an area covering 524 400 km2). The maps from the two periods for quarter 1 were overlaid and density at all locations compared. Difference in density was classified to 12 levels (12 equal areas on the map) in a matrix model (spatial modelling in SPANS, Geomatica) – six areas of varying degree of change in density where density in the first period was higher, and six where it was lower. The resulting reclassified map illustrated where the density of fish had changed between periods and to what degree.

4.3.7.1 Atlantic cod *Gadus morhua*

This is a boreal species of prime commercial significance, which 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 1977–89 and 2000–05 (Figure 4.3.1). The reduction in density was highest to the southeast along the Dutch coast where density decreased by about a factor of 100, while 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%. 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 migrations (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) showed that Atlantic cod in the North Sea were found in deeper water during 1990–1999 compared to 1980–1989, but their distribution with respect to temperature was unchanged.
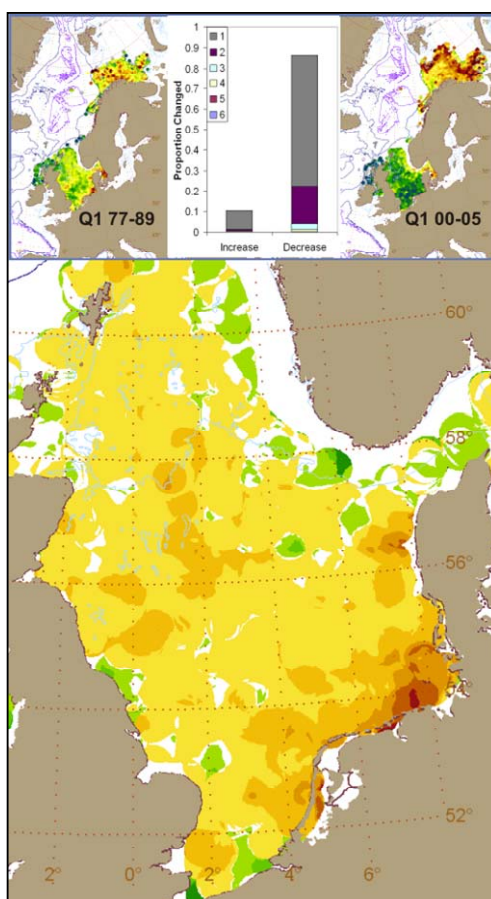

Figure 4.3.1   Change in distribution of Atlantic cod *Gadus morhua* between 1977–1989 and 2000–2005 in the North Sea, quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and upper right panel for 2000–2005. The large lower panel shows change in distribution between the two periods, where blue to green colours indicate an increase in density, dark colours indicating the largest change. Yellow to red indicate a decrease in density between the two periods, with red indicating the largest changes. The upper centre graph 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).

4.3.7.2 Monkfish *Lophius piscatorius*

The monkfish or anglerfish is a Lusitanian species that increased in density in the northern North Sea while densities remained largely unchanged in the southern part (Figure 4.3.2). Over the last two decades, an increase in density was observed over 45% of the survey area and a decrease over 18%.
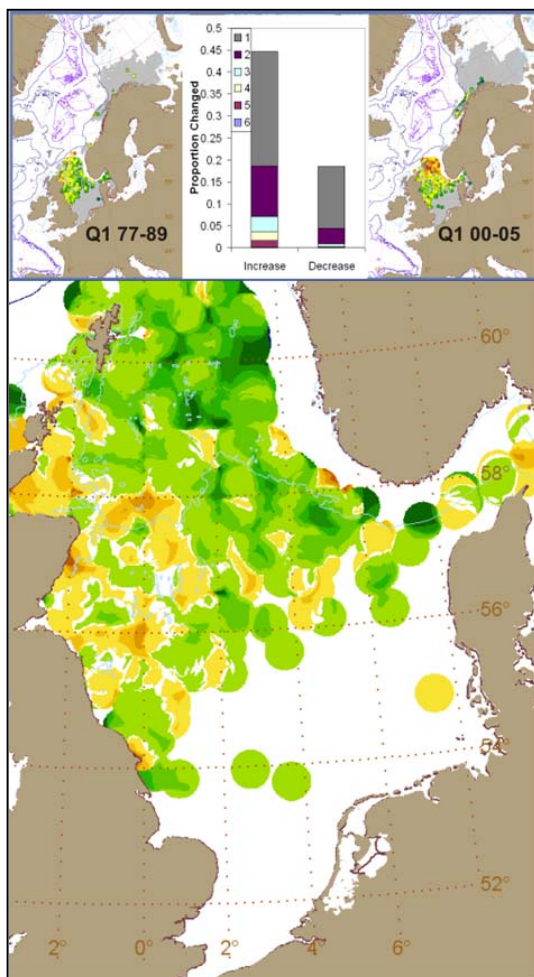

Figure 4.3.2   Change in distribution of anglerfish *Lophius piscatorius* between 1977–1989 and 2000–2005 in the North Sea, quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and upper right panel for 2000–2005. The large lower panel shows change in distribution between the two periods, where blue to green colours indicate an increase in density, dark colours indicating the largest change. Yellow to red indicate a decrease in density between the two periods, with red indicating the largest changes. The upper centre graph 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).

4.3.7.3 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 4.3.3). Where haddock concentrate in the northern half of the North Sea, 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%. In general, the spatial change for haddock occurred only where density was low and thus had little impact on the overall abundance of that species.
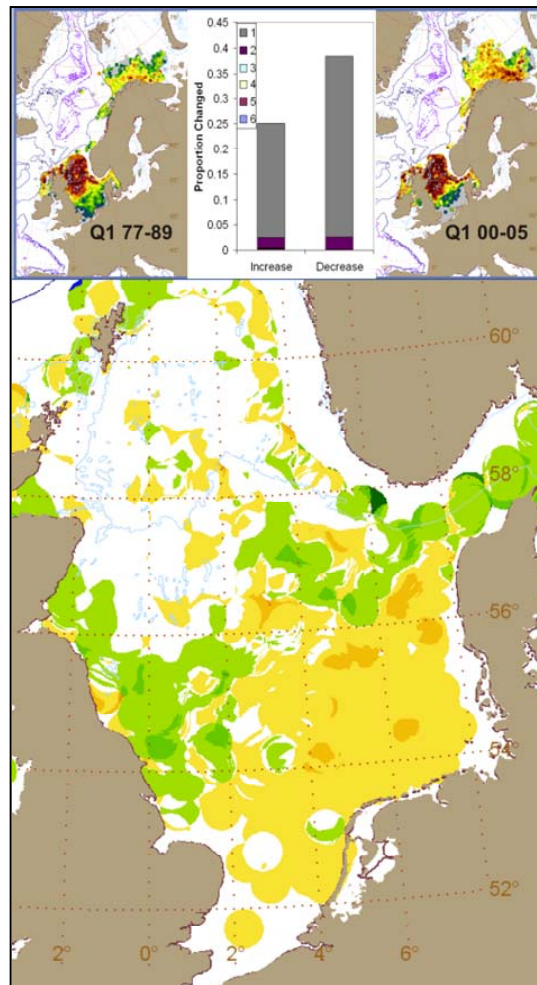
Figure 4.3.3   Change in distribution of haddock *Melanogrammus aeglefinus* (haddock) between 1977–1989 and 2000–2005 in the North Sea, quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and upper right panel for 2000–2005. The large lower panel shows change in distribution between the two periods, where blue to green colours indicate an increase in density, dark colours indicating the largest change. Yellow to red indicate a decrease in density between the two periods, with red indicating the largest changes. The upper centre graph 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).

4.3.7.4   Red mullet *Mullus surmuletus*

The red mullet is a Lusitanian species. Its distribution reaches north into coastal waters off Norway, northern Scotland, and to the Faroe Islands, south 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 and a comparatively smaller fraction 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, in particular from the Celtic Sea (Figure 4.3.4).
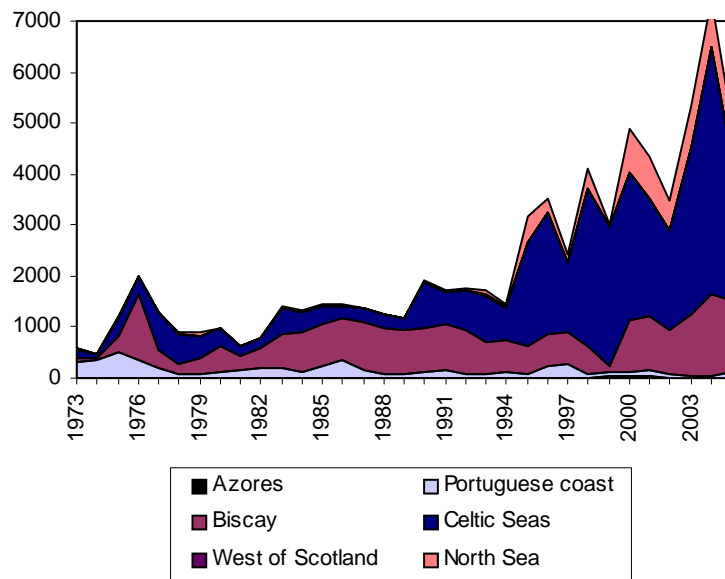
Figure 4.3.4   Northeast Atlantic red mullet: trends in total landings by fishing region (in t). Data from ICES Fisheries Statistics.

The very marked increases in landings of red mullet in recent years might be partly explained by a northward distribution shift, or 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.

Surveys showed that red mullet has increased in 48% of the North Sea survey area, and has decreased nowhere in the North Sea. It did not appear in surveys before 1989 (Fig. 4.3.5). It has been suggested that the North Sea population migrates northwards in winter, when water temperatures are higher there (Beare *et al.*, 2005).

The combination of 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 fast growth rate and a planktonic egg/larvae stage, which could enhance its ability to rapidly respond 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.
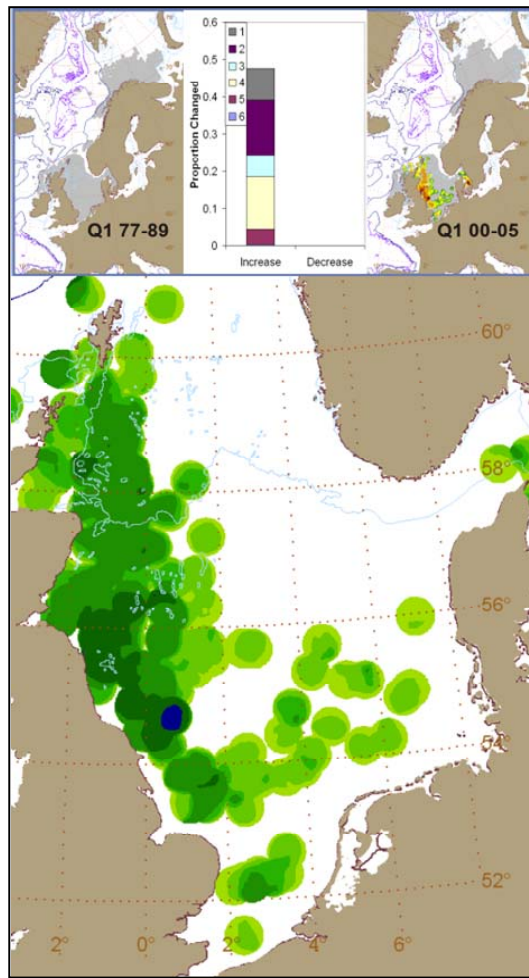
Figure 4.3.5   Change in distribution of striped red mullet *Mullus surmuletus* between 1977–1989 and 2000–2005 in the North Sea, quarter 1 (ICES, 2008c). The upper left panel shows distribution in the initial period (1977–1989) and upper right panel for 2000–2005. The large lower panel shows change in distribution between the two periods, where blue to green colours indicate an increase in density, dark colours indicating the largest change. Yellow to red indicate a decrease in density between the two periods, with red indicating the largest changes. The upper centre graph 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).

4.3.7.5 Herring *Clupea harengus*

The Atlantic herring is a pelagic, ocean- and coastal-dwelling species, covering a depth range from 0 to 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 biggest 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 *Calanus* peak abundance is further north, herring catches are also further north. Variations in the distribution of North Sea herring are driven by changes in stock size, the zooplankton production, and variability in the Atlantic inflow by the Fair Isle Current, but the interaction of year class strength and environmental signals are difficult to interpret. The variability in productivity and distribution in Norwegian spring-spawning herring appears to exhibit patterns that may be associated with climatic cycles such as the Atlantic multidecadal oscillation (Toresen and Østvedt, 2000). The collapse of the herring in the 1960s (Figure 4.3.6) can be ascribed to a combined effect of overfishing and deterioration of the environmental conditions (temperature). The degree to, and mechanism by, which temperature has an association with recruitment is unclear.
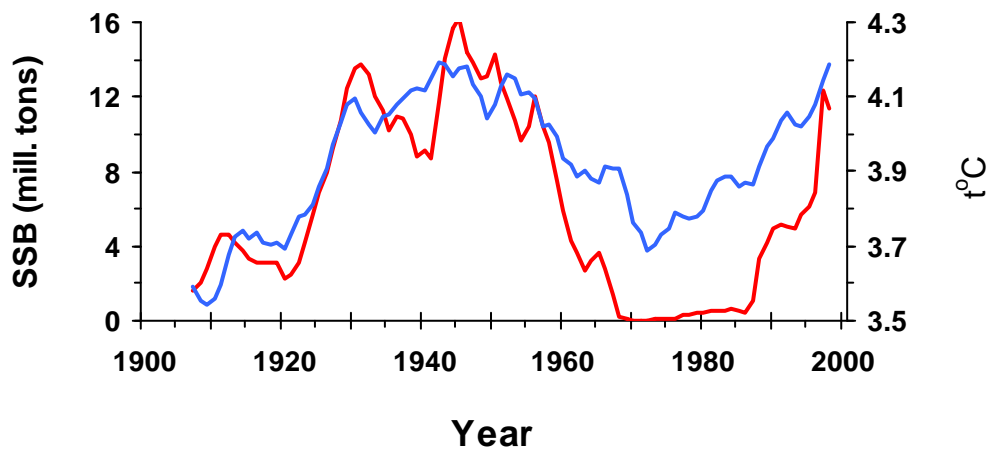
Figure 4.3.6   Variations in the spawning-stock biomass of Norwegian spring-spawning herring and sea temperature. Stock collapse in the 1960s was a combined effect of the decrease in sea temperature and high fishing pressure (from Toresen and Østvedt, 2000).

4.3.7.6   Anchovy *Engraulis encrasicolus* in the North Sea

The anchovy typically is a species with sub-tropical affinity (Petitgas, 2008). Survey data series confirmed the greatly increased densities of anchovy in the North Sea in recent years. In the period from 1977–1989, only occasional records of anchovy were made off Britain and in the Skagerrak. The species is presently 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 extent. An increase in density was observed over 75% of the survey area and a decrease over only 1% (Figure 4.3.7).

Figure 4.3.7   Change 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 upper right panel for 2000–2005. The large lower panel shows change in distribution between the two periods, where blue to green colours indicate a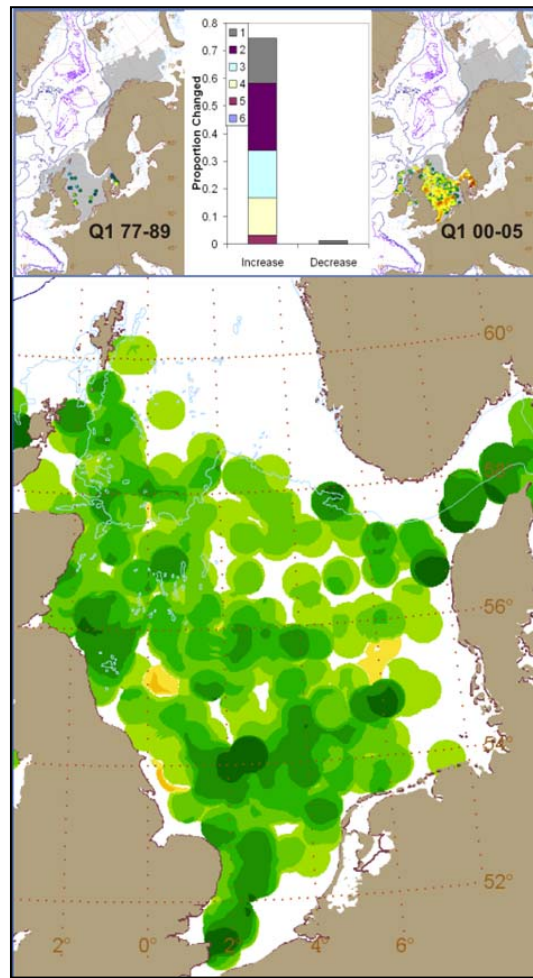n increase in density, dark colours indicating the largest change. Yellow to red indicate a decrease in density between the two periods, with red indicating the largest changes. The upper centre graph shows the proportion of the total survey area where an increase and decrease occurred, broken down by degree of increase or decrease (categories 1–6).

4.4   Seabirds

4.4.1   Data sources and related information

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

4.4.2   Main conclusions

The response of seabirds to climate change is generally mediated through trophic effects. The majority of the scientific data refers to analyses of variation in condition factors such as breeding success and annual survival. It is expected that these factors must be reflected in the population dynamics of the various seabird species, but quantitative evidence for this is lacking due 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, but some inferential conclusions can be produced.

4.4.3   Highlights of the published knowledge

4.4.3.1   Atlantic puffin *Fratercula arctica*

At the northern fringe of the latitudinal range, the fledging success of Atlantic puffin at Røst, Northern Norway, is principally governed by the availability and size-at-age of young-of-the-year herring, which are 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 of repeated breeding failures have coincided with a decrease in population size over several decades (Anker-Nilssen, 1992). However, fledging success is not in itself able to explain the rate of change in population numbers from year to year (Figure 4.4.1), 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 puffin in the North Sea at the southern fringe of the 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 SST during the sandeel larval period (January to May). Hence, warming would be expected to have a deleterious effect on fledging success of puffin 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 the abundance of sandeels. Overall, there is evidence that the response of Atlantic puffin to warming is likely to be in opposite directions at the northern and southern limits of the latitudinal range (Harris *et al.*, 2005).
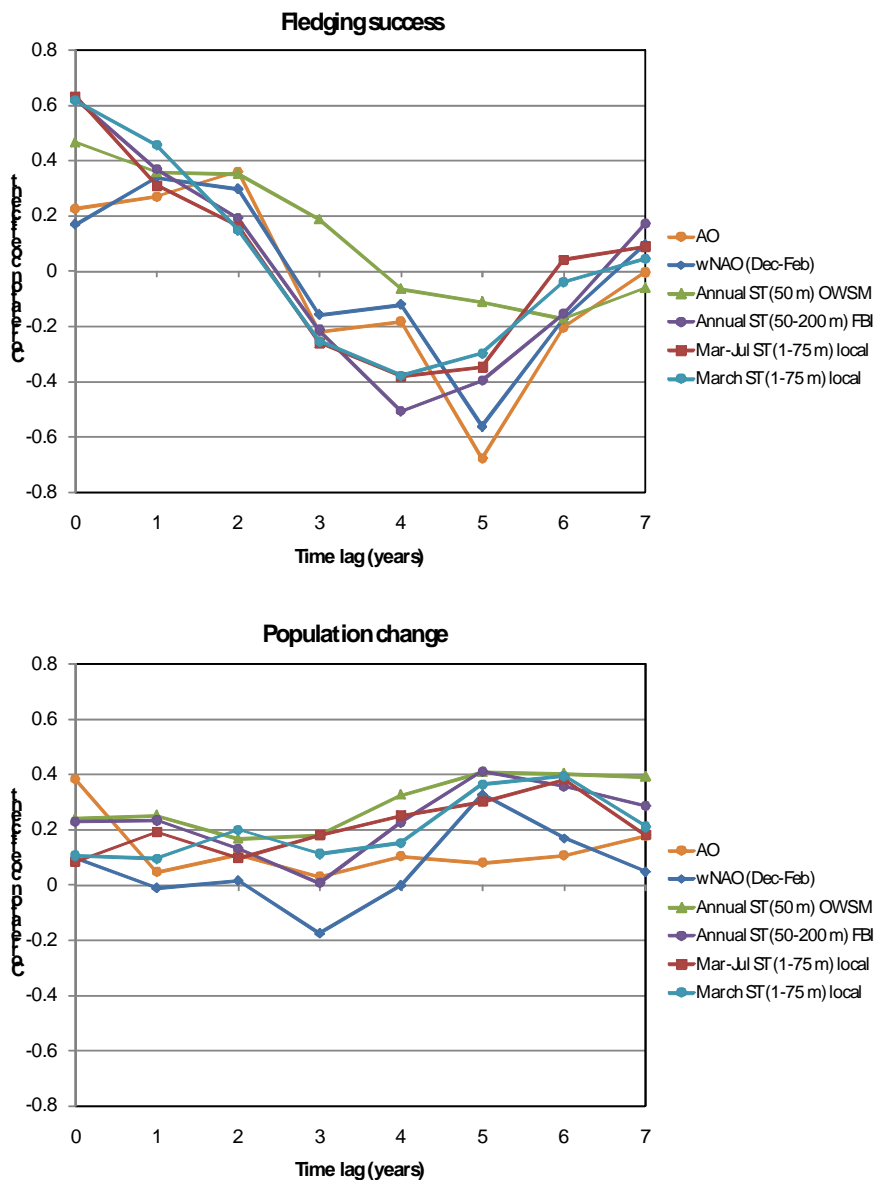
Figure 4.4.1   Degree of correlation between a selection of climatic variables and (a) the fledging success (upper) and (b) the ln-transformed change in annual breeding numbers of Atlantic puffins (lower) at Røst, northern Norway in 1979–2007. To test for indirect effects of trophic relationships and 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 unpubl. data).

4.4.3.2 Black legged *kittiwake Rissa tridactyla*

Frederiksen *et al*. (2004a) examined changes over time and correlations 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 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 kittiwakes breeding productivity in six areas around the UK and Ireland with sea temperature during the winter prior to breeding. Sea temperature in this case was assumed to be a surrogate for the abundance of young-of-the-year sandeel which form part of the diet of kittiwake. 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.

4.4.3.3 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 previously (Grosbois and Thompson, 2005). Thompson and Ollason (2001) investigated the survival/increased population breeding performance over time in fulmar populations, and warmer conditions were proposed to favour increased abundance.

4.4.3.4 Arctic tern *Sterna paradisaea*

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

4.4.3.5 Balearic shearwater *Puffinus mauretanicus*

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

4.4.3.6 Seabird community in OSPAR Region I

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

4.4.4 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 and in others breeding is retarded;
- Seabirds show some flexibility in dealing with climate change in this regard but 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; and
- Seabirds are vulnerable to both spatial and temporal mismatches in prey availability, especially when breeding at fixed colony sites with the foraging constraints that these entail.

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

Many factors influence range expansions, and while some changes in distributions have been identified, e.g. changes in breeding distribution in a few species (e.g. lesser black-backed gull *Larus fuscus*), it is not clear how changes in hydrodynamics and sea temperature are involved, but it is presumed to be an contributing factor (Mitchell *et al*., 2004; Wernham *et al*., 2002).

There is a substantial body of evidence for changes in seabird demography and population dynamics (Table 4.4.1). 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.

Table 4.4.1   Links between climate change and aspects of seabird condition and behaviour.

Seabird parameter	Species	Region	Climate variable	Sign of correlation with warming	Sources
Breeding range	Lesser black-backed gull	U.K.	Sea temperature	Positive	Mitchell *et al.* (2004)
	Northern gannet	U.K.	Sea temperature	Positive	Mitchell *et al.* (2004)
Non-breeding range	Lesser black-backed gull	U.K.		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 2 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, 2006)
	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)
Population change	Common guillemot	Circumpolar	Sea temperature	Increase with moderate cooling of SST	Irons *et al.* (in press)
	Brünnich's guillemot	Circumpolar	Sea temperature	Increase with moderate warming of SST	Irons *et al.* (in press)
	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	NAO index	Positive	Frederiksen *et al.* (2004b)
	Common guillemot	Isle of May	NAO index	Positive	Frederiksen *et al.* (2004b)

SEABIRD PARAMETER	SPECIES	REGION	CLIMATE VARIABLE	SIGN OF CORRELATION WITH WARMING	SOURCES
	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)

4.5   Marine mammals

4.5.1   Data sources and related information

There is a general lack of reliable baseline information and long-term datasets on 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 of 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.

4.5.2   Theoretical considerations

Mammals are different 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 impact on breeding success, though these are buffered by their longevity such that even sequences of a few years of breeding failure are of lesser consequence than, for example, in short-lived fish species. This presents problems for statistical analyses aimed at distinguishing between climate dependency and 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 responsive to the distribution of optimal prey and environmental conditions, leading to highly non-linear responses of population size to regional climate. For example, diminishing extent and duration of sea ice is considered to be an important factor for both resident and seasonal Arctic species based on understanding of the biology, but demonstrating statistical significance from time-series data is difficult (Heide-Joergensen and Lydersen, 1998; Härkönen *et al.*, 1998; Stirling *et al.*, 1999).

4.5.3   Case histories

Species whose habitat is dependent on ice extent and duration may show a disruption in breeding/reproductive output. This is evident in polar bears *Ursus maritimus* and seal species that depend on fjord or drift ice (ringed *Phoca hispida*, harp *P. groenlandica*, hooded *Cystophora cristata*, and bearded *Erignathus barbatus* seals; Ferguson *et al.*, 2005; Fischbach *et al.*, 2007; Regehr *et al.*, 2007). Adult body condition, litter production, and sub-adult survival are all dependent on the availability of ice so that 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 temperature-to-polar seas, such as beluga *Delphinapterus leucas*, narwhal *Monodon monoceros*, and bowhead whale *Balaena mysticetus*.

Species which undertake large-scale migrations (sperm whale *Physeter macrocephalus* and baleen whales) may also be possible indicator species (Learmonth *et al.*, 2006; Simmonds and Isaac, 2007) together with those species which are

identified in conservation legislation (e.g. harbour porpoise *Phocoena phocoena* and common bottlenose dolphin *Tursiops truncatus*).

Specific issues identified with respect to the possible indicator species are:

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

2) Within the OSPAR Maritime Area, long-term changes in large-scale distribution in the bottlenose dolphin, common dolphin *Delphinus delphis*, and the white-beaked dolphin *Lagenorhychus albirostris* populations over the last 100 years seem to have occurred. These may be a result of changes in sea surface temperature (and linked with changes in the North Atlantic Oscillation index);

3) Changes since 1995 in the distribution of harbour porpoises in the North Sea and English Channel, although the reasons for the southwards shift in their distribution have not been fully investigated (Camphuysen, 2004; Kiszka *et al.*, 2004);

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

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

In summary:

- Marine mammals that live in close association with the Arctic ice and/or in the cold temperate to polar seas influenced by Arctic ice will be the ones 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 harbour porpoises and bottlenose dolphins. Possible changes in distribution of the animals due to 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 due to 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 show a disruption to breeding, feeding habitat, and food availability, most other species should show fairly plastic responses, as they are long-lived and are likely to show some degree of adaptation to slowly developing change.

4.6   Invasive species

4.6.1   Data sources and related information

Establishing the absence of a species from an area is in principle more difficult than demonstrating 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 data extracted from country reports (not all countries reported each year) of the ICES Working Group on Introductions and Transfers of Marine Organisms (ICES, 2007e).

4.6.2   Theoretical considerations

Invasive species are those which have become a nuisance, while introduced species are those which are found outside their natural geographic range. Vagrant species are those which are indigenous to a region as a whole but spread into previously uncolonized parts as a result of, for example, geographical shifts in the temperature conditions corresponding to the tolerance range of the species. These are distinct from introduced species, i.e. those which have been transplanted intentionally or unintentionally (e.g. 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 due to warming. The invasive spread of species which 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 predator, disease, and competition constraints than in its native region, and is thus free to exploit its full physiological tolerance.

4.6.3 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), *Sargassum muticum* (a brown alga)), molluscs (slipper limpet *Crepidula fornicata*, Pacific oyster *Crassostrea gigas*), 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 which have been able to establish as a direct result of warming temperatures: (i) the Pacific oyster *Crassostrea gigas*, which is an escaped aquaculture species, and (ii) a barnacle species *Elminius modestus*.

Natural recruitment of *Crassostrea gigas* occurs in all areas of Europe where the species has been introduced for aquaculture purposes. This was unexpected since, at the time when the introduction occurred, temperatures in European waters were lower than in its native areas. Extended reproductive periods are occurring along the Belgium 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 Irish coasts (Boelens *et al.*, 2005).

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

Elminius modestus has extended reproductive periods due to 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).

5 Meta-analysis and synthesis

5.1 Interpretation of the meta-analysis

Full details of the meta-analysis are provided in the Technical Annex, including rationale for 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 is given in the tables in this section.

The red and yellow cells in Table 5.1 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 ($P < 0.0001$).

Table 5.1   Numbers are cases of change in distribution, abundance, or other characteristics (e.g. phenology, seasonality). Colour coding represents the percentages that were in the direction expected as a result of effects of climate (Red >75%; Yellow 50–75%, Blue <50%).

OSPAR Region	Zooplankton Distribution	Abundance	Other	Benthos Distribution	Abundance	Fish Distribution	Abundance	Seabirds Distribution and abundance	Total	% change in expected direction
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%	

Notes: For plankton the OSPAR Region I includes some species occurring also in Regions I–IV (Beaugrand *et al.*, 2002)

Table 5.2   Numbers of cases in which there was no change in either direction.

OSPAR region	Zooplankton Distribution	Abundance	Other	Benthos Distribution	Abundance	Fish Distribution	Abundance	Seabirds 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

Comparison of the numbers in Tables 5.1 and 5.2 shows that the cases where there was a change (in either direction) greatly outnumber the cases in which there was no change in either direction. Only for fish in Region IV did the number of cases with no change outnumber the cases where some change occurred.

The only area/taxon cells in which less than half the changes were in the expected direction were the plankton distribution changes in Region II and the seabird distribution and abundance changes in Region III (the two blue cells in Table 5.1).

In the case of fish, the group with the most available information, markedly more than half of the changes that were considered informative are in accordance with expectations from climate change. For the selection of records that had passed the criteria, and 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 we expect to happen as a consequence of climate change. For changes in distribution, these percentages vary 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 directly linked to species expanding their range and increasing in their abundance at their new limit of distribution; these changes are discussed under distribution. The meta-analysis reinforced the evidence that the observed changes are at least partly caused by the changing climate.

6   References

Aebischer, N., and Wanless, S. 1992. Relationships between colony size, adult non-breeding and environmental conditions for shags *Phalacrocorax aristotelis* on the Isle of May, Scotland. Bird Study, 32: 43–52.

Alcock, R. 2003. The effects of climate change on rocky shore communities in the Bay of Biscay, 1895–2050. PhD. Thesis, University of Southampton: 296 pp.

Anker-Nilssen, T. 1992. Food supply as a determinant of reproduction and population development in Norwegian puffins *Fratercula arctica*. PhD thesis, University of Trondheim.

Anker-Nilssen, T., and Aarvak, T. 2006. Long-term studies of seabirds in the municipality of Røst, Nordland. Results with focus on 2004 and 2005. Norwegian Institute for Nature Research, NINA Report 133.

Appenzeller, C., Stocker, T. F., and Schmittner, A. 2004. Natural climate variability and climate change in the North-Atlantic European region; chance for surprise? Integrated Assessment, 1: 301–306.

Arnott, S. A., and Ruxton, G. D. 2002. Sandeel recruitment in the North Sea: demographic, climatic and trophic effects. Marine Ecology-Progress Series, 238: 199–210.

Ashmole, N. P. 1971. Sea bird ecology and the marine environment. In Avian Biology, 1. Farner, D., King, J., and Parkes, K. eds. New York, Academic Press. 1: 224–286.

Attrill, M. J., Wright, J., and Edwards, M. 2007. Climate-related increases in jellyfish frequency suggest a more gelatinous future for the North Sea. Limnology and Oceanography, 52: 480–485.

Bañón, R., del Río, J. L., Piñeiro, C., and Casas, M. 2002. Occurrence of tropical affinity fishes in Galician waters north-west. Spain. Journal of the Marine Biological Association of the United Kingdom, 82: 877–880.

Beare, D., Burns, F., Jones, E., Peach, K., and Reid, D. 2005. Red mullet migration into the northern North Sea during late winter. Journal of Sea Research, 53: 205.

Beaugrand, G. 2003. Long-term changes in copepod abundance and diversity in the north-east Atlantic in relation to fluctuations in the hydroclimatic environment. Fisheries Oceanography, 12: 270–283.

Beaugrand, G. 2004. The North Sea regime shift: evidence, causes, mechanisms and consequences. Progress in Oceanography, 60: 245–262.).

Beaugrand, G., and Reid, P. C. 2003. Long-term changes in phytoplankton, zooplankton and salmon related to climate. Global Change Biology, 9: 801–817.

Beaugrand, G., Reid, P. C., Ibañez, F., Lindley, J. A., and Edwards, M. 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. Science, 296: 1692–1694.

Beukema, J. J. 1990. Expected effects of changes in winter temperatures on benthic animals living in soft sediments in coastal North Sea areas. In Expected effects of climatic change on marine coastal ecosystems. Ed. by J.J. Beukema. Kluwer Academic Publisher, 83–92 pp.

Beukema, J. J. 1992. Expected changes in the Wadden Sea benthos in a warmer world: lessons from periods with mild winters. Netherlands Journal of Sea Research, 30: 73–79.

Bhaud, M., Cha, J. H., Duchene, J. C., and Nozais, C. 1995. Influence of temperature on the marine fauna – what can be expected from a climatic-change. Journal of Thermal Biology, 20: 91–104.

Blindheim, J., Borovkov, V., Hansen, B., Malmberg, S. A., Turrell, W. R., and Østerhus, S. 2000. Upper layer cooling and freshening in the Norwegian Sea in relation to atmospheric forcing, Deep-Sea Research, Part I, 47: 655–680.

Boelens, R., Minchin, D., and O'Sullivan, G. 2005. Climate change: implications for Ireland's marine environment and resources. Marine Foresight Series No 2, Marine Institute, Oranmore, Co. Galway. 40 pp.

Boersma, M., Malzahn, A. M., Greve, W., and Javidpour, J. 2007. The first occurrence of the ctenophore Mnemiopsis leidyi in the North Sea. Helgoland Marine Research, 61: 153–155.

Bonnet, D., Richardson, A., Harris, R., Hirst, A., Beaugrand, G., Edwards, M., Ceballos, S., Diekman, R., Lopez-Urrutia, A., Valdes, L., Carlotti, F., Molinero, J. C., Weikert, H., Greve, W., Lucic, D., Albaina, A., Yahai, N. D., Umani, S. F., Miranda, A., dos Santos, A., Cook, K., Robinson, S., Fernandez de Puelles, M. L. 2005 An overview of Calanus helgolandicus ecology in European waters. Progress in Oceanography, 65. 1–53.

Boos, K., and Franke, H. 2006. Brittle stars (Echinodermata: Ophiuroidea) in the German Bight (North Sea) species diversity during the past 130 years. Journal of the Marine Biological Association of the United Kingdom, 86, 1187–1197.

Brander, K. M. 2005. Cod recruitment is strongly affected by climate when stock biomass is low. ICES Journal of Marine Science, 62: 339–343.

Camphuysen, K. 2004. The return of the harbour porpoise (*Phocoena phocoena*) in Dutch coastal waters. Lutra, 47(1): 135–144.

Caswell, H., Fujiwara, M., and Brault, S. 1999. Declining survival probability threatens the North Atlantic right whale. Proceedings of the National Academy of Science, 96: 3308–3313.

CIESM. 2001. Gelatinous zooplankton outbreaks: theory and practice. CIESM Workshop Series, no.14, 112 pp. Monaco: CIESM, Commission Internationale pour l'Exploration Scientifique de la mer Méditerranée.

Cushing, D. M. 1980. The decline of herring stocks and the gadoid outburst. Journal du Conseil, 39: 70–81.

Daan, N. 2006. Spatial and temporal trends in species richness and abundance for the southerly and northerly components of the North Sea fish community separately, based on IBTS data 1977–2005. ICES CM 2006/D:02.

Daan, N., Gislason, H., Pope, J., and Rice, J. 2005. Changes in the North Sea fish community: evidence of indirect effects of fishing? ICES Journal of Marine Science, 62: 177–188.

Dinter, W. P. 2001. Biogeography of the OSPAR Maritime Area. A synopsis and synthesis of biogeographical distribution patterns described for the North-East Atlantic Bundesamt for Naturschutz, Bonn, Germany. 167 pp.

Drinkwater, K. F. 2006. The regime shift of the 1920s and 1930s in the North Atlantic. Progress in Oceanography, 68: 134–151.

Dulvy, N. K., Rogers, S. I., Jennings, S., Stelzenmüller, V., Dye, S. R., and Skjoldal, H-R. (In press). Climate change and deepening of the North Sea fish assemblage: a biotic indicator of regional warming. Journal of Applied Ecology.

Durant, J. M., Anker-Nilssen, T., and Stenseth, N. C. 2003. Trophic interactions under climate fluctuations: the Atlantic puffin as an example. Proceedings of the Royal Society of London Series B-Biological Sciences, 270: 1461–1466.

Durant, J. M., Anker-Nilssen, T., Hjermann, D. Ø., and Stenseth, N. C. 2004. Regime shifts in the breeding of an Atlantic puffin population. Ecology Letters, 7: 388–394.

Durant, J. M., Anker-Nilssen, T., and Stenseth, N. C. 2006. Ocean climate prior to breeding affects the duration of the nestling period in the Atlantic puffin. Biology Letters, 2: 628–631.

Edwards, M., and Richardson, A. J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature, 430: 881–884.

Edwards, M., Johns, D. G., Licandro, P., John, A. W. G., and Stevens, D. P. 2006. Ecological Status Report: results from the CPR survey 2004/2005. SAHFOS Technical Report, 3: 1–8. Plymouth, U.K. ISSN 1744–0750.

Edwards, M., Johns, D. G., Beaugrand, G., Licandro, P., John, A. W. G., and Stevens, D. P. 2008. Ecological Status Report: results from the CPR survey 2006/2007. SAHFOS Technical Report, 5: 1–8. Plymouth, U.K. ISSN 1744-0750.

Ellis, J. R., Engelhard, G. H., and Pinnegar, J. K. 2008. Ecotypes. RECLAIM http://www.climateandfish.eu/.

Engelhard, G. H., Heath, M. R., and Pinnegar, J. K. 2008a. Climate and the distribution, abundance and productivity of cod *Gadus morhua* RECLAIM http://www.climateandfish.eu/.

Engelhard, G. H., Ellis, J. R., and Pinnegar, J. K. 2008b. Climate and the distribution, abundance and productivity of red mullet *Mullus surmuletus*. RECLAIM http://www.climateandfish.eu/.

Faasse, M. A., and Bayha, K. M. 2006. The ctenophore *Mnemiopsis leidyi* A. Agassiz 1865 in coastal waters of the Netherlands: an unrecognized invasion? Aquatic Invasions, 1: 270–277.

Ferguson, S. H., Stirling, I., and McLoughlin, P. 2005. Climate change and ringed seal (*Phoca hispida*) recruitment in western Hudson Bay. Marine Mammal Science 21: 121–135.

Finney, S., Wanless, S., and Harris, M. 1999. The effect of weather conditions on the feeding behaviour of a diving bird, the common guillemot *Uria aalge*. Journal of Avian Biology, 30: 23–30.

Fischbach, A. S., Amstrup, S. C., and Douglas, D. C. 2007. Landward and eastward shift of Alaskan polar bear denning associated with recent sea ice changes. Polar Biology, 30: 1395–1405.

Forbes, E., and Godwin-Austen, R. 1859. The Natural History of the European Seas. (Van Voorst) London, 306pp; Reprint (1977) (Arno Press) New York

Frederiksen, M., Wanless, S., Rothery, P., and Wilson, L. J. 2004a. The role of industrial fisheries and oceanographic change in the decline of North Sea black-legged kittiwakes. Journal of Applied Ecology, 41: 1129–1139.

Frederiksen, M., Harris, M. P., Daunt, F., Rothery, P., and Wanless, S. 2004b. Scale-dependent climate signals drive breeding phenology of three seabird species. Global Change Biology, 10: 1214–1221.

Frederiksen, M., Wright, P. J., Harris, M. P., Mavor, R. A., Heubeck, M., and Wanless, S. 2006. Regional patterns of *kittiwake Rissa tridactyla* breeding success are related to variability in sandeel recruitment. Marine Ecology Progress Series, 300: 201–211.

Frederiksen, M., Edwards, M., Richardson, A. J., Halliday, N. C., and Wanless, S. 2006a. From plankton to top predators: bottom-up control of a marine food web across four trophic levels. Journal of Animal Ecology, 75: 1–10.

Frederiksen, M., Edwards, M., Mavor, R. A., and Wanless, S. 2007. Regional and annual variation in black-legged kittiwake breeding productivity is related to sea surface temperature. Marine Ecology-Progress Series, 350: 137–143.

Furevik, T. 2001. Annual and interannual variability of Atlantic water temperatures in the Norwegian and Barents seas: 1980–1996, Deep Sea Research, Part I, 48: 383–404.

Furness, R., and Bryant, D. 1996. Effect of wind on field metabolic rates of breeding northern fulmars. Ecology, 77: 1181–1188.

Gollasch, S., Kieser, D., Minchin, D., and Wallentinus, I. 2007. Status of introductions of non-indigenous marine species to the North Atlantic and adjacent waters 1992–2002: Ten-year summary of national reports considered at meetings of the Working Group on Introductions and Transfers of Marine Organisms. ICES Cooperative Research Report 284. 156 pp.

Greene, C. H., and Pershing, A. J. 2004. Climate and the conservation biology of North Atlantic right whales: the right whale at the wrong time? Frontiers in Ecology and the Environment, 2: 29–34.

Grosbois, V., and Thompson, P. M. 2005. North Atlantic climate variation influences survival in adult fulmars. Oikos, 109: 273–290.

Häkkinen, S., and Rhines, P. B. 2004. Decline of subpolar North Atlantic circulation during the 1990s, Science, 304: 555–559.

Hansen, J., Ruedy, R., Sato, M., Imhoff, M., Lawrence, W., Easterling, D., Peterson, T., and Karl, T. 2001. A closer look at United States and global surface temperature change. Journal of Geophysical Research 106: 23947–23963.

Härkönen, T., Stenman, O., Jüssi, M., Jüssi, I., Sagitov, R., and Verevkin, M. 1998. Population size and distribution of the Baltic ringed seal (*Phoca hispida botnica*). NAMMCO Scientific Publications, 1:167–180.

Harris, M. P., and Wanless, S. 1988. The breeding biology of guillemots *Uria aalge* on the Isle of May over a six-year period. Ibis, 130: 172–192.

Harris, M. P., and Wanless, S. 1989. The breeding biology of razorbills (*Alca torda*) on the Isle of May. Bird Study, 36: 105–114.

Harris, M. P., Murray, S., and Wanless, S. 1998. Long-term changes in breeding performance of puffins *Fratercula arctica* on St. Kilda. Bird Study, 45: 371–374.

Harris, M. P., Anker-Nilssen, T., McCleery, R. H., Erikstad, K. E., Shaw, D. N., and Grosbois, V. 2005. Effect of wintering area and climate on the survival of adult Atlantic puffins *Fratercula arctica* in the eastern Atlantic. Marine Ecology-Progress Series, 297: 283–296.

Hatun, H., Sando, A. B., Drange, H., Hansen, B., and Valdimarsson, H. 2005. Influence of the Atlantic Subpolar Gyre on the thermohaline circulation. Science, 309: 1841–1844.

Heath, M. R. 2007. Responses of fish to climate fluctuations in the Northeast Atlantic. In L. E. Emery [Ed], The Practicalities of Climate Change: Adaptation and Mitigation. Proceedings of the 24th Conference of the Institute of Ecology and Environmental Management, Cardiff, 14–16 November 2006. Pp. 102–116.

Heath, M. R., *et al.* 2003. MS. An operational model of the effects of stock structure and spatio-temporal factors on recruitment. Final report of the EU-STEREO project. FAIR-CT98-4122. 1 December 1998–28 February 2002. Fisheries Research Services Contract Report No 10/03. 360 pp.

Hedger, R., McKenzie, E., Heath, M., Wright, P., Scott, B., Gallego, A., and Bridson, J. 2004. Analysis of the spatial distributions of mature cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) abundance in the North Sea (1980–1999) using Generalised Additive Models. Fisheries Research, 70: 17–25.

Hedgren, S. 1979. Seasonal variation in fledging weight of guillemots, *Uria aalge*. Ibis, 121: 356–361.

Heide-Jørgensen, M. P., and Lydersen, C. 1998. Ringed seals in the North Atlantic. North Atlantic Marine Mammal Commission, NAMMCO Scientific Publications. Vol. 1.

Heubeck, M., Harvey, P. V., and Okill, J. D. 1991. Changes in the Shetland guillemot *Uria aalge* population and the pattern of recoveries of ringed birds, 1959-1990. Seabird, 21: 3–21.

Holliday, N. P., Hughes, S. L., Bacon, S., Beszczynska-Moeller, A., Hansen, B., Lavin, A., Loeng, H., Mork, K. A., Østerhus, S., Sherwin, T., and Walczowski, W. 2008. Reversal of the 1960s–1990s freshening trend in the northeast North Atlantic and Nordic Seas. Geophysical Research Letters, 35, L03614, DOI:10.1029/2007GL032675.

Hsieh, C., Reiss, C. S., Hunter, J. R., Beddington, J. R., May, R. M., and Suguhara, G. 2006. Fishing elevates variability in the abundance of exploited species. Nature, 443: 859–862.

Hughes, S., and Holliday, N. P. 2007. ICES Report on Ocean Climate 2006. ICES Cooperative Research Report No. 289, 55 pp.

Hughes, S., and members of the ICES WGOH. 2008. Comparison of in situ time-series of temperature with gridded sea-surface temperature data sets in the North Atlantic. Poster presented International Symposium on Effects of Climate Change on the World's Oceans, Gijón, Spain.

Hurrell, J. W., Kushnir, J., Ottersen, G., and Visbeck M. (eds.) 2003. The North Atlantic Oscillation: climatic significance and environmental impact. Geophysical Monograph Series, 134.

Hutchinson, W. F., Carvalho, G. R., and Rogers, S. I. 2001. Marked genetic structuring in localised spawning populations of cod *Gadus morhua* in the North Sea and adjoining waters, as revealed by microsatellites. Marine Ecology Progress Series, 223: 251–260.

ICES. 1949. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 125. 52 pp.

ICES. 2006a. Zooplankton monitoring results in the ICES area, summary status report 2004/2005. ICES Cooperative Research Report No. 281. 43 pp.

ICES. 2006b. Report of the Study Group on Recruitment Variability in North Sea Planktivorous Fish (SGRECVAP), Dates, Venue. ICES CM 2006/LRC:03. 81 pp. http://www.ices.dk/pubs/crr/crr281/CRR281.pdf.

ICES. 2007a. Report of the Working Group on Zooplankton Ecology (WGZE), 26–29 March 2007, Riga, Latvia. ICES CM 2007/OCC:04. 68 pp.

ICES. 2007b. Report of the Working Group on Fish Ecology (WGFE). ICES CM 2007/LRC:03. 217 pp.

ICES. 2007c. Report of the Working Group on Seabird Ecology (WGSE), 19–23 March 2007, Barcelona, Spain. ICES CM 2007/LRC:05. 123 pp.

ICES. 2007d. Report of the Working Group on Marine Mammal Ecology (WGMME), 27–30 March 2007, Vilm, Germany. ICES CM 2007/ACE:03. 61 pp.

ICES. 2007e. Report of the Working Group on Introductions and Transfers of Marine Organisms (WGITMO), 21–23 March 2007, Dubrovnik, Croatia. ICES CM 2007/ACME:05. 160 pp.

ICES. 2007f. Report of the Working Group on Ecosystem Effects of Fishing Activities (WGECO). ICES CM 2007/ACE:04. 159 pp.

ICES. 2008a. Report of the Working Group on Oceanic Hydrography (WGOH). ICES CM 2008/OCC:01.

ICES. 2008b. Report of the Working Group on Zooplankton Ecology (WGZE), 31 March-3 April 2008 Sète, France. ICES CM 2008/OCC:03.

ICES. 2008c. Report of the Working Group on Fish Ecology (WGFE). ICES CM 2008/LRC:04.

ICES. 2008d. Report of the Working Group on Seabird Ecology (WGSE). ICES CM 2008/LRC:05.

ICES. 2008e. Report of the Working Group on Marine Mammal Ecology (WGMME). ICES CM 2008/ACOM:44.

ICES. 2008f. Report of the Working Group on Ecosystem Effects of Fishing Activities (WGECO). ICES CM 2008/ACOM:41.

IPCC. 2007. Climate change: impacts, adaptation and vulnerability. Ed. by Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Irons, D., Anker-Nilssen, T., Gaston, A. J., Byrd, G. V., Falk, K., Gilchrist, G., Hario, M., Hjernquist, M., Krasnov, Y. V., Mosbech, A., Olsen, B., Petersen, A., Reid, J. B., Robertson, G., Strøm, H., and Wohl, K. D. In press. Fluctuations in circumpolar seabird populations linked to climate oscillations. Global Change Biology.

JNCC. 2008. Joint Nature Conservation Committee; http://www.jncc.gov.uk/page-1704, accessed 30 May 2008.

Jouventin, P., and Mougin, J. 1981. Les stratégies adaptatives des oiseaux de mer. Revue Ecologie, Terre et Vie, 35: 217–272.

Kerckhof, F. 2002. Barnacles (Cirripedia, Balanomorpha) in Belgian waters, an overview of the species and recent evolutions, with emphasis on exotic species. Bulletin van het Koninklijk Belgisch Instituut voor Natuurwetenschappen. Biologie/Bulletin de l'Institut Royal des Sciences Naturelles de Belgique. Biologie, 72(Suppl): 93–104.

Kerckhof, F., and Cattrijsse, A. 2001. Exotic Cirripedia (Balanomorpha) from buoys off the Belgian coast. Senckenbergiana maritime, 31: 245–254.

Kerckhof, F., Haelters, J., and Gollasch, S. 2007. Alien species in the marine and brackish ecosystem: the situation in Belgian waters. Aquatic Invasions, 2: 243–257.

Kirby, R. R., Beaugrand, G., Lindley, J. A., Richardson, A. J., Edwards, M., and Reid, P. C. 2007. Climate effects and benthic-pelagic coupling in the North Sea. Marine Ecology-Progress Series, 330: 31–38.

Kiszka, J., Haelters, J. and Jauniaux, T. 2004. The harbour porpoise (*Phocoena phocoena*) in the southern North Sea: a come-back in northern French and Belgian waters? Document presented at the 11th Meeting of the Advisory Committee to ASCOBANS, 27–29 April 2004, Poland.

Kröncke, I., Zeiss, B., and Rensing, C. 2001. Long-term variability in macrofauna species composition off the island of Norderney (East Frisia, Germany), in relation to changes in climatic and environmental conditions. Senckenbergiana maritima, 31: 65–82.

Kröncke, I., Wieking, G., Neumann, H., and Dippner, J. 2007. Long-term studies reveal climate-induced changes in benthic communities of the North Sea. Ocean Challenge, Vol. 15 (1): 19–23.

Learmonth, J. A., MacLeod, C. D., Santos, M. B., Pierce, G. J., Crick, H. Q. P., and Robinson, R. A. 2006. Potential effects of climate change on marine mammals. Oceanography and Marine Biology: An Annual Review, 44:431–464.

López-Jamar, E., Francesch, O., Dorrio, V., and Parra, S. 1995. Long-term variation of the in-fauna benthos of La Coruña Bay (N.W. Spain): Results from a 12-year study (1982–1993). Scientia Marina, 59: 49–61.

Lynam, C. P., Hay, S. J., and Brierley, A. S. 2004. Interannual variability in abundance of North Sea jellyfish and links to the North Atlantic Oscillation. Limnology and Oceanography, 49: 637–643.

Mitchell, P. I., Newton, S. F., Ratcliffe, N., and Dunn, T. E. 2004. Seabird populations of Britain and Ireland. T. and A. D. Poyser; London.

Møller, A. P., Flensted-Jensen, E., and Mardal, W. 2006. Dispersal and climate change: a case study of the Arctic tern *Sterna paradisaea*. Global Change Biology, 12: 2005–2013.

Nehls, G., and Büttger, H. 2007. Spread of the Pacific oyster *Crassostrea gigas* in the Wadden Sea. Causes and consequences of a successful invasion, BioConsult SH, Husum, 54 pp.

Ottersen, G., Hjermann, D. Ø., and Stenseth, N. C. 2006. Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (*Gadus morhua*) stock. Fisheries Oceanography, 15: 230–243.

Perry, R. I., Cury, P., Brander, K., Jennings, S., Möllmann, C., and Planque, B. 2008. Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. Journal of Marine Systems In press.

Petitgas, P. 2008. Case study Bay of Biscay anchovy RECLAIM http://www.climateandfish.eu/.

Planque, B., Fromentin, J-M., Cury, P., Drinkwater, K. F., Jennings, S., Perry, R. I., and Kifani, S. 2008. How does fishing alter marine populations and ecosystems sensitivity to climate? Journal of Marine Systems. *In press*.

Purcell, J. E. 2005. Climate effects on formation of jellyfish and ctenophore blooms. Journal of the Marine Biological Association of the UK, 85: 461–476.

Rayner, N. 2000. HadISST1 Sea ice and sea surface temperature files. Hadley Centre, Bracknell, U.K.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., *et al*. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, Journal of Geophysical Research, 108(D14), 4407.

Regehr, E. V., Lunn, N. J., Amstrup, S. C., and Stirling, L. 2007. Effects of earlier sea ice breakup on survival and population size of polar bears in western Hudson Bay. Journal of Wildlife Management, 71: 2673–2683.

Regehr, H., and Rodway, M. 1999. Seabird breeding performance during two years of delayed capelin arrival in the Northwest Atlantic: a multi-species comparison. Waterbirds, 22: 60–67.

Reise, K., Dankers, N., and Essink, K. 2005. Introduced species. In Wadden Sea quality status report 2004. Ed. by Essink, K., Dettmann, C., Farke, H., Laursen, K., Lüerßen, G., Marencic, H., and Wiersinga, W. Common Wadden Sea Secretariat, Wilhelmshaven, pp 155–161.

Reiss, H., Meybohm, K., and Kröncke, I. 2006. Cold winter effects on benthic macrofauna communities in near- and offshore regions of the North Sea. Helgoland Marine Research, 60: 224–238.

Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., and Wang, W. 2002. An improved in situ and satellite SST analysis for climate. Journal of Climate 15: 1609–1625.

Richardson, A. J., and Schoeman, D. S. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. Science, 305 5690: 1609–1612.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T. L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S., and Imeson, A. 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature, 453, 353–357.

Sandvik, H., Erikstad, K. E., Barrett, R. T., and Yoccoz, N. G. 2005. The effect of climate on adult survival in five species of North Atlantic seabirds. Journal of Animal Ecology, 74: 817–831.

Sætre, R., Toresen, R., and Anker-Nilssen, T. 2002. Factors affecting the recruitment variability of Norwegian spring-spawning herring (*Clupea harengus* L.). ICES Journal of Marine Science 59: 725–736.

Simmonds, M., and Isaac, S. J. 2007. The impacts of climate change on marine mammals: early signs of significant problems. Oryx, 41:19–26.

Skagseth, Ø., Furevik, T., Ingvaldsen, R., Loeng, H., Mork, K. A., Orvik, K. A., and Ozhigin, V. 2008. Flux of heat, salt and mass to the Arctic Ocean via Norway Coast and Barents Sea. In Arctic–Subarctic Ocean Fluxes: Defining the Role of the Northern Seas in Climate. Eds. Dickson, R. R., Meincke, J., and Rhines, P. Springer, Netherlands.

Smith, D. M., Cusack, S., Colman, A. W., Folland, C. K., Harris, G. R., and Murphy, J. M. 2007. Improved surface temperature prediction for the coming decade from a global climate model. Science, 317: 796–799.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007: Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Spencer, B. E., Edwards, D. B., Kaiser, M. J., and Richardson, C. A. 1994. Spatfalls of the non-native Pacific oyster, *Crassostrea gigas* in British waters. Aquatic Conservation and Freshwater Ecosystems, 4: 203–217.

Stirling, I., Lunn, N.J., and Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climate change. Arctic, 52: 294–306.

Sundby, S., and Drinkwater, K. 2007. On the mechanism behind salinity anomaly signals of the northern North Atlantic. Progress in Oceanography, 73: 190–202.

Sundby, S., and Nakken, O. 2008. Spatial shifts in spawning habitats of Arcto-Norwegian cod related to multidecadal climate oscillations and climate change. ICES Journal of Marine Science, 65: 953–962

Sutton, R. T., and Hodson, D. L. R. 2005. Atlantic Ocean forcing of North American and European summer climate. Science, 309 (5731): 115–118.

Swaby, S. E., and Potts, G. W. 1999. The sailfin dory, a first British record. Journal of Fish Biology, 54: 1338–1340.

Thompson, P. M., and Ollason, J. C. 2001. Lagged effects of ocean climate change on fulmar population dynamics. Nature, 413: 417-420.

Toresen, R., and Østvedt, L. J. 2000. Variation in abundance of Norwegian spring-spawning herring (*Clupea harengus*, Clupeidae) throughout the 20th century and the influence of climatic fluctuations. Fish and Fisheries, 1: 231–256.

Valdés, L., Lopez-Urrutia, A., Cabal, J., Alvarez-Ossorio, M., Bode, A., Miranda, A., Cabanas, M., Huskin, I., Anadon, R., Alvarez-Marques, F., Llope, M., and Rodriguez, N. 2007. A decade of sampling in the Bay of Biscay: What are the zooplankton time-series telling us? Progress in Oceanography, 74: 98–114.

Van Damme, C. J. G., and Couperus, A. S. 2008. Mass occurrence of snake pipefish: result of a change in climate? Journal of Sea Research 57: 000-000. doi:10.1016/j.seares.2008.02.009.

Van Keeken, O. A., Van Hoppe, M., Grift, R. E., and Rijnsdorp, A. D. 2007. The implications of changes in the spatial distribution of juveniles for the management of North Sea plaice (*Pleuronectes platessa*). Journal of Sea Research, 57: 187–197.

Votier, S. C., Bearhop, S., Attrill, M. J., and Oro, D. 2008. Comment: is climate change the most likely driver of range expansion for a critically endangered top predator in northeast Atlantic waters? Biology Letters, 4, 205-206

Wernham, C. V., Toms, P. M., Marchant, J. H., Clark, J. A., Siriwardena, G. M., and Baillie, S. R. eds. 2002. The migration atlas: movements of the birds of Britain and Ireland. T and A. D. Poyser, London.

Worley, S. J., Woodruff, S. D., Reynolds, R. W., Lubker, S. J., and Lott, N. 2005. ICOADS Release 2.1 data and products. International Journal of Climatology, 25: 823–842.

Wright, P. J., Neat, F. C., Gibb, F. M., and Gibb, I. M. 2006. Evidence for metapopulation structuring in cod from the west of Scotland and North Sea. Journal of Fish Biology, 69 (Supplement C): 181–199.

Wynn, R. B., Josey, S. A., Martin, A. P., Johns, D. G., and Yesou, P. 2007. Climate-driven range expansion of a critically endangered top predator in northeast Atlantic waters. Biology Letters, 3: 529–532.

7 Technical Annex: methods

7.1 Assembly of information

Nine Expert Groups (EG) of ICES 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 URLs to obtain their reports are given in the table below. 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. The reports of the EG can be consulted 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

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

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

1. assemble and tabulate cases presented by the EG;
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.

7.3 Adoption of methodology

In order to detect the effects of climate change, WGECO decided to adopt a method based on the one used by the IPCC (2007). A similar paper which extends the IPCC analysis was published in Nature on 15 May (Rosenzweig *et al.*, 2008). The advantages of adopting this form of meta-analysis are:

1. it uses a recognized methodology to address the question "how strong is the evidence that changes in distribution, abundance and condition go beyond normal?";
2. it provides a means of summarizing and adding value to the material provided by the EGs;
3. 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);
4. it is straightforward and involves little additional computation or statistics.

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

(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

One must be aware of a number of potential biases in carrying out meta-analysis. The first is 'positive publication or reporting bias', when results which show a particular type of change are more likely to be transmitted than those which do not. The second potential bias (confirmatory) can develop in advice relying partially 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, to the extent possible, care was taken to develop expectations of patterns that would be present were oceanographic conditions to be a cause of population trends, and to infer the presence and nature of trends from independent information sources1 provided by different experts.

7.4   Assembly and tabulation of data for meta-analysis

The information on zooplankton, benthos, fish, and seabirds provided by the EGs was examined and tabulated. Experts provided information from literature sources considered to report scientifically sound studies, and from databases that had been subjected to suitable quality control in collection and handling of data. Long-term studies were particularly sought after and 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 includes: taxon (usually species, but occasionally 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) is presented. For some fish examples, the start and end dates of the studies is 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 the 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 and
http://www.ices.dk/committe/acom/comwork/report/2008/Special%20Requests/1.5.5.1a%20Additional%20references.pdf]

Each tabulation is intentionally as comprehensive as possible, to provide as large a starting basis as possible for evaluating the evidence for effects of climate change. However, the tabulations are likely to include cases where the selection of species to report may have been biased, and where there may be reasons 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 data set is screened to exclude studies where a confirmatory bias was likely, or where the case was otherwise considered likely to be uninformative or misleading.

7.5   Selection of cases for meta-analysis

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

   a)   remove cases which may have positive reporting bias – papers or reports which stated that they had only reported cases that showed responses to oceanographic conditions were screened out. If we do not know how many species had been examined and not reported then it is impossible to know how many misses, false alarms, and true negatives might correspond to the number of positive matches that were reported.
   b)   remove cases in which there was confirmatory bias, i.e. it was clear that the expectation of change arose from the observed changes and was therefore not a priori.
   c)   remove cases for which an a priori expectation of pattern of change was not given and could not be decided on – In some cases a time-series of a species abundance or range was reported, but too little independent information could be tracked down to make a biologically justifiable prediction of even first-order effects of climate.
   d)   remove cases which specifically report that some pressure other than climate was strongly affecting the species or population These cases would risk missing a true effect of climate, because some other pressure was aliasing its potential effects.
   e)   remove duplicate cases – If 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

---

1 Noting that the scientific literature is actually a web of cross-references, so information in one source may actually have been partially determined by information in an apparently independent source.

analysis. Some duplication may remain through trophic links. Thus, if the range of an important forage fish changes, then it would be expected that there would be parallel effects range on dependent predators (e.g. large fish, seabirds). As outlined earlier, ICES has not attempted to establish the mechanisms behind the changes observed.

7.6   Methods used for meta-analysis

The cases which passed the screening criteria are combined into an integrated meta-analysis which includes all species groups. The null hypothesis is that for cases which show a change the probability that this change is in the direction expected a priori (due to change in ocean climate) is the same as the probability that it is in the opposite direction (i.e. 50–50). The cases are divided into those which show no change, those which change in the expected direction, and those which change in the opposite direction. An example of the resultant numbers and frequencies is shown below. Thus for benthos in OSPAR Region II, nine cases showed no change and 40 showed a change (Table 7.6.1). Of the 40 cases which showed a change 65% (i.e. 26 cases) were in the expected direction and 14 were in the opposite direction. The null hypothesis is that 50% would be in each direction. The analysis depends on the assumption that the expected change is correct. Changes in the 'unexpected' direction could arise because the a priori expectation is wrong or incomplete.

Table 7.6.1   Occurrences of changes in benthos distribution that were in accordance with what is expected from climate change.

OSPAR REGION	SCREENED RECORDS		
	No change N	Change N	Expected %
II	9	40	65
IV	6	13	69

7.7   Choice of expected a priori change

The expected a priori changes due to climate are shown in the Annex. They were 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 abundance to decline and at the cold end an increase in temperature will cause abundance to rise.

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. effect of SST on abundance of pelagic fish (herring and sandeel) that are important in the diet of Atlantic puffins).

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 (positive effect of warming).

7.8   Statistical testing of the null hypothesis

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

7.9 Tables of data and results for meta-analysis

Colour coding represent the percentages that were in the direction expected as a result of effects of climate (Red >75%; Yellow 50–75%; Blue <50%)

Numbers which changed

OSPAR Region	Zooplankton Distribution	Abundance	Other	Benthos Distribution	Abundance	Fish Distribution	Abundance	Seabirds Both	Total	% expected
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 which changed with the expected direction

OSPAR Region	Zooplankton Distribution	Abundance	Other	Benthos Distribution	Abundance	Fish Distribution	Abundance	Seabirds Both	Total	%
I	4	1				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	
	100%	64%	100%	66%	66%	82%	71%	60%	77%	

% with expected change

OSPAR Region	Zooplankton Distribution	Abundance	Other	Benthos Distribution	Abundance	Fish Distribution	Abundance	Seabirds Both
I	100	100				100	62	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 Distribution	Abundance	Other	Benthos Distribution	Abundance	Fish Distribution	Abundance	Seabirds Both
I	0.06250	0.50000				0.25000	0.15710	0.6406
II	0.12500	0.24609	0.00000	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	