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Vulnerability Assessment of the North East Atlantic Shelf Marine Ecoregion to Climate Change

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CONTRIBUTIONS

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The views expressed in this report are the summation of a multi disciplinary gathering of expertise, collated to represent the views expressed and that in scientific journals, rather than the views of WWF.

1. Introduction

The North-East Atlantic Shelf has been identified as a priority ecoregion by WWF. The NEAME (North-East Atlantic Marine Ecoregion (Figure 1.1) has been recognised for its diverse range of coastal and offshore marine habitats including tidal mud flats, fjords and steep cliffs - from the shallow North Sea to the continental shelf break and deep sea. Millions of migratory waterfowl and waders depend on feeding and breeding grounds along the East Atlantic Flyway. The sea is rich in marine wildlife - sharks, seals, cetaceans and seabirds as well as commercially important fish stocks. There are highly productive plankton and bottom-dwelling communities, kelp forests, sea grass beds and even cold water coral reefs.

However, this fragile marine environment is at risk from a number of threats not least climate change. This will have many impacts on the marine environment, particularly upon fisheries and protected areas; but also when considering eutrophication, alien species and hazardous substances. In addition to addressing climate change *per se*, WWF considers it necessary to better understand climate change in order to devise comprehensive and robust work plans in its conservation work and to attempt to support the entire marine ecosystem by building resistance and resilience to climate change.

Consequently, WWF has commissioned a multi-phase project to predict and evaluate the threats to the NEAME from climate change and consider whether it is useful to determine what level of climate change will constitute an acceptable level of threat to coastal and marine environments. In the longer term, the results from this work will inform the development of an adaptation strategy, to build on natural resistance and resilience.

The project's first phase, the scoping study (Baker and Reidy, 2004), reviewed available literature and concluded that the vulnerability assessment would be best achieved by convening a workshop of delegates with substantial scientific and stakeholder expertise from a broad range of relevant disciplines and, over a two day period, consider what are the key potential impacts by focussing on:

- A comparison between the current environmental situation with predicted effects of the UKCIP02 high emissions scenarios where atmospheric CO_2 concentration would rise to 810 mgl^{-1};
- Focus the assessment on the current century only;
- Consider the NEAME as four Areas (Figure 1.1);
- Focus on seven principal characteristics (or pressures), for example sea level rise and as listed below (Section 2.2);
- Consider five principal threats to the ecoregion posed by these characteristics, for example changes to species distributions and as listed below (Section 2.3);
- Concentrate the vulnerability assessment using 19 receptors, representative of the ecoregion's fauna and flora, such as common seal and as listed below (Section 2.4); and
- Include a catastrophic scenario, presented as two separate potential effects.

The workshop consisted of a series of presentations summarising the current state of knowledge of the NEAME environment and climate change predictions to enable a full and consistent understanding of the issues that would then be subject to an assessment of climate change threats by applying the tools of environmental impact assessment. This approach therefore encouraged the use of professional judgement in determining best current thinking to predict the effects in the absence of certain scientific knowledge. This workshop took place in June 2005 and was attended by a wide range of experts and specialists as well as key stakeholders (see Appendix 1).
It should be noted that the workshop process developed the ideas of the scoping report, for example simplifying the scenario analysis, and these differences are covered in the following sections.

The remainder of this report describing the workshop, the assessment and the conclusions drawn, should be viewed as part of an ongoing process rather than an end product. Future progression of our understanding of the issues highlighted in this report will, hopefully, add clarity, resolution and quantification to the analysis. In this way, the means of managing and mitigating the effects described here, and in future, will be identified and developed to achieve successful outcomes in, and for the NEAME.

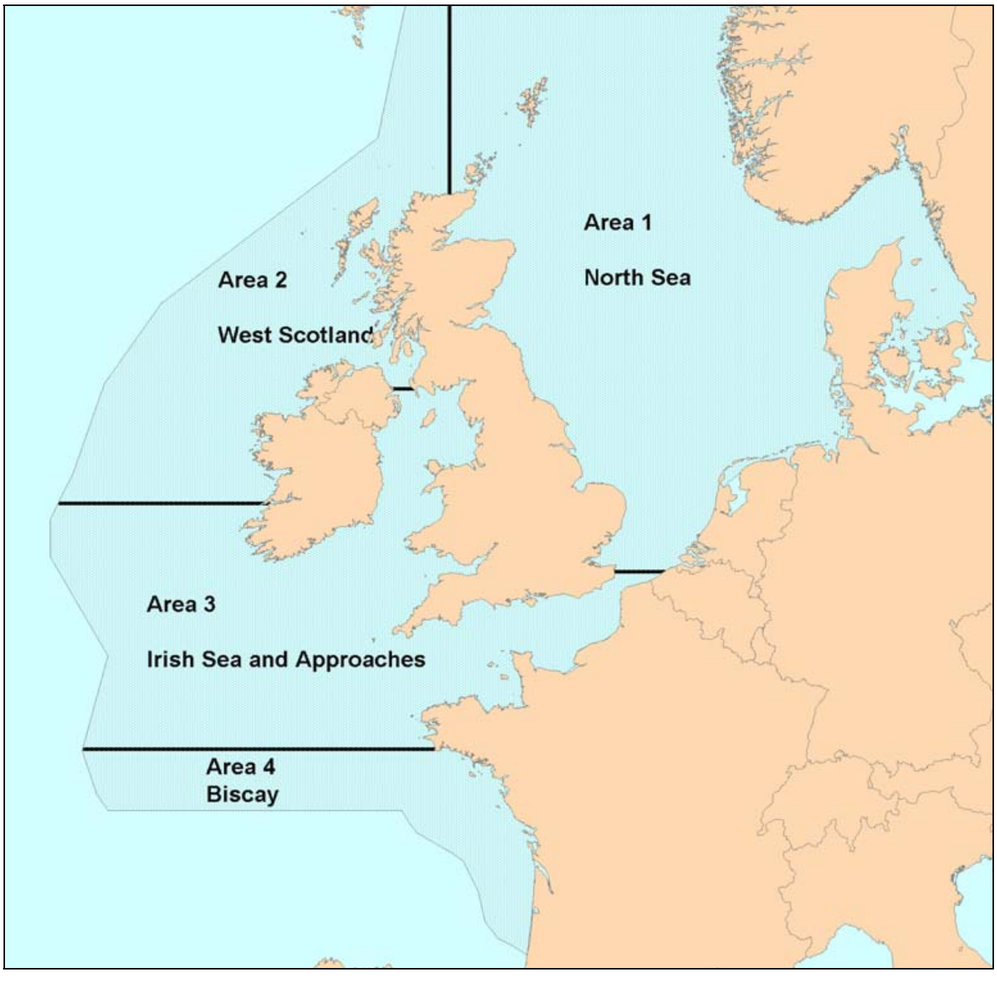

Figure 1.1 The NEAME and sub-divisions (areas) used in the vulnerability assessment. The Areas broadly correspond to ICES regions.

2. Scope of work

2.1 DEFINITIONS

For the purpose of this report, the following terminology has been applied:

- Characteristic: an aspect of environmental change attributable to climate change, typically the characteristic is either a physical or chemical variation from the current (or recent) value. One example would be sea level rise;
- Threat: As a consequence of the changing characteristic, some or all components of the ecoregion may be subject to an impact. It is the features of this impact that is described as a threat. One example would be loss of breeding habitat for terns;
- Receptor: Those species, habitats and other environmental components subject to consideration with respect to assessing the relative significance of the effects that the threats might have, in terms of the parameters of the characteristics covered in the assessment. These have been listed below; and
- Area: the NEAME was subdivided into four areas (Figure 1.1) to allow incorporating regional variation into the assessment.

2.2 CHARACTERISTICS

The scoping phase of this project (Baker and Reidy, 2004) rationalised the preferred approach to the vulnerability assessment and its focus. The workshop phase (see below) further refined this approach and, in so doing, it was determined that the assessment should concentrate on a change in characteristics over the remainder of the 21st century as follows:

- Ocean circulation and the NAO (North Atlantic Oscillation index);
- Sea surface temperature;
- Sea level rise;
- Storm surges;
- Air temperature amplitude;
- Acidification; and
- Nutrient and pollutant inputs, as a consequence of changes patterns of, for example, increased freshwater discharges.

Additionally, the potential for a catastrophic scenario was considered, whereby the effects of a low probability, high risk situation might arise. The characteristics of this were:

- Slowdown of the Gulf Stream; and
- Release of methane from methane hydrates.

The parameters considered for these characteristics are presented in Table 2.1, along with their source and the confidence in their accuracy (see Section 3.1 for further discussion on data confidence). The assessment was based on a comparison of existing conditions (Sections 4 and 5) and the likely effects of these characteristics which in general are from the UKCIP02 High Emissions scenario (Hulme *et al.,* 2002) or approximately similar. This scenario is characterised by the predicted atmospheric CO_2 concentration at the end of the century of 810 mgl^{-1} (Hulme *et al.*, 2002).

Table 2.1: Climate change characteristics considered in the assessment scenario for end of century time horizon.

Characteristic	**Basis: model and scenario**	**Level of confidence**
Average annual sea surface temperature: 1-4 ^oC rise	HadRM3 model, High Emission scenario.	High (UKCIP02)
Regional net sea level rise: 60-85 cm rise	HadCM3 model, High Emission scenario.	High (UKCIP02)
1.5 m storm surges: 1 in 7 years (from 1 in 120 years)	HadRM3 driving a separate high resolution model from POL, High Emission scenario.	Medium (UKCIP02)
Ocean circulation and NAO: Tendency to more positive NAO index mode.	Field observations being extrapolated (Visbeck *et al.,* 2001)	Medium
Ocean acidification: pH decreases by 0.4 (pH 8.2-7.8)	The Royal Society (2005). Projection for 840 mgl^{-l} atmospheric $C0_2$[1].	Not stated in report
Air temperature amplitude: Greater range and increased frequency of extremes	HadRM3 model, tested against measured trends in historic data	High (UKCIP02)
Nutrient and pollutant inputs: Increased runoff	Hypothetical forecasts	Low (workshop consensus)
Plankton seasonality: 4-6 weeks extension	Field observations	High (SAFHOS)

2.3 THREATS

For this assessment, it was necessary to focus attention on representative threats. The scoping report and subsequent refinement at the workshop resulted in the following principal threats being identified and taken forward:

- Changing trophic status with focus on the changes to phytoplankton abundance and composition (also effects of carbonate biochemistry);

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[1] The UKCIP02 High Emission Scenario is for an atmospheric CO_2 concentration of 810 mgl^{-1}

- Changes to growing season, particularly with respect both to plankton (especially *Calanus*) and asynchrony of interactions (phenology);
- Species redistribution, particularly with respect to regional extinctions, alien species with capacity to cause multiple-species impacts and/or have nuisance effect and decline of keystone and economically important species;
- Decline in biodiversity, as a consequence of the above (and others), with a focus on increased community vulnerability to perturbations; and
- In-combination pressures resulting in population crashes/local extinctions.

2.4 RECEPTORS

The focus during the assessment of these threats was on the following key or representative receptors of the NEAME:

- Plankton: diatoms and dinoflagellates, *Calanus finmarchicus* and *C. helgolandicus*, carnivorous zooplankton and meroplankton;
- Fish: Atlantic cod, sandeel (all species), salmon and herring;
- Birds: Waders (collectively) and terns;
- Marine mammals: Harbour porpoise, bottlenose dolphin, fin whale, common seal and grey seal ; and
- Benthos: Representative fauna or biotopes for rocky shore and sublittoral benthic habitats including:
  - Calcifying species;
  - Biogenic reefs such as maerl, *Modiolus* and *Serpula*;
  - Saltmarshes; and
  - Others for specific threats such as kelp forests (storm surges) and isolated water bodies (sea temperature rise).

3. Method

3.1 WORKSHOP PROGRAMME

The two day event initially considered and refined the scope and focus for the assessment after presentation and discussion of the scoping report. A series of presentations, by experts on the characteristics, and discussions followed that in seeking to identify the significant potential effects. Recognition of the most concerning of them was facilitated to enable the vulnerability assessment to progress. Thus, the current level of understanding with respect to the principal characteristics and the threats they pose to the NEAME was discussed (see Appendix 2 for workshop presentations). This was followed by the impact assessment sessions that have provided the basis for the following analysis (see Appendix 2 for workshop notes).

3.2 ENVIRONMENTAL ASSESSMENT

The application of Environmental Impact Assessment (EIA) practices to climate change impacts was considered an appropriate approach in an effort to reconcile the level of concern about the environment with our currently incomplete understanding of both the scale of climate change and the nature of the environmental response. In gathering the best available existing knowledge of the environment and prediction, the EIA approach was applied to consider the implications. The significance of identified environmental impacts can be broad ranging from the trivial to those that are of major concern. The EIA process seeks to identify and focus on those that are considered to be most significant and attempts to address them. In normal application, this would enable a proposed development to evolve its design to limit the degree or extent of an environmental impact and provide decision makers with sufficient information to determine whether the proposals potential significant impacts are acceptable in the face of other benefits (social, economic or other) accrued from consenting the project. In this instance, the output from the EIA process is the identification of the greatest impacts to the NEAME that might arise and inform the process of determining where and if measures can be implemented to mitigate against them. Judging the relative significance of an impact is often a subjective and imprecise to a greater or lesser degree. In order to manage these potentially contentious areas, key factors that inform the impact are considered individually. In this assessment, in an effort to maintain a straightforward approach, only four components of impact were considered as follows:

- Receptor sensitivity to change;
- Importance of the receptor to the ecosystem;
- Spatial scale of impact/change; and
- Magnitude of change.

To establish a consensus on the relative significance of impacts and identify key vulnerabilities, each of these four assessment components was scored on a scale of 1 to 3, with respect to the receptors and their predicted responses to each (where applicable) climate change characteristic. The scoring criteria are defined in Table 3.1.

Table 3.1: Impact assessment components and the scoring criteria

Component	Score	Definition	Note
Sensitivity to change	1	Low	The environmental component's response to an impact is manifest at low, medium or high levels of change in a characteristic. In particular, sensitivity is considered relative to responses to even low levels of incremental change in characteristics.
	2	Medium	
	3	High	
Importance to ecosystem	1	Low	The impact affects an environmental factor that has minimal ecological importance with respect to ecological functionality or community structure.
	2	Medium	The impact affects an environmental component has some ecological importance with respect to ecological functionality or community structure likely to have consequential effects on other parts of the ecosystem.
	3	High	The impact affects an environmental component that is of critical ecological importance with respect to ecological functionality or community structure.
Spatial scale of impact	1	Local	Impacts occur on a scale less than encompassed by a NEAME Area.
	2	Area-wide	Impacts occur across at least one NEAME Area.
	3	NEAME-wide	Impacts occur across the whole NEAME region.
Magnitude of change	1	Low	Changes unlikely to be substantially greater than natural variation within the NEAME.
	2	Medium	Change apparent but not critical to functionality/continued occurrence within the NEAME.
	3	High	Change substantial – functionality compromised, continued presence in the NEAME at risk/ceased.

Application of a simple, unweighted, scoring system for each of these components has provided an assessment of the significance of the potential impact as classified by Table 3.2 where:

- Significance = sensitivity + importance + spatial scale + magnitude.

Table 3.2: Levels of significance

Significance	**score**
Minor	3 – 6
Moderate	7 – 9
Major	10 - 12

3.3 DATA CONFIDENCE

In trying to forecast future changes in climate and the subsequent environmental response, it is inevitable that the accuracy of the predictions require consideration. In this assessment we have to consider both the level of confidence in the future climate change predictions that are the basis of our assessment and also our expectations of the response. The following two sub-sections outline the approach taken in highlighting this issue.

Climate change predictions

Predictions of how future climate change will develop are continually being improved in both their resolution and the extent to which climate change experts have confidence in those predictions. As part of the climate change prediction process, reports are now publishing the degree of confidence in the reliability and accuracy of the prediction to assist the process of considering their potential impacts. Statements on confidence in the predicted changes in characteristics considered in this report are presented in Table 2.1 alongside the parameters used for this vulnerability assessment.

In essence, for there to be a high degree of confidence in the predictions, one needs:

- Models to agree with present day observation and trends;
- Different models agree; and
- The underlying science is sound.

Environmental impact assessment

The robustness of predictions such as those being presented here will be subject to the confidence in the scientific basis of the information used and conclusion drawn. This applies not only to the predicted changes to the environment (the climate change characteristics) but also to the knowledge concerning the receptor, including its natural history, distribution and likely response to changes in the characteristic being scrutinized. As such, in this report we have highlighted the confidence that we have in the accuracy of our predictions (Tables 5.1 to 5.4).

The criteria applied when considering the level of confidence in the assessment are presented in Table 3.3.

Table 3.3: Definitions of levels of confidence in impact assessment forecasts

Confidence	Definitions
Low	Inferred from knowledge of the characteristics of a factor and/or general biology and distributional information of a species or evidence from a similar species.
Moderate	Derived from sources from recognised bodies that consider the likely effects of a particular factor and through extrapolation from similar events or experimental studies on ecological processes.
High	Derived from peer-reviewed sources that specifically deal with the issue under consideration and/or conclusions based on evidence including from experimental studies.

4. Existing Physical and chemical conditions, current trends and predicted changes

The assessment requires a baseline against which the potential impacts are considered. Comparison between the baseline conditions and the predicted changes provides the opportunity to assess the significance of the potential impact. This baseline, described below, as a necessity, needs to take into account climate change effects already considered to be occurring. This section, therefore, summarises the existing physical, chemical and biological environment in the NEAME. It also proceeds into a commentary on the predicted changes used in the subsequent impact assessment based on the scoping report (Baker and Reidy, 2004) and the information presented by the workshop speakers (Appendix 2 Workshop presentations).

4.1 SEA SURFACE TEMPERATURE

Sea surface temperatures in the NEAME range widely from 0°C to more than 21°C (OSPAR Commission 2000b, 2000c, 2000d) in both space and time. The mean sea surface temperature presented at the workshop for the NEAME (see Appendix 2) were:

- Area 1: 9.5 - 11°C;
- Area 2: 9.5 - 12°C;
- Area 3: 11 -13°C; and
- Area 4: 12 - 13°C.

The predicted future climate change for mean sea surface temperature for the UKCIP02 High Emissions scenario suggest that temperatures will increase by as much as 3 or 4°C, particularly in the south east of the NEAME (Figure 4.1). From this figure, it is evident that the temperature rise gradient has a northeast-southwest angle.

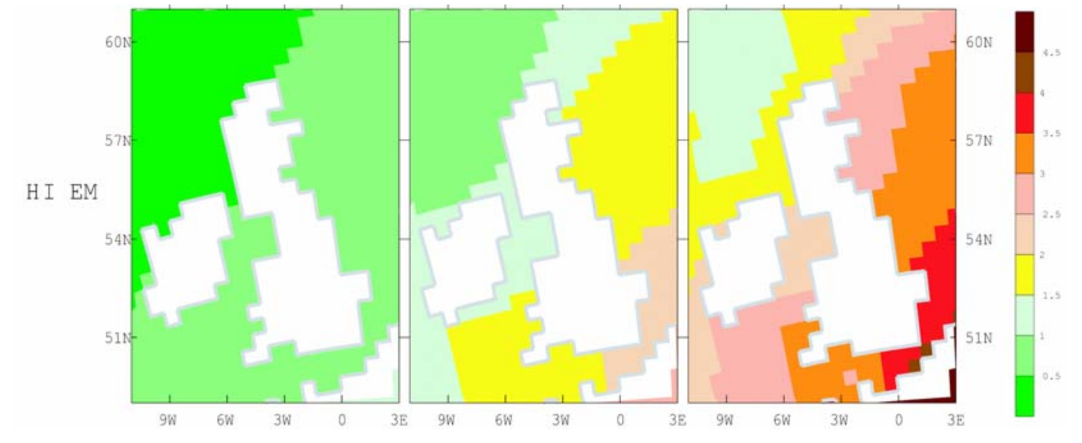

Figure 4.1 Changes in annual average sea-surface temperatures by the 2020's (left), 2050's (middle) and 2080's (right) with respect to model-simulated 1961-1990 average, for the High Emission scenario; results from the original model HadRM3. Source: UKCIP02 Climate change scenarios funded by DEFRA, produced by Tyndall and Hadley Centres for UKCIP.

4.2 NORTH ATLANTIC OSCILLATION

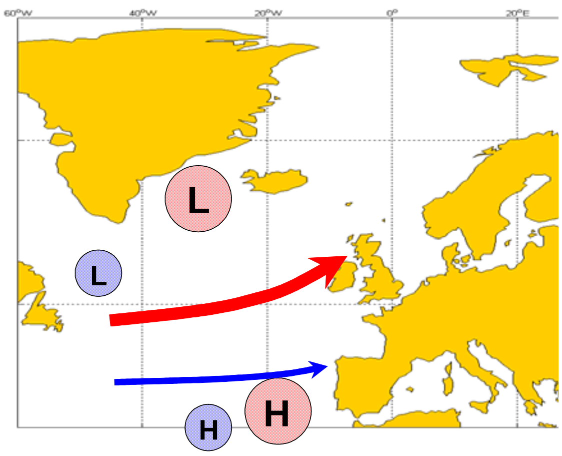

Figure 4.2: Simple schematic of the atmospheric conditions over the North Atlantic associated with the NAO. During the NAO's positive phase (indicated by red), the Icelandic Low and Azores High are intensified, producing strong westerlies (red arrow) that are shifted to the north. When the NAO is in the negative phase (blue), the difference between the pressure centers is diminished and both shift to the west. The westerly winds are weakened and shift to the south (blue arrow).

Normally, in the atmosphere over the North Atlantic, a low pressure area is situated in the north, near Iceland, and a high pressure area is situated in the south of the region near the Azores. This pattern of sea-level pressure causes westerly winds to blow across the northern North Atlantic and hence explains why winds in the NEAME are predominantly westerly.

It has long been observed that winter conditions across the North Atlantic seem to follow a seesaw pattern. For example, when a colder than normal winter is experienced in Greenland it is often true that there is a warmer than normal winter on the opposite side of the North Atlantic in Scandinavia and vice versa. A similar seesaw pattern can be seen in the winter rainfall across the North Atlantic. This seesaw pattern in climate variability is now known as the North Atlantic Oscillation (NAO). The 'oscillation' is a change in the intensity of the low and high pressure areas, which in turn affects the strength and location of the westerly winds blowing across the North Atlantic.

In the NEAME, when the NAO Index (NAOI), a measure of the winter sea level pressure difference between the low and high pressure areas, is positive, westerly winds are intensified and move further north, bringing warmer and wetter than average conditions (Figure 4.2). When the NAOI is negative, westerly winds are weaker and displaced further south. This causes cooler and drier than average conditions.

Although the NAO is an atmospheric phenomenon, there is also a strong link between conditions in the atmosphere and those in the ocean, particularly through the driving forces of wind, surface heating and rainfall. The NAOI can be correlated with sea surface temperatures across the North Atlantic and changes in the NAOI have been used to explain observed changes in many aspects of the marine ecosystem, from plankton to fish.

The NAO appears to vary on a decadal timescale. During the 1960s the NAOI was mainly negative and during the 1990s the NAOI was mainly positive (Figure 4.3). The NAO is thought to have a natural mode of variability, and so would be expected to continue with this decadal pattern in the future (Visbeck *et al.,* 2001).

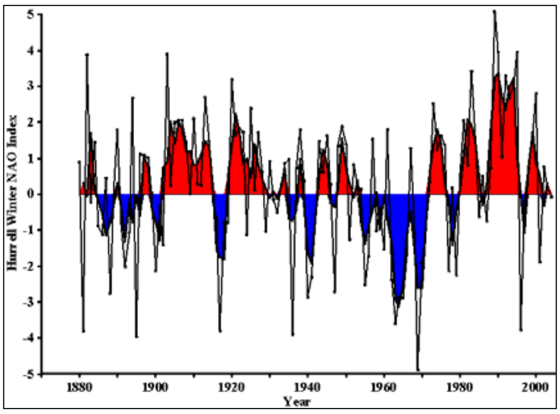

Figure 4.3: The Hurrell Winter (DJFM) Index from 1880 to 2005. Annual values are shown by dots. The think line is a 3-year running mean, shaded red to indicate positive values and blue to show negative values.
NAO Index available:
ww.cgd.ucar.edu/~jhurrell/nao.stat.winter.html

The upward trend in the NAOI between 1960 and 1990 accounts for much of the warming observed over that period and so it is possible that anthropogenic climate change is also influencing the NAO. It was therefore suggested that the positive phase of the NAO might continue into the future. However, since 2000 the NAOI has been weak and variable, as the pattern of sea level pressure anomaly across the North Atlantic has not fitted with what we think of as a typical NAO pattern. Despite the weakened, NAOI, during this time sea surface temperatures over the whole North Atlantic have continued to rise and warmer than normal conditions have been observed on both sides of the North Atlantic.

Future predictions for the North Atlantic Oscillation

Present thinking suggests that in the future, decadal variability in the NAOI will certainly continue, though there is the possibility of a trend towards a more positive mode.

4.3 OCEAN CIRCULATION

In terms of ocean circulation, conditions on the western continental shelf (NEAME Areas 2, 3 and 4) can be described as a single unit whereas conditions in the North Sea (NEAME Area 1) are slightly different.

The Gulf Stream

In order to understand ocean circulation on a regional level, it is first necessary to take a step back and look at ocean currents in the wider North Atlantic. The surface circulation of the North Atlantic has two main parts as shown in Figure 4.4; a clockwise rotating southern gyre of warm and quite salty water (sub-tropical gyre) and a cooler fresher anti-clockwise gyre further north (sub-polar gyre).

The sub-tropical gyre is driven by the pattern of winds blowing over the oceans. The effect of the earth's rotation intensifies the strength of the current on the western boundary of the ocean, therefore the sub-tropical gyre bunches up against the coast of North America and is more diffuse on the African coast. The strong intensified current flowing northward along the American coastline is known as the Gulf Stream.

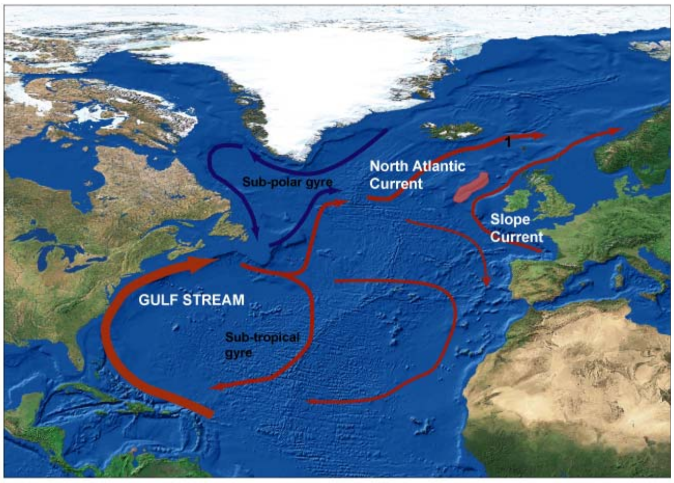

Figure 4.4: A simplified picture of the surface circulation of the North Atlantic. The cooler, fresher waters of the sub-polar gyre are shown in blue with the warmer saltier waters of the sub-tropical gyre shown in red. The shallow ridge that runs between Greenland, Iceland and Scotland and forms a barrier to the flow of deep waters between the Arctic basin and the North Atlantic basin is marked as (1).

The strength and position of the Gulf Stream can vary, and this is thought to be linked to the strength of the NAO. The Gulf Stream Index (a measure of the northward extension of the Gulf Stream) is sometimes used as an indicator of conditions in the NEAME. A positive NAO has been linked to a more northward position of the Gulf Stream.

The North Atlantic Current

A large percentage of the Gulf Stream water re-circulates around the Sargasso Sea. Some of the water makes it across to the eastern North Atlantic. Some of this flow turns south towards the Bay of Biscay, some of it takes a more northerly route. The current flowing from the tail end of the Gulf Stream across the Atlantic toward northern Europe is called the North Atlantic Current. It is not a well defined stream, and is still the subject of much research. This current is partly wind driven and partly driven by the density differences between the warmer southern water and the cooler northern water. About 10-20% of water delivered to the Flemish Cap, on the east coast of Canada, by the Gulf Stream makes it to the latitude of Scotland.

The European Slope Current

The western margin of the NEAME is marked by a sharp change in the depth of the seabed, from less than 250m, the continental slope drops rapidly into water deeper than 2000 m (Figure 4.5). A jet-like current, known as the European Slope Current (ESC) flows in a poleward direction along the edge of the continental slope. Some of the North Atlantic water that reaches the Bay of Biscay joins the ESC. The waters in the slope current also originate from the Iberian region.

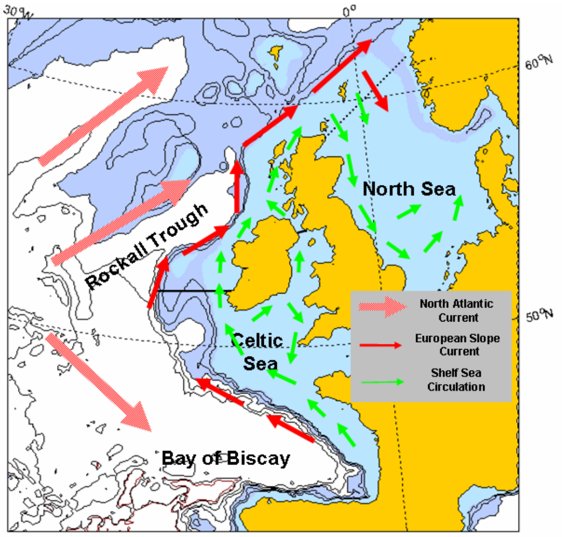

Figure 4.5: A simplified picture of the surface circulation of the NEAME

The steep bathymetry itself acts as a barrier, reducing the amount of water that can travel from the deeper waters of North Atlantic into the shallower waters of the continental shelf. As the slope current flows along the bathymetry, it can mix with waters from the Atlantic. The slope current sometimes changes direction, because of winds or other physical processes and these fluctuations help to bring Atlantic waters onto the continental shelf. The slope current is thought to have a very important role bringing Atlantic Waters into the northern part of the North Sea.

The ESC is important as it brings warmth, nutrients and plankton. Changes in the intensity of the ESC are thought to be linked to recent marked changes in the ecosystem of the North Sea (Reid *et al.*, 2001). The slope current appears to vary with the seasons, and can be stronger in winter than in summer. Its strength and direction can be affected by local winds.

Shelf sea circulation

Over most of the NEAME region, water depths are less than 250m, and average at around 100m. Currents on the continental shelf, in water depths less than 250m shelf are mainly driven by winds and tides, although narrow coastal currents and jets along seasonal fronts can be driven by density gradients. Tidal currents are reliable and predictable and stronger than the residual current in many areas. Tidal currents cause mixing in the water column and, particularly in the shallower areas in the Celtic Sea and southern North Sea, are the most important control on the location of stratification.

However, when we consider the way water circulates around the NEAME, the overall effect of the tides is quite small as tidal currents mainly move water back and forth. The residual current, which has an overall effect of moving water around the shelf areas of the NEAME region, is mainly driven by winds and density driven coastal currents and frontal jets.

The overall pattern of circulation is therefore quite variable, but over a year would average to give a pattern similar to that shown in Figure 4.5. Circulation in the North Sea (Area 1) is predominantly anti-clockwise. Circulation on the shelf west of Scotland (Area 2) is mainly northwards. There is a clockwise circulation in the Celtic Seas (Area 3). In the south of the NEAME region (Area 4) there is again a northward current flow. When the dominant wind direction becomes more south-easterly, the circulation in the North Sea becomes weaker and the dominant direction is less well defined, circulation on the shelf west of Scotland (Area 2) may be intensified and circulation in the south of the NEAME (Areas 3 and 4) becomes predominantly northward (Pingree *et al.,* 1980).

Thermohaline circulation

Whilst previous sections have discussed the effect of global climate change on regional ocean circulation, it is also necessary to consider the effects of changing global circulation on regional climate.

The bathymetry of the North Atlantic can be simplified by considering it as one deep basin connected to the shallower Nordic/Arctic basin by an even shallower sill, a ridge that goes all the way from Greenland to Scotland (Figure 4.4). This ridge plays an important part in the thermohaline circulation (THC).

The thermohaline circulation (THC) is that part of the ocean circulation that is driven by density differences. In contrast to the wind driven circulation, the thermohaline circulation is not confined to the surface waters. In the North Atlantic, in simple terms, the important aspects of the thermohaline circulation are:

- Cooling and sinking of water at high latitudes in the Nordic/Arctic basin.
- Flow of deep water over the Greenland-Scotland ridge from the Nordic/Arctic basin into the Atlantic basin.
- Flow of warm and salty surface waters northward into the Nordic/Arctic to replace the water leaving the Nordic/Arctic basin.

There is often confusion between the thermohaline circulation and the Gulf Stream. This is partly because in that region of the North Atlantic, the circulation of the Gulf Stream and the THC are linked and follow the same path. It is estimated that the THC contributes only 20% of the Gulf Stream flow. Another reason for the confusion is that in order to make it easier to get the message across to the audiences, who know about the Gulf Stream, the terms are often mixed up by scientists.

The salinity of the ocean is very important when considering this circulation; if water is fresh (less saline) it won’t sink even if it gets very cold. Freshening of surface waters can, therefore, disrupt the whole process.

Over the last few decades there has been increasing evidence that the flow of deep water over the Greenland-Scotland ridge has decreased and that the cooling and sinking of water at high latitudes has decreased or even stopped. This suggests that some changes to the northward flow of warm and salty surface waters should be expected. Investigation of ice core data has shown that, in the geological past, the THC has been weakened or even stopped and this has had a marked impact on the climate of the NEAME.

Ocean climate models have shown that if the THC stops, the annual average temperatures over Scandinavia and Britain could drop by between 5-10°C. However, the ocean-atmosphere system is complex and linked which means that our understanding is incomplete and the models available today are still an oversimplification.

A total collapse of the THC can be simulated with ocean-climate models, but with our current understanding, although this would have a high-impact it is currently an unlikely scenario. A more likely scenario is a weakening of the THC, reducing it by 20-50%. This scenario is already included in future climate models that still predict warming in the NEAME over and above the cooling effect of a reduced THC.

Future predictions for ocean circulation

The following predicted future changes with respect to ocean circulation represent the current scientific thinking as presented at the workshop:

- Predicted changes in the wind patterns in the North Atlantic may change slightly but it will not be enough to alter the clockwise flow of the Gulf Stream;
- With respect to the North Atlantic Current, changes in the pattern of winds and changes in density gradient by the end of the century may have a minor impact on the strength and location of the North Atlantic Current, although it will continue flowing towards the NEAME;
- Any changes in temperature and salinity distribution in the North Atlantic will affect the north-south density gradient and this may have an impact on the strength of the European Shelf Current;
- For Shelf Sea Currents, predicted changes in the mean sea level in the NEAME will be insufficient to have a significant impact on the strength or patterns of tidal currents. Any changes in the strength and direction of wind will have an effect on the residual circulation patterns, as will changes in freshwater runoff from the land;
- There is a remote possibility of total collapse of thermohaline circulation caused by global climate warming. This would lead to regional reduction in air and sea temperatures; and
- The more likely scenario would be of reduced THC caused by global climate warming with no overall regional reduction in air and sea temperatures as these will rise due to future climate change by an amount greater than the predicted fall from the THC shutdown.

4.4 NET SEA LEVEL RISE

The amount of net sea level rise in the North East Atlantic is presently 1 mm yr^{-1} but forecast to increase by as much as 86cm by the end of the 21st century (Hulme *et al.,* 2002). Even if greenhouse gas emissions were stabilised today, sea level rise will continue for the next 1000 years.

Predicted changes in sea level rise are varied, particularly on a regional scale, depending on the model used, the amount of isostatic adjustment in land elevation[2] and the regional variation in the extent of ocean warming and thermal expansion. UKCIP reports a global average sea level rise by the end of the century, relative to the 1961-1990 average, of an increase by upto 69cm for the High Emissions scenario. Taking this into account, a rise in sea level was considered of between 60 to 85cm. This value is the global-average mean sea level rise and isostasy.

4.5 STORM SURGES

Storm surges are temporary increases in sea level, above the level of normal tides, caused by low atmospheric pressures and strong winds. The change to the incidence of 1.5m storm surges is predicted to increase as the century progresses. For the purpose of this work, we have taken a change in probability of such an event occurring in 1 in 7 years, from the current situation of 1 in 120 years such as predicted at Immingham (Figure 4.6). This predicted change is given by the UKCIP02 Medium High Scenario (Hulme *et al.,* 2002).

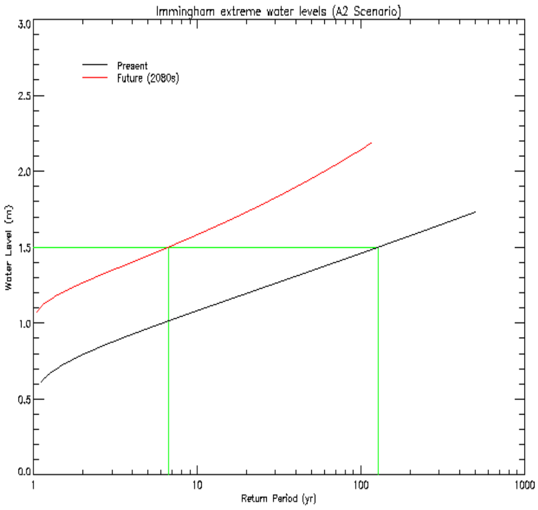

Figure 4.6. Predicted changes (by the 2080s) in storm surge return periods at Immingham for the UKCIP02 Medium High Emissions scenario in comparison with the baseline (1961-90) period. (From Hulme *et al.*, 2002)

4.6 OCEAN ACIDIFICATION

A recently published report (The Royal Society, 2005) summarised the current level of understanding with respect to how the pH of the ocean is changing as a consequence of an increase in the concentrations of atmospheric CO_2. CO_2 concentrations are currently at a level of 380 mgl^{-1}, compared with the pre-industrial level of 280 mgl^{-1}. Ocean surface waters have a pH of 8.2 ± 0.3[3] and are already 0.1 pH units below pre-industrial levels. Notably, this is equivalent to a 30% increase in concentration of hydrogen ions in the water and is a consequence of the absorption, each year, of some 2 Gt C into the oceans. Presently, some 6 Gt C yr^{-1} are released into the atmosphere by human activities.

Some forecasts suggest that by 2100, atmospheric CO_2 levels might reach 1000 mgl^{-1} unless emissions are substantially reduced. Present trends in emissions will lead to a decrease in pH of up to 0.5 units by 2100 in ocean surface waters. This is outside of the natural range and, critically, the rate of change is at least 100 times greater than any experienced during the previous several hundreds of thousands of years. Because of this unprecedented rate of change and substantial drop in pH value, the scientific community is greatly concerned about this threat, not just to the NEAME. As will be seen in Section 5, ocean acidification generated a great deal of concerned debate across the ecological disciplines at this workshop.

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[2] Post-glacial regional land movements, where changes in land elevation, are occurring as a consequence of the weight of ice being removed. For example in Scotland it is rising by 0.7/1.0 mm yr^{-1} and in Southern England it is falling by 0.6 to 1.5 mm yr^{-1} (Hulme *et al.* 2002).

[3] Where temperatures are lower and deep water upwellings occur, pH will be lower.

For the purpose of this assessment, a fall in pH by the end of the century was predicted to be from the current pH of 8.2 to 7.8. This corresponds to the published predictions assuming current trends with respect to CO_2 emissions continues for the remainder of the 21st Century, resulting in an atmospheric concentration of 840 mg l^{-1} (The Royal Society, 2005). This is the best approximation to the UKCIP02 High Emissions scenario, of 810 mg l^{-1} by 2100 (Section 2).

4.7 AIR TEMPERATURE AMPLITUDE

Changes in diurnal temperature range are forecast as a consequence of climate change. This is primarily driven by variation in cloud cover. For a High Emissions scenario, UKCIP02 forecasts, by the end of the century, a UK-wide increase of more than 1^oC in the summer diurnal range except around the coasts of Scotland and Northern Ireland. Data for other parts of the NEAME were not acquired or discussed in this regard. The predicted changes are summarised as follows:

- Nights warm by more than days during winter;
- Days warm by more than nights during summer;
- During autumn and spring, changes would be less marked; and
- In the northwest UK, there would be decreases in diurnal range whilst in the southeast UK experiencing increases.

During the workshop assessment, this parameter was considered to be a potential impact only upon intertidal invertebrate fauna and flora. No quantification was applied to the assessment, although consideration of the effect of an increase in mean annual air temperature was included (Section 5.2)

4.8 CATASTROPHIC SCENARIOS

The scoping report assessed the necessity to consider potential non-incremental and high impact characteristics of climate change, The scoping exercise considered it appropriate to consider, as a catastrophic scenario, the threat of a Gulf Stream slowdown, where the decline in this process would result in a multi-degree decline in temperature over a very short time period (a few decades at most). Though the scoping study dismissed the scenario of the mass release of methane trapped in methane hydrate reservoirs, this scenario was presented and discussed at the workshop. The main reason for this was that though the scoping study identified the lack of evidence for substantial and vulnerable reservoirs of methane hydrate in the NEAME, the large amounts in adjacent regions, particularly in the Arctic, suggested a potential risk to the NEAME might remain. The following sub-sections summarise the presentations and discussions at the workshop and explain why it was concluded that neither posed a significant threat to the NEAME within this century.

Methane release from methane hydrate sources

Methane hydrate is an ice-like substance that has molecules of methane trapped within a cage of water molecules. This cage allows the methane molecules to be held close together, much closer than in a free gas. There is up to $164m^3$ of gas at standard temperature and pressure, and $0.8m^3$ of water, in $1m^3$ of solid hydrate. However, methane hydrate is not stable at normal temperatures and pressures. Methane hydrate exists at higher pressures and generally lower temperatures (Figure 4.7). Such conditions exist on the continental slopes around the world and under permafrost in the northern hemisphere. Current estimates of global reserves of methane hydrate are 2×10^{14} m^3 of methane in natural gas hydrate (Soloviev, 2002). This is about 30 times the amount of methane in the present atmosphere, where it is a powerful greenhouse gas. As well as being found in water depths generally greater than 500m on virtually all continental margins, hydrates associated with permafrost have been encountered in Siberia, Alaska and the Canadian Arctic (Kvenvolden and Lorenson, 2001). However unlike other resources, their occurrence and relationship with host sediments is poorly understood, and it is only with improvements in this that their input to the global carbon cycle will be better understood[4].

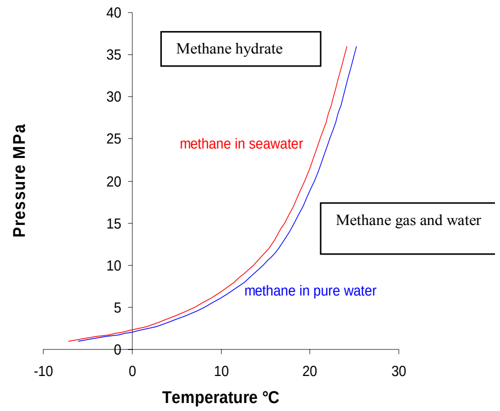

Figure 4.7. The relationship between temperature and pressure for the stability of methane hydrate in seawater and freshwater.

Generally in the NEAME, there is a paucity of evidence for the presence of methane hydrates, even in the deep waters west of the UK, despite the extensive surveys conducted as part of hydrocarbon exploration, as well as numerous academic studies. Adjacent to the NEAME, however, methane hydrates are known to occur in the Arctic, both terrestrially in permafrost and in marine sediment layers.

Methane hydrates trapped under pressure in marine sediments are not likely to be exposed to conditions resulting in their release in the coming centuries, given that sea levels (and hence pressure) is not predicted to fall. As such, it has been concluded that the potential for large-scale release of methane from a hydrate source in a catastrophic manner in or adjacent to the NEAME is too remote a possibility to consider further in this assessment.

Methane is around 25 times as effective a greenhouse gas as carbon dioxide, thus, methane from the global hydrate reservoir reaching the atmosphere represents a significant potential contributor to global warming. Already, the extent of permafrost is decreasing as it melts due to inundation by water (at temperatures above freezing) and air temperature rises. The loss of this permafrost (in arctic and other regions) that is trapping methane hydrate is already leading to the release of methane direct to the atmosphere. With climate change further increasing air and sea temperature as well as sea level rise, there is the probability of an increase in the amount of permafrost being melted. Thus, there is the real potential to develop a significant positive feedback system in which gas hydrate release responds to, and accentuates, global warming. It is striking that the melting of permafrost and the consequential release of methane at present seems to be unmeasured and is not being monitored.

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[4] Similarly, the potential for their exploitation as a carbon-based energy source is being researched.

Gulf Stream slowdown

As described above (Section 4.3), the ocean circulation of the NEAME in general and the Gulf Stream specifically (including, in this scenario thermohaline circulation), indicate that climate change impacts may be characterised by some directional and strength changes over the coming decades. However, these changes are relatively small and there remains only the remote possibility of a dramatic and rapid decline in the stream.

As such, for the purpose of this assessment, the potential for this catastrophic scenario being realised is considered not to be a likely threat to the NEAME.

5. Ecological baseline and current trends

5.1 PLANKTON

Over the last decade there has been a progressive increase in the presence of warm-water/subtropical species into the more temperate areas of the north-east Atlantic, with 2003 continuing with this trend. Sea Surface Temperature (SST) was very high in the North Sea during 2003, particularly in August and September (Edwards *et al.,* 2005). In the north-east Atlantic, over the past four decades, plankton characteristic of warmer water have advanced northwards by 10° latitude. In similar fashion cold water plankton assemblages have retreated north. There is no equivalent to this in terrestrial studies (Beaugrand *et al.,* 2002; Beaugrand, 2003; Edwards and Johns, 2005).

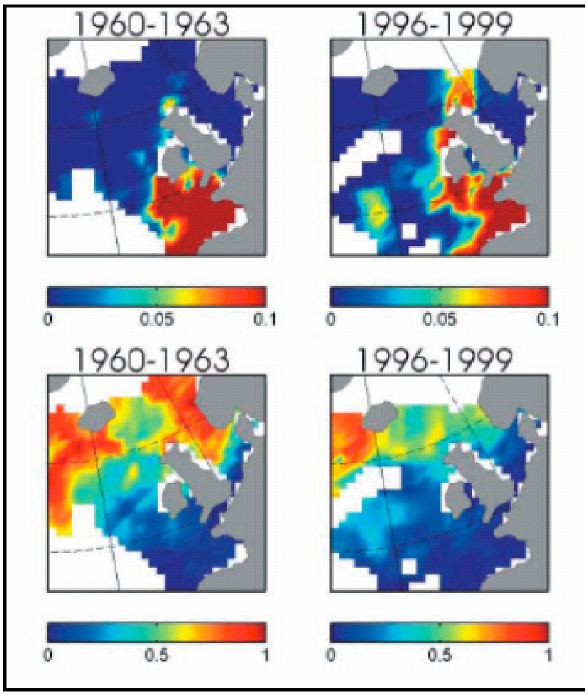

Figure 5.1: Maps showing the changing biogeographic distributions of a warm temperate (top) and sub-arctic assemblage (bottom) of planktonic copepods between the years 1960-63 and 1996-99 (Beaugrand *et al.,* 2002). Reproduced with permission of Martin Edwards, SAHFOS.

Beaugrand and Ibanez (2004) identify a regime shift for North Sea planktonic ecosystems during the period 1958-1999 (Figure 5.1). From 1962-1982 the regime is, ‘cold-biological’, from 1984-1999 it is, ‘warm biological’. This regime shift was forced by local and regional hydroclimatic (wind and temperature) changes in conjunction with the change in the location of the oceanic biogeographical boundary in the North-East Atlantic. The results of Beaugrand and Ibanez (2004) indicate a strong dependence of ecological processes in the North Sea to both hydro-climatic and biological variability in the north-east Atlantic Ocean. With current climatic warming, further regime shifts are possible, which may confound attempts to predict future responses of North Sea pelagic ecosystems.

Calanus finmarchicus and *C. helgolandicus*

The most abundant zooplankton species in the North East Atlantic are copepods (DEFRA, 2005c). In the NEAME, an estimated 90% dry weight of the total biomass of zooplankton may be attributable to species of the genus *Calanus* (OSPAR QSR 2000).

Against the backdrop of inter-annual variations, the Continuous Plankton Recorder (CPR) records show an overall downward trend in copepod abundance in much of Areas 1, 2 and 3 with the decline particularly evident on the Malin Shelf and to the west of Ireland in this latter region (OSPAR QSR 2000, 2000c). More recent analysis (Edwards *et al.*, 2005) of North Atlantic CPR data from 1946-2003 shows that copepod abundance is in long-term decline in many areas to the east of Iceland.

The ratio of the cold-temperate *Calanus finmarchicus* to the warm-temperate *Calanus helgolandicus* is a useful indicator of the warming trend in the North Sea (Figure 5.2). The dominance of *C. helgolandicus* over the last decade is clear. It should also be noted that the overall abundance of *Calanus* in the North Sea has considerably declined. This has important implications for other trophic levels (Edwards and Johns, 2005). A similar pattern has been observed in the Celtic seas (Nash and Geffen, 2004), with *C. helgolandicus* becoming more numerically abundant during warmer conditions (such as a positive NAOI).

The relative abundance of the two *Calanus* species has been shown to reflect both the northerly movement, by 10° latitude, of warmer water plankton in the last 40 years (as mentioned above) and changing patterns of inflow of oceanic water into the North Sea (DEFRA 2003, Reid *et al.,* 2003).

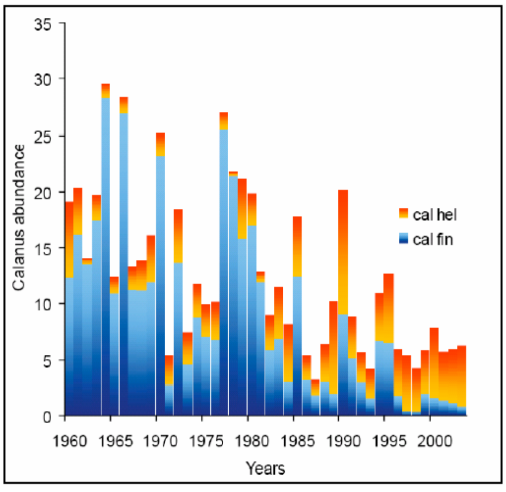

Figure 5.2: The abundance of *Calanus* populations in the North Sea from 1960 to 2003. The percentage ratio of *Calanus finmarchicus* (blue) and *Calanus helgolandicus* (red) are shown in relation to total *Calanus* abundance in each annual bar. Reproduced with permission of Martin Edwards, SAHFOS.

Calanus finmarchicus over-winter at depths of 500 to 1500m in the Norwegian Sea, Faroe-Shetland Channel and other seas. During mid-late summer, pre-adult stages become dormant and sink out of the surface waters. For up to six months they exist in a state of hibernation or, timing their return to near surface waters to coincide with the spring phytoplankton bloom (OSPAR 2000; Heath *et al.*, 2004 and FRS 2004).

In the north east Atlantic, *Calanus finmarchicus* emerge from dormancy in early February and over a period of about one month ascend to the surface waters. On arrival at the surface the females produce a small number of eggs, utilising residual lipid reserves, but the main reproductive output from the over-wintered stock is triggered by the spring phytoplankton bloom. In the surface waters, the animals encounter a different circulation regime from that at the over-wintering depths. In spring many are carried into the North Sea, maintaining the productive summer stock (Heath *et al.,* 1999).

Changes in wind patterns and a declining volume of bottom water have effectively reduced the supply of copepods to the North Sea (FRS 2004; Reid *et al.*, 2003). Other factors influencing *Calanus* distribution include:

- Northward biogeographic shift of cold boreal species like *C. finmarchicus* that has occurred over the last 40 years (Beaugrand *et al*., 2002); and
- A strong and warm Slope Current possibly preventing incursion of *Calanus* in the spring onto the shelf.

In the Celtic Seas (Areas 2 and 3) copepods accounting for up to 97% dry weight of the total zooplankton biomass. *C. finmarchicus* and *C. helgolandicus* are abundant in the Celtic Sea itself and over the Malin Shelf but *Calanus* are not dominant. Instead, small copepod species are the abundant form in both near shore environments and, to a lesser extent, any stratified regions. In the Celtic and Irish Sea these small species vary in abundance from year to year less than the larger *C. finmarchicus* and *C. helgolandicus* which can vary by an order of magnitude. In addition to the wide inter-annual variability, the CPR records also show an underlying downward trend in copepod abundance, compared with the North Sea, particularly on the Malin Shelf and to the west of Ireland, and is believed to be climatically induced (Edwards and Richardson 2002; OSPAR, 2000/2000c; Napier, 2004a; and Nash and Geffen, 2004).

Nash and Geffen (2004) found, from studies to the west of the Isle of Man (central Irish Sea) 1995-2001, that the maximum abundances of *C. finmarchicus* and *C. helgolandicus* occurred between May and July. *C. finmarchicus* maxima tended to occur earlier than *C. helgolandicus*.

A comparison of CPR data for the English Channel, Bay of Biscay and Celtic Sea between 1979 and 1995 showed that negative NAO strongly influences the copepod community in the Channel (*Acartia* spp., *Calanus helgolandicus*, *Centropages typicus*, *Oithona* spp. and *Para-pseudocalanus* spp.). This occurs through a number of mechanisms including turbulence, though this relationship could not be extended to other areas. The local physical environment and biological composition appear to modify the relationship between winter climatic conditions and inter-annual fluctuations in the plankton community (Southward *et al.,* 2005).

The movement of warm water copepod assemblages northward, with a southward retraction of cold-water assemblages has resulted in fewer cold water species in the western English Channel. Additionally there has been an increase in the generally warm water pseudo-oceanic temperate species assemblage comprising *Rhincalanus nasutus*, *Eucalanus crassus*, *Centropages typicus*, *Candacia armata* and *Calanus helgolandicus* (Southward *et al.,* 2005). The zooplankton community of Area 4 is characterised by the following seven species, listed in order of abundance: *Paracalanus parvus, Acartia clausi, Clausocalanus spp., Oithona plumifera, Calanus helgolandicus, Temora longicornis* and *Centropages typicus (*OSPAR QSR, 2000d).

Diatoms and dinoflagellates

Figure 5.3 illustrates that since the late 1980’s the growing period for phytoplankton in the North Sea has extended throughout the year. In particular the diatom dominated spring and autumn peaks in phytoplankton abundance, most obvious between 1946 and the mid 1980’s, disappear in sustained growth throughout the summer. The phytoplankton colour values of the spring and autumn blooms are relatively unchanged but the winter and summer values have significantly increased. The result is a large increase in phytoplankton biomass since the late 1980s. It is also suggestive of a shift in phytoplankton dominance from diatoms to flagellates and dinoflagellates (Edward and Johns 2005).

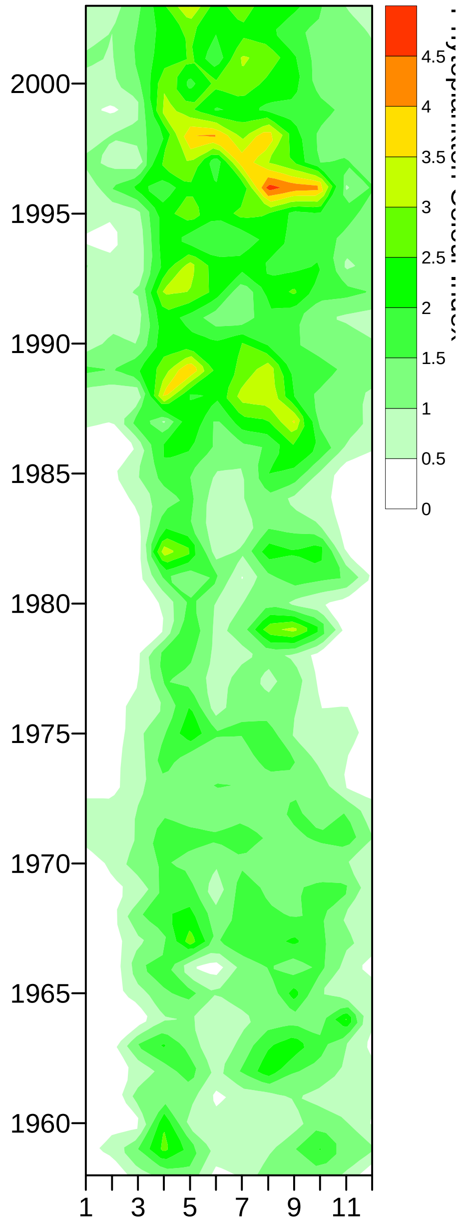

Figure 5.3. Monthly means of phytoplankton colour in the North Sea (1956 – 2004).

Nutrient input to the German Bight and Dutch coast from rivers such as the Rhine and Elbe have changed phytoplankton communities through the process of eutrophication. But the influence of increased nutrient concentrations does not extend far into the North Sea from these hydrographically isolated regions. The CPR phytoplankton colour analysis identified a marked increase in colour after 1986 not only for the nutrient enriched southern continental region, but also the central and northern North Sea and at least one oceanic region of the north Atlantic. This reinforces the interpretation that the long term changes seen in the plankton communities of the North Sea are climatically driven (Edwards *et al.,* 2001, Clark and Frid 2001)

Harmful algal blooms of some dinoflagellate species are consequently becoming more common in the north-east Atlantic. For instance in 2001 blooms of *Dinophysis* spp. in the North Sea were well above average. The frequency of these blooms is correlated with temperature. Research suggests that when cool regions become warmer, phytoplankton abundances increase, but when warm regions get even warmer the phytoplankton abundance decreases. The impacts of changes in phytoplankton production patterns may therefore vary from region to region with important consequences for the fish, seabirds and marine mammals which inhabit them and their subsequent struggle to adapt (Edward and Johns 2005, Richardson and Shoeman 2004, Edwards and Richardson 2002).

Meroplankton

Information on the meroplankton (temporary plankton consisting of the pelagic stages of organisms which also have benthic stages) is limited (DEFRA 2005c), though what is known suggests an increase in the relative and absolute importance of this component of the zooplankton (Lindley and Batten, 2002). Especially large changes in abundance of meroplankton have been evident in the North Sea in recent years. There is a poor understanding of the causes of these increases and of interactions between the benthos and pelagos (DEFRA 2005c).

A phenological study of decapod larvae showed that the seasonal life-cycle events were occurring earlier than over the previous decade and were 2-3 weeks earlier in 2001 than the long term mean. This trend was strongly correlated with the NAO and winter sea temperatures (Edwards and Richardson 2002). Similarly, the peak seasonal appearance of echinoderm larvae in shelf seas shows the same pattern, arriving some 4 to 5 weeks earlier (during the 1990's and against a base mean for 1960 – 2003 (DEFRA 2005c, Edwards *et al.,* 2005).

5.2 BENTHOS

Soft and hard substrates

Benthic species provide a source of food for a wide range of predatory fish (including commercially important populations of plaice and sole), birds and marine mammals (OSPAR, 2000c). Whilst the current distributions of seabed species are similar to those reported some 150 years ago (Hiscock *et al*., 2004), this situation may be changing rapidly. The distribution of individual species is typically mediated by sediment type, temperature, water depth and degree of exposure to wave and current action. The vast majority of the NEAME sea bed is sedimentary and hence predominantly populated by benthic fauna associated with this. Typically the larger (macro) fauna will therefore be numerically dominated by polychaete worms, crustaceans, molluscs and echinoderms. These species are typically wide ranging except those with specialist niches or those sensitive to human activities (such as the fan mussel, *Atrina fragilis*). Hard substrates, from stones to patches of exposed bedrock, are present across much of the NEAME and support a different fauna and flora. The greater the extent of substrate in any one location the more diverse the fauna and flora which consists of a range of encrusting fauna (including bryozoans, hydroids, molluscs, sponges, cnidarians, polychates and macroalgae).

Aggregations of some species can develop into biogenic reefs, such as maerl (the calcareous red algae), *Serpula* and *Sabellaria* worms and horse mussel beds. These aggregations provide the opportunity for an elevated level of inhabitation by other species to create biodiversity "hotspots". The occurrence of these reefs is typically very infrequent, which may be a consequence of a rare combination of required parameters and some are thought to be of substantial age.

Pockets of high abundance of other species have a modifying effect on the habitat, such as the burrowing activity of *Nephrops* prawns in deep mud, scallops, seagrass beds and brittlestar echinoderm aggregations.

Perennial macroalgae such as the fucoids *Fucus vesiculosus* (bladder wrack) and *Fucus serratus* (serrated wrack) compete for space with annual green algae in the littoral and upper sublittoral zones. Kelp, such as *Laminaria hyperborea* tend to dominate in deeper water. The most developed macroalgal communities in the NEAME are found on rocky shores and on hard bottoms in the sublittoral zone down to approximately 15 m in southern and 30m in northern parts of the North Sea (OSPAR, 2000b).

Changes in the benthos where long time series data exist, such as the western English Channel, suggest that these are driven by sea temperature, notably exceptionally cold winters, immigrant species, dinoflagellate blooms, and heavy fishing gear. Fluctuations in cold water species such as the anomuran crustacean, *Munida bamffica* and the sea urchin *Echinus acutus* and warm water species such as the common octopus, *Octopus vulgaris*, and the warty venus, *Venus verrucosa* (Southward *et al*., 2005).

Survey data over the past century has shown how organisms react to changes in temperature in the order of 0.5°C. In the last two decades sea temperatures have risen as much as 1°C with the distribution of some intertidal fauna changing significantly at the local level (Hiscock *et al.,* 2004). For example, a major resurvey of rocky shores, along the southern English coast recorded the eastward extension, for some species, in range by up to 100km. These include the flat topshell, *Gibbula umbilicalis*, the toothed topshell, *Osilinus lineata*, and one of the acorn barnacles, *Balanus perforatus* (Hiscock, 2003a; Hiscock *et al.*, 2004).

Non-native species have been more likely to extend their distribution due to introductions. One notorious example is the wire-weed, *Sargassum muticum* (Eno *et al.,* 1997 and Hiscock, 2003a). Another is the Japanese kelp, *Undaria pinnatifida*, which, originally found in the Hamble estuary in 1994, has spread from Torquay to Ramsgate on the hulls of boats (Eno *et al.*, 1997 and Farrell and Fletcher, 2004). Eno *et al.*, (1997) found no common patterns to the distribution of non-native species, but it was noted that there were far more introduced species on the south and west coasts of Britain. Furthermore certain areas such as the Solent and Poole Harbour were noted to 'abound with non-natives', probably as a consequence of the large volume and history of shipping in these areas.

There is a strong coupling between benthic and pelagic processes in shallow shelf seas such as the North Sea which helps to create a very productive environment (OSPAR, 2000b). In the shallow coastal waters of the North Sea, the spring phytoplankton bloom occurs when the water temperature is 2-4°C. It has been suggested that such low temperatures reduce the ability of the planktonic copepods to exploit the spring bloom. Consequently the bulk of production is exported to the benthos (Gowan *et al.*, 1999). Similarly, in the western Irish Sea between 50% and 60% of gross spring bloom production is exported to the benthos (Gowen *et al.,* 1999). Liverpool Bay contrasts with both the western Irish Sea and the coastal waters of the North Sea in that there is little evidence of a significant input of spring bloom phytoplankton into the benthos (Gowen *et al*., 2000).

Further, nutrient increases, for example from land-based inputs, have indirectly affected the macrobenthos in the shallow south-eastern North Sea and the Skagerrak-Kattegat area, which is an important area for flatfish, but less important for gadoids and the industrial species. These latter species reside in the areas of the North Sea where variations in benthic food resources are primarily climate driven (OSPAR 2000b; Clark and Frid, 2001).

Maerl

Maerl is a collective term for several species of calcified red seaweed that grows as unattached nodules on the shallow (to, exceptionally, 40m) seabed, and can form extensive beds in favourable conditions. Maerl is slow-growing but, over long periods, its dead calcareous skeleton can accumulate into deep deposits (an important habitat in its own right), overlain by a thin layer of pink, living maerl. These beds of live, and to some extent accumulations of dead maerl as well, are species rich and are valuable nursery areas for commercially valuable species such as scallop (Kamenos *et al*., 2004).

However, maerl is susceptible to damage from siltation, eutrophication and commercial exploitation (Hall-Spencer *et al*., 2003; Hall-Spencer and Moore, 2001).

Biogenic reefs

All biogenic reefs have a limited distribution within the UK and Europe. These reefs are typically regarded as a haven for other marine wildlife and represent biodiversity “hotspots” and are protected under the Habitats Directive. Such biodiversity includes both the invertebrate fauna and macroalgal flora that live on and within the reef structure but also mobile species, including fish species that use reefs for feeding and as refugia.

Deepwater corals, principally *Lophelia pertusa*, are present in deep and cooler waters in the NEAME, typically off the continental shelf but exceptionally in shallower (to 50m) depths. Key areas of known distribution (our knowledge is incomplete) within NEAME are off the Norwegian coast (Sula Ridge), the Wyville-Thomson Ridge and Rockall Bank (Area 1), Porcupine Basin, off western and northern Scotland and also Biscay (www.marlin.co.uk). Where coral aggregations are substantial (for example Sula Ridge, which is 13km long and up to 30m high and reef mounds in the Porcupine Basin, west of Ireland) they are known to support and enhanced biodiversity in comparison with adjacent habitat.

The horse mussel *Modiolus modiolus* forms dense beds at depths of 5-70m in fully saline, often moderately tide swept areas. It occurs throughout the NEAME, however, aggregations of sufficient density to be defined as a reef are rare but have been noted from:

- Area 1 – Occasional beds occur between Berwickshire and the Humber;
- Area 2 – A number of Scottish Lochs and around the western and northern isles; and
- Area 3 - Around the Isle of Man, several parts of Strangford Lough, off the Lleyn Peninsula and north-west Anglesey.

Serpula vermicularis is a marine worm which makes a hard, calcareous tube that can, exceptionally, aggregate into clumps or 'reefs' up to 1m across in shallow water (to

10m). However, very few extant examples are known: at Loch Creran, on the west mainland coast of Scotland, and in Galway, Ireland (Area 2).

Other benthic habitats

The greatest proportion of the European coast is chalk (57%) and many of the best examples of littoral and sublittoral chalk habitats are located on the coast of England. Chalk coastlines create a range of micro-habitats of a characteristic flora and fauna, notably rock-boring invertebrates such as the *Polydora* worm and paddocks molluscs. Littoral chalk also characteristically lacks species common on hard rocky shores (e.g. the macroalgae *Pelvetia canaliculata* and *Ascophyllum nodosum*) but supports distinct successive zones of algae and animals such as *Fucus* spp, kelps *Laminaria* spp and red algal turfs, or barnacles and mussels on wave-exposed shores.

Coastal saltmarshes comprise the upper, vegetated portions of intertidal mudflats, lying approximately between mean high water neap tides and mean high water spring tides. They are usually restricted to comparatively sheltered locations in estuaries, saline lagoons, behind barrier islands, at the heads of sea lochs or on beach plains. The development of saltmarsh vegetation is dependent on the presence of intertidal mudflats.

Saltmarshes are an important resource for wading birds and wildfowl. They act as high tide refuges for birds feeding on adjacent mudflats, as breeding sites for waders, gulls and terns and as a source of food for passerine birds particularly in autumn and winter. In winter, grazed saltmarshes are used as feeding grounds by large flocks of wild ducks and geese. Areas with high structural and plant diversity, particularly where freshwater seepages provide a transition from fresh to brackish conditions, are particularly important for invertebrates. Saltmarshes also provide sheltered nursery sites for several species of fish.

Saltmarshes can be found in most of the countries of Europe with a coastline subject to a macro- or meso-tidal regime. Although these areas cover a wide latitudinal range they virtually all fall within the geographic limits of saltmarshes. There are somewhat rudimentary saltmarshes in suitable areas in arctic northern Europe while the south of Europe is still too far north for mangroves to provide an alternative.

5.3 FISH

In assessing the potential environmental effects of climate change on the NEAME fish fauna, it was decided (Baker and Reidy, 2004) to focus on four representative taxa:

- Herring;
- Sandeels (all species);
- Atlantic cod; and
- Atlantic salmon.

Further, during the workshop it became evident that the key sensitivities were largely in regard to the early stages of the life cycle, i.e. eggs and larvae. Due to this, this section outlines the salient information about these species focussing on the key life-cycle stages.

Herring

Herring (*Clupea harengus*) is a pelagic species (but sediment spawner) and are found throughout the NEAME (Table 5.1). During daytime, herring shoals remain close to the sea bottom or in deep water to a depth of 200m. At dusk, they move towards the surface and disperse over a wide area, to feed mainly on crustaceans (shrimps and copepods) and young sandeels. In the North Sea, herring sub-populations spawn in shallow water (15-40m) at different times and localised groups of herring can be found spawning, in aggregations, on traditional spawning grounds in almost any month (Figure 5.4; FRS 2005 and Rogers and Stocks, 2001).

When the eggs hatch the larvae become pelagic and are transported by the prevailing water currents. In the North Sea most autumn spawned herring larvae drift in an easterly direction from the western North Sea towards important nursery grounds in the eastern North Sea and to the Skagerrak and the Kattegat. Their drift rate is variable and in some years, many do not reach the nursery areas. Some larvae from the west of Scotland are retained there but a large proportion is carried through the Fair Isle channel and travel well into the North Sea probably drifting into the Moray Firth. In spring the larvae reach the nursery areas where they develop into juveniles. Young herring spend some time in the inshore areas and sea lochs before migrating offshore to join the adult population. The pelagic larvae feed on copepods, euphausiids, juvenile sandeel, and fish eggs (FRS, 2005; Rogers and Stocks, 2001).

Presently, the herring stock in the NEAME is considered to be in a reasonable condition and that fishing is currently being carried out at sustainable levels (FRS, 2005).

Table 5.1: Distribution of fish species assessed.

Species	**Distribution**	**Environmental**
Herring *Clupea harengus*	Throughout NEAME south to northern Bay of Biscay 80°N - 33°N, 79°W - 70°E	Depth 0 - 200m Temperature 1 - 18°C
Atlantic cod *Gadus morhua*	Throughout NEAME 80°N - 35°N, 76°W - 61°E	Depth 1 - 600m Temperature; 0 - 20°C
Sandeel *Ammodytes marinus*	Throughout NEAME south to western English Channel 74°N - 49°N, 54°W - 60°E	Typically deeper than 30m
Sandeel *A. tobianus*	Throughout NEAME 72°N - 36°N, 23°W - 42°E	Depth 1 – 30m
Atlantic salmon *Salmo salar*	Throughout NEAME 68°N - 38°N, 76°W - 55°E	Depth 0 - 10m Temperature; 2 - 9°C

Atlantic cod

Atlantic cod (*Gadus morhua*) can be found from the shoreline down to depths of over 200m and shoals and individuals are wide ranging. Adult fish tend to be concentrated in the northern and central areas of the North Sea and this population is coherent with those found in the Skagerrak and eastern English Channel but are largely distinct from populations to the west of Scotland (Rogers and Stocks, 2001). Their distribution is across the whole of NEAME where temperatures do not exceed 20°C (www.fishbase.org), though in area 4, they are largely replaced, at least in commercial fishery terms, by hake.

Although Atlantic cod spawn across their range, there are several areas where spawning is concentrated (Figure 5.4 for examples). Spawning mainly takes place between January and April. Positively buoyant pelagic eggs float near the water surface over large areas and hatch within 3 weeks. Most larvae are distributed in the upper 30m of the water column, with peak concentration between 10m and 20m (FRS 2004b, 2005 and Rogers and Stocks, 2001).

Atlantic cod are active predatory feeders, primarily on a variety of fish (sandeel, Norway pout, whiting, herring, dab and Atlantic cod) and crustaceans (*Nephrops*, shrimps and crabs) (FRS 2004b; Rogers and Stocks, 2001).

Atlantic cod stocks are in decline because of heavy fishing mortality (FRS, 2005) and also because of variable recruitment as a consequence of fluctuations in planktonic food availability (Beaugrand *et al.*, 2003; Hays *et al.*, 2005).

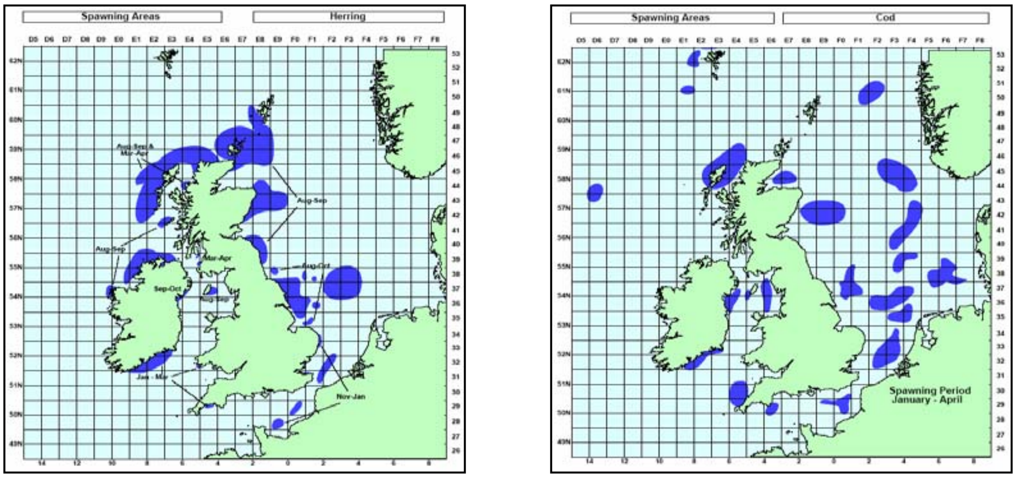

Figure 5.4 Herring (left) and Atlantic cod (right) spawning areas in British waters (Coull *et al.*, 1998).

Salmon

Atlantic salmon (*Salmo salmar*) is a migratory species that spends most of its adult life in the ocean but return to its native rivers to spawn. The species ranges from Portugal to the Baltic, Norway, Iceland, Greenland, Canada and north-east America (Hendry and Cragg-Hine, 2003). Salmon populations are in marked decline across the NEAME for several reasons (particularly overfishing, freshwater habitat degradation, impediments to upstream movement and possibly by-catch in marine fisheries) (ICES 2005b).

Salmon utilise rivers for reproductive and nursery phases, and the marine environment for adult development and rapid growth (Mills 1991), migrating from the Atlantic ocean to freshwater to spawn in rivers with clean gravel. As salmon only use the marine environment as adults, outwith the breeding season, only the adult stage is applicable to this assessment.

Salmon migrate to the sea, usually between April and June where thay feed primarily upon fish such as capelin and sandeels, and crustacea (particularly euphausids and amphipods) and growth is rapid (Hendry and Cragg-Hine, 2003).

Sandeels

Sandeels are an abundant and important component of food webs in the North Atlantic. Of the five species of sandeels inhabiting the North Sea, *Ammodytes marinus* comprises over 90% of sandeel fishery catches (FRS Website 2005).

Sandeels have a close association with sandy substrates into which they burrow, with individual species showing specific preferences to type of sand in which they dwell. They remain in close association with the preferred habitat, even during spawning. When larvae settle from the plankton, they preferentially seek this sediment and hence spawning, nursery and adult population areas are generally the same (Figure 5.5).

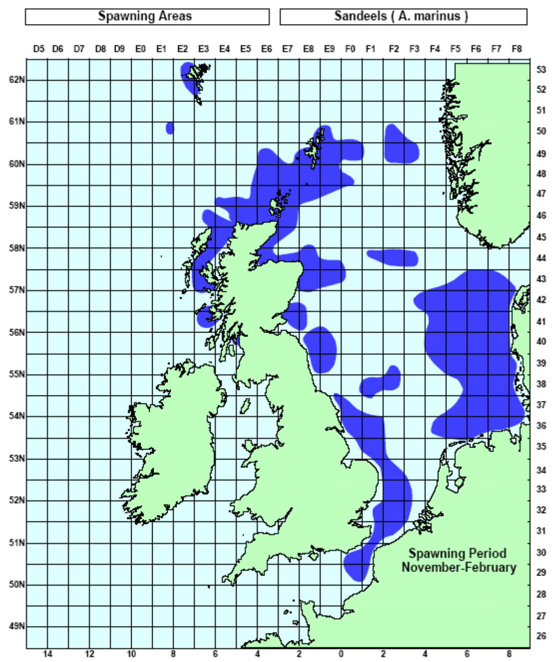

Figure 5.5 Sandeel spawning areas in British waters (Coull *et al.*, 1998).

Observations on the availability of *A. marinus* to fisheries and their occurrence in sediment suggests that this species rarely emerges from the seabed between September and March, except to spawn between November and February. (FRS Website 2005; Rogers and Stocks 2001).

The eggs are demersal and deposited in sticky clumps on sandy substrates. The larvae hatch after several weeks (usually in February-March) and become planktonic. They drift in the currents for one to three months resulting in a potentially wide distribution and after this they settle on the sandy seabed (FRS Website 2005; Rogers and Stocks 2001).

Sandeels are important prey species for many marine predators (such as seabirds and fish such as herring, haddock, whiting, saithe, mackerel, Atlantic cod, salmon etc). The magnitude of the fishery has led to concern over the potential impact of sandeel harvesting on the North Sea marine ecosystem, though in the North Sea, fishing mortality is lower than natural mortality.

5.4 BIRDS

For the vulnerability analysis, consideration of effects on birds concentrated on terns and waders as representative taxonomic groups.

Terns

At present there are five species of breeding terns in UK and Ireland. Their distribution in NEAME is provided in Table 5.2.

Table 5.2: Tern species distribution in the NEAME and breeding habitat preferences.

Species	**Distribution**	**Breeding and feeding**
Sandwich tern *Sterna sandvicensis*	NEAME wide to a southern limit along the coast of western France.	Breed in large colonies on low-lying offshore islands, islets in bays or brackish lagoons, spits (coastal shingle beaches), and remote mainland dunes. Feeding takes place within a few kilometres (exceptionally 70km) of the colonies.
Arctic tern *Sterna paradisaea*	NEAME distribution not south of UK and Denmark. (i.e. not Area 4)	Most feeding takes place within 3km of the colony and only exceptionally up to 10km.
Little tern *Sterna albifrons*	A widely scattered global distribution. In the NEAME they occur from UK and Denmark south (to Portugal).	Nests exclusively on the coast in well-camouflaged shallow scrapes on sand and shingle beaches, spits or tiny inshore islets of sand or rock. They forage no more than 1.5m offshore and a maximum of 6km from nest for small fish and invertebrates.
Roseate tern, *Sterna dougallii*	A fragmented breeding range in the north-east Atlantic. Includes small populations in Britain, Ireland and Brittany.	Breeding colonies on sand-spits and dunes, shingle beaches and low rocky islets. Inshore waters are used for feeding on small fish.
Common tern, *Sterna hirundo*	NEAME wide.	Colonies on coasts and inland on lakes, reservoirs and gravel pits. Most feeding takes place within 3-10km of the colony, but greater distances, up to 37km or even more have been recorded.

Of these, three are subject to population declines (Mitchell *et al.,* 2004; Mayor *et al.,* 2004):

- Sandwich tern *Sterna sandvicensis* due to persecution in northwest Africa;
- Arctic tern *Sterna paradisaea* due to sandeel declines; and
- Little tern *Sterna* due to egg and chick predation.

The population of common terns is stable and that of the roseate on the increase, albeit from a very low base population and because of active conservation management.

Sandwich tern populations fluctuate widely from year to year due to large variations in the proportion of mature birds attempting to breed, whilst distributions vary according to mass movements of birds among colonies.

The main threats appear to be loss of habitat, when nesting beaches or islets are washed away and predation, especially where persistent, such as from fox *Vulpes vulpes*.

Sandwich terns are highly nomadic even compared with other tern species, and whole colonies may move site within a year or two in response to changing conditions. Populations can therefore fluctuate erratically.

Sandwich terns that breed in Britain and Ireland spend the winter along the Atlantic coast of Africa, a few reaching the Indian Ocean on the south coast of Africa. Adults move south from August to December and back north to breed between March and May. Immature birds may not return to breeding colonies at all in their first year of life and return later than birds of breeding age until they are old enough to breed (most in their third summer).

Arctic terns are the commonest tern breeding in Britain and Ireland, but their northerly distribution (73% of the breeding population in the Northern Isles) means they are less familiar to most observers than other tern species. Sandeel stocks in waters around Shetland increased through the 1970s and early 1980s and this improvement in food availability may have also contributed to arctic tern population growth. However, a collapse of the sandeel stock around Shetland between 1984 and 1990 caused repeated abandonment of eggs and starvation of chicks throughout the archipelago. The population of arctic terns on the northern isles therefore declined between 1980 and 1989 in response to reduced recruitment and increased mortality or non-breeding.

Many arctic tern colonies at the southern range of the British and Irish population are increasing, probably in response to conservation management. The population along the west coast of Ireland is increasing at the expense of common terns, possibly due to changes in climatic or oceanographic conditions shifting the balance of inter-specific competition in favour of arctic terns.

Although little tern colonies may be found around much of the coastline, breeding is concentrated in the south and east of England, where the species preference for breeding on beaches (also favoured by people) makes it vulnerable to disturbance. Indeed the greatest threat to little tern colonies is thought to be from human disturbance. Predation is another factor at some colonies and fencing has been used to keep out red fox *Vulpes vulpes*. High summer tides (especially storm surges) regularly flood some colonies and blown sand can also cause significant nest losses.

European breeding little terns move south to winter off the coast of western Africa and perhaps even as far as South Africa. However, they most probably winter in the gulf of Guinea, an area that has enormous resources of small fish, which attracts large numbers of terns during the northern winter (though these fish stocks, e.g. *Sardinella*, may now be in decline).

Roseate terns have probably always been a rare and localised species of seabird in Britain and Ireland owing to their specialised foraging and nesting habitat requirements. The main pressure on populations in the present time is thought to be at their northwest African wintering grounds where deliberate trapping for food or sport in the Ghanaian wintering grounds and the decline in *Sardinella* fish stocks. Factors such as predation (by fox and rat) and nesting habitat loss (due to erosion, flooding, competition with gulls and/or disturbance) may also play a role.

Common terns are not the most abundant tern species in Britain and Ireland, but are probably the most familiar owing to their breeding range being among the widest of seabird breeding in Britain and Ireland. Over the last three decades, the population has remained broadly stable, although there have been marked variations in trends among regions. Habitat change accounts for much of this such as coastal development and increased disturbance, especially recreational. However all terns can desert breeding colonies for behavioural reasons, resettling again after a period of time. Declines in west Scotland and in England are likely to be due to increased predation by American mink *Mustela vison* and red fox *Vulpes vulpes* respectively. Conservation management to ameliorate these problems is being exercised.

Waders

Waders arrive in European estuaries and wetlands in large numbers in the autumn on route from summer breeding habitats further north or east. Some will stay in Britain and the Netherlands, while others continue south to over-winter in Africa. Waders are one of the most important groups of European estuarine shore-birds, especially in the autumn and winter (McLusky and Elliott, 2004).

They will feed on a variety of the abundant invertebrate fauna that inhabit the intertidal zone, varying their prey to what is available in a particular estuary. The waders which exploit this resource are highly mobile and typically exhibit clear tidal rhythms of foraging behaviour linked to water movement and the activity of their favoured prey in relation to the tides (McLusky and Elliott, 2004).

In general wader populations are in significant decline due to habitat loss and pollution, particularly in estuaries, but also in upland and grassland habitats where they breed (Goater *et al*., 2004; Eaton *et al*., 2003).

5.5 MARINE MAMMALS

Two species of seal and four species of cetacean have been used as examples of the anticipated climate change impacts in this assessment.

Grey seal

Grey seals, *Halichoerus grypus*, are found in temperate and sub-Artic waters on both sides of the Atlantic. Though they are among the rarest seals in the world, 95% of the world population is present in Europe and 40% in the UK alone. There are three discrete populations of grey seals, including the east Atlantic stock which is distributed from Iceland to northern France[5]. Consequently, the NEAME represents a key region for this species with the majority of breeding occurring around the UK and Ireland (124,000 in 2000).

Grey seals spend most of the year at sea ranging widely in search of prey. In the autumn they come inshore and form breeding colonies on rocky shores, beaches, caves on small, largely uninhabited, islands and occasionally on sandbanks. The size of these colonies varies widely with the largest on the Inner and Outer Hebrides, Orkney, Isle of May, Farne Islands and Donna Nook. These alone account for more than 85% of pups born. They disperse widely with distances of over 1000km not being uncommon. Grey seals prey upon schooling fish, cephalopods and occasionally sea birds (Barros and Clarke, 2002).

The major threats to grey seals include illegal culling, disturbance by man and dogs during lactation, oil and chemical pollution and entanglement in fishing nets (Arkive 2004).

Harbour seal

There are some 90,000 eastern Atlantic harbour seals, *Phoca vitulina vitulina*, resident from Iceland to Portugal (i.e. including throughout the NEAME). Other subspecies are present across the Arctic to subtropical in the north Atlantic and north Pacific.

Harbour seals haul out in more sheltered sites than the grey seal, and are largely residential to these all year round. They generally forage within a range of 50km, exceptionally 200km, and generally only offshore to a distance of 25km (exceptionally 100km). They feed primarily on a variety of fish species but the diet also extends to crabs, squid, whelks and mussels, depending on local availability.

Pressure on populations are the same as for grey seals.

Harbour porpoise

The harbour porpoise, *Phocoena phocoena*, is found over continental shelf areas in the sub-Arctic and cold temperate waters of the north Pacific and north Atlantic, including throughout the NEAME (Evans 1987; Reid *et al*., 2003).

The North Sea population was estimated in 1994 to be around 280,000. In the Skagerrak and Belt Seas the estimate was about 36,000 with the same number over the

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[5] The two other populations are in the Baltic and northern North America.

Celtic shelf between Ireland and Brittany. Norwegian surveys indicate numbers in the region of 82,000 for the northern North Sea and southern Norwegian waters. On the continental shelf off south-west Ireland an estimate of 19,000 was given in 1992 (Reid *et al*., 2003).

The highest population densities are found in north-western North Sea water, and in water depths of less than 100m. In the Atlantic off Britain and Ireland, locally high densities occur off the west coast of Scotland, south-west Wales and south-west Ireland (Reid *et al*., 2003).

In the eastern English Channel and southern North Sea, populations have declined or been eliminated and this has been linked to accidental mortality in fishing nets (Reid *et al*., 2003). Harbour porpoise have a short lifespan of up to 12 to 15 years (Evans, 1987). Their main prey is fish, including herring, sandeel and squid (Evans, 1987).

The factors causing loss or decline are entanglement in fishing nets ('drowning'), noise pollution (disturbance, especially recreational), lack of food and possibly climate change. Jepson *et al.,* (2005) have also examined the links between polychlorinated biphenyl pollution and disease in harbour porpoises, although other types of chemical pollution may also be a threat.

Bottlenose dolphin

In the NEAME, *Tursiops truncatus* principally occur along the Atlantic seaboard. They are locally frequent nearshore off the coasts of north-west France, western Ireland, north-east Scotland (especially the Moray Firth) and the Irish Sea (especially Cardigan Bay). There are smaller numbers in the English Channel, particularly in the western portion from the Channel Islands. Beyond this, they have also been reported from northern Norway and Iceland (Reid *et al*., 2003).

In coastal waters, they favour river estuaries, headlands and sandbanks, especially where there is uneven bottom relief and/or strong tidal currents (Reid *et al*., 2003).

There are no UK wide population estimates available. However the resident population in the Moray Firth numbers around 130 and that in Cardigan Bay in the region of 130-135. The inner Moray Firth population is shrinking at an annual rate of over 5%. In the Shannon estuary of western Ireland there is a cumulative minimum estimate of 115 dolphins, whilst in the Channel and north-west France area 85 individuals have been photo-identified. The largest numbers are seen off western Ireland and in the vicinity of the shelf break, south-west of Ireland south towards the French coast (Reid *et al*., 2003). Sightings of mixed groups of bottle-nose, Atlantic white-sided dolphins and long-finned pilot whales have been seen around Rockall and over the Wyville-Thompson Ridge and the Ymir Ridge (Reid *et al*., 2003).

They feed on a wide variety of demersal and pelagic fish, such as Atlantic cod, haddock, salmon and sandeels as well as cephalopods (octopus and others) and shellfish (Reid *et al*., 2003).

The causes of loss or decline come from human disturbance, entanglement in fishing nets, chemical and noise pollution. Climate change may also cause indirect threats in some areas. For example, increased precipitation or flooding events in coastal regions may cause greater pollutant run-off from agricultural land into estuaries.

Fin whale

The fin whale, *Balaenoptera physalus,* is distributed worldwide, mainly found in temperate and polar seas. In the northern hemisphere fin whales breed in warm temperate waters during the winter months and migrate northwards to summer in cold temperate and polar seas. Some remain in high latitudes in the winter months (Reid *et al*., 2003). They occur throughout the NEAME, in particular in the Norwegian Basin, Faroe-Shetland Channel, Rockall Trough, Porcupine Bight and the Bay of Biscay (Buckland *et al*., 1992; Reid *et al*., 2003). In northern Scotland and southern Ireland they have been recorded on the continental shelf but always close to the shelf edge (Reid *et al*., 2003). There are no current population estimates for the north Atlantic as a whole, though recent sight surveys have indicated numbers in the region of 47,300 individuals (Reid *et al*., 2003).

Fin whales feed on planktonic crustacean, especially euphausiid shrimps but also copepods (*Calanus*) and their distribution can be influenced by zooplankton abundance. Their diet includes variety of fish such as herring, capelin, sandeel, mackerel and blue whiting and cephalopods (Evans 1987; Reid *et al*., 2003).

The major threats are from environmental change/disturbance such as chemical and noise pollution and collision with boats (Evans 1987; UK BAP grouped plan for baleen whales).

6. Predicted effects and significance

This section describes the assessment carried out during the workshop. As noted earlier in this report, the purpose of the workshop was to seek an informed consensus view on what the effects of future climate change might be on the NEAME and its fauna and flora, by applying an environmental impact assessment (EIA) approach by way of compensating for the limited amount of certainty as to what these effects might be and to encapsulate the multidisciplinary issues into a readily accessible format. The EIA method was used to identify the principal significant effects of climate change on the NEAME and hence highlight the key vulnerabilities by taking into account four aspects of the receptors used in the assessment as follows:

- Sensitivity to change;
- Importance to the ecosystem;
- Spatial extent of predicted change; and
- Magnitude of the predicted change.

For each of these aspects, a score of 1 to 3 was applied (see Table 3.1) to enable the process of identifying where the key impacts lay. These scores are presented in Tables 6.1 to 6.4 and the following sub-sections provide an explanation of the assessment results, supported with published evidence where it has been sourced.

6.1 NUTRIENTS AND POLLUTANTS

It is thought that some climate change related changes such as rainfall patterns (particularly extreme events), and hence freshwater discharges to the sea, may result in an increased input of nutrients and pollutants into the NEAME. Further, changes in circulation and extreme weather events may bring deposited (and isolated) materials back into the wider ecosystem, keep them in suspension longer and generally increase their bioavailability. Temperature increases are likely to increase the toxicity of chemicals. The speciation and behaviour of chemical compounds will also change as a consequence of temperature, salinity, pH and seawater chemical composition, amongst other factors.

An increase in the size and frequency of storm events will also introduce more suspended solids with the capacity to smother habitats, fish spawn and also have sub-lethal effects associated with reduction in light penetration such as foraging efficiency of estuarine fish and other mobile species.

The forecasting of how much variation will occur and the consequences of this is fraught with complexity and uncertainty. During the workshop a plenary session rather than a presentation and questions session was held that brought out the following comments, firstly those with respect to the characteristics and secondly with respect to the ecological responses and consequences:

- Nutrient levels linked with terrestrial inputs;
- Wetter winters and drier summers are predicted;
- Enhanced primary productivity;
- Unlikely that ‘herbivore populations’ could ‘control’ nutrients. A more likely outcome is an increase in the occurrence of localised ‘dead zones’;
- Changes in some nutrients will increase deoxygenation (particularly as a consequence of phytoplankton blooms and their die off) and cause decline in productivity. This may give rise to a shortening and simplifying of food webs;
- Potential sea level rise may cause increased algal blooms and their consequent effects;
- Rising levels of nutrients may increase fish productivity in areas currently nutrient limited waters. However, there will be locations and thresholds where an increase in nutrient supply may lead to phytoplankton blooms (also toxic blooms) - oxygen may be stripped from water column – fish kills;
- Hazardous substance toxicity increases with temperature increases; and
- Increases in body burden of toxic chemicals, for example organophosphates, weakening the immune system of marine mammals.

The potential for in-combination effects of a rise in the nutrient and pollutant inputs (and availability) on the NEAME fauna and flora are perhaps the more concerning. This is a view driven by the additional stress that nutrient/pollutant changes might place on a system/species. The following in-combination effects were highlighted:

- In-combination effects of: increased stratification; increased CO_2 concentration; and higher temperature may result in greater frequency of de-oxygenation events and disease incidence;
- Biological changes, such as a decrease in the abundance of coccoliths (a potential consequence of falling pH, Section 6.1.2) could affect ocean nutrient chemistry and interact with nutrient availability;
- Weakened marine mammal immune systems (from pollutant runoffs) may make them more susceptible to disease and epizootics, which might also become more prevalent as a consequence of higher temperatures; and
- The intermittent accumulation and release of nutrients associated with changes in the pattern of stratification could enhance the impact of increased loadings of nutrients.
- Increased acidification – chemical form of nutrients in solution will change – such that species can no longer utilise these.

6.2 PLANKTON

At the outset of the vulnerability analysis, the fundamental importance of the plankton flora and fauna was recognised, given that all other parts of the ecosystem ultimately rely on plankton. As such, the score for importance to the ecosystem of the four representative components was always high (i.e. maximum score of 3). Similarly, the spatial scale was typically scoring a maximum value except in cases such as eutrophication, where effects were considered to only be of potential significance coastally or otherwise locally (Table 6.1).

The effect of sea surface temperature rise was considered the most important characteristic affecting the plankton, including all components discussed. The threat to the plankton community was considered to be either:

- Changes in growing season (phenology); and
- Changes in productivity.

Acidification is a second potential impact of major significance, particularly with respect to calcifying species, most notably the coccolithophores.

Additional effects discussed include the potential for changes in nutrient status in coastal regions and where stratification of the water column may increase in strength and duration. All of these effects are discussed further below.

Sea surface temperature rise

Seasonality

As the DEFRA report (2005c) states, ‘The inter-annual variability in the timing and degree of overlap between trophic production curves is presumed to govern larval survival rates of meroplankton and fish during their early life stages and the eventual year-class strength of commercially important fish and shellfish species (Platt *et al.,* 2003). In the marine environment, varying responses to climate change across functional groups and multiple trophic levels could lead, in theory, to a mismatch in timing and decoupling of phenological relationships. This in turn could have repercussions for trophic interactions, food web structure and eventually changes at an ecosystem-level (Beaugrand *et al*., 2003; Edwards and Richardson, 2004)'.

However, given that there is already evidence for changes in seasonality in growth and abundance of phytoplankton, this theory of future difficulties associated with trophic mismatch would appear to be being realised now. The traditional spring and late summer peaks in production and the near absence of phytoplankton production during winter months are becoming less well defined (Section 5.1, Figure 5.3, Beaugrand *et al*., 2003; Edwards and Richardson, 2004). Further, the late summer phytoplankton bloom has in recent decades (between 1958 and 2002; Edwards and Richardson, 2004) shifted to earlier in the summer by around 4 to 6 weeks. A link between these changes and difficulties in the recruitment of Atlantic cod larvae plankton has already been proposed. Atlantic cod, like many other fish species, are highly dependent on the availability of planktonic food during their pelagic larval stages (Edward and Johns, 2005). In the North Sea *Calanus* (from eggs to adults) are an important prey item for Atlantic cod larvae and juveniles until July–August each year. The progressive substitution of *C. finmarchicus* by *C. helgolandicus* in the North Sea has delayed the timing of occurrence of *Calanus* prey from spring to late summer at a time when larval/juvenile Atlantic cod feed more on euphausiids and other fish larvae. The consequent reduction in available prey earlier in the year is believed to contribute to a diminution in survival and poor recruitment (Beaugrand *et al*., 2003).

From this example, it is evident that the effect of changing seasonality could potentially result in major ecological effects, hence the assessment of a major significant impact on the NEAME. The difficulty in adapting to such changes is especially acute where different components of the ecosystem are responding to different cues. For example, temperature is increasing but day length remains unchanged, so for those species whose seasonal growth is mediated by the latter, will not necessarily be able to adapt to changes mediated by rising temperature.

Continued modification of trophic interactions will occur with further climate warming and the subsequent phenological and biogeographical shifts imposed on planktonic organisms. The dramatic changes in the ecology of the North Sea already observed are a powerful signal of the profound changes in ecosystem function yet to be seen.

Although this assessment considers specific species, it is accepted that, given the seasonality of a temperate climate, many organisms within the pelagic assemblage are responding rapidly to temperature mediated change in the timing of their cyclical or seasonal behaviour and not just those considered here (Edwards and Richardson, 2004).

Distribution

Over the last decade there has been a progressive increase in the presence of warm-water/subtropical species in the more temperate areas of the north-east Atlantic (Edwards *et al.*, 2005; Hays *et al*., 2005). In the north-east Atlantic over the past four decades plankton characteristic of warmer water have advanced northwards by 10° latitude. In similar fashion cold water plankton assemblages have retreated north (Beaugrand *et al*., 2002, Beaugrand, 2003, Edwards and Johns, 2005). This redistribution of species is most concerning with respect to *Calanus finmarchicus* and *Calanus helgolandicus* as described above (Section 5.1.1).

Although productivity in phytoplankton is predicted (and has been observed in recent years) to increase in Areas 1 and 2 (see below), species composition may shift toward a greater abundance and diversity of flagellates and dinoflagellates and decline in diatoms.

Productivity

The changes in *C. helgolandicus* and *C. finmarchicus* in the northern portion of the NEAME is of significance not just because of seasonal differences in reproductive biology, but also because the total biomass is declining (see Figure 5.2).

The phytoplankton biomass of the North Sea has been increasing in the last decade as the growing period has extended throughout the year. In warmer regions, however, increases in sea surface temperature are having/or are likely to have an opposite effect, with production declining.

Acidification

A drop in pH from 8.2 to 7.8 is predicted during this century. This has been considered of potential major significance with respect to the potential for both growth inhibition, particularly in phytoplankton, and potential to change nutrient chemical speciation and hence availability. Structural changes in the calcifying species, principally, coccolithophores are also anticipated.

Calcification

Laboratory experiments to date have observed deleterious effects (Riebesell, 2000, The Royal Society, 2005) on calcification at pH values less than 7.5 or elevated $C0_2$ levels, albeit above predicted levels even for high emissions scenarios (Figure 6.1). In the absence of detailed studies at pH values considered in this assessment, it is difficult to predict potential impacts, and their scale, with any degree of confidence. In spite of this lack of scientific understanding of ecosystem response processes that a drop in pH by 0.4 units might cause, concern remains high that ocean acidification is potentially of major significance.

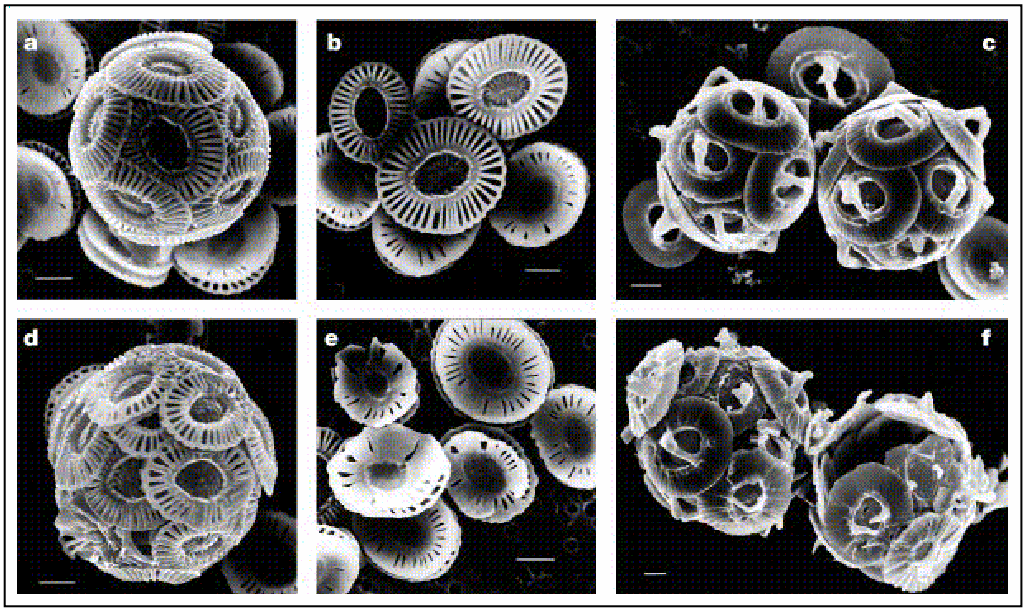

Figure 6.1. Changes to coccolith form as a consequence in experimental alteration of CO_2 concentrations. SEM examples (from Riebesell *et al.*, 2000).

Growth inhibition

There is a complex interrelationship between CO_2 concentrations, pH, photosynthesis, nutrient availability, cell composition and growth, amongst other aspects (The Royal Society, 2005). Consequently, it has been difficult, on the basis of current knowledge including an absence of sufficient experimental data examining the range of pH change considered here, to predict the extent of growth inhibition in phytoplankton with any level of confidence. Tentatively, though, the majority of studies suggest relatively little direct effect on growth rate and elemental composition of marine phytoplankton at least with respect to increases in CO_2 concentrations.

Nutrient inputs

It has been speculated (Section 4.7) that climate change may result in an increase in nutrients entering and/or becoming bioavailable in the NEAME. Although there appears to have been no quantification of this possibility, the potential effects on phytoplankton (in this assessment, diatoms and dinoflagellates) have been considered as follows:

- In coastal environments (i.e. a local spatial context), a medium magnitude of change may occur such that a moderately significant effect would result; and
- In offshore environments a lower magnitude of change would suggest an impact of only minor significance.

The confounding possibility of acidification altering the bioavailability of nutrient and other physiologically important chemicals (Section 4.6) has not been considered. The far greater significance, with respect to the impact of an increase in sea surface temperature and ocean acidification, means that such analysis is unnecessary in informing the conclusion of this vulnerability assessment.

Stratification

Increased water column stratification is thought to favour the growth of dinoflagellates which may have an effect on higher trophic levels. Even so, this possibility is considered of only moderate significance if, as is currently understood for the NEAME

(Sarah Hughes, *pers comm*.) that present patterns of seasonal stratification, at least in Areas 1 and 3, will largely remain unchanged, other than a minor, but detectable, increase in the spatial extent and duration. It has been recognised, however, that the level of confidence in data is currently low.

Confidence in the assessment

The data from the continuous plankton recorder (CPR) demonstrate that changes in the plankton community are taking place and that much of this would appear to be temperature related. As such, there is a moderate to high degree of confidence in the assessment that this effect is real, at least with respect to *Calanus* and diatoms/dinoflagellates.

Although individual species are showing different (or in some cases no) response to changing environmental conditions, it is striking that there are examples across all of the groups assessed here (diatoms, dinoflagellates, carnivorous zooplankton, meroplankton and *Calanus*). As such, there is moderate or high confidence in the understanding of the effects of temperature on the plankton and moderate confidence on ocean acidification impacts on diatoms and dinoflagellates. Beyond this, however, the level of confidence declines substantially.

Impacts on plankton

With respect to plankton, this impact assessment has highlighted the most significant climate change impacts in the NEAME in this century. The key points are:

- Sea surface temperature rise is already driving changes in the plankton fauna and flora, including distributional shifts, changes in biomass and shifts in seasonality. This is already described as a regime shift, and this is predicted to change further over coming years;
- Ocean acidification may have a major impact on the plankton community but our present level of knowledge restricts us to drawing this conclusion only tentatively; and
- Further, the central role of plankton in the ecosystem means that any deleterious effects and fundamental changes in natural cycles will have corresponding effects elsewhere in the NEAME ecosystem.

Table 6.1. Impact assessment for plankton

Characteristic	Receptor	Impact	Confidence	Sensitivity	Importance	Spatial scale	Magnitude of change	Significance
Sea surface temperature rise (SST)	Diatoms and dinoflagellates	Changes in phenology: Sea surface temperature rise can affect seasonal peak in abundance of phytoplankton, potentially causing trophic mismatches.	High	3	3	3	3	12
		Productivity changes are region dependent: In "warmer" southern areas SST warming decreases phytoplankton abundance, whereas in the "cooler" northern areas, it increases phytoplankton abundance => projection = up.	High	3	3	3	3	12
		Changes in productivity: Primary productivity increase with SST but maybe a shift in community composition, favouring flagellates/dinoflagellates	Moderate	3	3	3	3	12
	Calanus finmarchicus/ helgolandicus	Biogeographical shifts: SST rise; C. *finmarchicus* shift northwards (boreal species). *C. helgolandicus* population increase but so far in NEAME it is not a simple replacement *(Calanus* biomass dropping)	Moderate	3	3	3	3	12
	Carnivorous zooplankton	Biogeographical shifts: SST rise resulting in redistributions and species substitutions.	Moderate	3	3	3	3	12
	Meroplankton	Biogeographical shifts: SST rise resulting in redistributions and species substitutions.	Moderate	3	3	3	3	12
Ocean circulation	All	Displacement and redistribution (plus new species)		unknown	3	unknown	unknown	unknown
Acidification	Diatoms and dinoflagellates	Growth inhibition and structural changes. Also effect on speciation of nutrients (chemical form).	Moderate	3	3	3	3	12
	Others	Growth inhibition and structural changes. Also effect on speciation of nutrients (chemical form).	low	3	3	3	unknown	unknown
Nutrient	All (coastal)	Eutrophication	low	3	3	1	1	8
Stratification	All	Restriction on transport of nutrients	low	2	3	1	2	7

6.3 BENTHOS

With respect to the animal and plants inhabiting the marine sediments and coastal environments of the NEAME, this assessment focussed attention on the following potential significant impacts (Table 6.2):

- Biogeographic changes;
- Unknown threat of acidification; and
- Physical damage to inshore and isolated habitats and water bodies.

Sea surface temperature

Biogeographic changes

Temperature mediated dramatic movements of benthic species north, in contraction or expansion of their ranges is predicted to occur. This will be influenced by additional factors that will affect the speed of changes and will be species specific. These factors include:

- The presence of suitable habitats;
- The hydrodynamic characteristics of water masses (currents);
- The presence of hydrographical and geographical barriers to spread;
- Water quality; and
- Life history characteristics (reproductive mode, dispersal capability and longevity).

Changes in the range of benthic species is already being noted in long term data sets and other surveys (Southward *et al.*, 2005; Hiscock *et al.*, 2004). With increasing air and sea surface temperature means, southern species are extending their range in the NEAME whilst northern species are retreating to higher latitudes. The distribution of all benthic species is considered to be sensitive to change in temperature.

In considering the significance of changes to the benthic fauna and flora as a consequence of an increase in temperature, the workshop delegates discriminated between three groups of species:

- Northern sedentary species;
- Biogenic reef-forming species (e.g. horse mussel, maerl, *Serpula* worms and file shells); and
- Southern sedentary species.

Further, particular emphasis was made for those species with either key functional or structural roles in the benthic communities of NEAME.

Initially, as temperatures rise (and this is a process that has already commenced) there will not be a wholesale movement northwards of southern species or retreat northwards of northern species because many additional factors will influence the responses of the different organisms. Such factors include the hydrodynamic characteristics of water masses, the presence of hydrographical and geographical barriers to spread and the life history characteristics (reproductive mode, dispersal capability and longevity) of species. Survey data over the past century show how organisms react to changes of the order of 0.5°C, and in the last two decades, when sea temperatures have risen by as much as 1°C, there have been significant local changes in the distribution of intertidal (and probably also subtidal) organisms. These past changes provide a clue to more extensive changes expected in the future if climate change develops as predicted.

The potential for impacts of moderate or major significance were registered for all faunal types. In cases where a change in species, such as where a northern species is replaced by a southern species that had no material effect on the function of the ecosystem, the importance to the ecosystem was considered to be low. However, for species with a structural and functional role, their importance to the ecosystem was considered to be high. This was a consequence of the possibility that the loss of such species would have a knock on effect on those other species whose occurrence is enhanced or reliant on their presence.

Consequently, for species where importance to the ecosystem is considered to be high, the impact of increasing sea surface temperature in the NEAME is considered to be of major significance[6]. The spatial scale of these changes is considered to be regional (i.e. relevant to the NEAME areas rather than the NEAME as a whole) as distributional changes are unlikely to result in the majority of species becoming regionally extinct and the number of species new to the region would similarly be few. However, of the latter, it was noted that “less beneficial” species may become more numerically dominant and those species that are introduced to the NEAME by artificial means (such as in ship’s ballast) would probably have a greater chance of survival, establishment and potential to become nuisance species as temperatures increase.

There are habitats in the NEAME where the capacity to migrate north with changing temperatures is restricted, the potential impact is considered to be greater in these instances. In the case of biogenic reef building species such as *Serpula* worms and horse mussels (*Modiolus*), the loss of a reef, which may have a substantial historic record of being located in a specific place, may not necessarily be mitigated by the development of another (replacement) at an alternative location. The rarity of, for example *Serpula* reefs, strongly suggests that an unlikely combination of factors need to be present to facilitate a reef’s development. Further, the biodiversity of such a habitat is considered to be integral to its longevity (i.e. a new reef would not represent an identical replacement in terms of its richness in biodiversity of an ancient reef). The structural importance of such species, therefore, makes these habitats of the highest degree of importance in this assessment.

In Britain and Ireland, localised warming, perhaps in combination with increased levels of nutrients resulting from human activities, may cause some severe adverse effects similar to the mortalities of seabed species observed in the north-eastern Mediterranean in 1999 (Perez *et al*., 2000).

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[6] Dramatic distributional changes are going to be most apparent at the extremes of the NEAME where species may establish a presence not previously recorded, for example in Area 4, or where their occurrence is lost (i.e. becoming regionally extinct) for example northern species migrating northwards and totally out of Area 1)

Since Britain and Ireland straddle biogeographical regions, the main effect of warming will be a shift in boundaries (see Figure 6.2 by way of an example). Overall, more species are likely to be 'gained' than 'lost'. The extent of some valued biotopes may increase but the extent of others decrease in the British Isles.

Another implication of an increase in average temperature is the reduction in habitat availability. For example, fucoid seaweed cover on rocky shores would be expected to lessen on shores in Britain and Ireland with implications for primary production and associated epiphytic species. Thus, whilst the faunistic and floristic composition may not change much, there may be implications for functioning of coastal ecosystems.

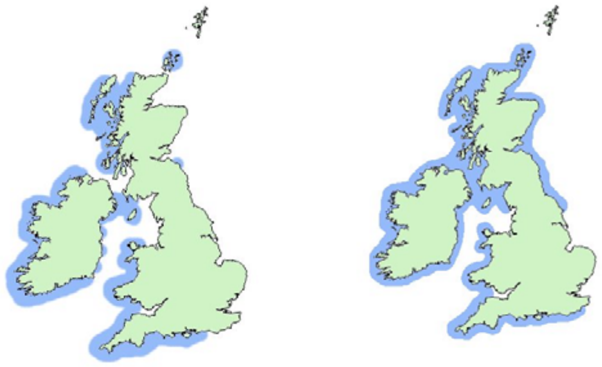

Figure 6.2. Present (left) and predicted (right) distribution in the UK, for a 2°C increase in sea temperature, of the snakelocks anemone *Anemonia viridis*.

Stratification

Semi-enclosed and enclosed water bodies are expected to be subject to greater frequency and increased persistence from periods of stratification of the water column. In areas of low flushing rates this had the potential to increase deoxygenation of deep water. Some species that only occupy such habitat will therefore be subject to greater risk of large-scale mortality and potentially total extinction from individual water bodies. Recruitment and recovery in the latter possibility could be problematic if the population had been isolated. This has been noted as an impact of major significance (but bordering on a moderate level) albeit on a local scale.

Acidification

Acidification of seawater has only recently been highlighted as a potential climate change characteristic. Concern rose of the potential impacts of a reduction in pH focuses on the calcified benthos including echinoderms, maerl, corals, molluscs and calcified reef-building species. Consensus at the workshop was that this characteristic represents an highly significant potential impact on the benthic fauna and calcifying flora (particularly maerl and deep water coral), there was substantial concern over the lack of understanding of the threats acidification poses.

With respect to deepwater coral, this habitat is already under pressure from trawling damage (Hall-Spencer *et al*., 2002) and it is feasible that ocean acidification may add additional pressure by compromising the calcifying process should evidence from tropical reefs be applicable (The Royal Society, 2005). As a major producer of carbonate substrate, particularly in locations of high abundance, such as off Norway, where extensive reefs are formed and also valuable structural species supporting a diverse associated fauna, their importance to the NEAME is of medium concern.

For soft sediment environments burrowing fauna are generally in close proximity to variable pH conditions due to microbial and chemical processes resulting in hypoxic and anoxic acidic conditions at variable depths below the sediment surface. However, many remain in superficial layers only and interact closely with the overlying water, particularly in the context of this discussion, with respect to respiration. Those species that live in the anoxic sediments and irrigate their burrows, such as the *Nephrops* prawn, will be tolerant of variable pH conditions. Conversely, other species that play a major role, in the same way that *Nephrops* does, in having a controlling effect on the habitat through their bioturbating activities, such as the sub-surface burrowing echinoderms may not be exposed to pH changes as they remain in oxic conditions. These species may be very sensitive to pH change. Shirayama *et al.,* 2004) suggest that echinoderms are significantly impacted by a drop in pH of as little as 0.3 units.

Benthic species often recruit through a planktonic larval stage. At the time of settlement and immediately following that event there is usually a very high mortality rate. One possible cause of this, at least in the case of bivalve molluscs is the stress associated with calcification in conditions of under saturation (Green *et al.,* 2004). Consequently, a drop in pH could have a significant additional contributory effect to mortality rates at this particularly sensitive stage.

Given, therefore, the potential differential effects on key structural species (burrowing echinoderms) and particular taxa (molluscs at the larval settlement stage), ocean acidification has the potential to effect community structure in a manner that is difficult to predict at this stage of our understanding.

Notwithstanding this lack of active research, it was felt that the effects would be of major significance, though the magnitude of change was not forecast, and be felt in the coming years of this century.

Sea level rise

Coastal environments in general are at risk as a consequence of the following:

- Net sea level rise, with respect to local tidal range;
- Sediment availability and transport patterns;
- Capacity for the habitat to realign with increasing sea level; and
- The consequences of increased frequency and size of storm surges.

With an increase in mean sea level, the principal threat is with respect to loss of habitat (coastal squeeze) for intertidal mudflats and saltmarshes or inundation of isolated water bodies (of different salinity regime). Changes in erosion and sediment transport patterns are also an outcome in sea level rise and may affect easily erodable habitats.

The issue of sea level rise, as it applies to intertidal sedimentary habitats and saltmarsh is particularly relevant to locations where managed realignment cannot be achieved as a consequence of hard flood defence and where there may be land use conflicts.

The key ecological issue here is with respect to the resource value of these habitats as bird feeding and fish nursery areas. Other habitats were not considered in the assessment because they were considered to be of less ecological importance even though they face the same potential impact (habitat loss). Though local in spatial context in as much as the impact only occurs in intertidal areas, such habitat loss is of course NEAME-wide. It has been concluded by workshop delegates that the spatial scale of effect are likely to be area wide, once regional variation is taken into account. The predicted greater amount of sea level rise in, for example, the southern North Sea, compared with Scotland (Hulme *et al.*, 2002), suggests that the potential impact will be greater in Areas 3 and 4 and the southern portion of Area 1 and less in Area 2 and the northern portion of Area 1. Further, areas where static sea defences and reclaimed land are common place, such as the low countries, the pressure is more pronounced.

The relative importance of the intertidal habitat, its sensitivity to sea level rise, and the forecast level of sea level rise considered in the assessment all support the conclusion for a major significance impact. Even though affected habitats are spatially localised, they remain at least of area-wide extent and so this does supports the conclusion of a major significant impact.

It has been estimated that sea level rise will result in a loss of 8,000 to 10,000 hectares of intertidal flats in England alone between 1993 and 2013. Already, saltmarshes are subject to a decline in their extent from a number of pressures. Current estimates suggest a decrease in extent by approximately 100 ha yr^{-1}. Further in South East England, 20% of the 1973 saltmarsh area was lost by 1988. Much of the coming loss is expected in southern and south-east England although research suggests that the major firths in Scotland will also be affected.

On the other hand, this is one impact that can potentially be mitigated at least in some locations through the application of managed realignment. This, however, does not apply to intertidal chalk reef platforms which will largely become inundated.

Brackish pools, saline lagoons and even coastal freshwater water bodies will be increasingly at risk from the threat of inundation, particularly in conjunction with storm surges. As the fauna and flora of these habitats are characterised by fauna and flora specialised to the particular salinity regime, inundation will inevitably affect them in a negative manner. The implications have been considered to be of major importance.

Storm surges

Shallow water and intertidal habitats are adapted to respond to periodic storm events. However, with climate change and the increase in frequency (for example, the 1.5 m storm surge frequency at Immingham, from 1 in 120 to 1 in 7 years, Figure 4.5) and probably also strength of storms, the capacity for recovery between events will be reduced. The threat that storm surges pose includes physical destruction, displacement, increased erosion and smothering (by displaced sediments). There will be a point where recovery of parts or all of a particular habitat is not achievable in the long term. The expectation therefore would be for an increase in the abundance of more robust species and those with a shorter recovery time. Habitats considered to be particularly sensitive to this impact include fragile reefs (maerl, serpulid reefs), easily erodable habitats (chalk reefs) and those exposed to most storm surges events (kelp forests).

It was concluded, therefore, that this potential impact should be considered to be of major significance at least on an area-wide spatial scale. The topography of the North Sea and prevalent meteorological conditions dictates that the southern North Sea reaches of Area 1 (south-east England and the European mainland from Denmark to north eastern France) would be most affected. This is illustrated by the increase in height of the 50 year storm surges (Figure 6.3, where, for the IPCC A2 (UKCIP medium-high) scenario suggests an increase by as much as 1.4 m.[7]

For comparison between the 1.5m return period for Immingham (Figure 6.3) and the 50 year storm surge height, the return period for the present 1 in 50 yr storm surge height will reduce to 1 in 3 years by the end of the century, for the medium-high emissions scenario[8].

Consequently, it was considered reasonable at the workshop to describe the potential impact on nearshore and intertidal habitats as being of major significance.

Confidence in the assessment

In general, the conclusions drawn in this assessment have been regarded as being based on moderate or high levels of confidence in the data and processes involved. The exceptions to this are the recently raised issue of ocean acidification and also the supposition that species substitution will occur in a manner that would avoid any short term major impacts during the readjustment process.

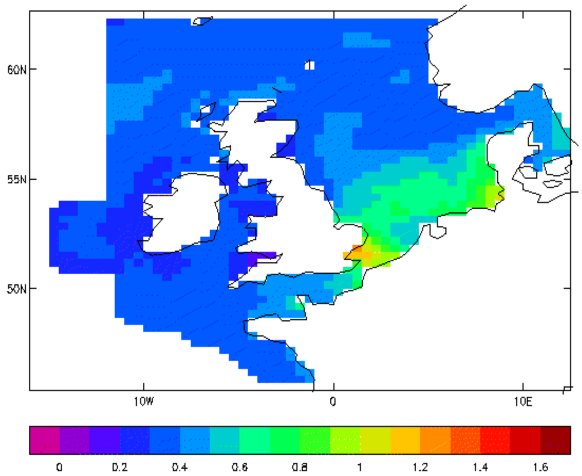

Figure 6.3. Changes in 50-year storm surge height (m) due to changes in storminess, mean sea-level rise and vertical land movement.

Impacts on benthic fauna and flora

In conclusion, significant impacts on the benthos as a consequence of rises in air and sea temperatures are greatest for:

- The few species that may be lost to the region;
- Rare and isolated habitats, particularly reefs with high biodiversity. Examples would include *Serpula, Modiolus*, maerl and file shell reefs; and
- Southern species increasing their distribution in NEAME and increasing their abundance at the expense of other fauna and flora (i.e. become nuisance species). Examples of these would include the non-native species Sargassum weed and the slipper limpet *Crepidula fornicata*.

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[7] For the UKCIP02 high emissions scenario, the general pattern is as shown in this figure but the change in height is genreally 0.3 m higher (see Hulme *et al.* 2004, Figure 73)

[8] UKCIP02 does not offer similar information for the high emissions scenario nor were values presented at the workshop.

In terms of sea level rise saltmarsh and intertidal mudflat habitats, in particular, are facing a major significant impact where there is a conflict between rising sea level and the capacity for managed realignment to allow natural adjustment of distribution.

Overall, however, the capacity for southern species to replace northern ones suggests that climate change will have limited impact on the functional integrity of the NEAME’s ecosystems, subject to a greater understanding being developed on how ocean acidification might have an effect.

Table 6.2: Impact assessment for benthic fauna and flora

Characteristic	Receptor	Threat	Confidence	Sensitivity	Importance	Spatial scale	Magnitude of change	Significance
Temperature rise	Northern (structural) species sedentary.	Biogeographical range decrease	high	3	1	3	2	9
	Northern (functional) species sedentary.	Biogeographical range decrease	high	3	3	3	2	11
	Northern biogenic reef forming species. Modiolus, *L. glaciale*, *Serpula* reefs.	Loss of ancient habitats	high	3	3	1	3	10
	Southern species sessile and sedentary	Increase in abundance and range of native species. Increasing dominance of less beneficial species, esp. non-natives. Increased survival of introduced species.	high	3	3	1	3	10
Stratification	Isolated water bodies.	Deoxygenation of lower waters	high	3	3	1	3	10
Changed stratification	Wider continental shelf waters	Lowering of thermocline and change in ecological so we related to thermocline. (speculative)	moderate	1	1	3	2	7
Sea level rise	Salt marsh/mud flats	Coastal squeeze, habitat loss, conflict between land use	high	3	3	2	3	11
Storm surges	Easily erodable and fragile habitats Coastal/shallow habitat (e.g. maerl, serpulid reefs, chalk reefs, kelp forests).	Smothering, increased erosion, physical destruction and displacement (strand lines)	unknown	3	2	2	3	10
Acidification	Calcified benthos Maerl, long lived corals, Echinoids, calcified habitats/reefs	Unknown - active research area	High	3	3	3	Unknown	9+
Overall climate change	Ecosystem goods and services - energy flow, nutrients, genes etc	Species replaced so low impact	Low	1	1	3	3	8
	Certain species, *Nephrops*	Economic species may be displaced	high	3	3	2	3	11

6.4 FISH

The fish fauna of the NEAME was considered to be very sensitive to change, particularly with respect to egg and larval stages, and in general regarded as an important component of the ecosystem. It was predicted that any changes that would occur in response to climate change would be NEAME-wide. Consequently for many of the analyses presented in Table 6.3, the conclusion with respect to the significance of the effect was major. In particular, concerns were greatest for the effects of:

- Sea surface temperature rise;
- Ocean acidification; and
- Trophic mismatch.

Additional impacts were predicted as a consequence of sea level rise, stratification of the water column, storm surges and increase in nutrients and pollutants. These characteristics are briefly included in the discussions below.

Sea surface temperature

With respect to sea surface temperature the principal threats were considered to be effects on larval recruitment and changes in species distribution. Increases in seasonal stratification of the water column were thought to be of minor importance overall, largely having a potentially moderate impact on a local scale and with respect to Atlantic cod.

Recruitment

It is known with high confidence that fish recruitment, year class strength and energetic demand are all highly sensitive to temperature change. It was felt that the egg stage of both herring and Atlantic cod in particular would be subject to an impact of major significance from a 4^{o}C temperature rise where a corresponding decline in recruitment would be anticipated. Studies support the link between temperature and recruitment in cod (Planque *et al.,* 2003). It is also evidenced by the correlation noted between sandeel recruitment and periods of positive NAO (i.e. warm spells). The effect would be felt across the whole of the NEAME and could represent very large changes in the level of recruitment, perhaps even failure of a whole year class, particularly during periods of highest temperature increase (for example during periods of positive NAO). Whereas herring eggs are benthic, Atlantic cod eggs are planktonic, hence more vulnerable to temperature changes.

As noted in Section 5.3, these species spawn across the NEAME region. However with upper lethal temperatures for eggs (12^{o}C for Atlantic cod, 16^{o}C for herring), elevated temperatures during the breeding season may prove lethal to, or at least substantially weaken, the level of larval recruitment or the strength of that year class.

Sandeel populations are currently in decline. There was widespread failure for Scottish seabird colonies in recent breeding seasons. Particularly significant was the unprecedented impact on guillemots (in 2004), which though they can dive up to 100m hunting for food, were still impacted by the sandeel decline.

Distribution

As has also been noted above for plankton and benthos, temperature increases will drive a shift in the distribution of species and this is likely to include the northward relocation of the southern limits of occurrence in herring, Atlantic cod and the present sandeel species of the NEAME (primarily *Ammodytes marinus*), amongst others. The distribution limits of these species are presented in Table 5.1 and note should, in particular, be made with respect to temperature range. The present average temperature is 16°C in the southeast of England, and for example, the predicted increase of 4°C would exceed the temperature distribution limits of herring and Atlantic salmon and coincide with the upper limit for Atlantic cod. The loss of Atlantic cod, herring, and Atlantic salmon to at least Areas 3 and 4 is a possibility and also a change in the species composition of the sandeel species, with *Ammodytes. marinus* in particular being effected. The shallow reaches of the North Sea (Area 1) may also become, seasonally, hostile to some of these species. It is anticipated that the niches occupied by these species will be filled by southern equivalents, for example sardines may replace herring. The ecological consequences are hard to predict and will be determined by a combination of factors, such as any time lag in species substitution, differences in biology and ecology that might result in their potential productivity (such as the sandeel example below) and their availability as prey items.

Because sandeel species have preferences for particular sediment types, any redistribution of species driven by increasing temperature may not result in a species substitution, or comparable productivity, if this is substrate limited. If this occurred, then the consequences for the NEAME would be of major significance given the large number of species (fish, marine mammals and birds) that prey on them.

With respect to salmon, although a large part of their life cycle occurs outside of the NEAME, there are likely to be direct impacts on them as a consequence of a temperature rise in the NEAME environment. Emerging evidence suggests that sea temperatures affect migration speeds and routes and that they may also influence the extent to which migrating salmon are killed by predators (ICES 2005b). Furthermore sea temperatures will affect food availability (ICES 2005) and there is strong evidence that the return of salmon to home waters in the north-east Atlantic is related to the availability of plankton to juvenile salmon at sea (Hays *et al*., 2005). It is thought that the key to their decline could be found in the changes in the climate of the North Atlantic over the last 50 years (FRS 2004a).

Ocean acidification

As with other climate change characteristics, the focus of concern with respect to impacts of ocean acidification on fish species is with respect to the sensitivity of the egg stage. Circumstantial evidence (The Royal Society, 2005) suggests that this is a reasonable assumption. The expectation is that a drop in pH will lead to an increase in the mortality of eggs and hence decrease in recruitment. However, there is a high degree of uncertainty as to how sensitive these species[9] may be. The tentative conclusion coming from the workshop, subject to investigation of existing literature or yet to be carried out testing, is that a drop to a pH of 7.8 by the end of the century will have an impact of major significance.

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[9] Excluding Atlantic salmon, which spawn in freshwater.

Trophic mismatch

As changes occur in the NEAME's ecosystem there is the threat that adjustments by component parts will take place at different rates. As ecosystem components are intimately interrelated, this will undoubtedly have major consequences, possibly with long term ramifications.

During their larval stages, all fish consume zooplankton. Synchrony between the peak in plankton abundance and the arrival of fish larvae in the plankton (the so called 'match-mismatch hypothesis') is thought to be crucial in determining the survival of fish larvae. Consequently, the abundance and timing of mesozooplankton might affect fish recruitment (Beaugrand *et al*., 2003; Hays *et al*., 2005).

For example, in the North Sea, *Calanus* (from eggs to adults) are an important prey item for Atlantic cod larvae and juveniles until July–August each year. The progressive substitution of *C. finmarchicus* by *C. helgolandicus* in the North Sea has delayed the timing of occurrence of *Calanus* prey from spring to late summer at a time when larval/juvenile Atlantic cod feed more on euphausiids and other fish larvae (Edward and Johns, 2005). The consequent reduction in available prey earlier in the year and the resultant diminution in growth contributes to reduced survival and poor recruitment (Beaugrand *et al*., 2003). Further, there has been a reduction in biomass of both *Calanus* (Figure 5.2) and the euphausiid shrimps, which further contributes to fewer Atlantic cod larvae developing into adults (Beaugrand *et al*., 2003; Hays *et al*., 2005).

Further evidence of changes in plankton phenology and a fish response was obtained during the first years after the re-opening of the North Sea herring fishery in 1983, when a relatively high proportion of the catches in early summer was taken in the eastern North Sea. After 1986, the proportion of the catch in the eastern North Sea gradually declined. It has been proposed that the high catches in the eastern North Sea in the early 1980s were due to a delayed migration of the herring from the eastern to the western part of the North Sea. This delayed departure of the herring from the eastern North Sea could have been caused by favourable food conditions in this area. Data on *Calanus finmarchicus* from the Continuous Plankton Recorder show that the seasonal cycle of this copepod in the eastern North Sea was delayed during the period 1976-1984, which resulted in a prolonged food supply for the herring in this area. It is likely that this extension of the feeding season induced the herring to delay their departures from the eastern North Sea. When the *Calanus* season shortened after 1985, the herring advanced their departure from the eastern North Sea. There was a delay of one or two years between the shortening of the feeding season and the earlier departure of the herring from the eastern North Sea. This suggests the existence of a certain conservatism in the migrations of the herring. It seems that the time of departure from the eastern North Sea is based not only on the food situation in the current year, but also on the average timing of food production in earlier years (Corton, 2000).

Sea level rise and storm surges

The direct effects of sea level rise and storm surges on fish are largely limited to changes in the availability of coastal and other shallow water habitats. The extent of the effect on inshore nursery, feeding and spawning grounds will, however, be as a consequence of how much coastal squeeze occurs.

Another potential impact will occur if the frequency of storm surges results in changes to shallow submerged sandbanks that support populations of sandeels. There are two elements to this threat. Firstly storm surges may change the amount of available habitat, and this is assumed to be a reduction, as sandbanks are washed away and given insufficient time to redevelop between major storm surge events. Secondly, populations of sandeels might suffer high mortalities from storm events and, with an increase in their frequency, be allowed less opportunity to recover population levels.

Our knowledge of the risk of these impacts occurring is limited. However, given the importance of these habitats, and the sandeels' central role in the overall ecosystem (including as a prey item for Atlantic cod, herring and Atlantic salmon), it was considered appropriate to conclude that an impact of major significance would occur based on the characteristics parameters discussed.

Nutrient inputs

Should nutrient levels increase in the NEAME, primarily coastal waters, then it is anticipated that there would be a related increase in productivity. This is, however, assuming that productivity is nutrient limited. The level of significance of such a change is considered to only be moderate and the level of confidence in such a prediction is low.

Confidence in the assessment

Consensus and confidence existed in the conclusions being drawn with respect to the effects of sea surface temperature rise and its effects on species redistribution and recruitment and also the effects in changes to the NAO index and ocean circulations. Beyond that, however, confidence in the assessment was low for all other aspects.

Impacts on fish

In conclusion, it has been suggested that the fish fauna of the NEAME is likely to be subject to a number of impacts that will be of major significance. These are a direct consequence of an increase in sea surface temperature and indirectly by the effects of temperature rise on seasonal variations, particularly in the plankton fauna and flora. The potential for negative changes in ocean circulation (and trends in NAO), which may be temperature related, have also been considered of major significance.

The threat posed by ocean acidification may also be of major significant if it is determined that the egg stages are particularly sensitive to amount of change in pH that is currently being predicted. Coastal squeeze will be a more likely manifestation of sea level rise and therefore a negative impact on nursery and spawning grounds. Further, the increasing frequency and strength of storm surges could potentially have a deleterious effect on sandeel habitats (shallow subtidal sandbanks) and populations.

Table 6.3. Impact assessment for marine fish.

Characteristic	Receptor	Impact	Confidence	Sensitivity	Importance	Spatial scale	Magnitude of change	Significance
Sea surface temperature	Herring – eggs	Controls of recruitment/year class strength > temps = decreased recruitment	High	3	3	3	3	12
	Herring - larvae	Controls of recruitment/year class strength > temps = decreased recruitment	Low	1	3			
	Atlantic cod – eggs	Controls of recruitment/year class strength > temps = decreased recruitment	High	3	3	3	3	12
	Salmon – adults	Increase temperature = faster growth, more energetic demand (eat more food)	High	1/2	3	2	1	8/9
	Sandeels	As above. But possible change in predation if herring and Atlantic cod stores crash	Low	1	3	3	?	?
Sea surface temperature	Salmon	May shift southern boundary north	Low	1	3	1	1	6
	Herring	Southern limit shifts north	High	3	3	3	3	12
	Atlantic cod	Southern limit shifts north	High	3	3	3	3	12
	Sandeel	Southern limit shifts north	High	3	3	3	3	12
Stratification	Atlantic cod	Possible reduction in habitat?	Low	2	3	1	1	7
Sea level rise	All species above	More habitat. But inshore feeding/spawning grounds may reduce	Low	1 to 3	3	3	1	8 to 11
Storm surges	Sandeels habitat	Shifts in habitat? If habitat lost, decrease in population density	Low	2	3	3	3	11
	Atlantic cod, salmon, herring, trophic relations	If sandeel populations fall, no food!	Low	3	3	3	3	12

Ocean circulation and NAO	All four species of fish	If currents shift pelagic life stages may get shifter from preferred habitats and loose access to food? (Transport of larvae)	Low	1	3	1	?	?
	Salmon	In west Atlantic, negative relationships between salmon landings and positive NAO BUT unknown in east Atlantic.	Moderate	3	3	3	3	12
	Herring	Warm waters - shift to warm water specialists e.g.. Sardines	High	3	3	3	3	12
	Atlantic cod	West Atlantic variation in NAO linked with fluctuations in Atlantic cod recruitment. * May be switched in east Atlantic?	Moderate	3	3	3	3	12
	Sandeel	Negative relationship between sandeel recruitment and positive NAO	High	3	3	3	3	12
Acidification	Atlantic cod, herring and sandeel eggs	Increase mortality, decrease recruitment	Low	3	3	3	3	12
Nutrients	All species	Increase production (if food web nutrient limited)	Low	1	3	3	1	8
Increase plankton growing season	All species	Could break down seasonality - lead to shifts in plankton composition	Low	1 or 3	1 to 3	3	1	6 to 10

6.5 BIRDS

Assessment of the potential climate change effects on birds have concentrated on terns and waders as a means of keeping the focus of the assessment straightforward but as representative as practical. With this approach it has been possible to identify the principal major threats to birds to be as follows:

- Effects on sandeels;
- Storm surges and sea level rise;
- Increases in air temperature amplitude;
- Nutrient and pollution increases; and
- Ocean acidification.

Unlike previous sections, describing the predicted impacts on plankton, benthos and fish, for birds (and also marine mammal in Section 6.5), in addition to the significance to the NEAME, workshop delegates highlighted the relative significance to the global populations of these receptors, using a 1 (low) to 3 (high) score. This is considered further in Section 8.

Effects on sandeels

Table 6.3 summarises the impact assessment of bird and marine mammal receptors for each of the climate change characteristics considered. In the case with terns, against these characteristics the most significant responses are believed to be an increased risk of breeding failure. Whether the driver is sea surface temperature rises, ocean acidification (but see also Section 6.4.4), changes in nutrient and pollution inputs or plankton growth, the key effect is the impact on sandeel populations. That is to say, these characteristics impact terns and other seabirds (particularly puffins, guillemots and kittiwakes) via their effects on sandeel and other prey species. As noted in Section 6.3, sandeel populations are vulnerable to negative effects from climate change. A link between sandeel populations and arctic tern and other species has been noted in Section 5.4.1. As such, any climate change related decline in sandeels, in particular, could result in near total breeding failure for any one year, a sequence of years, for individual breeding colonies or across the region as a whole. Already, breeding seabirds such as terns (but also, kittiwakes and auks especially puffin and guillemot) are failing to breed or raise significant numbers of chicks to adulthood.

In this assessment, each of the characteristics listed above in this subsection, were noted to have an impact of moderate significance. However two points should be noted here:

- The combined effects of each on sandeels could push their abundance to levels too low to support a viable tern (particularly arctic tern) population in the NEAME[10] resulting in a higher assessment score for the magnitude of change; and
- As top predators, their importance to the ecosystem, with respect to other species that rely on their continued presence, scores low and hence favours a significance score below “major”.

It is therefore appropriate to deliberate whether the appropriate conclusion on how significant these potential impacts are, in terms of both the overall pressures on prey

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[10] Additonal in-combination impacts are considered further in Section 7.

items and also any judgement value placed on the importance of terns to the NEAME, outside of purely ecosystem functionality.

Storm surges and sea level rise

Terns tend to nest on low lying nearshore ground and as such are vulnerable to sea level rise resulting in a loss in nesting habitat, particularly where coastal flood defence structures prevent a natural realignment of the coastline and its associated habitats. Additional pressure on breeding success comes from the threat of nests being washed out by storm conditions, particularly as a result of increasing frequency of storm surge events (Section 4.5). It is thought that in the case of arctic terns at least, that a population requires around three years to recover from a poor breeding season. The breeding populations in southern North Sea are thought to be particularly vulnerable, not least as a consequence of the predictions of higher sea level rise here than in other parts of the NEAME (see Section 4.4; Hulme *et al.*, 20002). Effects, therefore, become critical to long-term viability of tern (and other seabird species) if breeding failure become too frequent, subject to capacity elsewhere (other regions where failures do not occur) to repopulate diminished colonies. The in-combination impacts are discussed further in Section 7.

Waders in general are also moderately sensitive to sea level rise and increase in the frequency of storm surges, though some species will be more sensitive than others dependent on their breeding and feeding behaviours. The key impact would be loss of suitable feeding and breeding habitat.

For terns and waders alike, sea level rise and an increase in storm surge frequency are considered to be impacts of moderate significance.

Air temperature

Rises in air temperature and the range of temperatures that might be experienced are believed to be capable of impacting terns and waders to an extent considered, respectively, of moderate and major significance. The effects of air temperature rises are primarily concentrated on their distribution and feeding. These impacts are thought to be well understood, albeit more so for waders.

For terns, it has been concluded that the impact will extend across a spatial scale of at least a NEAME Area, and with resulting in a medium magnitude of change. It is likely that the arctic tern, in particular, will be subject to a redistribution of breeding colonies to higher latitudes, potentially excluding them from Area 4 and perhaps much of Area 3.

For waders, the spatial scale for changes as a consequence of air temperature rises is considered to be NEAME wide, with a magnitude of change considered of medium scale (i.e. detectable without affecting ecological integrity and presence). In all, it is considered that effects on waders are of major significance.

Ocean acidification

As noted in Section 4.6, this characteristic of climate change is very concerning, but the implications are little understood. In the case of birds, it was proposed that there may be consequences in the form of changes to egg shell structure and integrity and ramifications from change (or loss) of prey items. Earlier sections have outlined the potential effects on plankton, benthos and fish. With respect to waders the issue of ocean acidification rests on how benthic invertebrates, are effected and it is suggested that the answer rests on understanding how a reduction in pH will effect larval settlement of, in particular, calcifying species. Should recruitment of molluscs and barnacles become compromised then it is evident that those species relying on these species and unable to adapt to other food sources, will be most sensitive to changes. The risk that a pH reduction of 0.4 units will be of major significance to the productivity of tern prey species (such as sandeel) as tentatively suggested in Section 6.3.2, has been taken to indicate an impact of moderate significance, where a change in species distribution and abundance is predicted to be of medium order of magnitude but occurring throughout the NEAME.

Impacts on birds

The bird fauna of the NEAME is considered to be under pressure from two main factors:

- Decline in food supplies; and
- Loss of habitat.

Already under pressure from these factors (see Section 5.4), the additional effects of climate change are a major cause for concern. Although this assessment has, in the majority of individual cases, regarded the impacts to be of moderate significance, this is a conclusion largely influenced by the relatively low "ecological importance" (see Table 3.1 for definition), the scale of change spatially and in population terms, the "magnitude", have typically been regarded at a medium level of change (Table 6.4).

From this it can be concluded that it is thought that terns and waders will respond to a changing climate over the remainder of this century by showing shifts in distribution and population size. The expectation is that these changes will typically be without compromise to their overall persistence within the NEAME. Key risks to this not being the outcome are:

- Loss of habitat for waders caused by sea level rise;
- Breeding failure becoming an event of too great a frequency to provide sufficient scope for population recovery in terns (and comparable seabirds); and
- In-combination effects which are described further in Section 7.

6.6 MARINE MAMMALS

The effect of climate change on marine mammals in the NEAME has been considered to be generally of low or moderate significance (Table 6.4). The most significant is related to possible changes in food supply as a consequence of sea surface temperature rise, ocean acidification and changes to plankton biomass and phenology. Thus, changes to the populations, distribution or physiology of fish and cephalopod species[11], the primary prey items for many marine mammals, may have knock-on effects for

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[11] The effects of ocean acidification may be, in particular, strongly felt by cephalopods which have a high metabolic demand for dissolved oxygen. Increases in dissolved CO_2 might compromise uptake and carrying of oxygen in blood (The Royal Society, 2005).

cetaceans. Suggested impacts of climate change on marine mammals (for two indicator species) include:

- Grey seal population size may decline; and
- Fin whale distribution and feeding strategy may adjust due to climate change effects. There may also be a decline in breeding success.

Additional minor impacts have been noted including potential breeding failure for harbour porpoise and bottlenose dolphin associated with changes in amount and bioavailability of pollutants in the system and the potential loss of breeding/ haul out sites for harbour seals, particularly in the southern North Sea, due to sea level rise.

The level of understanding of the predicted responses of marine mammals to climate change, across all of the deliberations described here, does not allow us to arrive at universally agreed assessments, and there is also a low level of confidence in the data and assessment conclusions. However, this is not to suggest that climate change may not have strong impacts on certain cetacean species; it merely reflects a lack of scientific data. Moreover, the effects of climate change on marine mammals within the NEAME region are unlikely to be restricted to the indicator species mentioned above.

Table 6.4. Impact assessment for marine predators (birds and marine mammals).

Characteristic	Receptor	Impact	Confidence	Sensitivity	Importance	Spatial scale	Magnitude of change	Significance	(Global Significance)
Sea surface temperature and stratification	Terns	Breeding failure	Moderate	3	1	3	2	7	2
	Grey seal	Change in abundance	Low	1	1	3	2	7	3
	Fin whale	Redistribution eventually, possible lower breeding success	Low	2	2	2	2	8	1
Storm surges and sea level rise	Terns	Breeding failure, habitat loss	High	3	1	1	2	7	2
	Waders	Habitat loss/change	High	2	2	2	3	9	3
	Harbour seals	Redistribution and potential loss (breeding) haul out sites	Low	2	1	1	1	5	2
Ocean circulation and NAO	Waders	Distribution and abundance	Moderate	3	2	2	2	9	3
Acidification	Terns	Loss/change of food. Egg shells	Low	1	1	3	2	7	2
	Waders	Changed food. Egg shells	Low	3	2	3	3	11	3
	Fin whale	Changed food	Low	2	2	2	2	8	1
Air temperature amplitude	Waders	Feeding distribution	High	3	2	3	2	10	3
	Terns	Feeding distribution	Moderate	3	1	2	2	8	2
Nutrient and pollution	Waders	Distribution. Feeding	Moderate	2	2	3	2	9	3
	Harbour porpoise	Breeding failure - loss of immune system – toxicity effects	Low	2	1	1	1	5	1
	Bottlenose dolphins	Breeding failure - loss of immune system – toxicity effects	Low	2	1	1	1	5	1
Plankton	Fin whale	Feeding distribution	Low	3	2	2	2	9	1
	Terns	Breeding failure - redistribution	Moderate	3	1	3	2	9	2

7. In-combination effects

In Section 6 the principal potentially significant impacts on the NEAME have been discussed individually. The degree of confidence in the predictions has also been noted. When considering the interaction of these individual impacts and their combined effects, the level of uncertainty rises dramatically. As such, consideration of the in-combination effects has remained at an unquantified discussion, with the intention of highlighting the key issues with which to be most concerned.

7.1 EXAMPLES OF IN-COMBINATION EFFECTS

The rise in the annual average sea surface temperature has been noted across the fauna and flora of the NEAME as the main driver for the majority of impacts. The in-combination effects with other factors, such as ocean circulation and NAO or ocean acidification could have deeper implications with respect to the magnitude of effect. However, the spatial and temporal scales for changes in these parameters and their interactions is not understood, and as such, it is not possible to identify where or when critical points will be encountered in species and habitats, and their temporal and spatial features. Existing natural variation in population abundances of, for example, certain fish species is controlled by NAO-driven variation in the oceanographic conditions. Further, biogeographic shifts in species distribution by one factor, such as ocean circulation, are likely to be superimposed on temperature-driven changes. However, our level of understanding of these processes is not completely understood. It is not surprising, therefore, that, working from this tentative knowledge base, considering the potential impacts of multiple climate change effects is difficult in the extreme.

The fundamental importance of the plankton in supporting the whole of the NEAME ecosystem draws attention to the threats caused by any changes here. Trophic mismatch has been highlighted on a number of occasions in Section 6. The knock-on effects of mismatch across the food web, the so-called trophic cascade, is cause for concern. With additional pressures from other impacts, it becomes self evident that the various ecosystem components will be subject to substantial pressures.

For waders and terns, the combined effects of sea level rise and storm surges has been highlighted in the preceding sections as a key concern with respect to habitat loss and, for terns, breeding failure due to nest wash out. For terns, and other species with comparable sensitivity to storm surges, the additional pressure from the periodic the failure of sandeel stocks could result in a unrecoverable degradation of the NEAME population. For every failed breeding season, it is suggested (Peter Evans, *pers. comm.*) that a period of up to three or four years of good breeding may be required for recovery. Recent failures in breeding at colonies of guillemot, puffin and terns in northern Scotland have been blamed on a decline in sandeels.

Waders are subject to pressures across their range and habitat, including loss and degradation of habitat away from the marine environment, and thus the extent of loss of intertidal habitat due to sea level rise could conceivably result in population crashes should a critical threshold be passed.

For marine mammals and sea birds, particularly the former, the in-combination effects of multiple stressors is of major concern. The combined effects of existing and future pollutant levels (and toxicity), increased sea temperature, variation in plankton phenology, and potential rise in toxic bloom events all add to the pressure on immune systems and reproductive success. In species with low reproductive rates and, for some species, low existing population levels, even a minor reduction in breeding rate could compromise the prospects of long-term survival.

Because the coastal zone is a heavily used locality by both man and many fauna and flora, its vulnerability to in-combination effects has to be considered to be of fundamental importance. The in-combination effects of increased sea temperature, rise in the frequency and persistence of seasonal water column stratification and potential rise in nutrient loads is likely, will only add to the existing pressures. Addressing these (existing) issues through coastal zone management is ongoing. However, the added burden of climate change impacts increases the complexity and the urgency of the task, particularly where predictability of disturbance events, such as storm surges, and the NEAME's resilience to these is reduced as a consequence of climate change.

7.2 SUMMARY OF IN-COMBINATION EFFECTS

This section has briefly highlighted the potentially major issues associated with the in-combination impacts of climate change. As noted here, it is evident that a series of pressures on a population of anything from diatoms to cetaceans, whether they are individually significant or not, could in-combination, have an huge deleterious effect on their viability in the NEAME.
The key concerns are therefore considered to be:

- The pressures associated with the increased pressure from multiple stressors, either by the addition of further stressors, most notably higher sea temperature, or increases in existing ones, such as pollutants; and
- The effects of changes in seasonal patterns of growth and abundance of the various components of the plankton and how this impacts growing seasons and recruitment of other fauna in the NEAME.

8. Vulnerability Analysis

This section summarises the findings of the preceding sections (Sections 6 and 7) with the main purpose of highlighting the key conclusions particularly with reference to:

- The most functionally important parts of the NEAME ecosystem; and
- Those parts most vulnerable to change.

It will be apparent from Section 6 that the impact assessment process has identified major significant impacts on the majority of the receptors. Consequently, this section will also include some rationalisation of this to ensure that the key vulnerabilities are highlighted to aid the focus of further debate, assessment and planning.

The fundamental role of plankton to the ecosystem is incontestable. As such, predicted changes (and those already evidenced) are considered key to the vulnerability assessment of the NEAME. The temporal changes in growth and productivity of both phytoplankton and zooplankton (Section 5.1) are causing particular concern in the scientific community because of the risk of trophic mismatch and knock-on effects (trophic cascade) across the ecosystem as a whole. Changes, even minor ones, in ocean circulation are also anticipated to contribute to biogeographical shifts that may further change the composition and seasonality of the plankton and its productivity. The potential deleterious effects of ocean acidification on calcifying phytoplankton, such as coccolithophores, also contributes to the conclusion that the phytoplankton flora, and hence closely coupled zooplankton fauna, is of paramount concern to this vulnerability assessment (Table 6.1 for summary).

Also with an important role in the ecosystem are fish, in particular sandeels because of their importance as a prey species for other fish, many birds and also marine mammals (Section 6.3). The scale of their commercial exploitation has previously caused concern (FRS website, 2005; Rogers and Stock, 2001) and this adds to the pressures on them, hence their vulnerability. Sandeels are at risk from sea temperature rise, and these effects are thought already to be affecting the NEAME. They are also potentially at risk from increases in storm surges (where spawning beds in shallow sand banks may be washed away). Though biogeographical shifts in sandeel spices is likely to occur, it is unclear at this stage, whether those southern species whose range is anticipated to move north, will have access to appropriate habitat (in terms of sediment type and preferred water depth etc.) available or if available in sufficient extent to support a suitably extensive population for the range (and biomass) of predators currently inhabiting the NEAME.

Concerns with respect to other fish, such as cod and herring, primarily focus on the physiological issues associated with, in particular, temperature rise but also ocean acidification. Ecological concerns are primarily drawn to the issues of trophic mismatch, or reductions in sandeel populations as prey. In regard to these particular issues it is appropriate to express genuine concern about the vulnerability of stocks that are already known to be under intense pressure, not least from fishing (Rogers and

Stocks, 2001) although some, such as herring are not necessarily being fished unsustainably (Fisheries Research Services, 2005).

Benthic fauna are likely to be subject to changes, principally distributional shifts (Table 6.2), however, as functional effects of this are likely to be limited to only a few species, such as those with a structural role, their overall importance to the vulnerability analysis is limited to maerl, horse mussel, and deepwater corals as structural species and for these, the spatial distribution is typically limited.

In terms of the climate change characteristics, the rise in sea surface temperature was felt to be the most important driver and ocean acidification the most concerning factor that is less well understood.
Sensitivity to ocean acidification was considered to be most relevant to:

- Calcifying species, particularly phytoplankton, maerl and deep water corals and benthos (echinoderms and calcifying species particularly at the settlement stage);
- Fish species, particularly with respect to egg viability; and
- Cephalopods, particularly in light of their high metabolic rates and hence sensitivity to effects that acidification may have on decreasing ocean oxygen levels.

However, understanding how marked these potential effects might be is presently unclear.

The coastal environment is already subject to conflicts of use and climate change effects will add additional or new pressures.

The principal concern in this respect is the vulnerability of intertidal soft sediments and associated saltmarsh habitats. Though easily erodable habitats, such as chalk reefs, and isolated water bodies, such as voes and sea lochs, vulnerable to deoxygenation events associated with stratification of the water column, will also be subject to loss of area. The importance of the intertidal soft sediments is considered to be greater because of their wider role in supporting substantial populations of birds and fish.

During this assessment, the importance to the ecosystem of birds and marine mammals was considered to be low or medium as a consequence of limited reliability on them by other components of the ecosystem (Table 6.4). Their sometimes localised occurrence (Section 5.6, Table 6.4) also tended towards a lower score. As a consequence of these values, impacts on these receptors generally suggested impacts of only moderate significance. However, this assessment does not take into account any other value judgements. The continued presence of fin whales, for example, might be considered of high importance and suggest any impact should actually be considered of major significance. It is important to remember, when looking at the assessment matrices (such as Table 6.4) that even an impact of moderate significance could be considered of sufficient concern to warrant particular note in the vulnerability assessment. For this reason, the impact of breeding failure in terns (and species with similar sensitivities) due to a lack of food (in Table 6.4, indicated under changes in plankton phenology), should be registered as of key importance.

8.1 CONCLUSIONS

The most significant impacts that climate change is thought to present to the NEAME are:

- Temperature effects on the growing season, species distribution and productivity of phytoplankton and zooplankton;
- Temperature effects on the distribution, abundance and recruitment of sandeels;
- Temperature and ocean acidification effects on the physiology of fish, particularly at the egg stage;
- Loss of intertidal habitats through sea level rise, storm surges and coastal squeeze; and
- Breeding failure in seabirds such as terns as a consequence of lack of food (sandeels).

In regard to the climate change characteristics giving rise to most concern, it is evident that sea surface temperature is the principal driver for many of the impacts discussed in this report. The recently raised issue of ocean acidification has caused alarm, with particular concern with respect to the potential implications for:

- Calcifying processes in coccolithophores, deep water corals and benthic calcifying species at the larval settlement stage; and
- Reduction in egg viability and recruitment in fish.

The potential for catastrophic events to occur this century have been discussed and are not considered to be of significance, as existing knowledge and evidence suggest there is very little risk of their occurring within this century.

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Appendix 1

Workshop delegates

Delegates	**Affiliation**
Jason Anderson	International Institute for European Environmental Policy
Laura Bateson	WWF
Simon Brockington	English Nature
Iain Brown	Tyndall Centre
Michelle Colley	UK Climate Impact Programme
Andy Deacon	DEFRA
Richard Emmerson	OSPAR
Peter Evans	Sea Watch Foundation
Astrid Fischer	Marine Climate Change Impact Programme
Conor Graham	Max Planck Institute
Beth Greenaway	DEFRA
Jason Hall-Spencer	Plymouth University
Chris Harrod	Max Planck Institute
Keith Hiscock	Marine Biological Association
Sarah Hughes	Fisheries Research Services
Steve Isaac	Whale and Dolphin Conservation Society
David Johns	Sir Alistair Hardy Foundation for Ocean Sciences
Andrea Kaszewski	WWF
Beatice Klose	WWF
Dan Laffoley	English Nature
Dave Long	British Geological Survey
Jason Lowe	Hadley Centre
Jennie Mallela	Manchester Metropolitan University
David Palmer	Environment Agency
Mark Rehfisch	British Trust for Ornithology
David Prandle	Proudman Oceanographic Laboratory
David Schoeman	Scottish Association For Marine Sciences
David Viner	Climate Research Unit
Project team	
Emily Lewis-Brown	WWF - Project Leader
Trevor Baker	West Coast Energy Ltd - Project Manager
James Martin-Jones	WWF - Lead Facilitator
Kirsty Clough	WWF - Facilitator

Appendix 2

Workshop presentations

The following presentations are available as separate files by following the links:

Trevor Baker	Overview of the vulnerability assessment – scoping study	www.wwf.org.uk/neameworkshop/vulnerabilityassessment.pdf
Jason Hall-Spencer	In-situ effects of ocean acidification	www.wwf.org.uk/neameworkshop/oceanacidification.pdf
Keith Hiscock	Seabed species redistributions	www.wwf.org.uk/neameworkshop/seabedspeciesredistributions.pdf
Sarah Hughes	Ocean circulation and the NAO	www.wwf.org.uk/neameworkshop/oceancirculationnao.pdf
David Johns	Extension to growing season and changes in phenology of plankton	www.wwf.org.uk/neameworkshop/growingseason.pdf
Jason Lowe	Sea-level rise and storm surges	www.wwf.org.uk/neameworkshop/sealevelrise.pdf
Dave Long	Methane hydrates	www.wwf.org.uk/neameworkshop/methanehydrates.pdf
David Prandle	Sea surface temperature	www.wwf.org.uk/neameworkshop/seasurfacetemperature.pdf