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Report of the Study Group on Working Hypotheses Regarding effects of Climate Change (SGWRECC)

By correspondence

ICES
International Council for the Exploration of the Sea

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Contents

Executive Summary

Ten aspects of the response of temperate marine ecosystems to climate change were identified from published summaries. For each, the evidence of current change is listed, together with likely future changes and the level of confidence that we can have in these based on hypotheses concerning the underlying mechanisms.

1 Introduction

The Study Group was established to carry out preparatory work to position the Expert Groups meeting in 2008 to conduct analyses that can be presented and interpreted in a consistent and systematic manner across Expert Groups, for integration as a response by ICES to a request for advice from OSPAR regarding "*an assessment of the changes in the distribution and abundance of marine species in the OSPAR maritime area in relation to changes in hydrodynamics and sea temperature'.*

The assessment should look at ecologically indicative species, including threatened and declining species identified by OSPAR, for which adequate time series data exist, in order to assess to what extent there have been changes in distribution, population and condition of species beyond what might have been expected from natural. The aim is to prepare an overview as a major contribution towards JAMP Product BA-3 and material that can be included in the Quality Status Report in 2010.

Terms of reference of

a) Develop *a priori* hypotheses for the major ways that ecosystem components at as many levels as feasible could be altered by the effects of climate change and climate variation, and by other major drivers of ecosystem change, particularly (but not restricted to) fishing;

b) Propose guidance for what patterns would be expected in the types of data that are available on the status and trends of various ecosystem components, as reviewed by WGECO in 2007; were the hypotheses posed in a) to be true; with particular emphasis on differences in patterns that would allow strong inference to be used in interpreting any trends found on the data.

The Study Group worked by correspondence. Participants contributing to the report are listed in Section 6.

2 Patterns of change in marine ecosystem components and hypotheses regarding the role of climate change

The SG identified changes in marine ecosystem components, functions and habitats which have been hypothesised to be due to climate change. In the following pages, the evidence for each of these issues is summarised. In large part, the summaries were based on the scientific reviews carried out by the UK Marine Climate Change Impacts programme (MCCIP) (http://www.mccip.org.uk/default.htm).

2.1 Poleward shifts in the latitudinal distributions of species, with consequent changes in species composition and species richness at any given location

Patterns in data or expected in the future

Plankton

- The important decadal climate indicator for the North Atlantic, the NAO, has been rising along with Northern Hemisphere Temperatures over the past 30 years and the surface waters of the European Continental shelf have been warming. These factors have been correlated with changes in the planktonic ecosystem in terms of plankton production, biodiversity and species distribution (Reid and Edwards, 2001; Edwards *et al.*, 2001, 2002; Beaugrand *et al.*, 2003a,b, 2004; Richardson and Schoeman, 2004; Southward *et al.*, 2004; Alheit *et al.*, 2005; Heath, 2005).
- There has been a northward shift in the distribution of many plankton species by more than 10º latitude (over 1000 km) over the past fifty years. This shift is particularly associated with the shelf edge current running north along the European continental margin (Beaugrand *et al.*, 2002; Brander *et al.*, 2003; Genner *et al.*, 2004).
- In the North Sea the population of the previously dominant and important zooplankton species, (the cold water species *Calanus finmarchicus*) has declined in biomass by 70% since the 1960s. Species with warmer-water affinities are moving northward to replace the species but are not numerically as abundant (Beaugrand *et al.*, 2004; Edwards *et al.*, 2007).

Confidence in relationships between observed patterns and climate change

There is a medium to high level of confidence in what is happening to the plankton now based on information from the CPR survey and corroborated through smaller-scale surveys and satellite observations. For example, changes in the biogeography and phenology of plankton are highly significantly correlated with Northern Hemisphere Temperature changes. We are less (medium to low) confident of future scenarios.

Source document

Edwards, M., Reid, P.C. and Heath, M. (2008). Plankton. MCCIP Annual Report Card 2007–2008 Scientific Review. 6pp. http://www.mccip.org.uk/arc/2007/PDF/Plankton.pdf

Fish

- Abundances of warm-water fish species (e.g. red mullet, john dory, triggerfish) have increased in UK waters during recent decades, while many coldwater species have experienced declines.

- There has been a massive influx of snake pipefish to UK waters since 2004, but unusual fish occurrences or sudden proliferations of species cannot definitively be attributed to climate change.
- A number of commercial and non-commercial fish species are suggested to have exhibited shifts in mean latitude over the past 25 years.
- Poor 'recruitment' in traditional fishery target species such as cod, plaice and herring may be related to a climate related shift in the composition of zooplankton, which are a key prey for developing larvae.
- In some parts of the southern North Sea, cold-water species, such as cod and eelpout, have been shown to experience metabolic stress during warm years, as evidenced by slower growth rates and difficulties in supplying oxygen to body tissues.
- An important complication in assessing the impact of climate change on fish populations is to disentangle its effect from the effect of other drivers such as fishing. Fishing mortality rates have been higher in the southern North Sea than in the north (Heath *et al*., 2003; Heath *et al*., 2007), and so apparent changes in distribution (as indicated by Perry *et al*., 2005) could be a consequence of local patterns of fishing pressure and different rates of depletion in spatially segregated sub-stocks (Hutchinson *et al*., 2001; Wright *et al*., 2006). Daan *et al*., 2005 also raised the issue of more rapidly declining populations in the south of the North Sea compared to those in the North, whilst highlighting an absolute and relative increase in abundance of the smaller size classes and species. The effect of fishing may thus interact with the effect of climate and have enhanced the apparent northward shift of the smaller sized fish species reported by Perry *et al*., 2005 and more recently by Rindorf and Lewey, 2006.

Confidence in relationships between observed patterns and climate change

We have medium-high confidence in the observations that there have been changes in the distribution of commercially important fish species, but only low confidence that these are due to climate change because of spatial patterns in fishing mortality. Less is known regarding the likely responses of non-commercial species to marine climate change, largely because of the lack of data spanning sufficient time interval to analyse changes. Nevertheless, we can say with high confidence that since 1980 the distribution of many warm water northeast Atlantic fish species has shifted northwards to occupy latitudes at which they were previously unobserved or rare.

Source document

Pinnegar, J.K., Sims, D.W. and Heath, M. (2008).Fish and Fisheries. MCCIP Annual Report Card 2007–2008 Scientific Review. 32pp. http://www.mccip.org.uk/arc/2007/PDF/Fish-and-Fisheries.pdf

Birds

- Many of the common breeding seabirds in the UK are at or near the southern edge of their range, and it therefore seems likely that they would be affected by current and future climate change, and that populations may decline and ranges contract northwards. At the same time, very few seabird species currently breeding south of the UK seem likely to take up residence here.

Confidence in relationships between observed patterns and climate change

There is considered to be medium confidence that there are changes in the distribution patterns of birds and that these are due to climate.

Source document

Mitchell, I. and Frederiksen, M. (2008). Seabirds. MCCIP Annual Report Card 2007–2008 Scientific Review. 8pp. http://www.mccip.org.uk/arc/2007/PDF/Seabirds.pdf

Mammals

- Apparent range shifts have been observed in a number of odontocete cetacean species and these could be associated with changes in water temperatures, but at present it is not possible to differentiate between short-term responses to regional resource variability and longer-term ones driven by climate change.

Confidence in relationships between observed patterns and climate change

Our knowledge of gross status changes is good for seals but moderate-poor for cetaceans, whilst our understanding of links between demography and climate for both groups is poor. We therefore can only have a low level of confidence in what is happening now in relation to climate. As for what may happen in the future, without any clear understanding of impacts on marine mammals, in most cases it is impossible to make confident predictions.

Some marine mammal scientists are more confident than others that we are witnessing ecological effects of climate change as opposed to responses of individuals and local populations to local environmental variability. The statistical power to discriminate between the two remains low. Although more could be done to improve the current level of confidence, there will always be an upper limit to our ability to link population changes to the physical or biological drivers associated with climate change, particularly for some of the less accessible cetacean species.

Source document

Evans, P.G.H., Boyd, I.L. and MacLeod, C.D. (2008). Marine mammals. MCCIP Annual Report Card 2007–2008 Scientific Review. 12pp. http://www.mccip.org.uk/arc/2007/PDF/Marine-Mammals.pdf

Intertidal species

- The northern limits of southern, warm-water species that reach their northern biogeographical limits on rocky shores in the UK have increased in since the mid-1980s. Between 2001 and 2005 a number of these species increased their range around N. Scotland and along the English Channel. These range extensions were not trimmed back by the recent cold winter of 2005/2006 (the coldest since 1995/1996 for England and Wales, since 2000/2001 for Scotland and Northern Ireland).
- Decreases in the abundance of northern, cold-water species have been observed, however, there is less evidence on rocky shores of northern cold-water species retreating northwards.
- These observed shifts reflect predictions by climate models based on increased sea surface temperatures, and are occurring faster than most recorded changes in the terrestrial environment, but they are highly species-specific. This is likely to have consequences for biodiversity as the

rate and extent of changes will not be synchronous, and biological interactions will be affected. Sea-level rise and storms may have an important indirect impact as sea defences create artificial habitats in areas between natural rocky shores, acting as "stepping stones" by allowing intertidal species to extend their range.

Confidence in relationships between observed patterns and climate change

Overall, scientific experts have 'moderate confidence' that climate is already affecting distributions of species This is based on the existence of a large archive of high quality time-series data with wide geographical coverage that has been collected over long time periods prior to and during the current period of climate warming (see supporting evidence). Modelling undertaken to date has accurately replicated past and present observed species' distributions using changes in marine climate variables.

There is 'moderate confidence' in predictions for the future due to the current limitations in climate scenario forecasts and limited knowledge of the impacts at the community and ecosystem levels. The confidence level can only be increased by continuing monitoring surveys to validate model forecasts and increase the amount of baseline data and by investigating the bioprocesses governing species responses to climate change. Continued annual observations are critical to prevent anomalous environmental or anthropogenic events from being misinterpreted as climate-induced effects on the ecosystem. The rate of temperature increase is accelerating and ecological observations therefore need to be made on a regular basis in order to accurately map and predict future responses to climatic drivers. In summary, we have medium confidence in future predictions due to limitations with future climatic data predictions and incomplete knowledge of how ecosystems will be affected as changes accelerate.

Source document

Mieszkowska, N., Moore, P., Hawkins, S. and Burrows, M. (2008). Intertidal species. MCCIP Annual Report Card 2007–2008 Scientific Review. 9pp. http://www.mccip.org.uk/arc/2007/PDF/Intertidal-species.pdf

2.2 Rising temperature could enable more human introduced species to invade and become established, replacing current native species

Patterns in data or expected in the future

- The number of species of non-indigenous flora, fauna and algae is increasing in marine habitats and some are causing major ecological changes.
- Distributions of some non-native species are currently limited by water temperature.
- Warmer waters over the last three decades are facilitating the establishment of some of these species.

Confidence in relationships between observed patterns and climate change

Experts suggest a medium level of confidence regarding "what is happening now". This applies to non-native species overall as the information available in is moderate, and consensus is also only moderate.

There is a high level of confidence as to future effects; there is a growing body of evidence worldwide that climate change can facilitate marine invasions, and the potential risks from new introductions in the future are both high and potentially disastrous.

Source document

Elliott, P., Reid, P.C., Edwards, M. and McCollin, T. (2008). Non-native species. MCCIP Annual Report Card 2007–2008 Scientific Review. 9pp. http://www.mccip.org.uk/arc/2007/PDF/Non-native.pdf

2.3 Stratification and spring blooms of plankton in our shelf seas will occur earlier in a warmer climate

Patterns in data or expected in the future

- Freshwater Stratification: As stratification of the regions of freshwater influence depends on the balance between the rate of supply of the estuarine water and the strength of the mixing processes, changes in winds and rainfall will modify this balance.
- Onset of Thermal Stratification and the Spring Bloom: Away from sources of freshwater, large areas of the European shelf seas stratify in response to sunlight in spring and summer (e.g. the Celtic Sea, the North Sea north of Dogger Bank, the Malin Sea). The onset of thermal stratification in spring locks phytoplankton in the surface layer, where they receive lots of sunlight and grow rapidly. Following limited growth through the winter this "spring bloom" is the year's first appearance of significant concentrations of organic fuel to feed the rest of the ecosystem. There is evidence of a recent trend to earlier stratification and blooms largely in response to warming air temperatures. Our understanding of how shallow seas respond to meteorology suggest that stratification and the associated spring bloom will, on average, occur earlier in a warmer climate.
- Sub-surface Production: The interface between the warm surface layer and the deeper cold water (the thermocline) becomes a layer of significant growth for phytoplankton once the spring bloom has decayed. Growth here is a response to the supply of sunlight from the surface and weak flow of nutrients mixing up from deeper water. These controlling factors are likely to be influenced by changing climate but exactly how remains an area of limited understanding.

Confidence in relationships between observed patterns and climate change

There is medium confidence in the changes that are observed at the moment, based upon a high level of agreement between the observation and modelling studies and good understanding of the basic controls of stratification, but only a moderate amount of evidence being available (there are no long-term time-series of direct observations of stratification). There is a low level of confidence regarding what could happen in the future. The amount of understanding is probably moderate given that we have a fairly good knowledge of how the process of stratification is driven but a low level of certainty in how the drivers will change and how they will interact.

Source document

Sharples, J. and Dye S. (2008). Shelf sea stratification and the spring bloom. MCCIP Annual Report Card 2007–2008 Scientific Review. 5pp. http://www.mccip.org.uk/arc/2007/PDF/Stratification.pdf

2.4 Changes in the productivity of species in a given area, dependent on location relative to the latitudinal range. Some species may be adversely affected leading to reductions in sustainable yield whilst others may be positively affected leading to enhanced fishing opportunities

Patterns in data or expected in the future

- Key points in the life-cycle where fish may be vulnerable to the physical and biological effects of climate change in the sea are 1) the timing of spawning in relation to the seasonal production of planktonic crustaceans, especially copepods, which form the larval diet of most species, 2) the dispersal of eggs and larvae by water currents, 3) physiological effects of temperature on growth and maturation, 4) biological or physical alteration of habitat for juveniles and adults, 5) complex food web effects (changes in prey and/or predator community composition), 6) alteration of migration cues for adult fish, and 7) vulnerability of life stages to fishing gears. The combination of these factors means that responses of fish to climate may not be explainable in all cases by a niche or climate envelope approach, especially for species and communities which are subject to exploitation.
- Community responses to climate will be particularly difficult to predict. Of all fish species, the schooling pelagic species (herring, mackerel, sardines) should be most responsive to climate fluctuations. These species are highly mobile, rely on planktonic food throughout their life, and have plasticity in growth, survival and reproductive output. Changes in their abundance and production are often accompanied by changes in distribution.
- Long-term climate change may affect the overall productivity of fish stocks in a given area. Some species may be adversely affected leading to reductions in sustainable yield whilst others, for example seabass, red mullet and John Dory, may be positively affected leading to enhanced fishing opportunities.
- There is evidence that climatic processes are influencing the abundance and composition of seabed faunal communities. These variations directly affect the availability of food for bottom feeding fish such as cod and haddock, impact on shellfish populations (*Nephrops* and scallops/clams) and potentially alter patterns of biodiversity and ecological functioning.
- For cod, plaice and sole in the North Sea, where there are extensive data and many published analyses, we can say with high confidence that climate change has compromised the ability of the stock to withstand fishing mortality. Fishing mortality rates, which were considered sustainable 30 years ago, are now unsustainable due to negative effects on recruitment. However, at present we are 'not sure' of the precise mechanisms by which climate change affects recruitment, beyond that the effects are correlated with sea temperature and to some extent with plankton abundance and composition.
- For other commercially important species in UK waters (herring, mackerel, haddock, saithe, whiting, monkfish) we have only medium or low

confidence in the effects of climate change. This may be partly because a variety of other factors obscure any relationships with temperature, or simply because of a lack of adequate data.

- Much less is known regarding the likely responses of non-commercial species to marine climate change, largely because of the lack of data spanning sufficient time interval to analyse changes. Nevertheless, we can say with high confidence that since 1980 the distribution of many warm water northeast Atlantic fish species has shifted northwards to occupy latitudes at which they were previously unobserved or rare.

Confidence in relationships between observed patterns and climate change

For cod and plaice in the North Sea, where there are extensive data and many published analyses, we can say with high confidence that climate change has compromised the ability of the stock to withstand fishing mortality. Fishing mortality rates, which were considered sustainable 30 years ago, are now unsustainable due to negative effects on recruitment. However, at present we are 'not sure' of the precise mechanisms by which climate change affects recruitment, beyond that the effects are correlated with sea temperature and to some extent with plankton abundance and composition. For other commercially important species in UK waters (herring, mackerel, haddock, saithe, whiting, monkfish) we have only medium or low confidence in the effects of climate change. This may be partly because a variety of other factors obscure any relationships with temperature, or simply because of a lack of adequate data.

Source documents

Frid,, C.L.J. and Moore, D. (2008). Seabed ecology. MCCIP Annual Report Card 2007–2008 Scientific Review. 7pp. http://www.mccip.org.uk/arc/2007/PDF/Seabed-Ecology.pdf

Pinnegar, J.K., Sims, D.W. and Heath, M. (2008).Fish and Fisheries. MCCIP Annual Report Card 2007–2008 Scientific Review. 32pp. http://www.mccip.org.uk/arc/2007/PDF/Fish-and-Fisheries.pdf

2.5 Excessive fishing pressure over many decades may have resulted in fish populations less able to 'buffer' against occasional poor year classes and the impacts of natural climate variability

Patterns in data or expected in the future

- Excessive fishing pressure has caused fish populations to become more vulnerable to short-term natural climate variability by removing the oldest individuals, and making such populations less able to 'buffer' against occasional poor year classes.
- In the short term, climate change will have little influence on fish stock recovery, which depends instead upon reducing fishing effort to allow existing year classes to survive to maturity.
- Climate-related shifts in species distribution, behaviour and depth preference may affect the 'catchability' of certain stocks to fishing fleets.

Confidence in relationships between observed patterns and climate change

There is a low level of confidence regarding the interaction between climate change and the vulnerability of fish stocks to exploitation.

Source document

Pinnegar, J.K., Sims, D.W. and Heath, M. (2008).Fish and Fisheries. MCCIP Annual Report Card 2007–2008 Scientific Review. 32pp. http://www.mccip.org.uk/arc/2007/PDF/Fish-and-Fisheries.pdf

2.6 Coastal habitat loss will be accelerated by sea-level rise

Patterns in data or expected in the future

- Wetland areas are already declining with around 1% of the global coastal wetland stock lost each year (Hoozemans *et al.*, 1993).
- Significant losses are likely to continue without climate change, both from land subsidence or glacial isostatic adjustment and anthropogenic impacts, but they will be exacerbated by sea level rise (Nicholls *et al.,* 1999) and by changes in wave climate (Pethick, 1992; Burd, 1992).

Confidence in relationships between observed patterns and climate change

There is amedium level of confidence that what is happening now is due to climate change. Saltmarsh loss recorded anecdotally but detailed, repeat surveys of marsh area to a common methodology lacking. 'What could happen in the future'-low to medium confidence-(many unknowns e.g. regional variations in sea level rise; changes in wave climate; plant responses to global environmental change; changes in sediment supply; coastal management strategies).

Source document

Gardiner, S., Hanson, S., Nicholls, R., Spencer, T. and Friess, D. (2008). Coastal habitats. MCCIP Annual Report Card 2007–2008 Scientific Review. 8pp. http://www.mccip.org.uk/arc/2007/PDF/Coastal-Habitats.pdf

2.7 Changes in nutrient fluxes due to advection, vertical diffusion and mixing, river flows and atmospheric deposition, leading to changes in primary production

Patterns in data or expected in the future

- Current world patterns suggest nutrient inputs are increasing, while inputs to European seas may be decreasing.
- If summers get drier as a result of climate change, these inputs may continue to decrease although sudden summer storms may deliver nutrient pulses with consequences that are difficult to predict.
- Denitrification is the major process that removes nitrate from the shelf seas. Consequently inputs of ocean waters are critical to maintaining concentrations in shelf sea waters. Studies suggest increased temperatures may decrease denitrification.
- Increased storminess will increase concentrations of nutrients at the ocean surface and may increase transfer into shelf seas. Our understanding of the transfer process is poor.
- Models of productivity in the ocean in a warmer climate suggest increased stratification in summer will limit nutrient supply to surface waters during the productive seasons and inhibit mixing due to storms in winter. Similar model scenarios have not yet been run for shelf seas.

- The few existing long-term data sets have proved useful in identifying the path of eutrophication and relative impacts in different regions of the North Sea. The data record changes in nutrient concentration but it has proved extremely difficult to discriminate between the effects of human discharges and those which may be due to climate change through rainfall and ocean transport.

Confidence in relationships between observed patterns and climate change

Understanding of climate effects on nutrient concentrations and eutrophication is poor. Insufficient data exists on changes in nutrients with time and over sufficiently large areas to be able to make similar assessments to those done for plankton (CPR work e.g. Beaugrand *et al.*, 2000). If pulses of ocean flow are occurring (e.g. Reid *et al.*, 2001) and generating regime shifts then it would be expected that there may be changes in nutrient loads and that changes in biological activity would be feeding back into changes in nutrient concentration cycles. In the only case where nutrients have been considered as part of an analysis of regime shifts-Weijerman *et al.*, 2005-there is little evidence of shifts in nutrient concentrations consistent with shifts in salinity. To better understand the likely impact of climate change on eutrophication the key areas that require research are:-(1) Likely changes in river inputs-this research is underway. (2) Better understanding of the role of denitrification-little research on this is currently been done. The paper by Brion *et al.*, 2004, shows that estimates of its importance have large uncertainties. The consequences of increasing temperature on the ratio of denitrification to ammonification are only considered in one paper (Kelly-Gerreyn *et al.*, 2001). (3) Changes in the flow of Atlantic water may be an important control of the North Sea ecosystem (Reid *et al.*, 2001) but numerical models that might be used to assess these changes with climate change have only a poor skill level when determining cross-shelf exchange. (4) The relative effects of increased storminess and increased stratification have not yet been examined for shelf sea systems.

Source document

Hydes, D., Mills, D. and Heath, M. (2008).Nutrient enrichment. MCCIP Annual Report Card 2007–2008 Scientific Review. 8pp. http://www.mccip.org.uk/arc/2007/PDF/Nutrient-enrichment.pdf

2.8 Rising temperatures and reduced mixing of the water column (increased stratification) may favour many HAB-causing species

Patterns in data or expected in the future

- While the relative contributions of climate and enhanced nutrients to HAB formation are still under debate there is now a general consensus that ocean climate forcing is the dominant factor.
- HABs have increased in some areas of the north-east Atlantic over the past 50 years, as the seas around Great Britain and Ireland have become warmer, especially since the mid-1980s. There is regional variability within this trend and some places, such as the east coast of Britain, have experienced reduced incidences of HABs.
- Expected higher temperatures, which may lead to better growth conditions, and increased stability, leading to increased water clarity in the future, has the potential to favour the growth of some toxic and other HAB species in UK waters. However, for some HAB species such as *Dinophysis*, there is still a lack of knowledge on the controls of its life cycle.

- The effects of storms (decreasing stability, lower light levels) and increasing nutrients due to greater runoff are less predictable and will most likely favour some species and be detrimental to others. Some of the UK regions that are likely to be more susceptible to hydroclimatic fluctuations such as the eastern Irish Sea and estuaries such as the Fal are also thought to be vulnerable to elevated nutrient concentrations.
- The geographic extent of phytoplankton species distribution has the potential to change as it has for other species, and the possibility of alien species is increased with the changing environment. There are still some uncertainties as to what governs the mechanisms that promote this range expansion.

Confidence in relationships between observed patterns and climate change

There is medium confidence in what is already happening. A variety of different HAB species exist which have the potential to impact UK waters. Currently there are very different levels of knowledge about the biological controls of each one. There is a great deal of evidence available on the occurrence of HABs, and general agreement that there has been an increase in the reported number of HABs and that many of these are primarily linked to climatic forcing. Thus this leads to medium confidence on both axes (amount of information and agreement) as to the level of confidence in what has already happened.

Confidence in likely future changes is also medium. The paucity of long term time series data, coupled with the fact that most observations occur when blooms are already established, means there is little information on the processes that lead to their development and, depending on the species, a sparsity of knowledge on life cycle, cell division and environmental cues. There is therefore a lack of consensus on what the climate change effects are likely to be. Modelling is, in consequence, at an early stage of development although there is now a general consensus that hydroclimatic forcing is the dominant factor behind bloom variability. The clear linkage with temperature related effects of the dominant group causing blooms means that the level of confidence that HABs may increase with climate change is high. However, because each species is sublty different, there is little consensus on which climate change factors are most important and there is low agreement on the importance of other affects such as nutrient supply. Thus a moderate for evidence and moderate (it is climate but which elements) for agreement becomes a medium level of confidence overall.

Source document

Raine, R., Edwards, M., Reid, C., Bresnan, E. and Fernand, L. (2008). Harmful Algal Blooms (HABs). MCCIP Annual Report Card 2007–2008 Scientific Review. 8pp. http://www.mccip.org.uk/arc/2007/PDF/HABs.pdf

2.9 Climate change may influence terrestrial inputs of pollutants and the release of pollutants currently locked in seabed sediments

Patterns in data or expected in the future

- Although pollution monitoring is currently inadequate for identifying climate change related impacts there are many potential impacts that climate change could have on the UK marine environment.

- Changes to rainfall patterns may result in changes to the movement and distribution of chemicals e.g. increased leaching of pesticides applied to agricultural land during certain periods of the year.
- Increased storm events during the winter will increase storm water flows in rivers and potentially inputs of untreated sewage effluent.
- Decreased river flows in the summer particularly in the South of England will result in higher relative contributions of treated sewage effluent. The biological oxygen demand will increase because of the increase in organic matter from treated sewage as well as any rise in temperature, which will increase bacterial respiration.
- Heavy storm events during summer periods are likely to result in flushing of untreated sewage effluent and diffuse pollutants from surface runoff in storm overflows.
- The release of sediment-associated contaminants present on the seabed may also be changed by increases in temperature, changes in salinity regimes and increased storm events.

Confidence in relationships between observed patterns and climate change

There is low confidence in the connection between climate change and pollutants. Much monitoring effort has focussed on selected chemicals identified as of priority concern (e.g. metals such as mercury and organics such as hexachlorocyclohexane). In many cases, the concentration of these chemicals has declined with the introduction of tighter discharge consents and the improvement of sewage effluent treatment. With a few exceptions (e.g. in relation to sewage sludge disposal sites (Rees *et al*., 2006), Tributyltin (Rees *et al*., 2001) and steroidal chemicals), where contaminant-related biological effects are well characterised, changes in chemical concentrations have not been linked to changes in biological effects. Links between chemical concentrations, biological effects and climate change factors are not yet developed in the literature and where time series datasets do exist confidence in showing these links is low.

Source document

Sheahan, D. (2008) Pollution. MCCIP Annual Report Card 2007–2008 Scientific Review. 8pp. http://www.mccip.org.uk/arc/2007/PDF/Pollution.pdf

2.10 Future increases in ocean acidity will have major negative impacts on some shell/skeleton-forming organisms

Patterns in data or expected in the future

- The uptake of anthropogenic carbon since 1750 has led to the oceans becoming more acidic with an average decrease in pH of 0.1 units. Surface ocean and UK coastal water pH will continue to rapidly decline in the future as they take up more atmospheric CO_2.
- Although the effects of the current reduction in pH on the marine biosphere are as yet undocumented this is due, in part, to lack of research in this area. However, unless CO_2 emissions are substantially reduced, experiments, observations and modelling indicate that future reductions in ocean acidity will have major negative impacts on aragonitic and calcitic (shell/skeleton) forming organisms this century and their dependent species.

- There is growing evidence that the physiology (e.g. growth and reproduction) of adults, larvae and juveniles of some species are sensitive to acidification.
- Impacts of decreasing pH on key biogeochemical processes other than calcification is theoretically possible and serious (e.g. impact on nutrient speciation, primary production and nutrient, carbon and sulphur cycling) but there has been little research on this.
- The knock-on effects of ocean acidification on marine ecosystems, biogeochemical cycles, food webs and biodiversity could be considerable but difficult to quantify.

Confidence in relationships between observed patterns and climate change

There is high confidence that the acidity of the oceans is changing. The uptake of anthropogenic carbon since 1750 has led to the oceans becoming more acidic with an average decrease in ph of 0.1 units (IPCC, 2007a) (High certainty). However, the effects of current, observed ocean acidification on the marine biosphere are as yet undocumented (IPCC, 2007b) due, in part, to lack of research in this area and long term time series. High confidence, that ocean pH is changing and will change in the future and unless we substantially and urgently reduce CO_2 emissions that these will have major impacts on aragonitic organisms this century. 'What could happen in the future' – Medium confidence. We have a moderate level of confidence that this will have a knock-on effect on marine ecosystems and foodwebs, according to evidence from modelling and experimental observations. Impacts of pH on other organisms than aragonitic and calcitic organisms is theoretically serious (e.g. impact on nutrient speciation and therefore primary production and biodiversity) but there has been little research on this. We have a high degree of confidence that reducing emissions is the only way of reducing ocean acidification.

Source document

Turley, C. (2008) Ocean Acidification. MCCIP Annual Report Card 2007–2008 Scientific Review. 7pp. http://www.mccip.org.uk/arc/2007/PDF/Ocean-Acidification.pdf

3 Background concepts

3.1 Ecotypology

The impact of climate change is expected to differ between marine species. Species inhabiting areas that are most affected by climate change are likely to be affected more. Further, species with narrow habitat requirements or low dispersal capacities will be more sensitive. Species with a slow population turnover rate (low reproductive rate R, low natural mortality M, slow growth, high longevity) are expected to respond less as a change in M or R might not show up for several decades. Recovery would take comparably long if conditions reversed, but the impacts could be very gradual in both directions. In a similar vein for a species with fast turnovers M and R are both large and a change due to climate might show up fairly quickly in data series. The response of fish species may be more complicated if the characteristics interact. For instance, a high turnover species with high mobility and narrow tolerance range might be much more vulnerable to temperatures or salinities. They may die off locally but if there are lots of recruits in the sea which disperse readily and suitable conditions exist somewhere, some will find the right areas and increase quickly.

Based on these criteria ecotypes can be defined that can be used as a basis to extrapolate the findings of case studies of specific species to other species of the same ecotype. An ecotypology of fish species recorded in the North Sea, the Irish Sea and the northeast Atlantic have recently been developed by Ellis *et al*., 2008 taking account their bio-geographic affinity, reproductive mode, habitat, feeding mode as well as information on the maximum body size and trophic position. An ecotypology for other species groups (phytoplankton, zooplankton, benthic invertebrates) still need to be constructed.

3.2 Climate change

3.2.1 Climate variability

Historically climate has varied on decadal and multi-decadal time scales. On geological time scales climate showed large changes for example between the glacial and inter-glacial eras. Decadal scale oscillations in the pressure fields over the north Atlantic (NAO: (Hurrell 1995)), the southern Pacific (El Nino Southern Oscillation ENSO:) and the Pacific Decadal Oscillation (PDO: Bond and Harrison, 2000) have major impacts on fish populations and ecosystem functioning (Francis *et al*., 1999). Recently, multi-decadal variations (e.g. AMO) have been reported in ecosystem properties (Johansen *et al*., 2004; Sutton and Hodson, 2005)). Historic variability in ocean climate may be used to study the key processes on climate impact on marine organisms.

3.2.2 Scenarios on Climate Change

The latest IPCC (2007) report concludes that anthropogenically induced global warming is well under way and temperatures are projected to continue to rise. These projections or scenarios are generated from coupled atmosphere-ocean global circulation models (GCMs). These suggest that annual air temperatures will rise throughout Europe relative to recent conditions, with the lowest increase (1° to 2°C) in the Mediterranean, Iberian, North Sea, Northeast Atlantic and south Nordic Sea regions. Temperature increases will be higher (4° to 6°C) in the more northern regions such as the northern Nordic Seas and the Barents Sea, and highest (up to 7°C) in the

Arctic (ACIA, 2005). Due to its high capacity to store heat, the ocean will not warm quite as much as the land. The frequency of extreme high air and ocean temperatures will increase and extreme low temperatures will decrease throughout Europe. There will be a decrease in the daily temperature range with night time lows increasing more than daytime highs.

Precipitation and runoff will increase in northern Europe and the Arctic but decrease in warmer regions such as the Mediterranean (IPCC, 2007). In the Arctic annual precipitation is projected to increase by 20%, with a 30% increase during the winter (ACIA, 2005). With the increase in temperature, more precipitation will fall as rain in northern and upland regions resulting in an increase in winter runoff and a decrease in spring. At higher altitudes, much of the precipitation will continue to fall as snow in winter, but the spring peak in runoff will occur slightly earlier. The intensity of winter rainfall events north of 45°N are expected to increase while to the south there will be an insignificant change or a decrease (Frei *et al.*, 2006). In central Europe river runoff will change by approximately ~10% by the 2050s but this is smaller than the observed natural multi-decadal variability (Hulme *et al.*, 1999). In Mediterranean regions, the range in river flows between winter and summer will likely increase considerably while in maritime Western Europe the increase will be less.

As temperatures rise, sea-ice coverage will decrease with most climate models suggesting an ice-free summer in the Arctic by 2100 (Teng, 2006). In the Barents Sea, the winter ice edge is projected to retreat at an approximate rate of 10 km per year northward and be ice-free by 2070 (Furevik *et al.*, 2002). A significant loss of ice cover in the western Nordic Seas is expected, which by 2070 will be restricted to the northwestern Greenland Sea and the Baltic. The projected melting ice and increased precipitation and river runoff in northern latitudes will lead to decreases in surface salinity of the order 0.5 to 1 in the Arctic Ocean, the western regions of the Nordic Seas and in the Baltic by the 2070s (Furevik *et al.*, 2002). Atlantic waters in the Nordic Seas will spread farther eastward and northward, there will be more continental runoff but this will be partially compensated by high salinity Atlantic water, and the surface mixed layer depth will increase due to stronger winds.

During the 21st century there might be a gradual weakening by about 20% in the Meridional Overturning Circulation (Hadley Centre; www.met-office.gov.uk/corporate/scitech0304/ MetOfficeScience0304.pdf). Modelling studies to date, however, suggest that cooling of northern Europe due to the reduced MOC is unlikely to happen in the next 100 years and that the current trend of warming is likely to continue with increases of 2°C and more over this time frame.

With melting ice caps and higher ocean temperatures, sea level is expected to rise throughout the globe by 13 to 68 cm by the 2050s. Low-lying areas adjacent to regions with low tidal range such as along the coasts of the Mediterranean, Baltic and Black Sea are more vulnerable than most of the Atlantic Ocean and North Sea coasts (Nicholls and Mimura, 1998).Because of the strong tidal regime and the effects of storm surges many of the coastal regions of the North Sea, especially in the south, are particularly susceptible to rising sea levels and an increase in the frequency and severity of storms.

Climate change simulations for the Baltic suggest temperature increases during all seasons with a mean annual warming of 3 to 5ºC in the atmosphere and 2 to 4°C in the sea surface temperature by the end of the 21st century (Graham *et al.*, 2006). One consequence is a decrease in sea ice extent by 50% to 80% over the same period. Winters will probably be wetter and in the southern parts of the region summers will likely be drier. As a consequence, winter river flows are expected to increase by as much as 50% with the opposite pattern in summer.

Regional climate change scenarios around the North Sea predict an increase in air temperature of 2°C to 3.5°C by the 2080s, with high summer temperatures becoming more frequent and very cold winters becoming increasingly rare (e.g. Hulme *et al.*, 2002, van den Hurk *et al*., 2006). Water temperatures will also increase, but not as rapidly as over land. In the Bay of Biscay and English Channel the predicted rise in temperature are of the order of between 1.5° and 5°C over the next 100 years. Temperature changes along the northwest Iberian and Atlantic French coasts should be evident in the first half of the 21st century (Alcock, 2003).

The changes in wind over European marine areas remains uncertain although the expectation is that there will be an increase in average and extreme wind speeds over Northern Europe (IPCC, 2007). The total number of cyclones in the Mediterranean Sea are expected to decrease but it is unclear whether the number of intense cyclones will change (Pinto *et al*., 2006).

3.2.3 Identification of important abiotic factors affecting marine ecological processes

To generated future ecosystem scenarios under climate change there are several abiotic factors that will be needed. On the atmospheric side, these include air temperatures, precipitation, cloud cover, air pressures and wind. The first two variables are important due to their effect on the ocean's temperature and salinity, respectively. Precipitation also determines river runoff and together with the air temperatures the seasonal freshwater discharges to the ocean. Cloud cover affects the solar radiation reaching the ocean surface and is therefore important for determining phytoplankton production. It can also affect feeding rates of some organisms through light availability in the water column. Changes in large-scale air pressure patterns give rise to the NAO and other climate indices. They also are related to the winds, which in turn determine the amount of vertical mixing in the water column and hence influence nutrient replenishment to the near surface layers and feeding rates of small organisms through turbulence levels. Wind also affects ocean circulation patterns. Models predicting future climate scenarios, although producing high variability between models are presently consistent with regards to air temperatures and precipitation has vastly improved in recent years. Cloud cover and winds, however remain highly uncertain.

On the oceanic side, the important variables for ecosystem studies include temperature, salinity, stratification, circulation patterns, upwelling, sea ice and pH. Temperature is important through its affects on metabolism and influencing feeding and developmental rates. Salinity appears to have less of an effect, though salinities of approximateoy 30 in estuarine waters appear to be an effective boundary for many marine plankton. Only a few euryhaline species are able to survive on lower salinities.

Stratification affects mixing and hence nutrient fluxes to the surface layer. Also, higher stratification tends to result in more energy recycled in the upper layers of the water column and hence favours pelagic organisms while lower stratification tends to result in more energy making it to the benthos and demersal fish species. Circulation patterns influence water mass boundaries, which in turn influence species distributions. Currents also affect drift of particles including phytoplankton, zooplankton and fish eggs and larvae. Upwelling influences nutrients and hence phytoplankton production that in turn affects higher tropic levels. Sea-ice formation and melting affects the salinity and stratification of the underlying waters. It is also used for habitat for large marine mammals. Increased CO_2 levels will lead to a decrease in the pH (acidification).

The ability to generate future ocean scenarios that includes these variables varies both regionally and with the particular variable but in most cases regional modelling is still in its infancy but rapidly improving. For ecosystem modelling, these regional physical models are paramount as the large ocean-atmosphere General Circulation Models are not of high enough resolution for ecosystem impact studies.

Is it possible to rank the importance of these atmospheric and oceanic variables in regards to influences on the marine ecosystems for different regions such as the open ocean, shelf areas, and coastal waters? Although the importance of the variables changes regionally, some general conclusions can be reached. Temperature, because of its pervasive effect on organisms will be important in all of the regions. Stratification is also of major important in all regions because it directly affects primary productivity and the vertical distribution of several marine organisms. The effect of the winds is usually through mixing and circulation changes in the open ocean but in the shelf and coastal regions upwelling may become more important, depending upon the wind direction and coastal orientation. Sea-ice is only important in the more northern regions such as the Barents Sea and the Baltic. Climate change induced acidification may affect calcareous structure forming autothropic and etherothropic organisms that provide habitat for other species. It is important to note that not only the magnitude of these physical and meterological variables that matters, but also the timing of patterns of their annual changes is crucial for biological processes.

3.3 Lower trophic levels

Primary and secondary production is highly variable in space and time, although typical seasonal patterns occur that are related to the balance between day length, radiation, availability of nutrients and temperature. Climate change will affect primary production through the effect on the availability of nutrients due to for instance upwelling or stratification depth. Phytoplankton species composition, and hence trophic processes, is affected by the ratio in which different nutrients are available (Philippart *et al.*, 2000) and by temperature regime (Hare *et al.*, 2007). Temperature will positively influence growth rate. Increased CO_2 levels in the atmosphere will lead to higher CO_2 levels in the ocean which may promote primary production. The change in temperature may alter the seasonal timing of phyto- and zooplankton production (Edwards and Richardson, 2004). These changes will propagate up the food web to zooplankton filter-feeders and zooplankton predators. Changes in temperature conditions and ocean currents may also affect zooplankton production and species composition as illustrated by the shift in dominance of *Calanus finmarchius* to *C. helgolandicus* and a more-diversified warmer-water plankton community in the north-eastern Atlantic (Beaugrand *et al.*, 2002; Edwards *et al.*, 2007). Moreover, warmer coastal waters have been related to a significant increase of meroplankton (i.e. temporary plankton species) and a decrease in holozooplankton (i.e. permanently plankton species), due to competitive exclusion (Kirby *et al.*, 2007). Higher CO_2 levels and the resulting reduction in pH may negatively affect organisms, in particular those which build up calcareous skeletons such as corals, coccolithophores, molluscs pteropods (Riebesell *et al.*, 2000).

Key questions to address are: (i) What are the key environmental variables influenced by climate change that mostly affect phyto- and zooplankton (temperature, nutrients, acidification)? ; (ii) how do climate change influence the timing, production level and species composition of both phytoplankton and zooplankton communities; (iii) do autotrophs and heterotrophs differ in their response to temperature? (iv) does climate change influence the primary and secondary production through the alteration of competitors and predators abundance? An increase in temperature will influence the rate and quantity of energy that is transferred up into the food chain. As primary production is consumed by filter feeders a difference in the temperature response in filtration rate will affect the energy transfer. In coastal waters affected by eutrophication, both primary and secondary production processes will be affected by changes in the river discharge.

3.4 Eco-physiology

Key factors affecting the physiology of marine organisms are temperature, salinity, oxygen and pH. Organisms can only survive within a certain range of environmental conditions (tolerance range). Temperature determines the rate of the physiological processes. Salinity affects the cost for osmoregulation and may influence the buoyancy pelagic stages and play a role in the motility of spermatozoa of organisms with external fertilization. Acidification affect building opportunities of external skeletons in organisms like corals and some plankton, e.g. coccolithophores, molluscs pteropods , but is less likely to be important for fish.

The tolerance ranges will differ among species due to local adaptation, but may also differ among life history stages. There is some evidence that early life history stages such as eggs and larvae have smaller tolerance ranges than juveniles or adults ((Irvin 1974)) and that the optimum temperature decreases with body size (Imsland *et al.*, 1996; Lafrance, 2005). Important question to address are: (i) are early life history stages more sensitive for climate change because of their narrower tolerance range; (ii) does the relationship between physiological rate and temperature (and other abiotic variables) differ in a systematic manner between life history stages; (iii) does the relationship between physiological rate and temperature differs in a systematic manner between species with different bio-geographic affinities; (iv) do primary, secondary and tertiary producers differ in their temperature response? Differences in the temperature response of species, size classes or trophic groups will have important implications for trophic interactions.

3.5 Population dynamics

A consequence of the complex life cycle of fish species is that the population abundance may be determined by the quantity of suitable habitat for one (or more) specific life history stage. As the life cycle is embedded in a specific landscape, populations may differ in the life stage that determines the overall population abundance. Herring population abundance appears to be determined by the size of the larval retention areas (Sinclair, 1988). In cod, population abundance in the Baltic is determined by the available spawning habitat affecting the survival of eggs (Sparholt, 1996; MacKenzie *et al.*, 2000). It is unknown whether this bottleneck also applies to other cod stocks that spawn in more stable oceanic conditions. Flatfish abundance, both across species as across populations of the same species, appears to be related to the available nursery habitat (Rijnsdorp *et al.*, 1992; Gibson, 1994; Le Pape *et al.*, 2003). Those species that inhabit calcified biogenic structures during part of their life cycle may be impacted by climate change is their habitat may be negatively affected by acidification.

Fishing is known to have a major effect on the abundance of fish populations and on the processes that control and regulate the abundance. Fishing acts as a top-down control that increases the mortality of fish above the retention size, reducing the biomass and the age- and size structure of the population. As a result, growth and survival of recruited fish may no longer be affected by density-dependent processes, although an increase in abundance of small sized fish may trigger or increase the strength of density-dependent processes.

Temperature is the controlling factor for reproductive activity and interannual variability in the duration of the reproductive period for several plankton species (e.g. Ianora *et al.*, 2007). A few studies have shown that temperature, food availability and also salinity at critical life stages control the recruitment *in situ* of dominant plankton species (e.g. Durbin *et al.*, 2003; Peck and Holste, 2006).

Based on the above population dynamic considerations, the largest impact of climate change is expected on the (i) size and location of suitable habitat; (ii) the retention of eggs and larvae; (iii) the match in timing of the fish larvae and their plankton food; (iii) the connectivity between the successive habitats; (v) growth; (vi) predation mortality. As life history stages require different habitats, the key processes in population regulation will be species and area specific as the complex life cycle is embedded in a specific geographical landscape.

Climate change will undoubtly affect the quality of suitable spawning and nursery areas. If the (eco-) physiological characteristics of the successive life history stages are known, the envelopes of suitable abiotic conditions can be derived to overlay habitat suitability maps of successive life stages as a basis for estimating climate effects. Whether an area is suitable for spawning depends on the retention of eggs and larvae as well as the timing of the egg production in relation to the plankton production which is the larval food. Climate change may affect the occurrence and stability of retention areas through its effect on ocean currents and the strength and frequency of storm surges. An increase in temperature may affect the probability of a mismatch between the production of larval fish and the plankton if the temperature response differs between the fish and its larval food. Also, the survival of fish larvae may be affected by a climate-induced change in the timing of the stratification.

The connectivity between habitats may be influenced by changes in ocean currents, the melting of sea ice and changes in river discharge patterns. It is expected that in particular the effect on egg and larval transport will be more sensitive than the impact on migration cycles of adult fish. Climate may influence growth rate either through an effect on physiological rates or indirectly on the available food. Finally, climate change may impact the timing of predators, disease agents and competitors.

Key questions to address are: (i) How is the size of suitable habitats affected by climate change/variability; (ii) What are critical life-stages affected by climate change/variability. In particular can we distinguish and make generalisations whether the effects will mainly occur in the pelagic egg and larval stages of the larger juvenile and adult stages; (iii) Which species are especially vulnerable and are thus suitable climate-change indicator; (iv) are plankton good indicator of climate change? (v) are fish good indicator of climate change ? (vi) How does exploitation affect the sensitivity of fish population to climate change? (vii) How do disease agents respond to an increase in temperature.

3.6 Ecosystem

The abundance and distribution of marine organisms are determined by ecosystem processes that affect biological cycles, the availability and suitability of food and the presence/absence of predators and disease. Marine ecosystems are generally considered to be regulated by bottom-up processes (Aebischer *et al.*, 1990, Ware and Thomson, 2005), although it has been suggested recently that this generalization need modification as latitude, species diversity and exploitation rate play a role as well (Frank *et al.*, 2007). In high latitude ecosystems which are generally species poor, or intensively exploited systems, top-down control appears to predominate (Worm and Myers, 2003, Frank *et al.*, 2005). The effect of climate change on ecosystem dynamics will differ between bottom-up or top-down regulated systems. In bottom-up regulated systems, fish and shellfish production and distribution will be affected by climate induced changes in primary and secondary production. In top-down regulated systems, the indirect effect will be through the climate effect on predators. Ecosystem regulation may change from bottom-up to top-down and vice versa in response to changes in the environment (Hunt *et al.*, 2002).

The size structure of the community is an important factor of marine ecosystems that affects ecosystem processes such as the transfer of energy in the food web. Physiological efficiencies and predator-prey relationships are strongly dependent on species composition and their size. The size spectra of the community are an important factor when associated with the taxonomic composition of the different size classes. Plankton that shares the same size may have different physiology, behaviour and seasonal timing, which is the case for example of the two copepods *Calanus helgolandicus* and *C. finmarchicus*. The increasing dominance of *C. helgolandicus* over *C. finmarchicus* has determined an important change in the plankton community with significant consequences at higher trophic levels (Beaugrand et al., 2003). The fact that climate change may change the community composition and size structure of the phytoplankton and zooplankton may have important implications for the survival chances of fish larvae.

Another property of ecosystems that will be affected by climate change is the production cycle which may result in the match or mismatch between the production cycles of fish larvae and their plankton preys. Seasonality also affects the availability and quality of food for early juvenile and later stages. Different plankton species may have different contents of lipids, glucides etc. so they may be more or less nutritious. Food shortages occur in certain seasons, and fish build up energy reserves to survive these periods. If temperature affects the timing and the duration of these periods, it will affect the growth rates and the survival probabilities. As many ecological relationships are non-linear, climate-induced changes in these relationships may result in changes in alternative stable states. Ecosystems characterized by a low species diversity and top-down control may be more sensitive for regime shifts.

Important questions to address are: (i) how does climate change affect the species composition and size structure of ecosystems; (ii) how does climate change affect bottom-up and top-down control; (iii) how does climate change influence the benthic-pelagic coupling; (iv) are species-poor ecosystems more prone to climate-induced regime shifts between alternative stable state than species-rich systems?

4 Guidance on analysis of available data set

The time series data on marine organisms that are available to test the impact of climate change on distribution and abundance is dominated by fish data (landings of commercial fish species by management area, fish surveys data, egg survey data on a selected number of species) and plankton data from the Continuous Plankton Survey programme. In addition, time series information is available for single study sites such as the Helgoland Roads, Stonehaven,L4, Santander/A Coruna (plankton, see Report of WGZE to OSPAR, 2007 in annex), Balgzand benthos time series, the Dove time series.

4.1 Plankton

The data provided by the CPR Survey and by other time series at single sites and along transects in the OSPAR area may be used to monitor plankton abundance, biodiversity and population dynamics (e.g. phenology) as well as plankton species that act as indicator of climate change. Plankton monitoring should be expanded to cover some unsampled and poorly sampled areas in the OSPAR regions and zooplankton should be included as a mandatory biological variable in the management of the marine OSPAR area.

The analysis of plankton data should monitor the changes observed in the plankton that have been related to hydroclimatic changes (see Report of WGZE to OSPAR, 2007 in annex):

- biogeographical changes and northwards movement of plankton species/communities with warm-water affinities;
- changes in the composition and abundance of plankton;
- changes in seasonal timing and phenology (e.g. earlier seasonal cycle) of several plankton species;
- changes in the size of the plankton;
- match/mistmach between predator (zooplankton or higher trophic levels) and prey (phyto- and zooplankton);
- increasing abundance of meroplankton (i.e. temporary plankton species) in coastal waters;

The analysis of plankton data could allow the test of the following hypotheses:

- More stratified waters due to climate change will determine a decrease of primary productivity.
- In warmer waters the duration of the phytoplankton bloom will increase;
- In a given region, eurytherme plankton species will increase and stenotherme plankton species will decrease;
- Plankton filter-feeders able to filter small-size phytoplankton will increase in warmer waters;
- invasive plankton species that benefit from new environmental conditions determined by climate change will extend their distribution;
- in warmer coastal waters the transfert of energy towards the benthic component will increase due to the increase in meroplankton;
- in warmer waters plankton life cycle will be shorter than before;

- in warmer waters plankton asexual reproduction and fecundity will increase;
- the development of organisms with calcareous skeleton will be compromised due to acidification, favouring non-calcareous competitive groups;

4.2 Fish

Fish survey data from many parts of the OSPAR area could be analysed for a wide range of community attributes. The following lists are the ones, based on all the WGECO analyses that are most likely to be informative.

1) Comparison of the changes in abundance of species across ecotypes in relation to changes in temperature

2) Comparison of changes in the distribution range (northern border, southern border, depth range) across ecotypes in relation to changes in temperature

3) For species where we have time series of recruitment estimates, there will be greater variance in recruitment of species where there is greater variance in the timing of the onset of "spring" conditions or their equivalent (like onset of upwelling). Test by using spatial units small enough to have contrast among them in timing of "spring"-however measured, but large enough to be able to estimate numbers of "recruits" from survey data within the unit. Then calculate the frequency distribution of variances in recruitment across as many species as possible in each spatial unit. The centres of these frequency distributions and/or some measure of their upper tail will correlate with the variance in spring timing by square.

4) For species where we have time series of recruitment estimates, there will be greater variance in recruitment of species where there is greater variance in the degree of stratification in spring/summer, however it can be measured. Test same as for 1, but with an annual stratification index.

5) The more that a species relies on transport of eggs and/or larvae to suitable nursery grounds, the more likely that year-class strengths will be extreme (high or low) in years when transport timing or trajectory was anomalous. Test: For species where spawning and nursery grounds are known, rank orders them by the distance between those two areas. For each of those species identify the X (say, 20) % of year-classes most deviant from the centre of mass of year-classes for the species. (How the extreme year-classes are divided among booms and busts will be species specific-what matters is, that one isolates the deviant ones.) Independently, use historic physical oceanographic data or models to identify the same x% of years when transport processes were most atypical. Simple binomial or Chi-square tests can estimate the probability that the typical years in the two data sets are independent. What matters is not whether each individual pattern is significant, but whether the estimated probabilities correlate with transport distance.

6) Species with stronger temperature preferences within years are going to show greater differences in their ranges over time. Test: Split the survey data into two batches, say the even years and the odd years, and select species which are relatively widespread, but not abundant everywhere in

their ranges. Use one batch to rank-order species by the degree to which are “temperature-keepers”-as documented in the simple analyses in Steve Smith and Ian Perry’s publication from the early 1990s. For the other batch, make a suitable range analyses, such as the convex hull boundary or the number of squares needed to include 80% of their abundance. The more strongly a species shows the patterns of being a temperature keeper, the greater the variation in the range estimate over time.

7) Explaining the implications of any patterns at the species level will at least require a few analyses of patterns at the community level. These would include:

7.1) For the spatial units used above, do changes in richness correlate with changes in the indices of timing or stratification? This could be explored within spatial units over time, and/or as correlations in variances across spatial units over time.

7.2) For the spatial units used above, do changes in size composition indices correlate with changes in the indices of timing or stratification? This could be explored within spatial units over time, and/or as correlations in variances across spatial units over time.

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