variability, in particular relating to ENSO events. Off California, anchovy spawning expands northwards during El Niño events (Checkley et al., 2009). Likewise, the northern limit of California sardines in Canadian waters is broadly related to sea surface temperature, expanding north during the months of June through August and returning south when sea temperatures begin to cool (McFarlane et al., 2005). Rodríguez-Sánchez et al. (2002) have described how Pacific sardine (Sardinops caeruleus) in the California Current System changed its core habitat locations from the central to the southern and then back to the central parts of its full distributional range over the period 1931 to 1997 as the prevailing climate regimes shifted. Cross-shelf habitat is also affected by productivity conditions. California sardine shows significant interannual variation in the geographic extent of spawning, extending further offshore during La Niña and being compressed shoreward during El Niño (e.g. Lynn, 2003).
In the California Current upwelling system, the extent of the northwards migrations by Pacific hake (*Merluccius productus*) is positively correlated with increasing water temperatures (Ware and McFarlane, 1995). Philips *et al.* (2007) have also observed a northward expansion of the spawning areas for Pacific hake in the California Current system. Distributions of other species in the southern parts of the California Current System in relation to ENSO variations are provided by Lluch-Belda, Lluch-Cota and Lluch-Cota (2005). Variations in Peruvian anchoveta have been explained by changes in carrying capacity (Csirke *et al.*, 1996), based on habitat productivity regimes (Chavez *et al.*, 2003). Skipjack tuna (*Katsuwonus pelamis*) in the western Pacific alter their distribution to follow the convergence zone between the tropical Pacific warm pool and the eastern Pacific cold tongue as it moves in response to ENSO cycles (Lehodey *et al.*, 1997).

Marked shifts have been observed in Arctic ecosystems. Diatom and invertebrate assemblages in Arctic lakes have shown huge species’ turnover, shifting away from benthic species toward more planktonic and warm-water-associated communities (Smol *et al.*, 2005). Sea ice decline in the Arctic has been more evenly distributed than in the Antarctic. Polar bears (*Ursus maritimus*) have suffered significant population declines at both of their geographic boundaries. At their southern range boundary, polar bears are declining both in numbers and in mean body weight (Stirling, Lunn and Iacozza, 1999). It is likely that climate change will extirpate polar bears from many areas in which they are presently common and will fragment the total population into a few isolated populations (Wiig, Aars and Born, 2008). Penguins and other seabirds in Antarctica have shown dramatic responses to changes in sea ice extent over the past century (Ainley *et al.*, 2003; Croxall, Trathan and Murphy, 2002; Smith *et al.*, 1999), particularly those sea ice dependent species like the Adelie and emperor penguins (*Pygoscelis adeliae* and *Aptenodytes forsteri*, respectively) (Gross, 2005; Barbraud and Weimerskirch, 2001; Emslie *et al.*, 1998; Fraser *et al.*, 1992). In the long-term, sea ice-dependent birds will suffer a general reduction of habitat as ice shelves contract or collapse. In contrast, open-ocean feeding penguins — the chinstrap and gentoo — invaded southward along the Antarctic Peninsula between 20 and 50 years ago, with paleological evidence that gentoo had been absent from the Palmer region for 800 years previously (Emslie *et al.*, 1998; Fraser *et al.*, 1992).

If changes in climate conditions persist, then demersal species will also alter their distributions and migration patterns. However, because habitat for demersal species often includes particular bottom features (such as kelp forests or coral reefs) and sediment types (rock or sand), they are likely to alter their distribution patterns more slowly than pelagic species. This suggests that changes in the distributions of such demersal species might be used as an index of persistent longer-term changes in habitat conditions. Such large-scale changes, persisting for at least a few decades, have occurred in the past. The effects of the warming event in the North Atlantic from the 1920s to 1940s and later, are particularly well-documented (Cushing, 1982; Brander *et al.*, 2003; Rose, 2005; Drinkwater, 2006). Tåning (1949) and Fridriksson (1948) described how Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), redfish (*Sebastes spp.*) and Greenland halibut (*Reinhardtius hippoglossoides*) all expanded northwards, with cod spreading 1 200 km farther north along West Greenland that its previous distribution (Jensen, 1939, cited in Drinkwater, 2006). Such shifts involved benthic invertebrates as well as demersal finfish (Drinkwater, 2006). In general, species adapted to warmer waters expanded their distributions northwards, whereas species adapted to colder waters retracted their distributions northwards. More recently, major range extensions northwards of tropical and warm water marine species have been observed in the eastern North Atlantic (Quero, Du Buit and Vayne, 1998; Brander *et al.*, 2003) and in the North Sea (Brander *et al.*, 2003; Perry *et al.*, 2005; Clemmensen, Potrykus and Schmidt, 2007; Dulvy *et al.*, 2008).
It has been suggested (Harley et al., 2006) that a warming-associated weakening of alongshore advection (Pisias, Mix and Heusser, 2001) could actually break down certain marine biogeographical barriers that currently prevent range expansions. For example, two particularly cold-sensitive coral species (staghorn coral, *Acropora cervicornis*, and elkhorn coral, *Acropora palmata*) have recently expanded their ranges into the northern Gulf of Mexico (first observation in 1998), concurrent with rising SST (Precht and Aronson, 2004). Although continued poleward shift will be limited by light availability at some point (Hoegh-Guldberg, 1999), small range shifts may aid in developing new refugia against extreme SST events in future.

Long-term monitoring of the occurrence and distribution of a series of intertidal and shallow water organisms in the southwest of the United Kingdom has shown several patterns of change, particularly in the case of barnacles, which correlate broadly with changes in temperature over the several decades of record (Hawkins, Southward and Genner, 2003; Mieszkowska et al., 2006). It is clear that responses of intertidal and shallow marine organisms to climate change are more complex than simple latitudinal shifts related to temperature increase, with complex biotic interactions superimposed on the abiotic (Harley et al., 2006; Helmuth, Kingslover and Carrington, 2005). Examples include the northward range extension of a marine snail in California (Zacherl, Gaines and Lonhart, 2003) and the reappearance of the blue mussel in Svalbard (Berge et al., 2005).

### 2.5 Abundance changes

Change in the abundance and biomass of marine populations are due to changes in their recruitment and growth rates, and ultimately to the productive capacity of the region in which they live. For example, changes in temperature can have direct impacts on fish abundance and biomass by stressing the physiological systems of individuals (as described in Section 2.1), causing them to change their locations or ultimately die. Temperature can also have indirect effects on fish abundance through its influences on growth and recruitment. Populations at the poleward extent of their ranges, such as Atlantic cod in the Barents Sea, increase in abundance with warmer temperatures, whereas populations in more equatorward parts of their range, such as cod in the North Sea, tend to decline in abundance as temperatures warm (Ottersen and Stenseth, 2001; Sirabella et al., 2001; Fig. 9).

Higher individual growth rates translate to greater productivity for the entire population, with the most productive stocks associated with higher bottom temperature and salinity conditions (Dutil and Brander, 2003), although Pörtner et al. (2001) found the growth performance of cod was optimal at 10 °C regardless of the latitudinal population investigated. This relatively simple picture becomes more complicated when food availability is also considered. Since increasing temperatures increase the metabolic demands of fish, it is possible that increased food supplies along with increasing temperatures may lead to faster growth and improved recruitment success for populations at equatorward locations in their range. Beaupre et al. (2003) found that an index of plankton prey explained 48 percent of the variability of North Sea cod recruitment, with periods of good recruitment coinciding with higher abundances of its preferred prey. Cod populations living in the Irish Sea and on Georges Bank, therefore, have individuals whose sizes are substantially larger than those living off Labrador or in the Barents Sea (Brander, 1994). These findings lead to the hypothesis that, for cod in the North Atlantic, increasing temperatures improve recruitment for stocks in cold water, but decrease recruitment for stocks in warmer water (Planque and Frédoù, 1999; Figure 9). When food supply is good, however, stocks in southern areas may be able to overcome this increased metabolism due to the warmer temperatures, and capitalize on their increased food resources to increase growth rates. These relationships can be countered if the warmer temperatures also cause changes in the species composition of the plankton, such that its energetic quality as food is decreased. For example, Omori
(1969) found low carbon to nitrogen ratios in zooplankton from the warmer tropical Pacific compared with those from the colder sub Arctic Pacific.

Taylor and Wolff (2007) have suggested that differences in plankton quality may be a key factor explaining the exceptional production of anchovy in the Peru upwelling system. In summary, warmer temperatures increase metabolic rates, but for populations at the equatorward parts of their ranges, if food is either insufficient or is of poor quality then both growth rates and recruitment will decline. Studies in freshwater systems show similar results, such that cold- and cool-water species like lake trout (Oncorhynchus mykiss), whitefish (Coregonus commersoni), and perch (Perca spp.) increase their growth rates in response to increased temperatures only when food supply is adequate to these increased demands (Ficke, Myrick and Hansen, 2007).

In Section 1.3 we noted that global warming is increasing the intensity of monsoon winds and, through increased upwelling, has resulted in increases in average summertime phytoplankton biomass in the Arabian Sea (Goes et al., 2005). The intensification of the hydrological cycles in this region is expected to influence limnological processes as well. Snow and glacier melt in the Eurasian mountains may result in changes in the flows of the Indus, Brahmaputra, Ganga and Mekong rivers, which sustain major river and floodplain fisheries and supply nutrients to coastal seas. Predictions for consequences of flow regimes are uncertain but increased runoff and discharge rates may boost fish yield through more extensive and prolonged inundation of floodplains. In Bangladesh, a 20 to 40 percent increase in flooded areas could raise total annual yields by 60 000 to 130 000 tonnes. These potential gains may be counter balanced by greater dry season losses due to lower dry season flows and greater demands on dry season water resources for irrigation, threatening fish survival and making the fish more susceptible to capture. Damming for hydropower, irrigation and flood control may also offset any potential fishery gains (Mirza, Warrick and Ericksen, 2003).

Recent declines in fish abundance in the East African Rift Valley lakes have been linked with climate impacts on lake ecosystems (O’Reilly et al., 2003). Lake Tanganyika, in particular, has historically supported one of the world’s most productive pelagic fisheries. A 30 to 50 percent decline in clupeid catch since the late 1970s has been attributed partially to environmental factors, because the lake had sustained high yields under similar fishing pressure for the previous fifteen to twenty years, although contrasting views have been expressed (Sarvala et al., 2006). The decline in catch was accompanied by breakdown of the previously strong seasonal patterns in catch, suggesting decoupling from ecosystem processes driven by the weakening of hydrodynamic patterns. These changes in the pelagic fishery are consistent with a lake-wide shift in ecosystem functioning (O’Reilly et al., 2003).

In freshwater ecosystems one of the most significant impacts of global warming would be a reduction in suitable habitat. In a simulation based on a doubling of the atmospheric CO₂ Mohseni, Stefan and Eaton (2003) estimated a reduction of 36 percent and 15 percent of the suitable thermal habitat for cold and cool water species, respectively, while the habitat for warm water species would increase by 31 percent. This study was based on the maximum and minimum temperature tolerances for 57 species in 764 stream stations in the United States of America.

### 2.6 Phenological changes

Parmesan and Yohe (2003) estimated that more than half (59 percent) of 1 598 terrestrial, freshwater or marine species exhibited measurable changes in their phenologies and/or distributions over the past 20 to 140 years. They were systematically and predominantly in the direction expected from regional changes in climate (Parmesan and Yohe, 2003; Root et al., 2003). A surprising result is the high proportion of species that responded to recent, relatively mild climate change (global average warming of 0.6 °C). The
proportion of wild species impacted by climate change was estimated at 41 percent of all species investigated (655 of 1598; Parmesan and Yohe, 2003).

2.6.1 Ocean environments
Shifts in the timing of blooms of primary or secondary producers can cause a mismatch with their predators (the match-mismatch hypothesis proposed by Cushing (1969), Section 2.1.3). Efficient transfer of marine primary and secondary production to higher trophic levels such as commercially important fish species is largely dependent on temporal synchrony between successive trophic production peaks in temperate systems. For example, the demographic timing of zooplankton in both the North East Pacific (Mackas, Batten and Trudel, 2007) and the Northeast Atlantic (Greve et al., 2004, 2005) is strongly correlated with the temperature that the juvenile zooplankton encounter during early spring. There is concern that marine trophodynamics may have already been radically altered by ocean warming through predator-prey mismatch (Stenseth and Mysterud, 2002; Abraham and Sydeman, 2004; Edwards and Richardson, 2004; Visser and Both, 2005). In the North Sea, for example, dinoflagellates have advanced their seasonal peak by nearly one month, while diatoms have shown no consistent pattern of change (Edwards and Richardson, 2004; Figure 16) because their reproduction is triggered principally by increases in light intensity. Responses of copepods have been more variable but some species have their seasonal maximum earlier in the year (Edwards and Richardson, 2004). Beaugrand et al. (2003) and Reid et al. (2003) showed that fluctuations in plankton abundance in the North Sea due to climate change affected larval cod survival because of a mismatch between the size of prey (calanoid copepods) and cod larger than 30 mm after the mid-1980s. The timing of Macoma balthica spawning in Northwestern Europe is also temperature dependent. Recent warming trends have led to earlier spawning but not earlier spring phytoplankton blooms, resulting in a temporal mismatch between larval production and food supply (Philippart et al., 2003). A further complication regarding match-mismatch is the need to consider the amplitude of the peak and possibly a threshold effect (Stenseth and Mysterud, 2002; Durant et al., 2005). Durant et al. (2005), for example, demonstrated that in the case of the herring/puffin match-mismatch the abundance of herring was structuring the match between predator and prey.

Mackas, Batten and Trudel (2007) review copepod abundance and phenology time series from net tow and Continuous Plankton Recorder surveys in the sub-Arctic North East Pacific over recent decades. The two strongest responses observed are latitudinal

shifts in centres of abundance of many species (poleward under warm conditions), and
changes in the life cycle timing of Neocalanus plumchrus (earlier by several weeks in
warm years and at warmer locations). Observations of zooplankton and high trophic
level indices (fish, birds) in the North Pacific showed consistent patterns that are
strongly correlated with large scale year-to-year and decade-to-decade ocean climate
fluctuations, as reflected by spring season temperature anomalies in the surface mixed
layer. The change in zooplankton developmental timing cannot be explained solely by
physiological acceleration, and thus differential mortality rates between cohorts are
conclude that, in strongly seasonal environments, anomalously high temperature may
provide misleading environmental cues that contribute to timing mismatch between
life history events and the more-nearly-fixed seasonality of insolation, stratification
and food supply. There are indications that such changes in timing may be coherent
among different ocean basins (Figure 17; Perry et al., 2004). Edwards and Richardson
(2004) also noted that water temperature affects the timing of ontogenetic transitions,
which would decouple changes in the larval environment from the cues used by the
adult population.

FIGURE 17
Schematic drawing showing North Pacific (PDO) and North Atlantic (NAO) climate
indices, and timing of changes in the trends of plankton abundance and phenology
time-series. Arrows indicate time of change, not direction of change. Data are from:
California (Rebstock, 2002a, b; McGowan et al., 2003); British Columbia, Canada, and
Oregon (Mackas et al., in press); winter season Kuroshio region, Japan (Nakata and
Hidaka, 2003); Korea (Kang et al., 2002); Neocalanus peak timing (Mackas, Goldblatt
and Lewis, 1998); North Sea plankton (Edwards et al., 2002); NE Atlantic plankton
(Beaugrand and Reid, 2003); NW Atlantic copepods (Jossi et al., 2003)

Source: Perry et al., 2004.
2.6.2 Inland waters
With the earlier ice break-up and warmer water temperatures, many lakes are responding with phenological adaptations. The spring algal bloom now occurs about four weeks earlier in several large European lakes (Gerten and Adrian, 2000; Straile and Adrian, 2000). In many cases where the spring phytoplankton bloom has advanced, zooplankton have not responded similarly, and populations are declining because their emergence no longer corresponds with high algal abundance (Gerten and Adrian, 2000). For example, in a lake in the Northwestern United States, the phytoplankton bloom has advanced by 19 days from 1962 to 2002 whereas the zooplankton peak is more varied, with some species showing advance and others remaining stable (Winder and Schindler, 2004a,b). Phenological shifts have also been demonstrated for some wild and farmed fish species (Ahas, 1999; Elliott, Hurley and Maberly, 2000). Because not all organisms respond similarly, differences in the magnitude of phenological responses among species has affected food-web interactions (Winder and Schindler, 2004a).

2.7 Species invasions and diseases
On a global scale, outbreaks of disease have increased over the last three decades in many marine groups including corals, echinoderms, mammals, molluscs and turtles (Ward and Lafferty, 2004). Causes for increases in diseases of many groups remain uncertain, although temperature is one factor that has been implicated (Harvell et al., 2002). Previously unseen diseases have also emerged in new areas through shifts in distribution of hosts or pathogens, many of which are in response to climate change (Harvell et al., 1999).

The ecology of some of the human pathogenic microorganisms associated with the aquatic environment has also been linked to temperature change. *Vibrio parahaemolyticus* is a pathogen often involved in gastroenteritis associated with consumption of raw oysters and though the organism has worldwide distribution, it is rarely isolated when water temperatures are less than 15 °C (ICMSF, 1996). The outbreak of gastroenteritis associated with Alaskan oysters in 2004 extended by 1 000 km the northernmost documented source of oysters that caused illness due to this organism (McLaughlin et al., 2005). It has been reported that since 1997, mean water temperatures during July and August at the implicated region increased by 0.21 °C per year. This suggests that increases in sea surface temperatures might lead to microbial hazards in areas where they were never considered before (e.g. the outbreak of *V. parahaemolyticus* diarrhea in Puerto Montt, Chile, in 2004, 2005 and 2006; Gonzalez-Escalona et al., 2005; Fuenzalida et al., 2007). *Vibrio cholerae* has a symbiotic association with zooplankton and extreme events related to climate change may lead to increased hazards as a result of this pathogen being transmitted through water and fish (Lipp et al., 2002). Events associated with climate change such as storms and flash floods might lead to the transport of pathogens like viruses (noroviruses, hepatitis A virus) from waste water sources to shellfish growing areas. Bivalves being filter feeders can bioconcentrate viruses to much higher levels compared to water (Richards, 2001). Therefore, fish safety management programmes need to consider these hazards for risk assessment.

There are also latitudinal shifts of diseases in terrestrial and marine environments, due either to direct response of the pathogen or to the response of its vector. Climate warming can increase pathogen development and survival rates, disease transmission and host vulnerability, although a subset of pathogens might decrease with warming, releasing hosts from disease (Harvell et al., 2002). Relatively little evidence exists in marine ecosystems except for marine mammals, marine invertebrates such as oysters, and eelgrass (although the mechanisms for pathogenesis are unknown for these last two groups) and most of all the growth rates of marine bacteria and fungi in coral ecosystems which could be positively correlated with temperature (Harvell et al.,...
Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture

An exception is the northward spread of two protozoan parasites (*Perkinsus marinus* and *Haplosporidium nelsoni*) from the Gulf of Mexico to Delaware Bay and further north, where they have caused mass mortalities of Eastern oysters (*Crassostrea virginica*). Winter temperatures consistently lower than 3 °C limit the development of the Multinucleated Spore Unknown (MSX) disease caused by the protozoan pathogen, *Haplosporidium nelsoni* (Hofmann et al., 2001) and the poleward spread of this and other pathogens can be expected to continue as such winter temperatures become rarer. This example also illustrates the relevance of seasonal information when considering the effects of climate change, since in this case it is winter temperature which controls the spread of the pathogen.

Some massive mortalities of pelagic fish have been proved to be caused by diseases, as in the case of sardine off Australia which was caused by a virus (Gaughan, 2002), but are related to human introduction of the pathogen agent rather than to climate change. Other massive mortalities, such as observed in the Moroccan sardine in 1997, seem more related to abrupt environmental changes. In a single year (1991), the oyster parasite *Perkinsus marinus* extended its range northward from Chesapeake Bay to Maine, a 500 km shift. Censuses from 1949 to 1990 showed a stable distribution of the parasite from the Gulf of Mexico to its northern boundary at Chesapeake Bay. The rapid expansion in 1991 has been linked to above-average winter temperatures rather than human-driven introduction or genetic change (Ford, 1996).

Marcogliese (2001) recognized that parasites of freshwater and marine organisms will be affected directly by climate change, but also indirectly through the effects of climate change on their hosts. Climate change may also influence the selection of different modes of transmission and virulence (Marcogliese, 2001).

In addition to allowing natural range expansions, warming temperatures can facilitate the establishment and spread of deliberately or accidentally introduced species (Carlton, 2000; Stachowicz et al., 2002b).

Some authors have suggested that harmful algal blooms (HABs) are increasing globally due to anthropogenic influences (Smyda, 1990; Hallegraeff, 1993), while others have stressed that climate variability (apart from increased monitoring and awareness) are equally important (Sellner, Doucette and Kirkpatrick, 2003). Edwards et al. (2006) showed that HABs are indeed increasing in some areas of the Northeast Atlantic, although the increase is not spatially homogenous and is restricted to specific habitat types. It is evident that increase in the ratio of dinoflagellates versus diatoms has been observed in the southern North Sea (Hickel, 1998) and the Baltic Sea (Wasmund, Nausch and Mattahaus, 1998), and predicted in many climate change models (see section 2.2.2). The dominance of dinoflagellates was related to milder winter temperatures. In the context of HABs, if these climatic changes persist, they may lead to the emergence of a new successional regime in phytoplankton (Edwards et al., 2006). Although not classed as an HAB, satellite-detected coccolithophore activity (Smyth, Tyrell and Tarrent, 2004) is strongly correlated with warm-temperature and low salinity events off the northern coast of Norway and the Barents Sea. For example, on the other side of the Atlantic in the Grand Banks region, changes in the diatom/dinoflagellate ratio have been observed, with an increasing abundance of dinoflagellate species (notably *Ceratium arcticum*) (Johns et al., 2003). These changes, since the early 1990s, have been linked to hydroclimatic variations, specifically increased stratification and stability in the region and indicate a progressive freshening of this region likely caused by regional climate warming.

According to geological records taken from Atlantic and Pacific Canada when summer SST was much warmer during the late glacial–early Holocene (up to 58 °C), there was a period of sustained high production of red-tide blooms (Mudie, Rochon and Levac, 2002). This led the authors to suggest that global warming is strongly implicated in the historical increase in the frequency of red tides and other HABs (see also Dale, 2001).
A final impact, yet to be evaluated properly, involves the depletion of the ozone layer in response to the increase of CO₂ concentrations (Austin, Butchart and Shine, 1992). This process will result in an increase in ultraviolet radiation at the ocean surface, which is likely to affect biological processes. The response of a given species to UV exposure might depend on the presence of other species (Harley et al., 2006). For example, marine phytoplankton were protected from UVB damage when co-cultured with marine viruses (Jacquet and Bratbak, 2003).

2.8 Food web impacts from plankton to fish
Climatically driven changes in species composition and abundance will alter species diversity, with implications for ecosystem functions such as productivity (Duffy, 2003) and resistance to species invasions (Stachowicz et al., 2002a; Duffy, 2003). Understanding links between species diversity and ecosystem function is a general research gap in marine ecology and is wide open to investigations in the context of climate change.

Climate change is likely to affect ecosystems and their species both directly and indirectly through food web processes, which at the same time differentially interact (Figure 7). Whether direct or indirect processes predominate is likely to vary between systems, often depending on whether they are structured from the top down, from the bottom up or from the middle (Cury et al., 2000). For example, increases in the frequency of blooms of gelatinous zooplankton have been observed (in the Bering Sea: Brodeur, Sugisaki and Hunt, 2002) and predicted to increase with global warming (in the North Sea: Attrill, Wright and Edwards, 2007). In the tropical Pacific, it appears that direct effects on the dominant pelagic fish species predominate, whereas food web processes are more significant in the western Gulf of Alaska and even more so in the Barents Sea (Ciannelli et al., 2005; Ottersen et al., 2008). Frank, Petrie and Shackell (2007) showed that the type of trophic forcing is strongly correlated with species richness and temperature. They suggest that very cold and species-poor areas might readily succumb to top-down control and recover slowly (if ever); warmer areas with more species might oscillate between top-down and bottom-up control, depending on exploitation rates and possibly, changing temperature regimes.

The connectivity of the food web also plays a role. While traditional food webs have a number of predators feeding on different prey in a balanced way, there are many examples where one species dominates as food, thus playing a significant control role: capelin (Mallotus villosus) in boreal seas of the North Atlantic, pollock (Theragra chalcogramma) in the Bering Sea, small pelagics in upwelling regions (Cury et al., 2000), etc. Even when there are several species of fish that serve as prey, there is often one species of invertebrate dominating the next level down (often a copepod, Ware and Thomson, 1992) whose decadal fluctuations are often accompanied by synchronous dynamics in their main fish larval and juvenile stages (e.g. Beaugrand et al., 2003; Beaugrand, 2004; Heath and Lough, 2007). In general, however, the presence of a single species as the primary channel for energy from lower to higher trophic levels makes it extremely difficult to relate the dynamics of any single upper trophic level to a single lower trophic level (Pimm, Lawton and Cohen, 1991; Rice, 1995). For this reason, models that analyse climate impacts on food webs have low predictive capacity. The following example details this complexity. The dynamics of the Barents Sea cod (Gadus morhua), capelin (Mallotus villosus) and herring (Clupea harengus) interact strongly and are all influenced by differential harvesting. Harvesting and predation of capelin by herring are capable of causing the population to collapse, whereas predation by cod (Gadus morhua) delays capelin recovery after a collapse (Hjermann, Stenseth and Ottersen, 2004a). Temperature and the NAO index are positively correlated with cod growth for ages up to four years old, but not for older fish, which are more affected by the ratio between cod and capelin (Hjermann, Stenseth and Ottersen, 2004b).
link between pairs of species can also vary between areas. For example, the time lag relationship of the Barents Sea system indicates that the indirect effect of herring on cod is more important than the direct effect (Hjermann, Stenseth and Ottersen, 2004a,b), while the opposite is true for the Baltic Sea (Köester et al., 2001). Thus, the effect of herring on cod depends on the size of the cod stock in the Barents Sea but less so in the Baltic Sea (Hjermann et al., 2007). This is the way lags between climate and biological effect are likely to develop, and trophic position alone is not a precise indicator of whether populations respond directly or are lagged to climate (e.g. Ottersen, Stenseth and Hurrell, 2004; Post, 2004).

Most common is to observe synchronized changes in several trophic levels, without a clear cause-effect relationship. In the North Sea, changes to planktonic and benthic community composition and productivity have been observed since 1955 (Clark and Frid, 2001), and since the mid-1980s may have reduced the survival of young cod (Beaugrand et al., 2003). Large shifts in pelagic biodiversity (Beaugrand et al., 2002) and in fish community composition have been detected (Genner et al., 2004; Perry et al., 2005). Changes in seasonality or recurrence of hydrographic events or productive periods could be affected by trophic links (Stenseth et al., 2002, 2003; Platt, Fuentes-Yaco and Frank, 2003; Llope et al., 2006). Elevated temperatures have increased mortality of winter flounder eggs and larvae (Keller and Klein-MacPhee, 2000) and have led to later spawning migrations (Sims et al., 2004). A 2 °C rise in SST would result in removal of Antarctic bivalves and limpets from the Southern Ocean (Peck, Webb and Bailey, 2004). Tuna populations may spread towards presently temperate regions, based on predicted warming of surface water and increasing primary production at mid and high latitudes (Loukos et al., 2003).

The direct effect of temperature on cod recruitment in different areas of the North Atlantic has been reinterpreted by Sundby (2000) who suggests that, in addition to its direct effect, temperature was likely to be a proxy for zooplankton abundance, which in turn has a major effect on cod larvae survival. Sundby (2000) argues that, at least in the Barents Sea, zooplankton changes are caused by the advection of warm and zooplankton-rich Atlantic water from the Norwegian Sea. In the Norwegian Sea itself, temperature could directly control the growth of copepods, especially *Calanus finmarchicus*. Additionally, Sundby (2000) suggests that the abundance of the zooplankton population also depends on the abundance of its prey, phytoplankton. In the end, the optimal temperature window observed for cod abundance by Planque and Frédoù (1999, Figure 9) could result from the combination and interaction of a direct effect of temperature on cod but also through indirect effects of temperature on the foodweb modulated by advective processes that, depending on the flux direction, will associate prey abundance for cod with cool or warm temperature. Sundby’s finding is likely to apply to these species in the North Sea and elsewhere because copepods are also a main prey of small pelagic fish such as herring and capelin.

### 2.9 Regime shifts and other extreme ecosystem events

A recently accepted mechanism through which climate variability and change interact in affecting ecosystem dynamics is based on the concept of “regime shifts”. A common definition of this term usually involves the notion of multiple stable states in a physical or ecological system, a rapid transition from one semi-permanent state to another and a link to climate forcing (deYoung et al., 2004). Although they have been observed in terrestrial, freshwater and marine ecosystems (Scheffer et al., 2001a; deYoung et al., 2004) the underlying dynamics remain contentious (deYoung et al., 2008). In an ecological context, regime shifts propagate through several trophic levels (Cury and Shannon, 2004; Scheffer et al., 2001; Carpenter, 2003) and are thus ecosystem-wide processes with a single forcing mechanism. While regime shifts in marine ecosystems are generally attributed to climate forcing, they can also result from overfishing,
pollution or a combination (Hare and Mantua, 2000; Jackson et al., 2001; Beaugrand et al., 2002; Daskalov, 2002; Frank et al., 2005; Greene and Pershing, 2007). Equally, regime shifts in lakes have been found to be both climate-driven (Carpenter, 2003; Smol et al., 2005) as well as mediated by overfishing and pollution (Carpenter, 2003; Scheffer and Van Ness, 2004). In comparing the dynamics of freshwater and marine regime shifts, Scheffer and Van Nes (2004) concluded that similar mechanisms may be involved in causing alternative attractors (and thus occasional regime shifts) in both systems. However, they hypothesized that benthic regime shifts might happen easily but be relatively local, while open ocean shifts might not arise so easily but would be larger in magnitude and scale.

An important consideration highlighted by Hsieh et al. (2005) is that biological responses to shifting climatic conditions can be non-linear (e.g. a change in regime), even though the underlying abiotic changes may be linear and stochastic. This sensitivity of ecosystems to amplify climatic signals (Taylor, Allen and Clark, 2002) suggests that gradual changes in future climate may provoke sudden and perhaps unpredictable biological responses as ecosystems shift from one state to another (e.g. Smol et al., 2005). For this reason the pattern of the biological shift can vary from a smooth, quasi-linear relationship between the forcing and the biological response (Collie, Richardson and Steele, 2004), to an abrupt, non-linear relationship between the forcing and the response variables (Scheffer et al., 2001a; Collie, Richardson and Steele, 2004). Such patterns may include discontinuous relationships which exhibit a hysteresis response in which the forcing variable exceeds a critical threshold causing the response variable to pass through unstable conditions while transiting from one equilibrium state to another (Scheffer et al., 2001; Collie, Richardson and Steele, 2004). The difference between the three responses emerges when the forcing variable is reversed. For a discontinuous regime shift to be reversed, the forcing variable must exceed a second critical threshold, which is lower than the first, thus exhibiting hysteresis (Collie, Richardson and Steele, 2004).

Large scale regime shifts are particularly significant considering their potential consequences. At basin scales, regime shifts have been identified in the North Atlantic in the early 1960s and late 1980s (Reid, Borges and Svendsen, 2001; Beaugrand, 2004; Genner et al., 2004; Clark and Frid, 2001, Figure 18), and in the North Pacific in 1925, 1945, 1977, 1989 and 1998 (Hare and Mantua, 2000; Benson and Trites, 2002; King, 2005).

A high biomass and large mean size of calanoid copepods and a high abundance of *Calanus finmarchicus* characterized the Northeast Atlantic during a negative NAO phase in the 1960s (Beaugrand et al., 2003). Changes in North Atlantic planktonic community structure were observed coincident with the climatic regime shift that occurred in the mid-1980s, with a decrease in mean size of calanoid copepods, delayed timing in the occurrence of *Calanus* from spring to late summer, decrease in the total biomass of copepods and a decrease in the abundance of Euphausids (Beaugrand et al., 2003, Figure 18). The shift in zooplankton biomass coincided with changes in climate, commercial fish recruitment and in spawning stock biomass (SSB; Parsons and Lear, 2001). The signal of change in the zooplankton biomass occurred two years later than the signal evident in the NAO index (Lees et al., 2006). During the 1960s (negative North Atlantic oscillation phase), recruitment of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*) and saithe (*Pollachius virens*) in the North Sea rose to record levels, in a period called “the gadoid outburst” (Hislop, 1996; Beaugrand et al., 2003). No strong year classes in saithe, cod or whiting have been observed following the late 1980s, shortly after the North Atlantic climatic regime shift and the shift in zooplankton biomass. This may be attributable to high fishing mortality, climate change or a combination of both (Beaugrand et al., 2003; Lees et al., 2006). North Sea saithe, cod and whiting recruitment appeared to change
from relatively high mean recruitment to relatively low mean recruitment around the late 1980s and were positively correlated with zooplankton biomass with time lags of two, five and six years, respectively (Lees et al., 2006). Cod spawning stock biomass appeared to shift from a high to low quasi-stable state in the late 1980s. Saithe and whiting SSB show evidence of a low quasi-stable state from the late 1970s and mid-1980s, respectively (Lees et al., 2006).

Climatic regime shifts evident in the Pacific Decadal Oscillation (PDO) in 1977, 1989 and 1998 have each been associated with large-scale ecological changes (Hare and Mantua, 2000; Benson and Trites, 2002; King, 2005). Total North Pacific zooplankton biomass was in its most persistent and positive phase on record between 1965 and 1970, reaching its most positive value in 1968. It decreased to the lowest on record in 1989.
and remained persistently low between 1990 and 1997 (Lees et al., 2006). This shift occurred coincident with the proposed 1989 climatic regime shift. However, no shift in North Pacific zooplankton biomass was observed following the 1977 climatic regime shift. Coincident with the climate shift, Bering Sea Greenland halibut (Reinhardtius hippoglossoides) recruitment decreased from a high to low phase between 1978 and 1982. In the Gulf of Alaska, sablefish (Anoplopoma fimbria) recruitment declined from a high to low phase between 1980 and 1981. Pacific halibut (Hippoglossus stenolepis), shortspine thornyhead (Sebastolobus alascanus) and arrowtooth flounder (Atheresthes stomias) recruitment increased from low to high regimes in the late 1970s. Clark and Hare (2002) incorporated this concept of high and low ocean productivity regimes into a generalised stock-recruitment model for Pacific halibut, based on their finding that recruitment was higher during warm regimes. They concluded that Pacific halibut recruitment could double for the same spawning stock size depending on the productivity regime. More recently, a number of large-scale ecological changes are reported to have occurred coincident with the proposed 1998 North Pacific climatic regime shift. King (2005) reported a decreased productivity throughout the central North Pacific food web, increased productivity in the California Current system and increased productivity in some areas of the Gulf of Alaska and the western North Pacific, but no apparent response in the Bering Sea and the Aleutian Islands.

Chavez et al. (2003) noted that several characteristics of the entire North and South Pacific Ocean changed in the early 1950s and late 1970s (Figure 19). In the subtropical regions of both ocean basins, warmer conditions favoured sardine populations whereas cooler conditions favoured anchovy, although several other changes in nutrient supply, rockfish, salmon, tuna and seabirds also coincided with these warm and cool conditions. Chavez et al. (2003) attributed these changes to large spatial and long temporal scale alterations in the slope of the sea level, and therefore the proximity of the thermocline to the sea surface and subsequent supply of nutrients to the upper ocean layers. Several authors have noted an apparent synchrony in fluctuations (or regimes) based on abundances of fish stocks from different parts of the same ocean basin, and even across ocean basins. This has been most apparent for small pelagic species (e.g. Kawasaki, 1992) although not exclusively (e.g. Bakun, 1996; Klyashtorin, 2001; Chavez et al., 2003; Weijerman, Lindeboom and Zuur, 2005). The implication would be that planetary-scale changes in atmospheric circulation patterns can induce seemingly related fluctuations in widely separated fish populations. These analyses have been criticized, however, based on statistical and mechanistic issues (Fréon, Mullon and Voisin, 2003; Stenseth et al., 2003). Overland et al. (2008) concluded that while climate variables can have strong teleconnections within individual ocean basins, between-basin teleconnections and potential climate-driven biological synchrony over several decades are usually much weaker. Overland et al. (2008) also noted the cumulative effects of monthly weather anomalies, El Niño-type events, plus broad-band “red noise” variability at multi-decadal time scales. When transferring this variability to biological systems, the various time lag and feedback effects plus non-linearities, cause them to respond to climate changes with a mix of slow fluctuations, prolonged trends, and step-like changes that may be difficult to predict, and yet that cannot be avoided. Added to these natural system influences on possible large-scale synchrony of fish populations are human influences, such as the movement of fishing boats and expertise from California to South America following the collapse of the California sardine fishery in the 1940 and 1950s (Ueber and MacCall, 1992) and common trends in herring catches between Iceland and British Columbia, Canada, as a result of the development of similar technologies and markets (Hamilton, Otterstand and Ögmundardóttir, 2006).

De Young et al. (2008) present a conceptual framework to enhance the ability to detect, predict and manage regime shifts in the ocean and conclude that the ability to adapt to, or manage regime shifts, depends upon their uniqueness, our understanding
of their causes and linkages between ecosystem components and our observational capabilities. Because the likelihood of climate-driven regime shifts increases when humans reduce ecosystem resilience (understood as the disturbance an ecosystem
can tolerate before it shifts into a different state, e.g. Scheffer et al., 2001a; Cropp and Gabrica, 2002; Folke et al., 2004), for example by removing key functional species, age groups, trophic levels, or adding waste and pollutants (Folke et al., 2004), a primary issue remains whether ecosystem resilience will be sufficient to tolerate future anthropogenic climate change.

Of interest in the context of global climate change, are a separate set of non-linear biological events that can be generated not by linear climate influences but by greater storminess. Two studies raise this point. Trenberth et al. (2007) recently reported a 75 percent increase (since 1970) in tropical storms in the North Atlantic and western North Pacific, and Saunders and Lea (2008) demonstrated a high correlation between sea surface temperature and hurricane frequency and activity in the Atlantic Ocean. Greater storminess can alter disturbance regimes in coastal ecosystems and lead to changes in diversity and hence ecosystem functioning. Salt marshes, mangroves and coral reefs are likely to be particularly vulnerable (e.g. Bertness and Ewanchuk, 2002; Hughes et al., 2003). Coral reefs are also well known to be susceptible to fresh water as well as the effects of turbidity and sedimentation that vary with coastal weather patterns. Numerous examples of coral communities being killed off or adversely affected purely as a result of extreme rainfall events have already been reported (e.g. Alongi and McKinnon, 2005; Fabricius, 2005).

3. SCENARIOS OF CLIMATE CHANGE IMPACTS ON FISH PRODUCTION AND ECOSYSTEMS

3.1 General impacts

Climate change represents several factors associated with increasing atmospheric concentrations of greenhouse gases. These are detailed in Section 1 of this report and include increasing sea temperatures, increasing acidification of the oceans, increasing sea level and related factors such as changes in winds, strengths of storms, precipitation patterns, etc. To these must be added non-climate stresses on marine environments such as harvesting, contaminants, non-native species introductions, habitat and coastal zone modifications and changes in nutrient additions and freshwater runoff patterns, which vary in the spatial pattern of their impacts (Halpern et al., 2008). Non-climate related stresses to freshwater systems include over-exploitation, flow obstructions such as dams, habitat change, non-native species introductions, and contaminants and nutrient additions (Schindler, 2001). These will interact to make sweeping generalised conclusions of the impacts of global climate change on marine and aquatic systems difficult, but should improve the predictions for local areas if the correct sets of global, regional and local stressors can be identified. For example, whereas the oceans are warming in general, they are not warming at the same rate everywhere, and some locations are cooling (Section 1.1). Similarly, the global ocean is decreasing in salinity, but with large regional variations (Section 1.2).

General impacts on marine and aquatic systems as a result of large-scale changes related to temperature, winds and acidification can be predicted however, in some cases with a high degree of confidence. These impacts will occur on a variety of time scales from rapid (a few years) to slow (multiple decades). They generally can be grouped into changes in: distributions and abundance, phenology (timing), species community composition and community structure and dynamics, including productivity (Hennessy et al., 2007).

3.1.1 Rapid time scales

There is high confidence that increasing temperatures will have negative impacts on the physiology of fish because of limited oxygen transport to tissues at higher temperatures. Specifically, at some temperature the evolved circulatory system will be unable to deliver sufficient oxygen to meet tissue metabolic demands (Pörtner and
Knust, 2007). This process forms the physiological basis for the observed and predicted changes in distributions and recruitment (abundance). It may be more significant for high-latitude and polar species, many of which have low tolerances for temperature changes (stenothermic). Many fish species in polar regions have reduced numbers of red blood cells and therefore are less efficient at carrying oxygen when temperature-related metabolic demands increase (Roessig et al., 2004). This physiological constraint is likely to cause significant limitations for aquaculture. In the short term, higher temperatures may produce increased food conversion efficiencies and increased growth rates, but as temperatures continue to increase and because cultured species cannot move, their productivity is likely to decline (medium confidence). Optimal locations for aquaculture species are expected to move polewards (Stenevik and Sundby, 2007).

These constraints on physiology will result in changes in distributions of both freshwater and marine species and likely cause changes in abundance as recruitment processes are impacted by changing temperatures and circulation patterns (Section 2.5). Strongest and most rapid changes will be to those stocks at the edges of their species' ranges, such that stocks at both the equatorward and poleward limits will move poleward (high confidence). These responses will be most rapid for highly mobile pelagic species (Harley et al., 2006) as has already been demonstrated by tuna in the tropical Pacific in response to ENSO variability (Lehodey et al., 1997), zooplankton and pelagic fish in the Northeast Pacific (Ware and McFarlane, 1995; McFarlane and Beamish, 2002; Mackas, Batten and Trudel, 2007), small pelagics in the English Channel (Hawkins, Southward and Genner, 2003) and Norwegian herring in the Northeast Atlantic (Sissener and Bjørndal, 2005). Less mobile, often demersal, species have also been observed to move poleward (Perry et al., 2005; Drinkwater, 2006) or to deeper depths and cold upwelling centres (Clark, 2006).

Changes in the timing of life history events (phenology, Section 2.6) are expected with climate change (high confidence). Short life span rapid turnover species, for example plankton, squid and small pelagic fishes, are those most likely to experience such changes. This will lead to earlier spring plankton blooms (Mackas, Goldblatt and Lewis, 1998; Edwards and Richardson, 2004) for some species but not for others (Greve et al., 2005; Hays, Richardson and Robinson, 2005). It will also lead to changes in species composition as the development times for different components of marine communities are altered. This will result in mismatches between early life stages of fish and their prey, with recruitment failures and declines in abundance as consequences (e.g. Platt, Fuentes-Yaco and Frank, 2003; Section 2.1.3).

### 3.1.2 Intermediate time scales

At intermediate time scales of a few years to a decade, temperature-mediated physiological stresses and phenology changes will impact the recruitment success and therefore the abundances of many marine and aquatic populations (high confidence). The earliest impacted species are again likely to be those with shorter life-spans and faster turnover rates, since biomass of species with longer life-spans tends to be less dependent on annual recruitment. These impacts are also likely to be most acute at the extremes of species' ranges, and may manifest themselves as changes in fish distributions (e.g. loss of more southerly populations and stocks). Changes in abundance will alter the composition of marine and aquatic communities, with possible consequences to the structure and productivity of these marine ecosystems (Worm and Duffy, 2003) in particular if keystone or “high leverage” species are affected (Harley et al., 2006). Since these processes involve many unknowns, predicting impacts and directions for any specific case can only be done with low confidence. Predicting net community impacts such as total biomass or productivity may be done with intermediate confidence, however, because of compensatory dynamics among the members within the various
Increasing vertical stratification is predicted for many marine areas (e.g. Houghton, 2001) and lakes (Ficke, Myrick and Hansen, 2007). It is expected to reduce vertical mixing and therefore reduce nutrient supply to the productive photic layers, thereby decreasing productivity (intermediate confidence). In addition, increasing stratification is predicted to alter the balance between pelagic and benthic recycling of nutrients, favouring the pelagic pathway and pelagic fishes at the expense of the benthos (Frank, Perry and Drinkwater, 1990). This will drive changes in species composition (e.g. in the Baltic, Mackenzie et al., 2007) and affect the timing of life cycle processes (e.g. in the Pacific, Mackas, Batten and Trudel, 2007, and Atlantic, Greve et al., 2005). Evidence of such increasing vertical stratification is available for the North Pacific Ocean (Freeland et al., 1997) and the North Atlantic (Curry and Mauritzen, 2005; see also Section 1.2); its impacts on lower trophic levels of the Northwest Pacific (Chiba et al., 2004) and fish productivity in East African lakes (O’Reilly et al., 2003) have also been demonstrated.

3.1.3 Long time scales
Predicted impacts to marine systems at long (decadal) time scales are dependent upon predicted changes in net primary production in the oceans and its transfer to higher trophic levels, about which there is still low (Brander, 2007) but increasingly promising (Jennings et al., 2008; Cheung et al., 2008) confidence. Section 2.2 describes several studies which have modelled the global responses of ocean primary production to climate change. There are significant differences between models. Regional predictions may have improved confidence because of better knowledge of the specific processes involved, e.g. as for the Arabian Sea, Goes et al. (2005). Future net primary production may increase in some high latitude regions because of warming and reduced ice cover, but decrease in low latitude regions because of reduced vertical mixing and replenishment of nutrients (Sarmiento et al., 2004) and changes in circulation and direct human impacts (Cruz et al., 2007). The result is that primary production may increase in some areas but decrease in others, with the net global impact unknown (Brander, 2007). Modelling and paleo oceanographic studies suggest a 50 percent decline in the plankton biomass in the North Atlantic during periods when the Meridional Overturning Circulation is weak (Schmittner, 2005). In contrast, coupled bio-physical models suggest global increases in net marine primary production of 0.7 percent to 8.1 percent but with large regional differences (Sarmiento et al., 2004). Most simulation studies, however, conclude that – in general – global net marine primary production will decrease with climate change, although there is large regional variation. Empirical observations of changes in net primary production over the past few decades have actually shown a decrease, but also with large regional variability (Gregg et al., 2003). Other simulation studies have shown that changes in phytoplankton composition are likely towards smaller forms (Bopp et al., 2005) and with changes in seasonality (Hashioka and Yamanaka, 2007). Such changes in regional production and species composition will impact all other trophic levels, including marine mammals, in particular those whose ranges are already restricted with little opportunity for expansion (Learmonth et al., 2006).

A new approach to estimating climate change impacts on global fish production based on ecosystem properties has been recently proposed by Jennings et al. (2008). They observed that marine ecosystems have remarkably constant and simple relationships between body size, energy acquisition and transfer and suggested that this approach could be used to assess the role of changing climatic temperature and primary production on production at higher trophic levels and to set baselines for assessing the impacts of fisheries (Jennings and Blanchard, 2004). This work is still in
progress (see http://web.pml.ac.uk/quest-fish/default.htm). Cheung et al. (2008), using a somewhat different approach based on observed current geographic ranges, trophic levels, primary production and fish catch, found a significant relationship between primary production and fisheries catch, with a high probability of shifts in locations of maximum catches. However, many impacts of global change on marine ecosystems are likely to be non-linear, in which small changes in the forcing can result in large responses. For example, Beaugrand et al. (2008) identified a critical thermal boundary in the North Atlantic at which abrupt shifts have been reported.

3.2 Case studies

A case studies approach illustrates the general and particular responses of specific marine and freshwater ecosystems to climate change. We focus on Arctic, North Atlantic, North Pacific, upwelling, South West Pacific, coral reef and freshwater systems, and aquaculture systems.

3.2.1 Arctic

The Arctic Climate Impact Assessment (ACIA), (Symon, 2005; see also Schrank, 2007) provides an assessment and predictions of climate change impacts to Arctic ecosystems. Climate change scenarios for Arctic marine systems are very uncertain because most models have focused on atmospheric effects (Schrank, 2007). Predicted physical changes by 2050 include increases in air temperature of 5 °C, a 6 percent increase in precipitation, a 15 cm rise in sea level, a 5 percent increase in cloud cover, a 20 day reduction in sea ice duration and 20 percent reduction in winter ice with substantial ice-free areas in summer (Schrank, 2007). The ecological consequences of these physical changes are expected (high confidence) to be (Table 2; Loeng, 2005; Schrank, 2007):

- decreased sea ice may allow primary production to increase two to five times over present conditions, although consequences of these changes for match or mismatch of this production with zooplankton and the rest of the food web are unclear;
- increased temperatures are very likely to shrink the ranges of cold water fish and benthic species but expand the ranges of Atlantic and Pacific species northwards.
- Long-lived Arctic species with narrow temperature tolerances and with late reproduction are likely to be first to disappear from more southerly habitats;
- changes to migration timing are likely, as are increases in growth rates;
- non-native species are likely to increase in Arctic waters but the assessment considers the extinction of any present Arctic fish species unlikely.

Endemic marine mammals (seals and whales) are expected to face severe habitat changes, most significant of which is the reduction of sea ice. Thinner ice and substantial ice-free areas will impact ice-associated mammals such as seals and may lead to extinction of some populations within decades, and possibly species extinctions at longer time scales (Kovacz and Lydersen, 2008).

3.2.2 North Atlantic

Large areas of the North Atlantic Ocean have already been impacted by climate warming-related changes, including phytoplankton (Edwards and Richardson, 2004), zooplankton (Beaugrand et al., 2002) and fish (Quero, Du Buit and Vayne, 1998; Perry et al., 2005; Dulvy et al., 2008). Climate conditions in the North Atlantic are strongly modulated by the atmospheric pressure shifts that are indexed by the North Atlantic Oscillation. Details of future climate change impacts in the North Atlantic are therefore likely to continue to vary with the state of the NAO. If the warming trend with a high NAO index continues, then sea temperatures in the North Sea, Nordic seas and Barents Sea are likely to increase by 1 to 3 °C over the next 50 years, with the largest changes occurring in the northernmost regions (Stenevik and Sundby, 2007).
In addition, increased wind-induced fluxes of warm Atlantic waters into these regions can be expected, which will increase the vertical stratification (Stenevik and Sundby, 2007) and reduce ice cover (Ellingsen et al., 2008). Simulations suggest that primary production is likely to increase in the Barents Sea, although zooplankton production is likely to decrease as production by Arctic zooplankton declines (Ellingsen et al., 2008). These will cause northward shifts of the distributions of all species, increase biomass production of species in Arcto-boreal regions, but introduce southern invaders into the southern North Sea (Stenevik and Sundby, 2007). Spawning areas for capelin in the Barents Sea are predicted to shift eastwards and spawning is predicted to occur earlier because of warmer temperatures (Huse and Ellingsen, 2008). A significant change in the meridional overturning circulation would have substantial impact on the Barents Sea (see Section 1.3). The North Sea is likely to become dominated by pelagic species such as herring and mackerel in the north and sardine and anchovy in the south, although the total system productivity may not be too different than today (Stenevik and Sundby, 2007). The Baltic Sea is predicted to become warmer and fresher, with significant increases in its vertical stratification (Mackenzie et al., 2007). The biodiversity of the Baltic is particularly sensitive to salinity changes; decreased salinity is predicted to exclude many marine-tolerant species and to favour those more tolerant of low salinities (Mackenzie et al., 2007). Non-native species may enter the Baltic, but few are expected to be able to colonise because of the salinity stress (Mackenzie et al., 2007).

In the Northwest Atlantic, predictions of climate change impacts are similar to those in the Northeast Atlantic in regards to distributions and migration changes. Populations at their range limits will be most affected, with additional changes to growth rates and recruitment success which will depend on the species and location (Drinkwater, 2000). In some locations and at some times, decreased temperatures may occur as a result of increased glacial melting in Greenland. This may provide refuges for some cold water species or may provide lethal cold shocks to other species such as Atlantic cod (Vasseur and Cato, 2008). Species adapted to cool and narrow temperature conditions, such as Atlantic salmon, may be extirpated from their present habitats because of the combined

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**TABLE 2**

<table>
<thead>
<tr>
<th>Phytoplankton</th>
<th>Zooplankton</th>
<th>Benthos</th>
<th>Fish</th>
<th>Marine mammals and seabirds</th>
</tr>
</thead>
</table>

| Production | Difficult to predict; depends on timing of phytoplankton blooms and water temperature. | Difficult to predict; depends on timing of plankton blooms and water temperature. | Depends on timing of plankton blooms and drift patterns of eggs and larvae. | Declines in ice-associated species and increases by temperate species; seabird production dependent on changes in food availability. |

| Species composition and diversity | Depends on mixing depth; deep mixing favours flagellates. | Adaptable Arctic copepods favoured. | Cold water species decline in abundance; warm water species increase. | Cod, herring, pollock, some flatfish likely to move north and become more abundant; capelin, polar cod, Greenland halibut will have restricted range and decrease in abundance. | Declines of polar bears, ringed, harp, hooded, spotted, ribbon and possibly bearded seals. Increases of harbour and grey seals. Possible declines of several whale species. Ivory gulls, small auk species likely to decline. |

Source: Loeng, 2005.
impacts of warming, changing habitats, introduced competitors and predators and increased parasitism (Vasseur and Cato, 2008). Atlantic cod is an important commercial fish species around the North Atlantic. In the south western parts of its range, in the Gulf of Maine and Georges Bank, cod are at their southern limit and so are vulnerable to warming and loss of thermal habitat (Fogarty et al., 2008). In model studies, cod survival in the Gulf of Maine declined with increasing temperatures which offset their increases in growth that occurred in the warmer conditions, with the net result being a loss in the yield to fisheries (Fogarty et al., 2008). In the middle of its range in the Northwest Atlantic, capelin (Mallotus villosus) are important prey of cod, but spawning times for capelin are susceptible to delays due to cold water from melting glaciers (Vasseur and Cato, 2008). In the Northeast Atlantic, climate model simulations of North Sea temperatures suggest that increasing temperatures will lead to declines in North Sea cod populations compared to simulations which exclude climate change effects (Clark et al., 2003).

3.2.3 North Pacific
Overland and Wang (2007) have examined the implications for the North Pacific Ocean of the results from ten models of atmospheric climate change. They conclude that anthropogenic impacts on the future North Pacific climate will be as large in 30 to 50 years as natural climate variability is today. This suggests that climate-ecosystem-fisheries relationships developed during the latter half of the twentieth century may not be robust in the twenty-first century. The implication is that relationships between fish production and indices of atmospheric state such as the Pacific Decadal Oscillation (PDO) may not be valid as the climate changes. As with the North Atlantic, the North Pacific is strongly influenced by variations in the strengths and positions of atmospheric pressures centres, which are indexed by east-west and north-south variations in sea surface temperature as captured in the PDO. Overland and Wang (2007) conclude that this pattern of decadal variability will continue into the twenty-first century, but it will occur on top of a persistent upward trend in sea surface temperature (Figure 20). Pierce (2004) modelled the impacts of increasing greenhouse gases to the plankton of the North Pacific and found the subpolar system changed from one with strong variability and winter lows to one with much more constant annual values and decreased yearly-averaged primary productivity. The productivity increased in other regions of the North Pacific as warmer temperatures enabled higher growth rates. Pierce (2004) found that his results were largely driven by changes in mixed layer depths (shoaling) and temperature (increasing). In contrast, the simulations by Hashioka and Yamanaka (2007) found that warmer conditions led to changes in the seasonal patterns of primary production in the North West Pacific. On the west coast of North America, northward shifts of fish populations are predicted (Overland and Wang, 2007) and have been observed (e.g. Okey, Wright and Brubaker, 2007). Welch, Ishida and Nagasawa (1998) predicted the restriction of suitable thermal habitat for sockeye salmon (Oncorhynchus nerka) in the North Pacific under a 2xCO₂ scenario to be reduced to the Bering Sea. The Bering Sea itself is predicted to be significantly impacted by climate change, including large-scale retreats of sea ice, losses of cold-water species and increasing abundances of species from the North Pacific (Overland and Stabeno, 2004). As noted above (Section 1.5), the sub-Arctic North Pacific is particularly sensitive to the effects of increasing acidification and by the the end of this century, some regions will become undersaturated in the aragonite form from surface to bottom (Feely, Fabry and Guinotte, 2008). Upwelling of aragonite undersaturated waters onto the continental shelf of western North America has already been reported (Feely et al., 2008). Various vertebrate and invertebrate species have been shown to be negatively impacted by these low pH concentrations, including pteropods (common prey for many open ocean fish) and squid (Fabry et al., 2008).
3.2.4 Wind-driven coastal upwelling systems

Major coastal wind-driven upwelling systems tend to occur on the eastern boundaries of the world’s oceans. The interaction of the wind-driven circulation with the bathymetry produces highly productive ecosystems, largely of pelagic species but which may also include demersal species. Predictions of the responses of coastal wind-driven upwelling systems are contradictory, however, partially because higher model resolution is required to resolve coastal upwelling at the global scale (see Section 1.3). Bakun (1990) proposed that with global warming the land-sea air pressure gradient would increase, thereby intensifying the alongshore wind stress and increasing coastal upwelling. This would have the effect of offsetting in these regions the global trend of increasing water temperatures and increasing vertical stratification, since such upwelled waters are cold and rich in nutrients. Synder et al. (2003) modelled wind-driven upwelling along the coast of California with increasing atmospheric CO₂ concentrations and found an intensified upwelling season with some change in seasonality. They concluded this effect should enhance the productivity of the system and possibly offset the local effects of increasing temperatures. McGregor et al. (2007) found that the upwelling system off North West Africa intensified during the twentieth century, and suggested it will continue to intensify with global warming. This should enable the system to retain its high productivity as the climate changes, although the composition of the predominant pelagic species may change (e.g. Zeeberg et al., 2008). Predicted impacts of climate change to parts of the Benguela upwelling system are different, however. This system is very productive, often with phytoplankton settling on the sea floor where it decomposes, consuming oxygen and producing hydrogen sulphide. When these oxygen-depleted waters are upwelled towards the surface, significant species displacements and mortalities can result (Bakun and Weeks, 2004). With climate change, intensified Benguela upwelling may therefore further increase nutrient inputs, primary production and low-oxygen events (Clark, 2006). The emergence of increasing areas of hypoxia and anoxia in the California Current upwelling system (Chan et al.,
Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture

2008) suggests that similar events may also occur in this system with climate change. Therefore, even with consistent predictions of increasing winds and coastal upwelling, each system may respond differently because of its unique characteristics of background productivity, consumer populations, etc. As outlined in Section 1.3, however, different predictions have been made of the physical responses to climate change, with some studies predicting weakening winds (Vecchi, Clement and Soden, 2006). The primary production model of Sarmiento et al. (2004) also showed no consistent global response of upwelling regions to climate change.

3.2.5 Tropical and subtropical seas

Tropical and subtropical marine regions have a wide variety of diverse habitats, each with highly diverse and distinct fauna (Roessig et al., 2004). There have been fewer studies of the potential tropical ocean responses to climate change than have been reported for temperate latitudes. A particularly important question, not yet resolved, is whether the tropical Pacific will take on a more “El Niño-like” character, in which the east-west gradient in time-mean SST is reduced, or will assume a more “La Niña-like” character with an increased east-west SST gradient (Vecchi et al., 2008). Simulations of the response of primary production in the tropical Pacific predict a decline because of increased stratification and decreased nutrient supply (Bopp et al., 2005). The combined effects of changes in circulation, temperature, nutrients and primary production cascade up the food web to influence prey availability and habitat conditions for tuna (Loukos et al., 2003). Tuna habitat conditions east of the dateline could improve, similar to El Niño-related warming events (Loukos et al., 2003; see also Section 2.2.2). A similar result was found by Watters et al. (2003) using a different modelling approach applied to the eastern tropical Pacific, in which a warming trend resulted in a persistent decline in abundances at all trophic levels as the region became more stratified and nutrient limited. Hennessy et al. (2007) concluded, for the waters about Australia and New Zealand, greatest impacts as a result of climate change would occur to coastal species and subtidal nursery areas, temperate endemic species rather than tropicals and coastal and demersal species rather than pelagic and deep-sea species. Hobday et al. (2006) and Poloczanska et al. (2007) provide a review of predicted climate change impacts to the marine ecosystems surrounding Australia. Models predict physical changes similar to other regions: ocean warming, increased vertical stratification, strengthening of poleward coastal currents, increasing ocean acidification, sea level rise and altered storm and rainfall regimes (Poloczanska et al., 2007). The analyses of Hobday et al. (2006) concluded that warming and increasing stratification will alter plankton community composition, alter their distributions polewards, and change the timing of their bloom dynamics so that transfers to higher trophic levels may be impaired. Benthic and demersal fishes will shift their distributions southward and may decline in abundance. Pelagic species will also shift their distributions southwards and some species may benefit from increased local wind-driven upwelling (e.g. anchovy). Hobday et al. (2006) concluded that the eastern-central and southeast marine regions of Australia were the most vulnerable to the impacts of climate and other stressors.

3.2.6 Coral reef systems

Coral reef ecosystems occur in warm and cold-water regions of the global ocean and are among the world’s most iconic places. They provide habitat for one-quarter of all marine species and are important sources of protein and income for many developing countries (Parry et al., 2007). They are at risk from climate change impacts related to increasing temperatures, acidity, storm intensity and sea levels (see Section 2.2.2), and non-climate factors such as overexploitation, non-native species introductions and increasing nutrient and sediment loads. The risks to coral reefs are not distributed equally, with increasing temperatures a significant issue for warm-water systems,
increasing acidity and decalcification a significant issue for both warm- and cold-water systems (e.g. Feely, Fabry and Guinotte, 2008), and direct human impacts a significant issue in more populous regions. Graham et al. (2006), however, suggested that even isolated and remote reef systems may be severely at risk from climate-related impacts alone.

Three different time scales can be identified for climate change-related impacts to coral reef systems:

- years: increased temperature effects on coral bleaching, which have become more frequent with recent ENSO events and may lead to steady degradation of reefs;
- a few decades: increasing acidification and dissolution of carbonate structures of reefs;
- multi-decades: weakening of structural integrity of reefs and increasing susceptibility to storms and erosion events as a result of increased temperatures and acidification, leading to large-scale composition shifts.

Coral reef ecosystems are usually able to recover from weak chronic environmental stresses, such as temperature increases or reduced calcification, as long as acute stresses such as temperature spikes associated with ENSO events, disease, or severe storms are not too strong or too frequent (Buddemeier, Kleypas and Aronson, 2004). Combination of chronic plus acute stress can lead to regime shifts with replacement of coral by algae-dominated systems (Hughes et al., 2003). In the Indo-Pacific, frequent ENSO-related bleaching events are believed to be inhibiting corals by not allowing enough time for recovery between successive events (Buddemeier, Kleypas and Aronson, 2004). Such bleaching events occur when sea temperatures are greater than 1 °C above mean summer temperatures for more than four weeks (Hoegh-Guldberg, 1999). Climate change models predict these thresholds will be exceeded more often and therefore bleaching events are likely to occur more frequently than corals can recover (Donner et al., 2005). If this same bleaching threshold remains, then more frequent bleaching events and increased coral mortality is likely for a majority of reefs by 2030 to 2050 (Parry et al., 2007).

Increasing acidity (decreasing pH) of the world’s oceans is a significant and pervasive longer-term threat to coral reefs. Although the in situ response of coral growth to increasing acidity is unknown (Parry et al., 2007), laboratory studies indicate that decreased aragonite saturation at reduced pH can disrupt coral calcification (Orr et al., 2005). This impact may be especially severe for deep cold-water corals such as occur along the continental slopes of the North East Pacific, where aragonite saturation levels are already shoaling at 90 to 150 m (Feely, Fabry and Guinotte, 2008). In warm waters, increasing acidity will lead to declining calcification and weakening of the coral skeleton, such that reduced coral cover and greater erosion of coral reefs is predicted by 2070 (Parry et al., 2007).

The potential for coral reef systems to adapt to these environmental stresses is uncertain. A change of symbiotic zooxanthellae to species more tolerant of high temperatures could reduce bleaching events and delay the demise of reefs from 2050 to 2100 (Parry et al., 2007). Migration of corals to higher latitudes is considered unlikely because of a lack of suitable substrates and decreasing aragonite concentrations at higher latitudes (Parry et al., 2007). Buddemeier, Kleypas and Aronson (2004) calculated that a 2 °C warming of the oceans would expand the thermal range of corals (which are presently limited by the 18 °C isotherm) by only a small amount. Declines in corals have had negative impacts on reef fish biodiversity in at least one study in Papua New Guinea (Jones et al., 2004). To date, however, there has been little evidence for a link between climate warming and bleaching events with impacts on coastal fisheries (e.g. Grandcourt and Cesar, 2003). However it is also clear that large-scale weakening and erosion of coral reefs over the longerterm will undoubtedly severely impact the animals which depend on these reefs for their food and habitat.
3.2.7 Freshwater systems

Freshwater lakes and their ecosystems are highly vulnerable to climate change. At very long time scales (greater than centennial) paleo records show that lakes have altered their shapes and distributions and have disappeared entirely, with the processes related to climate change as a result of the shifting dynamics among precipitation, evaporation and runoff (Poff, Brinson and Day, 2002). In general and at longer time scales (multiple decades) in North America, the anticipated response is for cold-water species to be negatively affected, warm-water species to be positively affected, and cool-water species to be positively affected in the northern but negatively affected in the southern parts of their range (Mohseni, Stefan and Eaton 2003; Field et al., 2007). A general shift of cool- and warm-water species northward is expected in North America and likely the rest of the Northern Hemisphere. However, the responses of particular lake ecosystems to climate change will depend strongly on the size, depth, and trophic status of the lake. In a modelling study of climate warming (2xCO2) effects on lakes in central North America, Stefan et al. (1995) concluded that cold-water fish would be most affected because of losses of optimal habitats in shallow, eutrophic lakes. Growth conditions for cool- and warm-water fishes should improve in well-mixed lakes, small lakes and those with oligotrophic nutrient conditions. Since the production rates of invertebrate prey in lakes increases logarithmically with temperature (rates increase two to four times for each 10 °C increase in temperature; Watson et al., 1997) this should lead to long-term increases in fish production, although changes in prey species composition may offset this effect (Watson et al., 1997). In the short-term, however, lags between fish predators and their zooplankton prey may initially decrease fish production due to timing mismatches (Watson et al., 1997). Similar issues regarding productivity and timing mismatches have been proposed as likely in shallow lakes in the Netherlands (Mooij et al., 2005). The rates of change of freshwater systems to climate will depend on the ability of freshwater species to “move across the landscape”, i.e. will depend on the existence of dispersal corridors; these can be strongly altered by human activities (Poff, Brinson and Day, 2002). Most affected are likely to be fish in lowland areas that lack northward dispersal corridors and cold-water species generally (Poff, Brinson and Day, 2002).

Freshwater ecosystems are also highly bio-diverse, supporting some 40 percent of all fish species despite accounting for only a small proportion (0.01 percent by volume) of aquatic habitats (Arthington et al., 2003). Accurate data are difficult to collect but approximately 20 percent of freshwater species are threatened, endangered or extinct in areas studied (Revena et al., 2000). The protection of freshwater biodiversity is increasingly recognized as a major conservation priority (Abell, Thieme and Lehner, 2002).

3.2.8 Aquaculture systems

Handisyde et al. (2006) and De Silva and Soto (2009) noted that climate change impacts on aquaculture have both direct (e.g. through physical and physiological processes) and indirect (e.g. through variations in fishmeal supplies and trade issues) impacts. Here we discuss only the direct issues. Handisyde et al. (2006) noted that the physical changes related to climate change, i.e. in temperature, solar radiation, current and wave actions, sea level rise, water stress, and the frequency of extreme events, will impact physiological, ecological and operational (e.g. species and site selection, containment technologies, etc.) processes. The Third Assessment Report of the IPCC (McLean and Tsyban, 2001) identified the impacts of climate change on aquaculture; these were reiterated in the Fourth Assessment Report (Easterling et al., 2007). Negative impacts include:

- stress due to increased temperature and oxygen demands;
- uncertain supplies of freshwater;
• extreme weather events;
• sea level rise;
• increased frequency of diseases and toxic events;
• uncertain supplies of fishmeal from capture fisheries.

Positive impacts of climate change on aquaculture include increased food conversion efficiencies and growth rates in warmer waters, increased length of the growing season, and range expansions polewards due to decreases in ice (Easterling et al., 2007).

If primary production was to increase in aquaculture areas, it would provide more food for filter-feeding invertebrates (Alcamo et al., 2007). There may also be additional problems with non-native species invasions, declining oxygen concentrations and possibly increased blooms of harmful algae (Alcamo et al., 2007), although these latter are also strongly influenced by non-climate related factors. Local conditions in traditional rearing areas may become unsuitable for many traditional species, which may then need to be moved polewards (Stenevik and Sundby, 2007) or to cooler offshore water, or replaced with other species (Clemmensen, Potrykus and Schmidt, 2007).

De Silva and Soto (2009) provide a review of potential impacts of climate change on aquaculture. They note that the greatest proportion (50 to 70 percent) of aquaculture activities occurs in the tropical and subtropical regions, particularly in Asia. The taxonomic group with the highest production is finfish. It takes place predominantly in freshwater, whereas the culture of crustaceans is greatest in brackish waters and that of molluscs is in marine waters. De Silva and Soto (2009) concluded that the impacts of climate change (e.g. sections 1.1.2, 2.2.3, and 3.2.7) to freshwater aquaculture in tropical and subtropical regions is difficult to predict. Increasing temperatures and increasing plankton growth as a result of eutrophication may increase the growth rates and productivity of cultured species (McCuaey and Beitinger, 1992). Changes in water availability, extreme weather events, vertical stratification and nutrient supply may have negative effects on freshwater aquaculture production, depending on local conditions. Aquaculture activities in brackish waters may be affected by changes in salinity (increasing or decreasing), again depending on local conditions of runoff, marine circulation, etc. Aquaculture in temperate regions may be adversely impacted by increased prevalence of pathogens as temperatures warm at a greater rate than low latitude regions (e.g. Handisyde et al., 2006), in addition to cultured species suffering from physiological stress. Table 3 summarizes potential impacts of climate change on aquaculture.

3.3 Uncertainties and research gaps
Predicting the impacts of climate change on marine and aquatic ecosystems has many uncertainties and needs for research. Some predictions, such as impacts and distributional changes to populations at the northern and southern limits of their ranges, can be made with high confidence, at least in general. Predicting impacts on any specific region or local area will have lower confidence because local factors may increase in importance. If those local factors can be identified and understood however, then it may be possible for local predictions of climate change impacts to be made with high confidence. This illustrates that one of the biggest uncertainties in predicting impacts are the synergistic effects to marine and freshwater populations of multiple climate and non-climate stressors. These are likely to manifest themselves with significant non-linear dynamics and interactions (e.g. Scheffer et al., 2001b). Perhaps foremost among these are the interactions of increasing temperatures (Section 1.1), decreasing oxygen (both in absolute concentrations, Section 1.5, and in the ability to meet metabolic tissue demands, Section 2.1.1), decreasing salinity (Section 1.2), increasing acidification (Section 1.5), and the effects of fishing (e.g. Planque et al., 2008; Perry et al., 2008). In freshwater systems, the impacts of changing water flows and water use demands can be added to this list (Sections 1.1 and 1.6). The information learned during
Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture

Aquaculture activities should be systematized to help establish bioclimatic envelopes for species’ tolerances. Research is needed to identify and determine the functional roles of keystone or “high leverage” species, which may have significant effects on system characteristics and function. Hsieh et al. (2006) suggest that at the ecosystem level, reduced complexity by elimination of species due to overexploitation could lead to reduced resilience to climate change perturbations. The consequences of climate change for net primary production is highly uncertain at both global and regional scales, as is how this production may respond to significant variations in the thermohaline circulation (Section 1.3).

Significant uncertainties remain as to the direction of effect (increasing, decreasing) that climate change will have on upwelling systems, in particular coastal wind-driven systems. This is an important research issue since these are highly productive regions supporting valuable fisheries.

Several research issues remain regarding the state of simulation models. These include model resolution (physical, biogeochemical and ecological), their integration across scales, levels of certainty of the projections and the lack of sufficient data to force and validate the models (e.g. Werner et al., 2007). General Ocean Circulation Models (GCMs) used to make projections of future marine ecosystem states, in response to climate, are presently run at spatial resolutions of one degree (i.e. grids of 100x100 km; e.g. Sarmiento et al., 2004). However, physical processes determining biogeochemical and biological responses require resolutions on the order of kilometres in the open ocean and finer in coastal regions. The use of regional climate models and methods for downscaling to regional models, e.g. through nesting (Hermann et al., 2002; Snyder

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**TABLE 3**

Potential impacts of climate change on aquaculture systems (modified from Handisyde et al., 2006)

<table>
<thead>
<tr>
<th>Drivers of change</th>
<th>Impacts on culture systems</th>
<th>Operational impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea surface temperature changes</td>
<td>Increase in harmful algal blooms</td>
<td>Changes in infrastructure and operation costs</td>
</tr>
<tr>
<td></td>
<td>Decreased dissolved O₂</td>
<td>Increased fouling, pests, nuisance species and predators</td>
</tr>
<tr>
<td></td>
<td>Increased disease and parasites</td>
<td>Expanded geographic ranges for species</td>
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<tr>
<td></td>
<td>Longer growing seasons</td>
<td>Changes in production levels</td>
</tr>
<tr>
<td></td>
<td>Changes in locations and ranges of suitable species</td>
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<tr>
<td></td>
<td>Reduced winter natural mortality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Enhanced growth and food conversion rates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Competition, parasitism and predation from altered local ecosystems, competitors, and exotic species</td>
<td></td>
</tr>
<tr>
<td>Changes in other oceanographic variables</td>
<td>Decreased flushing rates and food availability to shellfish</td>
<td>Accumulation of wastes under nets</td>
</tr>
<tr>
<td></td>
<td>Changes in abundance of species used for food and fishmeal</td>
<td>Increased operating costs</td>
</tr>
<tr>
<td>Sea level rise</td>
<td>Loss of areas for aquaculture</td>
<td>Infrastructure damage</td>
</tr>
<tr>
<td></td>
<td>Loss of areas providing physical protection</td>
<td>Change in aquaculture zoning</td>
</tr>
<tr>
<td></td>
<td>Greater flooding risks</td>
<td>Increased insurance costs</td>
</tr>
<tr>
<td></td>
<td>Salt intrusions into groundwater</td>
<td>Reduced freshwater availability</td>
</tr>
<tr>
<td>Increased storm activity</td>
<td>Larger waves</td>
<td>Loss of stock</td>
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<tr>
<td></td>
<td>Higher storm surges</td>
<td>Facility damage</td>
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<td></td>
<td>Flooding from precipitation</td>
<td>Higher costs for designing new facilities</td>
</tr>
<tr>
<td></td>
<td>Salinity changes</td>
<td>Increased insurance costs</td>
</tr>
<tr>
<td></td>
<td>Structure damage</td>
<td></td>
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<tr>
<td>Drought and water stress</td>
<td>Salinity changes</td>
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<tr>
<td></td>
<td>Reduced water quality</td>
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<tr>
<td></td>
<td>Increased diseases</td>
<td></td>
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<tr>
<td></td>
<td>Uncertain water supplies</td>
<td></td>
</tr>
</tbody>
</table>

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et al., 2003; Clark, 2006; Penven et al., 2006; Viøke et al., 2007) are yielding new insights. Methodological approaches linking basin-scale models to coastal domains (e.g. Chassignet et al., 2006) and advances in adaptive and unstructured grid refinements appear to be promising (e.g. Pain et al., 2005). Development of Atmosphere-Ocean GCMs should include the specific kinds of information and output needed to evaluate climate change impacts on marine systems. The relationship between expected long-term changes and decadal (and shorter) variability is extremely important in considering climate impacts on fisheries. Downscaling and regional modelling of ocean climate change is also critical in making realistic regional forecasts of impacts. Present models of change in global marine primary production are very sensitive to the effect of temperature, which should therefore be a prominent topic for further field study and theoretical work.

Marine and aquatic systems have experienced warm conditions in the past, and have responded with significant changes of distributions and reorganizations of species community composition (e.g. Finney et al., 2002; Drinkwater, 2006). What marine systems have not experienced, at least as estimated from pre-industrial times, are acidification conditions as high as at present (Orr et al., 2005) and predicted to increase further. The large-scale impacts on marine systems of this interaction between increasing temperatures and increasing acidification are unknown. In contrast to experiments where no adaptation is possible, Pelejero et al. (2005) observed that 300-year-old massive Porites corals from the south western Pacific had adapted to 50-year cycles of large variations in pH, covarying with the Pacific Decadal Oscillation. This would suggest that adaptation to long-term pH change may be possible in some coral reef ecosystems. Research into the impacts of high concentrations of CO2 in the oceans is in its infancy and needs to be developed rapidly.

The impacts of fishing on the detailed abilities of marine populations and ecosystems to respond to climate change are also unknown, but general features can be described (Planque et al., 2008; Perry et al., 2008). Fishing makes marine populations more sensitive to climate variability and change by removing older age classes and spatial subunits, and by changing lifehistory traits such as reducing the age-at-first spawning (Perry et al., 2008). Fishing also decreases the mean size and trophic level and increases the turnover rates of the fish component of marine communities, and causes marine ecosystems to change towards stronger bottom-up control (Perry et al., 2008). Hsieh et al. (2006) analysed the California Cooperative Oceanic Fisheries Investigations (CalCOFI) ichthyoplankton data and showed that interannual variability is higher in exploited species than in unexploited ones, including pelagic species. The major process seems to be the decrease in the number of fish of older ageclasses caused by exploitation. Older fish are more fecund than younger ones, produce eggs of higher quality, perform more extended migrations and buffer the interannual variability in recruitment (Beamish, McFarlane and Benson, 2006). The net result is that marine systems become less resilient and more susceptible to the stresses caused by climate variability and change.

Significant uncertainties in the responses of marine and aquatic individual animals, populations, communities, and ecosystems to climate change relate to the roles of feedbacks, critical thresholds and transition points to different stable states. Such thresholds clearly provide lethal tolerance limits, e.g. temperatures above which an organism will die of heat shock, but also occur at (initially) sublethal levels which overstress the physiological system (Pörtner and Knust, 2007) or disrupt commensal arrangements (coral bleaching). Significant shifts in the states of marine systems have already been observed (Scheffer et al., 2001a; de Young et al., 2008). The points at which such thresholds exist will differ for different species, systems and stressors, most of which are as yet unknown. When these thresholds are passed and significant changes occur, they are often called “surprises”.
The ability for marine organisms to adapt and evolve to climate change, on the relevant time scales is also generally unknown. There is some evidence that genetic differences in fish do occur between cohorts from warm and cold years (Smith, 1979). Rapid adaptation and evolution, at least to fishing-induced stresses, can occur on relatively rapid time scales of a few decades (de Roos, Boukal and Persson, 2006; Law, 2007). Berteaux et al. (2004), addressing the potential for evolutionary change in response to climate change in Arctic terrestrial animals, also concluded that evolutionary changes due to natural selection could occur on a time scale of a few decades, although they noted that all species may not have equal capacities for such changes. Species with longer generation times and clonal species (because of their low effective population size) may take longer to show an evolutionary response (Harley et al., 2006). Species with complex life histories, such as salmonids, may experience conflicting selection pressures due to the impacts of climate change on the various life stages (Crozier et al., 2008). As noted by Stockwell et al. (2003), evolutionary responses will be influenced by the strength of selection, population size, genetic variation and gene flow, making most species relatively unique.

Detecting the impact of climate change requires increased and more sophisticated monitoring of ocean biology and environmental change, both from space and with instruments in the water. Ideally, measures are needed not only of parameters such as chlorophyll concentration and productivity, but also of plankton taxonomy (what is there?) and physiology (how healthy are they?). New remote sensing technologies may help meet these challenges.

4. SUMMARY OF FINDINGS

4.1 Climate change: the physical basis in marine and freshwater systems

4.1.1 Heat content and temperature
- The oceans are warming, but with some geographical differences and showing some decadal variability.
- Warming is not exclusive to surface waters, with the Atlantic showing particularly clear signs of deep warming.
- Freshwater resources are vulnerable to, and have the potential to be strongly impacted by, climate change. Many lakes have experienced moderate to strong warming since the 1960s.
- Lake water levels (which affect temperature impacts) have been decreasing in many areas, mostly as a result of human use, but precipitation patterns are also important.
- River run off is expected to increase at higher latitudes and decrease in parts of West Africa, southern Europe and southern Latin America.
- There are concerns over future warming in African lakes, as atmospheric temperature predictions for the continent are larger than the global average and rainfall is projected to decrease in parts.

4.1.2 Salinity and stratification
- In general, salinity is increasing in surface ocean waters of the more evaporative regions, while there is a decreasing trend in high latitudes.
- The combined effect of the temperature and salinity changes due to climate warming would reduce the density of the surface ocean, increase vertical stratification and change surface mixing, but with some geographical differences.
- Large salinity anomalies have been observed in the past with important ecosystem responses.

4.1.3 Ocean circulation and coastal upwelling
- A reduction of about 30 percent in the meridional overturning circulation was observed in the second half of the twentieth century. Further reductions are
expected as a result of increased freshwater input in the Arctic and subArctic, increased stability of the surface mixed layer, reduction in salt flux, reduced ocean convection and less deepwater formation. This would have important consequences on the physical and biological components of the North Atlantic ecosystem.

- There is some evidence of increased upwelling intensity in recent decades in several areas (California, North West Africa and Arabian Sea), consistent with the hypothesis that global warming would lead to increased upwelling activity through intensification of alongshore wind stress. However, an alternative hypothesis suggests that different pole-equator warming and increased stratification would counteract this effect. Low-resolution ecosystem simulations indicate that there is no clearly discernable pattern of upwelling response to warming at the global scale, except within a couple of degrees of the equator, where a small reduction is expected.
- There are indications that upwelling seasonality may be affected by climate change, with important food web consequences.

4.1.4 Sea level rise
- Global average sea level has been rising at an average rate of 1.8 mm per year since 1961. The rate has accelerated since 1993 to about 3.1 mm per year. Higher rates in coming decades are likely. Sea level change is not geographically uniform, however, because it is controlled by regional ocean circulation processes.
- The largest losses expected from sea level rise are likely to be on the Atlantic and Gulf of Mexico coasts of the Americas, the Mediterranean, the Baltic and small-island regions.
- Intertidal and coastal wetland habitats may be substantially reduced in the future as a result of sea level rise.

4.1.5 Acidification and other chemical properties
- Surface seawater pH has decreased by 0.1 units in the last 200 years. Model estimates predict further reduction of 0.3 to 0.5 pH units over the next 100 years.
- Biological impacts of ocean acidification are uncertain because sensitivities at individual and population level are unknown. However, they are expected to be severe for shell-borne organisms, tropical coral reefs and cold water corals in the Southern Ocean.
- The oxygen concentration of the ventilated 100 to 1 000 m of the world’s ocean has been decreasing since 1970, driven by a reduced rate of renewal of intermediate waters.
- Global warming is likely to decrease nutrient supply to surface waters due to increased stratification.

4.1.6 Atmosphere-ocean and land-oceans exchanges
- Land-use change has significant hydrological impacts with consequences for ecosystem production, including changes in sediment loads, water flows (through damming) and physico-chemical consequences (hypoxia, stratification and salinity changes). The consequences of these processes cannot be generalized. However, they are known to impact community composition, production and seasonality processes in plankton and fish populations.
- The above will put additional pressure on inland fish and land-based, water intensive, food production systems (e.g. rice), particularly in developing countries.
4.1.7 Low frequency climate variability patterns

- Some studies indicate an increase in the intensity and frequency of particular atmospheric patterns (e.g. NAO, ENSO), but in general climate models predict a rather spatially uniform warming trend throughout the ocean basins combined with the continued presence of decadal variability similar to that of the twentieth century.
- Atmospheric patterns can have strong teleconnections within individual ocean basins, but between-basin teleconnections and potential climate-driven biological synchrony over several decades, are usually much weaker.

4.2 Observed effects of climate variability and change on ecosystem and fish production processes

4.2.1 Summary of physiological, spawning and recruitment processes sensitive to climate variability

- Organisms have specific ranges of environmental conditions to which they are adapted and within which they perform optimally. Physiological performance, often related to tissue metabolic oxygen demands, may degrade and cause stress at conditions (e.g. temperatures) which may be considerably below lethal limits.

4.2.2 Primary production

- Satellite observations suggest a 6 percent reduction in global oceanic primary production between the early 1980s and the late 1990s, but with substantial regional differences. For example, chlorophyll in higher latitudes has increased in the last 20 years, followed by a change in the relative dominance of diatoms over small phytoplankton.
- Increased vertical stratification and water column stability in oceans and lakes is likely to reduce nutrient availability to the euphotic zone and thus primary and secondary production in a warmed world. However, in high latitudes the residence time of particles in the euphotic zone will increase, extending the growing season and thus may increase primary production. Overall, a small global increase in primary production will be expected, with very large regional differences.
- Climate warming should lead to a contraction of the highly productive marginal sea ice biome and the seasonally stratified subtropical gyre, and an expansion of the low productivity permanently stratified subtropical gyre biome and the subpolar gyre biome.
- Simulations suggest that under global warming, the onset of the diatom spring bloom could be delayed and its peak biomass reduced. Changes in the dominant phytoplankton group appear possible.
- In general terms, in high-latitude or high-altitude lakes, atmospheric warming leads to reduced ice cover, warmer water temperatures, a longer growing season and, as a consequence, increased algal abundance and productivity. In contrast, some deep tropical lakes are experiencing reduced algal abundance and declines in productivity, likely as a result of reduced resupply of nutrients.
- The intensification of hydrological cycles is expected to influence substantially limnological processes. In general, increased run-off, discharge rates, flooding area and dry season water level may boost productivity at all levels (plankton to fish). Changes in the timing of floods may trigger production at the wrong time and flush biological production out of its habitat.

4.2.3 Secondary production

- There are no global assessments of the potential impacts of climate change on oceanic secondary production. Results tend to be dominated by local or regional conditions, although this is an area of active research (e.g. Mackas and Beaugrand, 2008).
However, regional results suggest that climate change effects may be more evident in the structure of zooplankton communities than in its total biomass.

### 4.2.4 Distributional changes
- Climate change is expected to drive most terrestrial and marine species ranges toward the poles, expanding the range of warmer-water species and contracting that of colder-water species.
- Observations of distributional changes consistent with the above have been recorded in, among others, the North Sea, the North Atlantic and the North American east and west coasts for copepods, demersal invertebrates, intertidal organisms and fish species. The most rapid changes in fish communities occur with pelagic species, and include vertical movements to counteract surface warming.
- The timing of many animal migrations has followed decadal trends in ocean temperature, being later in cool decades and up to one to two months earlier in warm years.

### 4.2.5 Abundance changes
- Populations at the poleward extents of their ranges tend to increase in abundance with warmer temperatures, whereas populations in more equatorward parts of their range tend to decline in abundance as temperatures warm.
- Increased growth rates in response to increased temperatures are only achieved when food supply is adequate to these increased demands.

### 4.2.6 Phenological changes
- More than half of all terrestrial, freshwater or marine species studied have exhibited measurable changes in their phenologies over the past 20 to 140 years. These were systematically and predominantly in the direction expected from regional changes in the climate.
- Observations in the North Sea indicate that plankton community structure is changing: dinoflagellates have advanced their seasonal peak in response to warming, while diatoms have shown no consistent pattern of change because their reproduction is triggered principally by increases in light intensity.
- Observations in many European and North American lakes suggest that the spring phytoplankton bloom has advanced due to warming but that zooplankton has not responded similarly, and their populations are declining because their emergence no longer corresponds with high algal abundance. There is concern that marine and freshwater trophodynamics may have already been radically altered by ocean warming through predator-prey mismatch.

### 4.2.7 Species invasions and diseases
- There is little evidence in support of an increase in outbreaks of disease linked to global warming, although spread of pathogens to higher latitudes has been observed.
- Harmful algal blooms seem to be more common, but whether this is caused by climate change is unclear. The expected change in the ratio of diatoms to dinoflagellates in a warming ocean may also play a role.
- Extinction risks due to climate change are possible, but there are no known examples yet. Evolutionary adaptations will occur, although on time scales and with characteristics that may be species-dependent.

### 4.2.8 Food web impacts from zooplankton to fish
- Climate change is likely to affect ecosystems and their species both directly and indirectly through food web processes. Whether direct or indirect processes
4.2.9 *Regime shifts and other extreme ecosystem events*

- It is increasingly appreciated that one of the mechanisms through which climate variability and change interact in affecting ecosystem dynamics is through non-linear “regime shifts”. The sensitivity of ecosystems to amplify climatic signals suggests that gradual (or even stochastic) changes in climate can provoke sudden and perhaps unpredictable biological responses as ecosystems shift from one state to another.
- Regime shifts have been observed in the North Atlantic and North Pacific oceans, among others, affecting productivity and species dominance in the pelagic and demersal domains.

4.3 *Scenarios of climate change impacts on fish production and ecosystems*

- General impacts on marine and aquatic systems as a result of large-scale changes related to temperature, winds and acidification can be predicted, in some cases with a high degree of confidence.
- At “rapid” time scales (a few years) there is high confidence that increasing temperatures will have negative impacts on the physiology of fish because of limited oxygen transport to tissues at higher temperatures. This physiological constraint is likely to cause significant limitations for aquaculture. These constraints on physiology will result in changes in distributions of both freshwater and marine species, and likely cause changes in abundance as recruitment processes are impacted. Changes in the timing of life history events are expected with climate change (high confidence). Short life span, rapid turnover species, for example plankton, squid and small pelagic fishes, are those most likely to experience such changes.
- At intermediate time scales (a few years to a decade), temperature-mediated physiological stresses and phenology changes will impact the recruitment success and therefore the abundances of many marine and aquatic populations (high confidence). These impacts are also likely to be most acute at the extremes of species’ ranges and for shorter-lived species. Changes in abundance will alter the composition of marine and aquatic communities, with possible consequences for the structure and productivity of these marine ecosystems. Predicting net community impacts (e.g. total biomass or productivity) has intermediate confidence because of compensatory dynamics within functional groups. Increasing vertical stratification is predicted for many areas, and is expected to reduce vertical mixing and decrease productivity (intermediate confidence). It will drive changes in species composition.
- At long time scales (multidecadal), predicted impacts depend upon changes in net primary production in the oceans and its transfer to higher trophic levels. Models show high variability in their outcomes so any predictions have low confidence. Regional predictions may have improved confidence because of better knowledge of the specific processes involved. Most models show decreasing primary production with changes of phytoplankton composition to smaller forms, although with high regional variability.
- Considerable uncertainties and research gaps remain, in particular the effects of synergistic interactions among stressors, extrapolating beyond historical conditions, reduced ecosystem resilience to climate variability as a result of changes caused by fishing, the locations and roles of critical thresholds and the abilities of marine and aquatic organisms to adapt and evolve to the changes.
Regarding freshwater systems, there are specific concerns over changes in timing, intensity and duration of floods, to which many fish species are adapted in terms of migration, spawning and transport of spawning products as a result of climate change. It is important to develop management systems capable of addressing the needs for fresh water by fish and land-based food production systems (e.g. rice) in the context of climate change, particularly in developing countries.

Anticipated responses of regional ecosystems to climate change are expected to include:

**Arctic**

Physical changes:
- 5 °C increase in air temperature;
- 6 percent increase in precipitation;
- 15 cm rise in sea level;
- 5 percent increase in cloud cover;
- 20 day reduction in sea ice duration;
- 20 percent reduction in winter ice with substantial ice-free areas in summer.

Ecological consequences:
- primary production increased two to five times over present conditions;
- reduced ranges of cold water fish and benthic species, but expanded ranges of Atlantic and Pacific species northwards;
- long-lived Arctic species with narrow temperature tolerances and late reproduction are likely to disappear from southerly habitats;
- changes to migration timing and increases in growth rates;
- non-native species are likely to increase in Arctic waters;
- extinction of any present Arctic fish species unlikely.

**North Atlantic**

Northeast Atlantic

Physical changes:
- future climate change impacts in the North Atlantic are likely to continue to vary with the state of the North Atlantic Oscillation;
- sea temperatures in the North Sea, Nordic seas and Barents Sea are likely to increase by 1 to 3 °C over the next 50 years, with largest changes in the northernmost regions;
- increased wind-induced fluxes of warm Atlantic waters into these northern regions;
- increased vertical stratification;
- reduced ice cover.

Ecological changes:
- primary production likely to increase in the Barents Sea;
- zooplankton production likely to decrease as production by Arctic zooplankton declines;
- northward shifts in the distributions of all species;
- increased biomass production of species in Arcto-boreal regions;
- fish species from south of the North Sea likely to appear in the North Sea;
- spawning areas for capelin in the Barents Sea likely to shift eastwards;
- North Sea dominated by pelagic species such as herring and mackerel in the north, and sardine and anchovy in the south, although the total system productivity may not be too different than today;
- Baltic Sea is predicted to become warmer and fresher, with significant increases in its vertical stratification;
• in the Baltic, exclusion of marine-tolerant species in favour of species more tolerant of low salinities;
• non-native species may enter the Baltic, but few are expected to be able to colonise because of the salinity stress.

Northwest Atlantic
• predictions of distributions and migration changes similar to Northeast Atlantic;
• populations at their range limits will be most affected;
• in some locations and at some times, decreased temperatures may occur as a result of increased glacial melting in Greenland. This may provide refuges for some cold water species, or may provide lethal cold shocks to other species such as Atlantic cod;
• species adapted to cool and narrow temperature conditions, such as Atlantic salmon, may be extirpated from their present habitats.

Atlantic cod:
• cod survival in simulations of Gulf of Maine declined with increasing temperatures which offset their increases in growth;
• in middle range in the Northwest Atlantic, capelin (*Mallotus villosus*) are important prey of cod, but spawning times for capelin are susceptible to delays due to cold water from melting glaciers;
• in Northeast Atlantic, model simulations suggest increasing temperatures in North Sea will cause declines in cod populations.

North Pacific
• anthropogenic warming in 30 to 50 years likely to be as large as natural climate variability today;
• climate-ecosystem-fisheries relationships developed during the latter half of the twentieth century may not be resilient to the new conditions in the twenty-first century;
• Pacific Decadal Oscillation pattern of decadal variability will continue into the twenty-first century, but will occur on top of persistent upward trend in sea surface temperature;
• changes in mixed layer depths (shoaling) and temperature (increasing);
• subpolar planktonic system change from strong variability and winter lows to more constant annual values and decreased yearly-averaged primary productivity;
• other areas (e.g. coastal) may experience higher growth rates as temperatures warm;
• in the North West Pacific, expect warmer conditions to cause changes in seasonal patterns of primary production;
• northward shifts of fish populations are predicted for west coast of North America;
• Pacific sockeye salmon may be restricted to Bering Sea;
• Bering Sea: extensive retreat of sea ice, losses of cold-water species and increasing abundances of species from the North Pacific;
• North Pacific is sensitive to the effects of increasing acidification, and likely to become under-saturated in aragonite from the surface to bottom;
• various species are negatively impacted by low pH concentrations.

Wind-driven coastal upwelling systems
• responses to global warming of coastal wind systems that drive upwelling ecosystem are contradictory;
Climate change implications for fisheries and aquaculture – Overview of current scientific knowledge

if alongshore wind stress increases coastal upwelling, this would offset in these regions the global trend of increasing water temperatures and increasing vertical stratification;

• other model studies predict decreasing upwelling-favourable winds;
• global models of primary production responses to warmer conditions are contradictory. In the Pacific, the model of Sarmiento et al. (2004) showed no consistent global response of upwelling regions to climate change;
• intensified Benguela upwelling may increase nutrient inputs, primary production and low-oxygen events. Such may also occur in other upwelling systems;
• there is considerable local variability among systems which makes generalizations difficult.

Tropical and subtropical seas

• highly diverse habitats and biology; poorly studied;
• not resolved whether tropical Pacific will become more “El Niño-like” (east-west gradient in SST is reduced), or more “La Niña-like” character (increased east-west SST gradient);
• primary production in the tropical Pacific expected to decline because of increased stratification and decreased nutrient supply;
• combined effects of changes in circulation, temperature, nutrients, primary production cascade up the food web to influence prey availability and habitat conditions for tuna;
• tuna habitat conditions east of the date line could improve, similar to El Niño-events;
• for waters of Australia and New Zealand, greatest impacts likely on coastal species and subtidal nursery areas, temperate endemic species rather than tropicaals and coastal and demersal species rather than pelagic and deep-sea species;
• models for Australia predict physical changes similar to other regions: ocean warming, increased vertical stratification, strengthening of poleward coastal currents, increasing ocean acidification, sea level rise and altered storm and rainfall regimes;
• warming and increasing stratification will alter plankton community composition, alter their distributions polewards and change the timing of their bloom dynamics so that transfers to higher trophic levels may be impaired;
• benthic and demersal fishes will shift their distributions southward and may decline in abundance. Pelagic species will also shift their distributions southwards and some species may benefit from increased local wind-driven upwelling (e.g. anchovies).

Coral reef systems

• at risk from climate change impacts related to increasing temperatures, acidity, storm intensity and sea levels and non-climate factors such as overexploitation, non-native species introductions and increasing nutrient and sediment loads;
• risks to coral reefs not distributed equally: increasing temperatures significant issue for warm-water systems; increasing acidity and decalcification a significant issue for both warm- and cold-water systems; direct human impacts a significant issue in more populous regions;
• three different time scales can be identified for climate change-related impacts to coral reef systems:
  – years: increased temperature effects on coral bleaching;
  – decades: increasing acidification and dissolution of carbonate structures of reefs;
- multidecades: weakening of structural integrity of reefs and increasing susceptibility to storms and erosion events.
- increasing acidity (decreasing pH) is a significant and pervasive longer-term threat to coral reefs. Potential for coral reef systems to adapt to these environmental stresses is uncertain: symbiotic zooxanthellae may adapt to be more tolerant of high temperatures. Migrations of corals to higher latitudes is unlikely;
- declines in corals had negative impacts on reef fish biodiversity in at least one study, however, to date there is little evidence for a link between climate warming and bleaching events with impacts on coastal fisheries.

**Freshwater systems**
- freshwater lakes and their ecosystems are highly vulnerable to climate change;
- paleo records show the shapes and distributions of lakes can change and they can disappear entirely with shifting dynamics among precipitation, evaporation and runoff;
- anticipated response is for cold-water species to be negatively affected, warm-water species to be positively affected and cool-water species to be positively affected in the northern, but negatively affected in the southern parts of their range;
- general shift of cool- and warm-water species northward is expected in North America and likely the rest of the Northern Hemisphere;
- responses of particular lake ecosystems to climate change depend on size, depth and trophic status of the lake;
- modelling studies concluded cold-water fish would be most affected because of losses of optimal habitats in shallow, eutrophic lakes;
- growth conditions for cool- and warm-water fishes should improve in well-mixed lakes, small lakes and those with oligotrophic nutrient conditions;
- rates of change of freshwater systems to climate will depend on ability of freshwater species to “move across the landscape”, i.e. use of dispersal corridors;
- most affected are likely to be fish in lowland areas that lack northward dispersal corridors, and cold-water species generally;
- river ecosystems are particularly sensitive to changes in the quantity and timing of water flows, which are likely to change with climate change;
- changes in river flows may be exacerbated by human efforts to retain water in reservoirs and irrigation channels;
- abundance and species diversity of riverine fishes are particularly sensitive to these disturbances, since lower dry season water levels reduce the number of individuals able to spawn successfully and many fish species are adapted to spawn in synchrony with the flood pulse to enable their eggs and larvae to be transported to nursery areas on floodplains.

**Aquaculture systems**
- direct impacts include changes in the availability of freshwater, changes in temperature, changes in sea level, and increased frequencies of extreme events (such as flooding and storm surges);
- indirect effects include economic impacts, e.g. costs and availability of feed;
- negative impacts include (Table 4):
  - stress due to increased temperature and oxygen demands;
  - uncertain supplies of freshwater;
  - extreme weather events;
  - sea level rise;
  - increased frequency of diseases and toxic events;
  - uncertain supplies of fishmeal from capture fisheries.
positive impacts of climate change on aquaculture include increased food conversion efficiencies and growth rates in warmer waters, increased length of the growing season, and range expansions polewards due to decreases in ice;
• increased primary production would provide more food for filter-feeding invertebrates;
• may be problems with non-native species invasions, declining oxygen concentrations, and possibly increased blooms of harmful algae;
• local conditions in traditional rearing areas may become unsuitable for many traditional species;
• temperature stress will affect physiological processes such as oxygen demands and food requirements;
• increased food supplies are needed for aquaculture activities to realise benefits from increased temperatures;
• freshwater aquaculture activities will compete with changes in availability of freshwater due to agricultural, industrial, domestic and riverine requirements, as well as changes in precipitation regimes;
• increases in precipitation could also cause problems such as flooding;
• sea level rise also has the potential to flood coastal land areas, mangrove and sea grass regions which may supply seed stock for aquaculture species.
References


Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture


