Impacts of climate change on fisheries

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ABSTRACT

Evidence of the impacts of anthropogenic climate change on marine ecosystems is accumulating, but must be evaluated in the context of the "normal" climate cycles and variability which have caused fluctuations in fisheries throughout human history. The impacts on fisheries are due to a variety of direct and indirect effects of a number of physical and chemical factors, which include temperature, winds, vertical mixing, salinity, oxygen, pH and others. The direct effects act on the physiology, development rates, reproduction, behaviour and survival of individuals and can in some cases be studied experimentally and in controlled conditions. Indirect effects act via ecosystem processes and changes in the production of food or abundance of competitors, predators and pathogens. Recent studies of the effects of climate on primary production are reviewed and the consequences for fisheries production are evaluated through regional examples. Regional examples are also used to show changes in distribution and phenology of plankton and fish, which are attributed to climate. The role of discontinuous and extreme events (regime shifts, exceptional warm periods) is discussed. Changes in fish population processes can be investigated in experiments and by analysis of field data, particularly by assembling comparative data from regional examples. Although our existing knowledge is in many respects incomplete it nevertheless provides an adequate basis for improved management of fisheries and of marine ecosystems and for adapting to climate change. In order to adapt to changing climate, future monitoring and research must be closely linked to responsive, flexible and reflexive management systems.

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1. Introduction

1.1. Purpose of the paper

There is increasing concern over the consequences of climate change for fisheries production and the state of marine ecosystems. Climate change is an additional pressure on top of the many (fishing mortality, loss of habitat, pollution, disturbance, introduced species) which fish stocks already experience. This means that the impact of climate change must be evaluated in the context of other anthropogenic pressures, which often have greater and more immediate effects. The main aim of this paper is to assemble and analyse evidence of effects of climate on fisheries in order to (i) show that climate affects the distribution, productivity and resilience of fish stocks, (ii) develop our understanding of the processes, and (iii) draw lessons from past experience.

The scientific study of the impacts of climate change on fisheries has developed very rapidly, but is unevenly spread geographically and methodologically. Until the past decade or so the principal subject for investigation was the effect of climate variability (i.e. decadal and shorter variability) on recruitment, with related work on regime shifts and on distribution changes. The methods were principally statistical, applied to populations and environmental factors, with few experimental studies or process models. There is an extensive literature in some fields and very little in others. This paper presents a broad overview in terms of scale, processes, methodology and geography, but does not aim to review all available literature and information. The examples are selected to illustrate particular issues and to provide an entry to the wider literature, but are inevitably also influenced by personal knowledge. The following paragraphs introduce the terminology and topics covered in the rest of the paper and some of the major issues which arise from them.

1.2. Climate time-scales and terminology

The terminology used when discussing climate change and its impacts can be confusing. A wide range of timescales of change in the physical and chemical environment may be included in the term "climate". In this paper "climate variability" denotes changes in temperature, wind fields, hydrological cycles, etc. at annual to decadal time scales and "climate change" denotes longer-term shifts in the mean values. It is also important to distinguish between natural climate change, natural climate variability and anthropogenic changes, but it is by no means simple to distinguish the underlying causes of a particular observed effect (IPCC, 2003). Changes in the physical and chemical environment occur naturally on daily, seasonal, and longer term (e.g. 18.6 year nodal tide) cycles, which can be related

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to planetary motion. Natural variability in the environment overlays these cycles, so that one can, for example, speak of a windy month or a wet year. Underlying such statements is the idea of a "normal" month or year, which is generally defined in relation to a climatology, i.e. by using a long-term mean and distribution of the variable in question. Fig. 1 shows an example of such a climatology, based on a 60-year time series. It also shows that short term events need to be considered, even when dealing with climate. The "abnormal" summer temperatures shown in Fig. 1 lasted for a short time and may not have affected the annual mean temperature, but they had a major negative impact on salmon survival (Canadian Standing Committee on Fisheries and Oceans, 2005). Climate change may alter the frequency and intensity of extreme events, (floods, droughts, heat-waves, hurricanes), therefore although it is difficult to attribute any particular extreme event to anthropogenic climate change, a change in its likelihood of occurrence can be estimated (IPCC, 2003). It is very likely (>90% chance) that hot extremes, heat waves and heavy precipitation events will continue to become more frequent (IPCC, 2007).

At short time scales–less than 10 years–the anthropogenic component of climate change adds only a small increment, compared with normal variability. For example interannual variability in the sea surface temperature of the North Sea is of the order of 2–3 °C, whereas the expected annual anthropogenic increment in temperature is of the order of 0.02 °C (IPCC, 2007). Organisms therefore normally experience variability, which is large relative to the climate change effect. However, even though the year-on-year rate of anthropogenic climate change may seem slow, this is very rapid compared with previous natural change and the accumulative value produces a significant difference from the "natural" state quite quickly.

The emission scenarios from which future changes in climate are predicted and on which impact assessments are based are those used for the third assessment report of the IPCC (2001). The Atmosphere-Ocean Global Circulation Models (AOGCMs) which use these scenarios (IPCC, 2007) treat the marine environment and changes in ocean climate in a simplified way, which lacks some of the detail necessary for assessing impacts on marine ecosystems. This deficiency is gradually being overcome, but there is still some way to go in providing sufficient resolution for features such as changes in the position of ocean fronts, which may have major consequences for marine ecosystems. Progress with downscaling and regional modelling of ocean climate change will undoubtedly help to improve our ability to forecast likely consequences for ecosystems and fisheries.
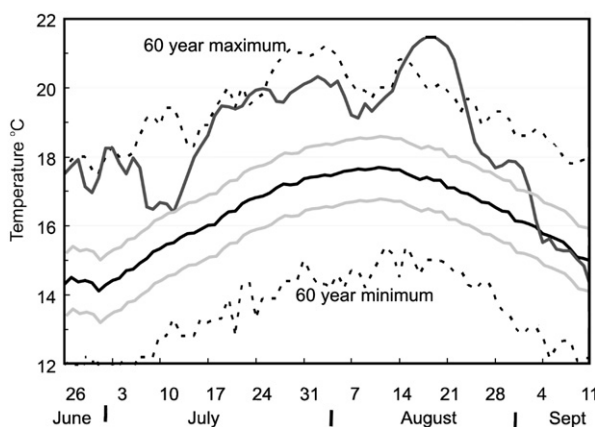

Fig. 1. Temperature profile at Hell's Gate (Fraser River, British Columbia) in 2004 (upper dark grey line), also showing 60-year mean (middle black line), ± 1 standard deviation (grey lines), and 60-year minimum and maximum (dashed black line). For several days in mid-August Fraser River water temperatures as measured at Hell's Gate were the highest ever recorded (from Canadian Standing Committee on Fisheries and Oceans, 2005).

1.3. Ascribing impacts to climate change and climate variability

Climate change has both direct and indirect impacts on fish stocks. Direct effects act on physiology and behaviour and alter growth, reproductive capacity, mortality and distribution. Indirect effects alter the productivity, structure and composition of the marine ecosystems on which fish depend for food. However many other factors, including fishing, biological interactions and non-climatic environmental factors can also have similar effects. When a change is ascribed to climate these other factors should also be evaluated and the degree of confidence in the ascription should be given.

Although our knowledge of the processes by which climatic and environmental factors affect fish at individual, population and ecosystem level remains far from complete, we are already able to observe some changes at all these levels, which can be confidently ascribed to climate variability and climate change. Examples of changes in distribution of fish and plankton are particularly striking because they are more rapid than the changes occurring in terrestrial fauna and flora (Beaugrand et al., 2002; Brander et al., 2003; Parmesan and Yohe, 2003).

Ocean climate is variable and there have been previous warm periods, notably from the mid-1920s to the 1960s in the North Atlantic (Jensen, 1939). The changes in species and ecosystems which took place then were very similar to those occurring now and we can use these past warm periods as analogues. However, these warm periods during the 20th century are examples of natural climate variability, whereas present climatic trends are expected to continue and conditions are moving outside the bounds of previous experience due to climate change. The trend will not be smooth and will continue to have large interannual and decadal variability superimposed on it (Sutton and Hodson, 2005; Smith et al., 2007). Decadal variability in ocean climate is one of the major causes of regime shifts (King, 2005), when the biology of large areas such as the North Sea (Beaugrand, 2004) changes quite rapidly to a different state (altered species dominance, production and seasonality). Understanding the way in which climate change may affect decadal and shorter time scale variability is therefore essential in predicting future climate impacts on marine ecosystems and fisheries.

Climate change and climate variability have occurred throughout history and natural systems have developed a capacity to adapt, which will help them to mitigate the impact of future changes. However two factors will limit this adaptive capacity in future (i) the rate of future climate change is predicted to be more rapid than previous natural changes and (ii) the resilience of species and systems is being compromised by concurrent pressures, including fishing (Planque et al., 2010-this issue), loss of biodiversity (including genetic diversity), habitat destruction, pollution, introduced and invasive species and pathogens.

2. Impacts of climate change on marine ecosystems and fisheries

New findings on climate change impacts on marine ecosystems and fisheries can be broadly divided into observational studies of past and current effects of climate change and modelling studies of future impacts. Some studies include both observation and modelling and some models are empirically based (i.e. they use functional relationships which are statistically derived from observations).

A number of books and major reports on climate impacts have been published recently and should be referred to for access to the wider scientific literature, particularly in relation to regional impact assessments. The ACACIA (2000) report, provided the European impact assessment for the IPCC Third Assessment (2001) and includes a chapter on Fisheries. The Arctic Climate Impact Assessment (http://www.acia.uaf.edu) includes chapters on Marine Systems (Loeng et al., 2005) and on Fisheries and Aquaculture (Vilhjalmsson et al., 2005). Effects of climate change on the North Atlantic are reviewed in Stenseth et al. (2004) and the North Atlantic Oscillation (NAO) is treated in more detail in Hurrell et al. (2003) and Hurrell and Deser

(2010–this issue). For the North Pacific the state of the marine ecosystem and the effects of regime shifts were reviewed by PICES (2004) and King (2005).

There is now a wealth of evidence of impacts of recent climate change on distribution, species composition, seasonality and production in marine and freshwater systems. A small selection from the large number of recent papers which analyse climate effects on a variety of taxa includes: phytoplankton (Richardson and Schoeman, 2004), global primary production (Gregg et al., 2003; Schmittner, 2005), krill in the Southern Ocean (Atkinson et al., 2004), plankton in the North Atlantic (Edwards and Richardson, 2004; Richardson and Schoeman, 2004), tropical tuna (Lehodey, 2001; Lehodey et al., 2003), sardine and anchovy in Eastern Boundary currents (Jacobson et al., 2001; McFarlane et al., 2002; Chavez et al., 2003) and fish species in North European shelf seas (Attrill and Power, 2002; Brander et al., 2003; Perry et al., 2005).

2.1. Changes in global marine primary production—models and observations

Modelling is a necessary tool for assessing future impacts of climate change. A major comparative study (Sarmiento et al., 2005) simulated the effect of greenhouse gas emissions using six Atmosphere-Ocean Global Circulation Models (AOGCMs) to examine which aspects of the models determine how ocean biology responds to climate. The study compared "realistic" emission scenarios for the period from pre-industrial to 2050 and 2090 with a control in which emissions remained at pre-industrial levels. The three groups of factors which govern the biological response are: (i) warming, (ii) light, as determined by ice cover, cloudiness and surface mixed-layer thickness, and (iii) altered nutrient supply due to changed vertical stability and nutrient flux. Predicted climate induced alterations in nutrient supply and production are predominantly negative, due to reduced vertical mixing. In high latitude regions the resultant increased stability of the water column may, however, have a positive effect on production in spite of reduced nutrient supply because phytoplankton will no longer be mixed down to depths greater than their compensation depth (the depth at which respiration loss exceeds photosynthetic gain) (Behrenfeld et al., 2006).

Primary production in the comparative modelling study (Sarmiento et al., 2005) was estimated using empirical models for a set of seven biomes (marginal sea ice; subpolar; subtropical seasonally stratified; subtropical permanently stratified; low latitude upwelling; tropical upwelling, tropical downwelling), which are further subdivided into a total of 33 biogeographical provinces resembling those of Longhurst (1998). A small global increase in marine chlorophyll and primary production is predicted (<10%) for 2050 and 2090, compared with the pre-industrial control scenario, but with quite big regional differences. Decreases in the North Pacific and the area adjacent to the Antarctic continent are slightly more than offset by increases in the North Atlantic and the open Southern Ocean.

The outcome of these simulations is uncertain, but very useful in identifying the major areas and causes of uncertainty. The most robust part of the outcome is the change in biome areas, with reductions in the marginal sea–ice biome and increases in the permanently stratified subtropical gyre biome. On the other hand the critical factor in determining the change in primary production seems to be the temperature sensitivity of primary production for a given chlorophyll level. This in itself determines whether primary production increases or decreases at low latitudes and whether there would be no change or quite large increases in primary production at high latitudes. Temperature sensitivity of primary production is therefore clearly an important subject for further measurement and theoretical work.

Another recent study which combines modelling with empirical evidence looks at the consequences for global primary productivity of a weakening of the Atlantic Meridional Overturning Circulation (AMOC) and concludes that a 50% reduction in North Atlantic primary production and 20% reduction in global carbon export production is

possible and was actually a feature of previous ice ages (Schmittner, 2005). Although the conclusions from these two studies appear to be very different, the results are probably compatible with each other when differences in time scales and processes are taken into account. In the Schmittner model, the spin-down time in AMOC is relatively slow, occurring over a period of 500 years, but there is evidence that changes can be more rapid (Cubash et al., 2001) and that reduction in meridional overturning may have begun in both the North Atlantic (Curry and Mauritzen, 2005) and the North Pacific (McPhaden and Zhang, 2002). Based on current model simulations it is very likely (i.e. >90% chance) that the AMOC will slow down during the 21st century (IPCC, 2007). Since even partial shutdown of the AMOC may result in substantial reduction of productivity, it is evident that the causes, likelihood and consequences merit close scrutiny (Kuhlbrodt, 2006).

Satellite observations of ocean chlorophyll indicate that global ocean annual primary production has declined by more than 6% since the early 1980s (Gregg et al., 2003). Global blended chlorophyll seasonal climatologies were used as inputs to the Vertically Generalized Production Model or VGPM (Behrenfeld and Falkowski, 1997) to compute seasonal ocean primary production. Nearly 70% of the global decline occurred in the high latitudes. In the northern high latitudes, these reductions in primary production corresponded with increases in sea surface temperature and decreases in atmospheric iron deposition to the oceans, i.e. the processes involve both direct and indirect effects on nutrient supply. In the Antarctic, the reductions were accompanied by increased wind stress. Note that these declines in primary production at high latitude have been offset by increases at low latitudes and that three of the four low latitude basins exhibited decadal increases in annual primary production.

2.2. Consequences of changes in primary and secondary production for future fisheries production

Changes in primary and secondary production will obviously have a major effect on fisheries production, but the complexity of the trophic systems leading from primary production to fish makes it difficult to establish reliable predictive relationships. Nevertheless, some progress has been made (Iverson, 1990; Ware and Thompson, 2005; Frank et al., 2006) and Jennings and Brander (2010-this volume) make some proposals for relating primary production to fish community production, rather than by trying to incorporate individual species dynamics.

Although global aggregated marine primary production is not expected to change substantially over the next 4 or 5 decades, there is a stronger basis for predicting changes in production at regional level and also good observational evidence, particularly for the North Pacific and North Atlantic. In both cases changes in production are driven mainly by regime-scale and event-scale (e.g. El Niño) changes. These are important components of the climate system whose predictability and impacts we are rapidly coming to understand. Further improvements in modelling and in monitoring at these time scales, with better resolution of regional impacts, is likely to yield great benefits to fisheries forecasting and management. To a certain extent this could resemble what is already occurring in agriculture (e.g. seasonal prediction of rainfall for marginal drought affected areas allows planting of appropriate crop varieties), but the differences are substantial, since there is no control of varieties or of other factors influencing production in "wild" capture fisheries[1].

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[1] The balance between capture fisheries and aquaculture is changing rapidly. World capture production of fish, crustaceans and molluscs in 2003 was more than twice the quantity of aquaculture, but capture production has decreased by nearly 5% since 1997, whereas aquaculture has increased by nearly 50%. Aquaculture resembles terrestrial animal husbandry more than it does capture fisheries and there will therefore be increased scope for human intervention to adapt to climate change.

In the Arctic Ocean, the reduction in ice cover will allow light to penetrate in new areas and therefore increase the productive area, but the retreat of the highly productive marginal sea–ice zone will disrupt the existing food web. In the "new" ice-free areas of the Arctic Ocean production is likely to be limited by nutrient supply due to the increased freshwater input from Arctic rivers. This will increase vertical stratification and hence reduce the vertical flux of nutrients. The riverine input is also nutrient poor. Some consequences of expected changes in the Arctic are set out in the report of the Arctic Climate Change Impact Assessment (Loeng et al., 2005; Vilhjalmsson et al., 2005).

Qualitative changes in production may have major impacts on food chains leading to fish regardless of changes in the absolute level of primary production. Examples of this include the observed switch from krill to salps as the major nektonic species in parts of the Antarctic (Atkinson et al., 2004) and the ascendance of gelatinous species to a dominant position in areas such as the Black Sea (Daskalov, 2002). In the former case climate change was probably a major factor, but in the latter it was not.

2.3. Regional examples of the consequences of changes in primary production

2.3.1. North Atlantic

A study based on over 100,000 plankton samples collected between 1958 and 2002 with the Continuous Plankton Recorder (CPR) (Richardson and Schoeman, 2004) showed an increase in phytoplankton abundance in the cooler regions of the Northeast Atlantic (north of 55°N) and a decrease in warmer regions (south of 50°N). The likely explanation for this apparently contradictory result is that although both areas have undergone warming over this period, with consequent reduction of vertical mixing, the nutrient supply in the cooler, more turbulent regions remains sufficient and plankton metabolic rates benefit from the increased temperature. In the warmer regions reduced supply of upwelled nutrients limits production. The effects of these changes in phytoplankton propagate up through herbivores to carnivores in the plankton food web (bottom-up control), because of tight trophic coupling. Similar effects may be expected for other mid-latitude pelagic ecosystems in which vertical mixing is influenced by warming, because the proposed mechanisms, involving alterations in nutrient supply, are general.

Another study based on the CPR attributed the observed decadal variability in phytoplankton biomass in the Northeast Atlantic to climate forcing, as expressed by the NAO (Edwards et al., 2001). In the North Sea this resulted in a shift in seasonal timing of the peak in phytoplankton colour from April to June which may have been accompanied by a taxonomic shift from diatoms to dinoflagellates, with consequences in terms of palatability for the food webs dependent on them.

2.3.2. Tropical Pacific

The tuna species skipjack (*Katsuwonus pelamis*) and yellowfin (*Thunnus albacares*) are among the top predators of the tropical pelagic ecosystem and produced a catch of 3.6 million tons in 2003, which represents approximately 5.5% of total world capture fisheries in weight and a great deal more in value. The catches and distribution of these species and other tuna species (e.g. albacore, *Thunnus alalunga*) are governed by variability in primary production and location of suitable habitat for spawning and for adults, which in turn are linked to varying regimes of the principal climate indices El Niño–La Niña Southern Oscillation Index (SOI) and the related Pacific Decadal Oscillation (PDO). The tropical tuna species, skipjack and yellowfin have higher recruitments during El Niño events, whereas the subtropical albacore has low recruitment during El Niño and high recruitment during La Niña. Both statistical and coupled biogeochemical models have been developed to explore the causes of regional variability in catches and their connection with climate (Lehodey, 2001; Lehodey et al., 2003). The model area includes the Pacific from 40°S to 60°N and includes the Kuroshio extension east of Japan. This is one of the best examples linking processes and scales from climate related upwelling and primary production to large geographic regions and decadal regime shifts. The model captures the slowdown of Pacific meridional overturning circulation and decrease of equatorial upwelling, which has caused primary production and biomass to decrease by about 10% since 1976–77 in the equatorial Pacific (McPhaden and Zhang, 2002).

2.3.3. Antarctic

Antarctic krill (*Euphausia superba*) is among the most abundant animal species on earth, providing the main food supply for fish, birds and whales. They have declined since 1976 in the high latitude SW Atlantic sector, probably due to reduction in winter sea–ice extent around the western Antarctic Peninsula (Atkinson et al., 2004). Krill are dependent on the highly productive summer phytoplankton blooms in the area east of the Antarctic Peninsula and south of the Polar Front. Salps, by contrast, which occupy the extensive lower-productivity regions of the Southern Ocean and tolerate warmer water than krill, have increased in abundance. These changes have had profound effects within the Southern Ocean food web. Penguins, albatrosses, seals and whales have wide foraging ranges but are prone to krill shortage. Thus the wide areal extent of change in krill density–not just its magnitude–is important.

2.3.4. Lake Tanganyika

A further example of changed productivity probably due to alteration of nutrient supply comes from Lake Tanganyika (O'Reilly et al., 2004). Although this is a freshwater example, it is included because it illustrates the same mechanisms that affect marine systems, but the bounded nature of a lake makes it easier to show the consequences for fisheries production than can be done for marine systems with their open boundaries. A decrease in primary production by about 20% over the past 80 years can be inferred from a combination of historical and palaeolimnological data. Surface temperature has been rising during this period and wind speed has been falling, which combine to reduce the nutrient supply to the shallower surface mixed layer. The lake has historically supported one of the world's most productive pelagic fisheries, which provided an annual harvest in recent years of between 165,000 and 200,000 metric tons, representing 25–40% of animal protein supply for the populations of the surrounding countries. A 30–50% 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 15–20 years. 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.

2.4. Regional examples of changes in distribution and phenology of plankton and fish

There are many examples of distribution changes in marine ecosystems throughout the world (Cushing, 1982; Beare et al., 2002; Beaugrand et al., 2002) and abundant evidence that they occur much more rapidly in marine than in terrestrial systems (Rosenzweig et al., 2007). The planktonic ecosystem is dependent on the properties and movement of the water in which it exists, and is intrinsically mobile. The life cycles of most marine fish have a planktonic phase, which often involves transport over long distances. The potential for rapid distribution change is therefore inherent, but requires favourable

conditions for survival, particularly if the developing juveniles settle to the bottom.

Survival of fish larvae during the planktonic stage is thought to depend strongly on the availability of sufficient suitable food (match–mismatch hypothesis). Therefore in addition to effects of changes in production, described in the previous section, climate-induced changes in distribution and phenology of fish larvae and their prey can also affect recruitment and production of fish stocks.

2.4.1. North Sea

Calanus finmarchicus has declined throughout much of the North Atlantic since 1958 due to warming and changes in the extent of cold, deep water masses in which the species overwinters (Beaugrand et al., 2002). In the North Sea it has been largely replaced by a southern congener *C. helgolandicus* (Beare et al., 2002), but there have also been substantial changes in phenology, which affect trophic interactions, food web structure and ecosystem functioning (Edwards and Richardson, 2004). This has consequences for plankton predator species, including fish, whose life cycles are synchronised to the seasonal production of particular prey species. The survival of young cod in the North Sea appears to depend on the abundance, seasonal timing and size composition of their prey. Changes in all of these since 1958 resulted in increased survival and good recruitment of cod throughout the 1960s and 1970s and then a progressive decline over the past 30 years (Beaugrand et al., 2003). Although the processes can as yet only be sketched, rather than unequivocally determined, there is good evidence that climate changes related to the North Atlantic Oscillation (NAO) are behind many of the observed changes in plankton production, phenology and fisheries. For example, the decline of the European cod stocks due to overfishing has been exacerbated by climate induced changes in plankton production and these stocks are no longer able to provide as much surplus for the fishery as in the 1960s and 1970s. As the stocks of cod have declined, they have become more sensitive to the effects of the climate indicator (the NAO), due to shrinkage of the age distribution and geographic extent (Brander, 2005; Planque et al., 2010-this issue).

2.4.2. Baltic

Calanus spp. are virtually absent from the Baltic but the copepod *Pseudocalanus elongatus* is a key species and a major food organism for fish larvae and adult pelagic planktivorous fish. Recent work shows that the species is *P. acuspes*, rather than *P.elongatus* (Renz et al., 2006). Large interannual and interdecadal changes in the hydrographic environment of the Baltic, in particular the decreasing salinity of the deep basins, are thought to be responsible for fluctuations in the standing stock of *P. elongatus* (Möllmann et al., 2000). This has an effect on the diet and condition of herring, resulting in large fluctuations in the growth rate of herring between 1977 and 1998 (Möllmann et al., 2003a). It also affects the stock dynamics of cod in the Baltic (Möllmann et al., 2003b). Variability in the seasonal timing and spatial distribution of zooplankton and cod larval production has significant consequences for survival of cod larvae and subsequent recruitment (Hinrichsen et al., 2002; Köster et al., 2003). The decadal changes in temperature and salinity in the Baltic, which cause these changes in the fish stocks, can in turn be linked to the regional climate indicators such as the NAO and in turn to global climate (Hänninen et al., 2000; Schrum, 2001; Meier et al., 2006). However the shallow, complex topography of the Baltic and its entrances and the short timescales of the weather events which drive inflows make it very difficult to predict the frequency of future Baltic inflows (Meier et al., 2006). The decadal scale changes in ocean climate and biology which have recently taken place in the Baltic and in the North Sea are sufficiently abrupt and persistent to be described as regime shifts (Beaugrand, 2004; Alheit et al., 2005; Alheit and Bakun, 2010-this issue).

2.4.3. Warming of the North Atlantic from 1920 to 1945

Large-scale distribution shifts in marine ecosystems are a feature of Preanthropocene climate change and climate variability and can in this respect be regarded as "natural". Perhaps the best studied example of the effects of climate variability occurred during the period of warming which affected the North Atlantic from the mid-1920s to the 1940s and later in some areas. The effects of this "warming in the north" have been extensively described (Cushing, 1982; Brander, 2003) and the excellent literature dating back to the 1930s and 1940s shows how much attention was already being paid to climate effects 65 years ago (Jensen, 1939).

The history of cod stocks at Greenland is a particularly well documented case, which shows how rapidly a species can extend its range (at a rate of 50 km y^{-1}) and then decline again. It also shows how massive transport of juvenile stages from an adjacent viable population (at Iceland) can build up a stock. Surveys of pelagic juvenile cod larvae show that in 21 of the 26 years of surveys, over 5% of all juveniles produced at Iceland are transported across the Denmark Strait towards Greenland and the average is 17%. This gives a huge boost to the cod population at Greenland, but also benefits the Icelandic stock and fishery, because the maturing adults return to spawn at Iceland 6 or 7 years later. The return of the 1945 year class in 1953 represented an increment of 700,000 t of 8-year-old mature fish to the Icelandic stock (Schopka, 1993), worth over 1 billion US$. Following the decline of the Greenland cod stock due to a combination of overfishing and adverse environmental change in the late 1960s there are quite promising signs of recovery as the environment has once again become favourable for the survival of the juvenile cod supplied from Iceland.

A further intriguing step in the possible links between North Atlantic cod populations is the one from Greenland to Labrador and Newfoundland, across the Davis Strait (Dickson and Brander, 1993). The distance between these populations is no greater than from Iceland to Greenland and there is observational and indirect evidence that larvae from West Greenland are transported across (Begg and Marteinsdottir, 2000). The frequency of such population exchange is however low, because it requires a viable offshore spawning population at Greenland, as well as favourable oceanographic conditions for transport and survival (ICES, 2002).

The warm period from 1920 to 1945 provides a useful analogue when trying to predict the consequences of the recent warming trends (Brander, 2003). In some areas, such as southern Greenland, the decadal mean temperature has even now barely reached the levels experienced at that time and many of the changes now being observed in the marine fauna are the same as were observed then. Nevertheless, there are also substantial differences, which cannot be overlooked when making comparisons. In relation to cod and a possible recovery of the stock, the present day fishery (including bycatches in the shrimp fishery) are an additional source of mortality which was not acting in the 1920s and the population of predatory marine mammals around southern Greenland is also considerably greater now (ICES, 2006).

2.4.4. Recent warming along the European shelf-break

New evidence showing the northward spread of fish species along the European shelf appears quite frequently. The northern limits of a number of tropical and subtropical species have shifted northwards, particularly along the continental slope, at rates (50 km y^{-1}) which match the shifts recorded in plankton (Quero et al., 1998). Catches of southern immigrant species to the southwest of England have increased as the water temperature of the North Atlantic has risen from 1960 to 2001 (Stebbing et al., 2002). Detailed records in many areas show increases in populations of southern species either in absolute terms or relative to the abundances of similar northern species (Fig. 2, Brander et al., 2003; Beare et al., 2004; Perry et al., 2005). A search for counter-examples produces only one or two
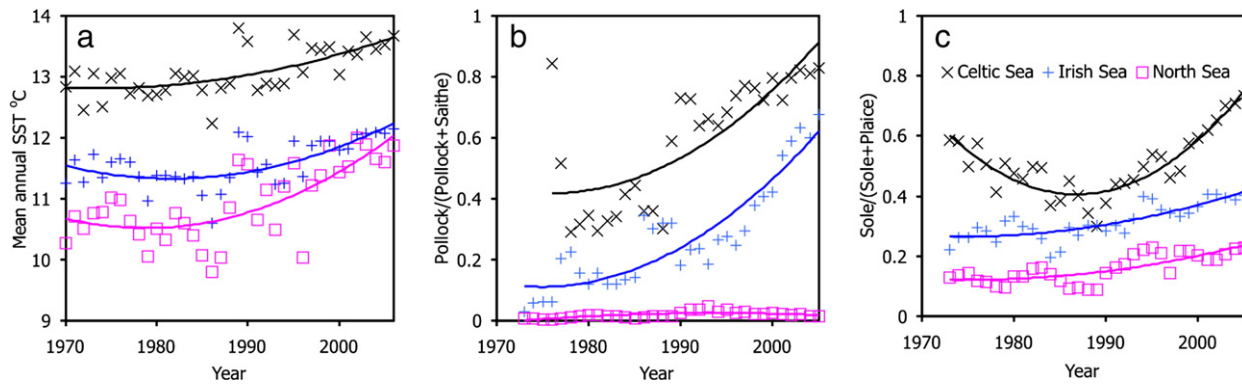
Fig. 2. Increasing abundance of southern species (Pollock, *Pollachius pollachius*, and sole, *Solea solea*) relative to similar northern species (saithe, *Pollachius virens*, and plaice, *Pleuronectes platessa*) as shown by catch ratios in the Celtic Sea, Irish Sea and North Sea.

(sardines off Portugal, haddock in the Irish Sea) which can generally be explained as resulting from local oceanographic anomalies produced by upwelling or by fisheries effects (Brander et al., 2003).

Very extensive information is available on large scale shifts in phenology and distribution of plankton, fish and marine mammals in the North Pacific, but since the observed changes are principally ascribed to regime shifts (i.e. episodic change) rather than gradual climate change, they are dealt with in the next section.

2.5. Regime shifts and their relation to climate change

The terms "regime" and "regime shift" have come into quite widespread use. A recent definition of "regime" (King, 2005) is:

"a period of several sequential years (often a decade or more) in which the state, or characteristic behavior, of the climate, the ocean conditions or an ecosystem is steady. It does not preclude year-to-year differences, but overall, the state of the system over the decades can be described as persistent, steady or "locked in". A regime shift refers to a relatively rapid change (occurring within a year or two) from one decadal-scale period of a persistent state (regime) to another decadal-scale period of a persistent state (regime)."

Regimes are a feature of natural climate change and are due to a combination of intrinsic variability of the atmosphere and ocean and forcing influences from other geographic areas (teleconnections). The processes causing regime shifts and the relationship between regimes and anthropogenic climate change are not well understood (Hsieh et al., 2005). Biological regime shifts may also be due to internal dynamic processes unrelated to climate change or to fishing.

2.5.1. The North Sea and Baltic Sea

The cod stocks in the North Sea and the Baltic Sea provide a good illustration of the complexity of the interaction between global and regional climate processes and also of the implications for fisheries management. A regime shift occurred in the North Sea and the Baltic in the late 1980s, with fairly abrupt changes in SST, wind field and a number of biological indicators (Beaugrand, 2004). The change in decadal wind speed and direction during February and March over the North Sea is particular striking (Fig. 3), with an extension of the winter wind conditions to these 2 months since 1987 (Siegismund and Schrum, 2001).

The changed wind field and other physical changes can be related to an apparently persistent change in the NAO (Schrum, 2001). Modelling studies using AOGCMs indicate that the NAO is likely to remain high due to climate change effects (Gillett et al., 2003; IPCC, 2007). The intensification of westerly winds has very different consequences for the salt content of the North Sea and Baltic Sea.

There is an increased inflow of warm, high salinity North Atlantic water into the northern North Sea, whereas inflow to the Baltic is inhibited and the salinity of the Baltic decreases, with reduced haline stratification (Schrum, 2001). Somewhat paradoxically these opposite trends in inflow have negative consequence for cod recruitment in both seas. The increase in salinity in the North Sea does not affect cod, but they are negatively impacted by the increased temperature, which the increased inflow of Atlantic water brings with it. Reduced salinity (<11) is unfavourable for survival of Baltic cod for two reasons. The eggs lose buoyancy and sink, which may carry them into deep anoxic layers, where they die, and the sperm lose mobility.

A critical question concerning management implications of this shift is whether ongoing, cumulative, anthropogenic-induced climate change makes it more or less likely that the regime will eventually revert to its previous state, change to some other state, or remain in its current state. The current regime, characterised by a high NAO appears to be unfavourable for survival of cod in the North Sea, the Baltic Sea and indeed all other areas of the European shelf south of 62°N (Brander, 2005), but it is not clear how to deal with this in developing a long-term management strategy for fisheries on the species. What is clear is that, because much of the variability in fisheries is at decadal scales (e.g. the 1960–1985 "gadoid outburst" in the North Sea) and since environmental forcing is a likely cause (ICES, 1999), research which explains the relationship between climate change and decadal change should be encouraged (Smith et al., 2007).

2.5.2. The North Pacific

Investigations into the effects of climate variability in the North Pacific have focussed strongly on regime shifts. The physical characteristics of these regime shifts and the biological consequences differ between the five major regions within the North Pacific, but some general conclusions concerning the implications for management of marine resources have been put forward (King, 2005; Polovina, 2005).

One of the principal indices of ocean climate state for the North Pacific is the Pacific Decadal Oscillation Index, which tracks the dominant spatial pattern of SST. The alternate phases of the PDO represent cooling/warming in the central subarctic Pacific and warming/cooling along the North American continental shelf. This "classic" pattern represents change along an east–west axis, but since 1989 a north–south pattern has also emerged. Other commonly used indices track the intensity of the winter Aleutian low pressure system and the sea level pressure over the Arctic. North Pacific regime shifts are reported to have occurred in 1925, 1947, 1977, 1989 and 1998 and paleoecological records show many earlier ones (King, 2005). The duration of these regimes appears to have shortened from 50–100 years to around 10 years for the two most recent. In some cases e.g. 1977 the regime shifts were not observed in all North Pacific ecosystems (Alheit and Bakun, 2010-this issue). Whether this
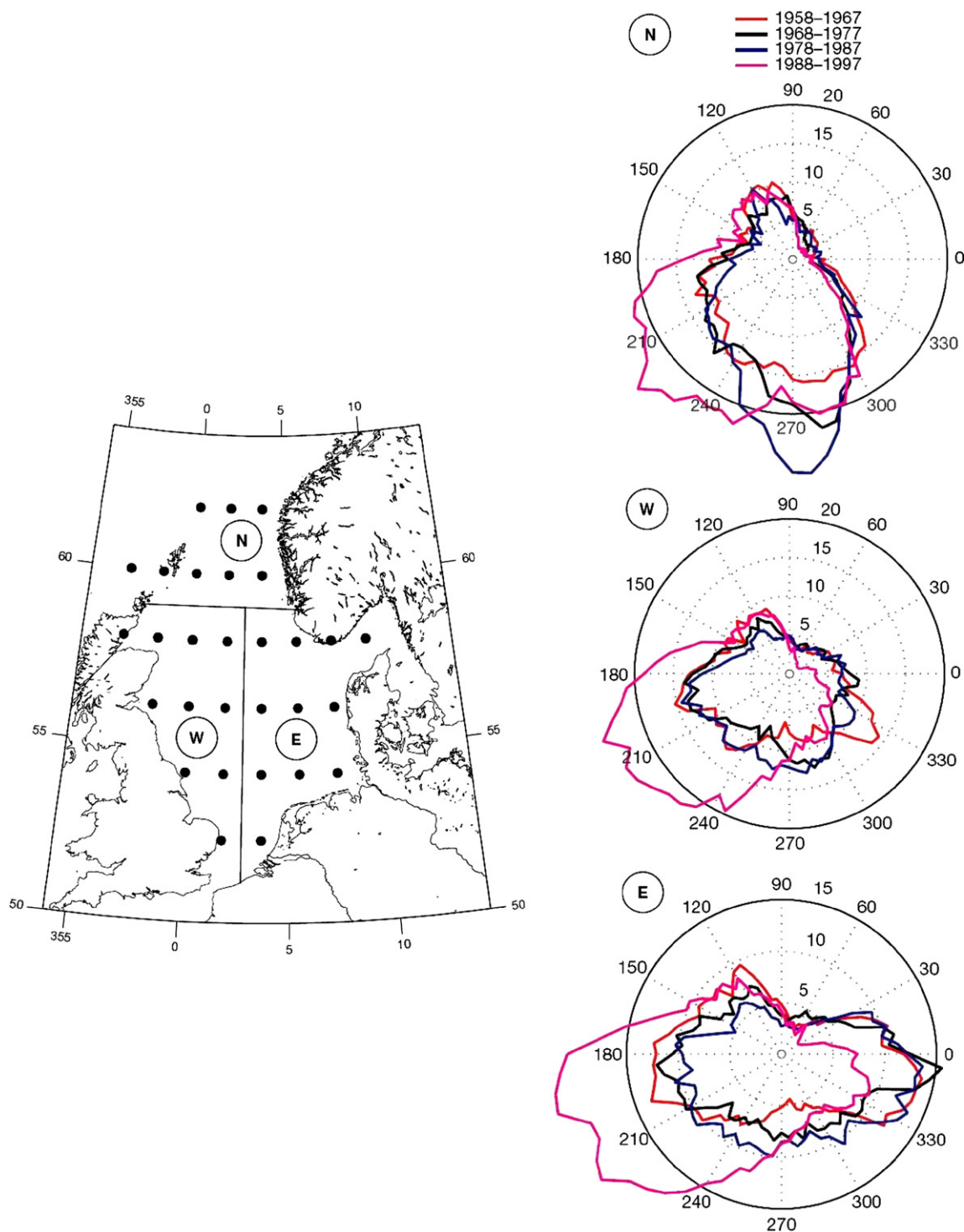
Fig. 3. Normalised decadal wind density functions for February–March for each of the 4 decades from 1958–1997 using NCEP reanalysis data for the grid points shown (after Siegismund and Schrum, 2001). The windspeed in ms^{-1} is represented by the radial distance, with the scales shown on each circle plot. (Note that the scale for area E is different from the other two.)

apparent shortening of regimes is real and whether it is related to other aspects of climate change is a matter of current debate and concern. The El Niño–La Niña Southern Oscillation (SOI) also has a large impact on the North Pacific, adding an episodic overlay with a duration of 1 or 2 years to the decadal-scale regime behaviour.

The impacts of regime shifts on the five major regions of the North Pacific are well documented (King, 2005 and references therein). Sea surface height (SSH) in the central North Pacific rose, indicating an increase in thickness of the upper mixed layer, while at the same time

SSH on the eastern and northern boundaries of the North Pacific dropped. The position of the Transition Zone Chlorophyll Front, which separates subarctic from subtropical waters and is a major migration and forage habitat for large pelagic species, such as albacore tuna, shifted northward (Bograd et al., 2004). In addition to its effects on pelagic fish species, shifts in the winter position of the Chlorophyll Front affect other species, such as Hawaiian monk seals, whose pup survival rate is lower when the front, with its associated production, is far north of the islands. Spiny lobsters (*Panulirus marginatus*)

recruitment in the Northwestern Hawaiian Islands is also affected (Polovina, 2005).

In the California Current System (CCS) zooplankton species characteristic of shelf waters have, since 1999, replaced the southerly, oceanic species which had been abundant since 1989, and northern fish species (Pacific salmon, cod and rockfish species) have increased, while the southern migratory pelagics such as Pacific sardines, have declined. The distribution of Pacific hake (*Merluccius productus*), which range from Baja California to the Gulf of Alaska, is closely linked to hydrographic conditions. During the 1990s it occurred as far north as the Gulf of Alaska, but following a contraction of range by several hundred km in 2000 and 2001, its northern limit has reverted to northern Vancouver Island, a return to the distribution observed in the 1980s.

The biological response to the 1998 regime shift was weaker in the Gulf of Alaska and the Bering Sea than in the Central North Pacific and California Current System. The northern regions of the western North Pacific resembled the southern regions of the eastern north Pacific in showing an increase in biological production. Zooplankton biomass increased in the Sea of Okhotsk and the previously dominant Japanese sardine (*Sardinops melanosticus*) was replaced by herring (*Clupea pallasi*), capelin (*Mallotus villosus*) and Japanese anchovy (*Engraulis japonicus*) (Shuntov et al., 2003).

Given the widespread and profound changes which regime shifts cause in the production and distribution of fisheries resources in the North Pacific it is not surprising that the PICES study from which the above information was taken came to a number of conclusions concerning the implications for management of marine resources and these are briefly introduced in Section 3.2.2 on medium term management.

2.6. Changes in fish population processes

Global, regional and smaller scale impacts of climate change on biological production are ultimately the sum of processes which act on individual organisms. Each species has particular characteristics which govern their resilience and tolerance of changes in their environment. The processes, whose response to environmental variability can be studied in exquisite detail, are growth, reproduction, mortality and behaviour (to find food, avoid predators and maintain themselves in favourable locations throughout their life history). To these responses can be added species interactions and ecosystem processes. The potential complexity generated by these processes and their interaction can make the task of understanding and predicting the impacts of climate on fisheries production seem very daunting. One possible solution is to look at the behaviour at a higher, system level (e.g. fish community), as proposed by Jennings and Brander (this volume). Nevertheless, reliable process understanding contributes greatly to the credibility of system level models.

2.6.1. Experimental studies

There are very few detailed, experimental studies of responses to climate change at individual level. Increasing temperature interacts with other global changes, including declining pH and increasing nitrogen and ammonia to increase metabolic costs. The consequences of these interactions are speculative and complex; an experimental study of Rainbow trout (*Oncorhyncus mykiss*) showed positive effects on appetite, growth, protein synthesis and oxygen consumption of a 2 °C increase in winter, but negative effects of the same temperature increase in summer. Thus rising temperature may cause seasonal increases in growth, but also increased risks to fish populations living towards the upper end of their thermal tolerance zone (Morgan et al., 2001).

2.6.2. Field data analysed empirically and using statistical models

There many examples of empirical studies, in which fluctuations in recruitment, growth and fisheries production of particular species are related to climatic factors. In general the credibility and usefulness of such studies, which rely mainly on statistical modelling (such as regression), depend on the degree to which the underlying processes are understood and can be specified. Comparative studies, in which the same form of statistical model can be shown to work in a number of different and clearly related cases (e.g. several stocks of the same species) also enhance confidence.

Following the pioneering observation by Kawasaki (1983) that there is a pattern of large scale synchrony in catch among many of the world's largest populations of sardine (*Sardinops sagax*), a number of other comparative studies have sought to establish similar relationships for other species and to link these to climate variability. A recent critical review and re-analysis of 22 major catch time series for the period 1950–1998 (Freon et al., 2003) casts some doubt on the robustness and causal interpretation of such synchronies. It suggests that process studies are required before causally-linked remote synchronies can be accepted and that regional synchronies, forced by climatic changes at basin scale may be easier to prove and understand (e.g. Myers et al., 1995).

An effective example of such an analysis of regional synchronies looked at survival rates of 120 stocks of Pacific salmon (*Oncorhyncus* spp.) (Mueter et al., 2002). Survival was related to regional scale variability in SST more strongly than to a large scale climate indicator (the PDO). The cause of the relationship may not be a direct effect of temperature, but warm anomalies were associated with increased survival for stocks in Alaska and decreased survival for stocks further south.

A second, basin-scale example related recruitment of cod stocks from all parts of the North Atlantic to the NAO (Brander and Mohn, 2004; Brander, 2005; Stige et al., 2006). The underlying processes probably involve the effects of abundance, seasonal timing and size composition of planktonic prey on survival of cod larvae and juveniles (Beaugrand et al., 2003). In the Baltic Sea, where the environment is more extreme (with respect to salinity and oxygen), the processes are somewhat different (Köster et al., 2001). The most recent statistical model for cod recruitment in the Baltic includes potential egg production (i.e. spawning biomass and reproductive output), oxygen related egg survival factors, and prey availability for first-feeding larvae (product of abundance of *Pseudocalanus elongatus* and turbulent velocity) (ICES, 2003).

A third basin-scale study analyses trends in weight-at-age and in total biomass of twelve North Atlantic cod stocks since 1970 (Fig. 4, from Brander, 2007). The average weight-at-age of Canadian shelf cod stocks declined from 1980 to 1992, coinciding with a decline in mean temperature over the same period. The decline of up to 97% in total biomass, began several years after the decline in average weight (Table 1). A number of tentative, but potentially very important implications can be drawn from this example concerning the interaction between overfishing and climate change:

- The evidence (Fig. 4) supports the conclusion of a number of authors (e.g. Drinkwater, 2002; Colbourne and Anderson, 2003) that the changing ocean environment in Newfoundland waters during the latter decades of the 1900s resulted in deteriorating conditions for productivity of a number of species, including cod.
- Decline in total biomass of cod was in every case preceded by decline in mean weight-at-age. Decline in growth rate provides valuable advance warning of reduced surplus production, which can result in decline in stock biomass.
- Reduction in weight-at-age contributes directly to the biomass decline—the size of this contribution can be judged from Table 1. Reduced weight-at-age also results in lower reproductive output (when energy is limited, it is used for maintenance and somatic growth), resulting in reduced recruitment.
- Northeast Atlantic stocks did not experience decline in mean weight-at-age or in total biomass, nor did the most southerly
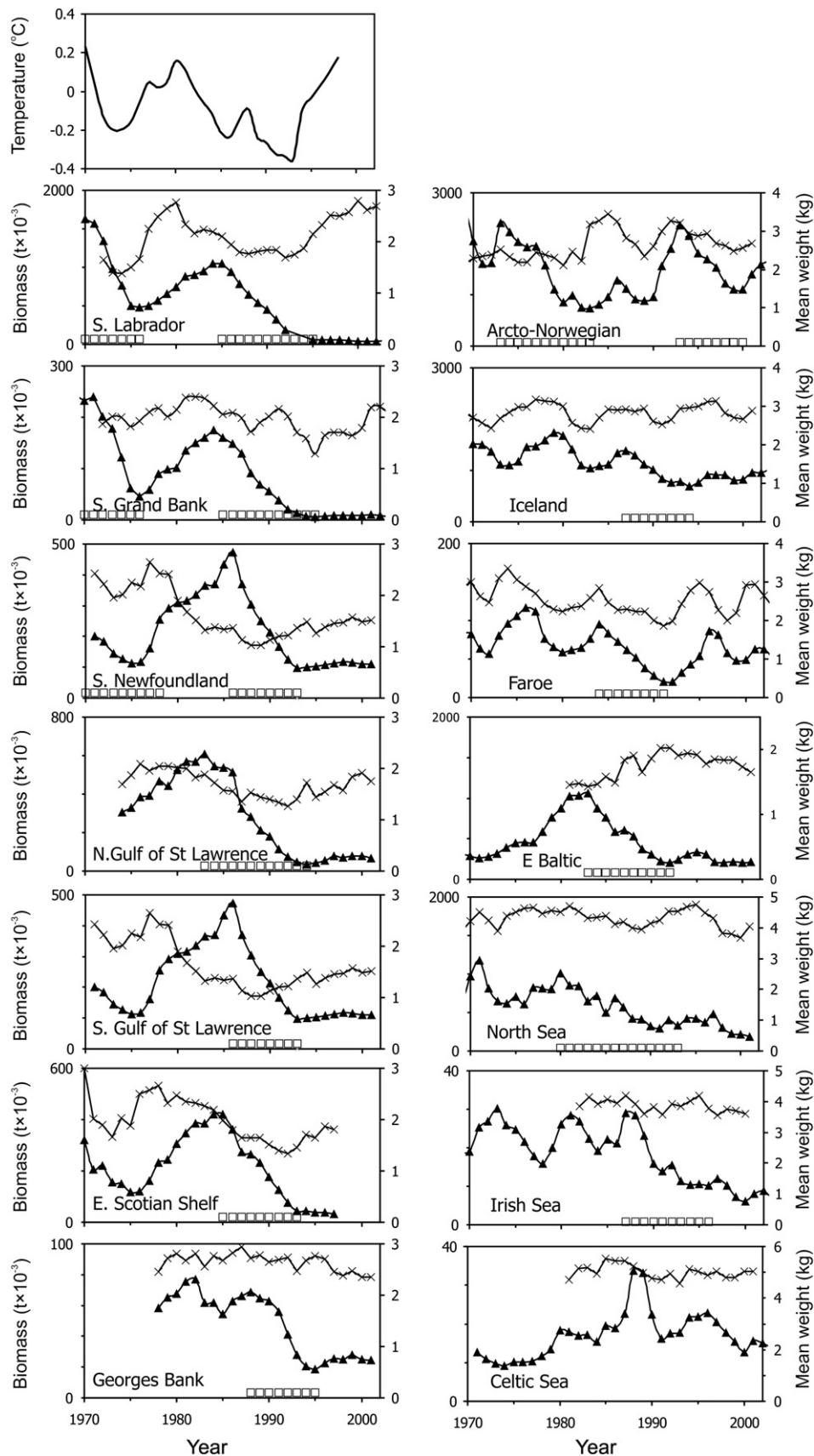
Fig. 4. Trends in total biomass (black triangles represent tons × 10³ on left axes) and mean weight-at-age (crosses represent kg on right axes) for North Atlantic cod stocks. The open squares along the X axis represent periods during which total biomass declined for at least 5 years out of seven. Data sources can be found in ICES (2005). The Canadian shelf stocks are the upper five on the left. The top panel on the left shows the depth averaged 5 year means of temperature at Stn 27 on the Newfoundland shelf (Colbourne and Anderson, 2003).

Table 1
The periods and magnitude of decline in total biomass and mean weight-at-age for North Atlantic cod stocks, based on data shown in Fig. 4.

Cod Stock	Total biomass		Average weight		Age at maturity
	Years	Declined to	Years	Declined to	
S. Labrador	1985–95	5%	1980–92	46%	5.4–7.5
S. Grand Bank	1984–98	3%	1982–94	72%	4.8–7.4
S. Newfoundland	1985–93	26%	1980–94	80%	5–7
N Gulf	1983–94	6%	1978–94	62%	5.4
S. Gulf	1986–93	20%	1978–88	34%	4–4.5
E. Scotian Shelf	1985–93	10%	1980–92	44%	
Georges Bank	1988–95	27%	No decline		2.1–2.9
Arcto-Norwegian	1993–2000	44%	No decline		Variable
Iceland	1987–94	50%	1977–83	76%	5.8–6.6
Faroe	1984–91	19%	1984–91	66%	3
E. Baltic	1983–92	20%	No decline		3
North Sea	1980–93	33%	No decline		2–3
Irish Sea	1987–96	38%	No decline		2
Celtic Sea	no decline		No decline		2.3

The decline is calculated as the percentage of the total biomass remaining at the end of the period relative to the beginning. Age at maturity is from ICES (2005).

Northwest Atlantic stock (Georges Bank). None of these stocks live at temperatures as close to the lower thermal limit as the Canadian shelf stocks.

- Reductions in stock productivity mean that levels of fishing to which a stock was previously resilient, become unsustainable. The decline will be exacerbated if underlying changes in growth are not recognised, because population projections of numbers are translated into catch limits using overestimates of weight-at-age. Hence weight quotas result in a catch of more (lighter) fish than expected and therefore a higher-than-planned fishing mortality.

- It is somewhat ironic that the Northwest Atlantic example off Newfoundland deals with the effects of climate cooling rather than warming, but the lessons are the same: fishing must be reduced when populations are subjected to extra stresses (including climate effects) which reduce their surplus production. The fact that part of the North Atlantic can cool, while the area as a whole becomes warmer, illustrates the need for careful attention to regional detail and for appropriate downscaling of global models.

The observed strong positive relationship between growth and ambient temperature across the entire geographic range of cod stocks (Brander, 1995), is consistent with results obtained from growth experiments and rearing in enclosures (Bjornsson and Steinarsson, 2002). There is much evidence that temperature causes variability (particularly interannual variability) within stocks (Brander, 2000), but it is not easy to measure the actual temperature experienced or to eliminate other causes of observed change (e.g. food). Two lines of research can help to resolve this difficulty in confidently attributing the causes of observed variability. The first is to use new technology to measure the ambient conditions and growth rate for individual fish; the second is to use the comparative approach in order to widen the range of conditions (e.g. temperature) and increase the number of observations.

2.6.3. Fisheries induced adaptive change

Given the additional mortality caused by fishing and its selective nature, it would be surprising if it did not cause some adaptive (genetic) changes and such changes have been observed, both in experimental systems (Conover et al., 2005) and in field data (Olsen et al., 2004; Marshall and Browman, 2007). This is a cause for concern in relation to climate change if the resultant loss of sub-populations, alleles and genotypes reduces the ability of species to adapt to climate change. However the rate at which fishing causes selective change and the methodology for determining such rates remains controversial (Marshall and Browman, 2007).

Populations at the edges of a species range are likely to have particular adaptations to extreme conditions, which makes them valuable sources of genetic material as climate changes. However such changes will also (at least until they are fully adapted) reduced their surplus production and make them vulnerable to levels of fishing which they were previously able to tolerate. This suggests that during conditions of changing climate, special protection should be extended to the populations at the edges of ranges, where the first adverse impacts (due to increasing temperature, declining salinity etc.) are expected to occur. The current rate of change may overwhelm the ability of species to adapt and it may be necessary to evaluate a policy of "managed retreat".

Research into both the speed and scale of fisheries induced adaptive change and the policy response would be worthwhile (ICES, 2007).

2.7. Spread of pathogens

Pathogens have been implicated in mass mortalities of many aquatic species, including plants, fish, corals and mammals, but lack of standard epidemiological data and information on pathogens generally makes it difficult to attribute causes (Harvell et al., 1999). 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 MSX disease caused by Perkinsus (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.

3. Implications and recommendations

3.1. Economic and social impacts

Fluctuations in fish stocks have had major economic consequences for human societies throughout history. The increase in distant water fleets during the last century reduced the dependence of that sector of the fishing industry on a particular area or species, but the resulting increase in rates of exploitation also reduced stock levels and increased their variability. Fishing communities which were dependent on local resources of just a few species became more vulnerable to fluctuations in stocks, whether due to overfishing, climate or other causes.

Many examples can be cited to show the effects of fish stock fluctuations. The history of herring in European waters over the past 1000 years influenced the economic fortunes of the Hanseatic League and had a major impact on the economy of northern Europe. Climate dependent fluctuations in the Far Eastern sardine population influenced their fisheries and human societies dependent on them (Kawasaki, 1992) while the effect of variability in cod stocks at Newfoundland, Greenland and the Faroe Islands on human societies and their migration has been documented by Hamilton and Haedrich (1999).

The investigation of economic effects of climate change on fisheries is a rapidly developing field, which can be expected to help considerably when planning strategies for adaptation or, in some cases, mitigation of future impacts (e.g. Hanneson, 2007). Some of the economic and social implications of climate change for European fisheries are set out in chapter 9 of the ACACIA report (ACACIA, 2000) from which Table 2, showing supply side and demand side adaptations of fisheries to climate change impacts, is taken. Chapter 13 of the

Table 2
Adaptations of fisheries to climate change (from chapter 9 of ACACIA, 2000).

Impact	Supply side	Demand side
Fish distribution changes	Revise fishing rights allocation	Changes in consumer preferences, eco-labelling and certification (MSC)
	Allocate species combinations and access at ecosystem level	Quality labelling (the last wild food…)
Decreased productivity	Economic incentives to switch target species or use other gear	Taxes on ecological costs of fish
	Improve product quality and life	Advertise unique nutritional value of fish, Inform customers
	Reduce production inefficiencies and waste	
	Introduce ecosystem management	
	Switch to new species	
	Increase imports	

recently published Arctic Climate Impact Assessment (Vilhjalmsson et al., 2005) analyses likely economic impact within the Arctic.

Given the uncertainties over future marine production and consequences for fish stocks, it is not surprising that projections of impacts on human societies and economies are also uncertain (Easterling et al., 2007), Global aquaculture production increased by nearly 50% between 1997 and 2003, while capture production decreased by nearly 5% and the likelihood that these trends will continue also affects the way in which climate change will affect fisheries production.

Some areas, such as Greenland, which have been strongly affected by climate variability and which have been undergoing a relatively cold period since the 1960s, can be expected to benefit from warmer oceanic conditions and changes in the marine ecosystem are occurring there quite rapidly. In other areas, such as Iceland, the positive and negative impacts are more finely balanced. It is also worth noting that the projected surface temperature changes for the periods 2020–2029 and for 2090 to 2099 show less warming over the area south of Greenland than anywhere else in the Northern Hemisphere (IPCC, 2007).

It is very difficult to judge at a global level who the main losers and winners will be from changes in fisheries as a result of climate change, aside from the obvious advantages of being well-informed, well-capitalised and able to shift to alternative areas or kinds of fishing activity (or other non-fishery activities) as circumstances change. Some of the most vulnerable systems may be in the mega-deltas of rivers in Asia, such as the Mekong, where 60 million people are in some way active in fisheries. These are mainly seasonal floodplain fisheries, which, in addition to overfishing, are increasingly threatened by changes in the hydrological cycle and in land use, damming, irrigation and channel alteration (Easterling et al., 2007). Thus the impact of climate change is just one of a number of pressures which require integrated international solutions if the fisheries are to be maintained.

3.2. Implications for fisheries management

3.2.1. Short term management

Climate change is one of a number of anthropogenic factors which currently have an impact on fisheries, but at short time scales (i.e. 1–5 years) the effects of long, slow changes in climatic means are relatively unimportant. However the frequency of extreme conditions may also be affected and if these have highly non-linear impacts then there can be major consequences even at short time-scales. Inter-annual variability, climate events such as El Niño and regime shifts can also have very large effects, therefore research and monitoring which increases our ability to detect such changes in a timely way and to predict the consequences, should be encouraged.

A striking recent example concerns the run of sockeye salmon in the Fraser River, British Columbia in 2004, which failed by about 1.3 million fish to reach the expected numbers, with serious economic, social and political consequences. The shortfall was probably largely due to the exceptionally warm summer (Fig. 1), which resulted in high mortality rates. One of the recommendations subsequently made to the Government of Canada (by the Canadian Standing Committee on Fisheries and Oceans, 2005) was that research should be carried out on the impact of elevated temperatures and the development of predictive models of river conditions. The majority of stock assessments do not currently take environmental conditions into account and are not set up to evaluate and respond rapidly to the possible consequences of extreme events such as occurred in this case.

At time scales of 1–5 years the main anthropogenic impacts are due to excessive levels of fishing, fisheries induced damage to the marine ecosystem, degradation or loss of coastal habitat, pollution, introduction of exotic species and undesirable side effects of aquaculture. These factors interact in complex ways, which means that they can rarely be considered in isolation. They may all cause additional stress on exploited fish populations and thus reduce resilience and surplus production. For example, there is evidence that European cod populations become more vulnerable to the effects of climate (as represented by the NAO index) when their populations are at low levels. This is probably because heavy fishing, which reduces population levels, also reduces the age structure and the geographic distribution, making the remaining population less resilient to unfavourable environmental conditions (Brander, 2005; Planque et al., 2010-this issue).

3.2.2. Medium-term management

Medium-term time scales ($\approx$5–25 years) span a period of several generations for most fish species and are therefore relevant to policy development and management plans for stock recovery and sustainable management. The role of climate change effects at these scales can be critical, since stock recovery and the maintenance of sustainable stock levels depends on future levels of surplus production, which may be altered by environmental factors acting on growth, maturity, distribution and recruitment. Scientists are regularly asked to provide strategic guidance for management of fisheries and marine ecosystems. In many cases the consequences of future climate impacts are not included in such strategies, which means that impacts are either assumed to be negligible in relation to the system being managed, or that they cannot be reliably predicted to differ from the past climate on which the assessment was based. There are good reasons, such as the information on regime shifts presented earlier, for doubting whether either of these assumptions is sensible. The work of the PICES study group, which dealt specifically with the issue of regime shifts in the North Pacific, was cited in Section 2.5. It recommended that marine resource management agencies should develop policies with explicit decision rules which specify the actions to be taken as soon as there are indications that a regime shift has occurred. It stated that human activities may worsen the effects of natural disturbances and that:

"Including the effects of regime shifts in the management of marine resources is critical to sustaining their productivity. There are numerous examples globally of the undesirable consequences of failing to detect or acknowledge climate impacts on fish populations. Stock assessment advice should consider the different environmental conditions and alternative management strategies that could be expected in different regime periods and how this may impact the productivity of stocks." (King, 2005).

Medium-term management strategies generally use biological reference points (BRPs) as either targets for managements (i.e. defining a goal to be reached) or limits (i.e defining a domain to be avoided) to maintain the spawning potential of the stock. BRPs

depend on population growth rates and in particular on the steepness of the relationship between spawning-stock biomass and recruitment. A recent study recommends that BRPs should be based on explicit assumptions about steepness and that accurate estimation of this should be a top-priority research goal, using experiments and meta-analyses (Williams and Shertzer, 2003). However it also points out that population growth rates for some stocks, as measured through steepness, may be strongly linked to environmental and ecological conditions, in which case the management strategy should not rely on BRPs assuming equilibrium conditions.

Strategies for fisheries management are part of the general field of environmental risk assessment and decision making and can benefit from the development of methodology within this field. Honest risk assessments have been defined as "those that are faithful to assumptions about the kinds of uncertainties embedded in an assessment, that carry these uncertainties through the chains of calculations and judgements and that represent and communicate them reliably and transparently" (Burgman, 2005). High priority should be given to the development and implementation of fisheries assessments, which evaluate and where appropriate include information about the consequences of climate change.

For example, given the evidence of a regime shift and ecosystem change in the North Sea (Beaugrand, 2004) and of the effects of a persistent increase in the NAO on cod and marine ecosystems in general (Drinkwater et al., 2003; Brander and Mohn, 2004; Brander, 2005; Stige et al., 2006), there is a solid basis for concern about the validity of BRPs for this stock. An assessment framework which allows such uncertainty to be evaluated and communicated in a transparent way is obviously needed (Kell et al., 2005).

3.2.3. Long-term management

The long-term impact of climate change on fisheries may be very large, but is also very uncertain. What can be said with a high degree of confidence is that future fisheries will depend on what progress is made over the next few years in reducing current levels of fishing and mitigating other anthropogenic impacts. An optimistic scenario would be that excessive fishing will have been curbed and other anthropogenic effects reduced, in which case the accumulating effects of climate change will at least be impacting on more resilient ecosystems. A pessimistic scenario would be that major capture fisheries continue to be overexploited, with consequent damage to marine ecosystems. In this situation the additional stress of climate change will have a greater impact, because it will be acting on stressed ecosystems with fish populations which are at lower levels and therefore are less resilient.

3.2.4. Adapting to climate change

The design of appropriate and effective measures to adapt to future climate change depends on adequate predictions of the consequences of possible management actions. This in turn requires sufficient understanding of the major processes determining fisheries responses and models which capture the relevant dynamics. Given the complexity of marine ecosystems and the incompleteness of our current knowledge it is evident that such models of future dynamics need to improve and that the management process must be designed to adapt to new understanding and to be flexible and reflexive. The latter requires monitoring of progress towards achieving the desired goals and adjustment in the light of experience. Well-designed and reliable monitoring of fish stocks and the marine ecosystem is essential in order to detect changes and give advance warning of alterations in the productivity of individual species and of the structure and functioning of the ecosystems on which they depend.

Improved management of fisheries and of marine ecosystems can undoubtedly play an important role in adapting to the impacts of climate change. Fish stocks will be more resilient to climate impacts if the stresses due to other factors, such as overfishing and pollution, are minimised (Perry et al., this volume). Many of the management improvements which are needed do not require new science or understanding; they require patient development of acceptable, effective, responsive social institutions and instruments for achieving adaptive management.

Best current projections of changes in global marine primary production, based on an ensemble of climate models show an increase of less than 10% by 2090, which seems a comfortably small change (Sarmiento et al., 2005). However, the underlying models are highly uncertain and there are likely to be big regional differences. Global climate modelling is developing rapidly and the particular requirements for making projections of marine production need to be addressed, including appropriate resolution in time and space, reliable regional downscaling and inclusion of relevant variables and processes.

3.3. Monitoring and research

Monitoring provides the information required to measure the current state (e.g. of a fish population, ecosystem, pollutant) and to evaluate progress in moving towards management goals. It provides the measurements for validating and checking the sensitivity of models, which are being used to predict future states. It also provides new knowledge which may be useful in revising assumptions, ideas, model structures and parameter estimates. Monitoring programmes need to be designed with all of these objectives in mind, as part of a dynamic and reflexive process which integrates science and management.

A great deal of research is already underway to examine the performance of fisheries management systems as a whole and to bring about improvements. To date the issue of climate induced changes has often been mentioned, but not addressed in such research (e.g. Kell et al., 2005). Assessment frameworks which include the consequences of climate change and the uncertainty resulting from them in a complete and transparent way need to be developed.

Monitoring provides the basic information (numbers caught, age and size composition, maturity) for assessing fish stocks. The quality of these data have in some cases been deteriorating and continuing effort is needed to maintain adequate standards.

Much of the weakness of attempts so far to relate individual life history characteristics (growth, migration, reproduction) to environmental conditions is that the latter could not be measured directly on individual fish. The advent of small, cheap, measuring, logging and transmitting devices opens the way for acquiring much better, more timely data and will rapidly improve our ability to monitor and forecast responses to environmental conditions and to respond appropriately.

The example of growth changes leading stock collapse by several years (shown in Fig. 4) suggests that quite simple biological indicators can provide information which is useful in evaluating future change and which is not fully utilised in current fisheries and ecosystem assessments. Research to evaluate indicators of the state and trends in individual species and in ecosystems should be encouraged, taking into account their utility, cost and foundation in understanding of the underlying processes.

Development of AOGCMs 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, as is change in the frequency of extreme events. 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.

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