J. Mar. Biol. Ass. India, **51** (1) : 1 - 13, January - June 2009

Invited Review

Impacts of climate change on marine ecosystems and fisheries

Keith Brander

Danish Institute of Aquatic Resources, Technical University of Denmark, DK-2920 Charlottenlund, Denmark. E-mail: kbr@aqua.dtu.dk

Introduction

Marine ecosystems are influenced by changes in their physical and biological environment at all timescales and we have evidence of the consequences from palaeological and archaeological records (Enghoff *et al*., 2007). Fish stocks are part of marine ecosystems and the fisheries which they support also fluctuate due to climate, with consequent impacts on the human populations that depend on particular fisheries (Hamilton *et al*., 2003). We know from historic records and from sediment cores that natural fluctuations in small pelagic fish, such as sardines and anchovies have occurred over hundreds and thousands of years (Baumgartner *et al*., 1992).

One of the most striking and globally significant recent fluctuations in marine production and fisheries arose from the effect of the El Nino – Southern Oscillation (ENSO) and decadal variability in ocean climate on the ecosystem off the west coast of South America. During the period 1970-2004 catches of Peruvian anchoveta (*Engraulis ringens*) varied from 94,000 tonnes to 13 million tonnes, largely due to ENSO (Barber, 2001; Jacobson *et al*., 2001). Such enormous natural variability of course creates problems for fishing communities and fisheries managers, but also provides a powerful incentive for scientists to investigate and understand the processes that cause variability. Fisheries managers, the fishing industry and dependent communities have to learn how to adapt to environmentally driven changes (Hamilton *et al*., 2003). Some of the lessons which have been learned from coping with historic natural variability can be transferred to help in adapting to the new problems generated by global climate change.

The impact of anthropogenic climate change on all aspects of the natural world and on human activity has become an issue of pressing political and social concern, as the rate of global warming, rising sea level, altered rainfall and falling pH becomes more apparent (IPCC, 2007). There has been an upsurge of scientific activity studying past and current impacts of climate change. I review some of this work and propose criteria to evaluate it and to improve the methods for predicting future impacts under different potential climate scenarios. I also identify gaps in our knowledge of impacts of climate on marine ecosystems and consider how these can be filled.

Information about likely future impacts of climate change is vital for identifying vulnerable fisheries and fishing activities in order to prepare possible adaptations and management strategies. The increasing urgency of planning for climate change should not obscure the need to deal with the continuing threats from other human activities such as pollution, habitat degradation, introduced species and of course overfishing; the emergence of new pressures, such as climate change, unfortunately does not cause the old ones to go away. I will argue that because of interactions between the various stresses on fish populations, measures that reduce any of the stresses due to these other human activities will also benefit fish populations in adapting to climate change (Brander, 2008 a, b). Dealing with the impacts of climate change is a growing strategic challenge which will be with us for centuries; the threats from other human activities are more immediate and in most cases we know what actions are required to deal with them.

Historical background and evidence of impacts of past climate variability

There are many examples of the impacts of past climate variability on marine ecosystems and fisheries (Brander, 2009). One of the biggest regional, multi-decadal climate fluctuations occurred from the early 1920s to the mid 1940s when the North Atlantic experienced a period of considerable warming. This had widespread impacts on marine and terrestrial life and generated some outstanding studies of climate impacts during a period when international cooperation in marine science was becoming well established (Rozwadowski, 2002). A paper published in 1939 documented the expansion in the range of Atlantic cod and other fish and invertebrate species along the west coast of Greenland and the rise of the fishery from a local catch of a few thousand tonnes per year (Jensen, 1939). Annual catches in the major international fishery, which subsequently developed, exceeded 400,000 tonnes and exploited cod from a latitudinal range of over 1000 km, but the stock collapsed during the 1960s due to a combination of heavy fishing and falling sea temperatures (Hamilton *et al*., 2003). Among the lessons which we can learn are (i) biogeographic changes in the sea can be very rapid and extensive; (ii) fishing communities historically had to adapt as their resource base altered due to climate change; (iii) a level of fishing pressure which was sustainable during favorable climate conditions may cease to be sustainable if conditions change; (iv) scientists have been studying climate change impacts for some time and (v) marine science requires good international cooperation because of the scale of distribution of marine ecosystems and of fish stocks.

Our historic records of past states of marine ecosystems are patchy. In some cases written records of trade and taxation allow the reconstruction of catch histories going back several hundred years. Archaeological remains may reveal the species composition and even size and age structure of comestible species of fish and shellfish going back several millennia. For example a study of over 100,000 fish bones from Mesolithic Stone Age settlements in Denmark (Enghoff *et al.*, 2007) reveals that a number of warm-water species (anchovy, sea bass, black sea bream, swordfish) were found during the Atlantic Warm Period (7000 to 3900 BC) when sea temperatures were around 2°C warmer than present. Even without this evidence it would be fairly easy to predict that such species would be found at these temperatures, however it was surprising to find that Atlantic cod also existed under these conditions. A widely cited recent paper (Drinkwater, 2005) predicted that cod would become locally extinct if temperature rose by 2°C, but the archaeological evidence and other information on the response of cod to increased water temperature indicate that such predictions, which are based on matching present species distributions to one or two climate variables, are not reliable.

A positive consequence of the recent upsurge of concern about climate change is that people are becoming much more aware of our dependence on the natural world and they are coming to realize that anthropogenic impacts can no longer be understood and dealt with as local problems. As we come to recognize the impacts of climate fluctuations at all time scales in earth history there has been an upsurge of research effort to find out what happened during past warm periods and how natural systems and human societies adapted to such changes (Rosenberg *et al*., 2005). This provides some basis for judging existing adaptive capacity and for predicting future impacts by analogy with the past, but as we will see, there are aspects of expected future climate change which are fundamentally different from past experience, notably the rate at which it is expected to occur and the accompanying biogeochemical changes such as acidification of the oceans.

Anthropogenic climate change and how it affects ocean climate

It would be wrong to give the impression that climate change is just a natural phenomenon which has occurred before in earth history. The rate at which the climate of the atmosphere and ocean is now changing as a result of anthropogenic greenhouse gas emissions is far more rapid than anything other than catastrophic events such as major eruptions or meteor impacts that altered the atmosphere and solar input. Since the industrial revolution in the 19th century, levels of CO_2 in the atmosphere have been higher than those experienced over the previous 600,000 years and the pH of the oceans has now dropped below the levels of the past 600,000 years (Fernand and Brewer, 2008). Such changes in global biogeochemistry will take tens or hundreds of thousands of years to reverse even if the rise in greenhouse gases is halted.

Awareness of biogeochemical changes (e.g. in pH, oxygen) is very recent and therefore the implications for marine life are only now being studied and evaluated. This shows how immature our scientific basis for interpreting and predicting impacts still is and it also highlights the need to remember that ocean climate is much more than just rising sea temperatures. Variables representing ocean climate are grouped in Table 1, but there may be others which are locally important or which we have not yet accounted for (e.g freshwater runoff, aeolian iron deposition). Another group of indices (not shown in the table) is used to represent climate modes on regional to global scales (e.g. the Indian Ocean Dipole (IOD), El Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) etc.).

Some of the climate variables shown in Table 1 are conservative and do not vary much geographically, seasonally or interannually (e.g. salinity), but most vary a good deal. The average global increase in air temperature over the past 100 years has been about 0.074°C per decade rising to 0.128°C per decade for the last 50 years (IPCC 2007). The rate of increase in global air temperature is expected to be at least 0.2°C per decade for the next few decades. Sea surface temperature (SST) has risen more slowly than air temperature, but with great geographic variability. The most rapid increases are in the North Atlantic region, where SST has risen by over 0.5°C per decade over the past 25 years. This is of course much faster than the global trend and is probably due to regional variability (at decadal time scales) which may reverse in future (Smith *et al*., 2007). SST in the Arabian Sea and Bay of Bengal has increased by about 0.1°C per decade over the past 25 years (NOAA NCEP Optimal Interpolation SST). The rate of warming due to anthropogenic climate change can seem very small (0.02°C per year) compared with interannual variability (which may be of the order of 0.6°C in the Arabian Sea and >1°C in the North Atlantic), however anthropogenic climate change has an upward trend and the effect is cumulative. Nevertheless it is axiomatic that the present climate state and natural climate variability will dominate predictions of climate over the next few decades, but after that the effect of the initial state will have merged back into the climatology and the size of the anthropogenic component will become increasingly dominant.

Table 1. Ocean climate variables grouped by type of property

Property type	Variable
Atmospheric and sea-surface	Wind Cloud cover Waves Sea level
Chemical and physical	Temperature Salinity pH Oxygen
Dynamic	Currents Stratification Turbulence Upwelling Frontal processes
Seasonal	Monsoon timing

Impacts of climate change on marine ecosystems

Ecosystem services

Ecosystems, including marine ecosystems, provide a range of services on which we depend and many of these are already being affected by climate change. Of greatest immediate concern are the effects on fisheries production, carbon sequestration, coastal protection and loss of biodiversity; however this review will only deal with fisheries impacts in any detail.

Table 2. Classification of ecosystem services (based on the Millennium Ecosystem Assessment, 2005)

Ecosystem service type	Ecosystem service
Provisioning	Food Fibre Medicine Cosmetics
Regulating	Carbon sequestration Water regulation

	Climate regulation Coastal protection Water purification Disease and pest control
Cultural	Spiritual values Aesthetic value Intrinsic value
Supporting (the other 3)	1^{o} and 2^{o} production Biodiversity

Fresh examples of climate related threats to marine ecosystem services appear frequently in the popular press as well as in scientific journals. Recent examples include a study reporting that calcification rates of massive porite coral heads on the Great Barrier Reef had declined by over 13% since 1990 due to a combination of higher temperature and lower pH (De'Ath *et al*., 2009). Another recent paper predicted from global biogeochemical models that oxygen levels would decline and stay low for tens to hundreds of thousands of years due to increase ocean stratification, with major consequences for marine life and productivity of the oceans (Shaffer *et al*., 2009).

Impacts depend on magnitude of climate change and sensitivity

The size of the response of a biological system (whether the system is a physiological process, an individual, population or whole ecosystem) depends on the magnitude of the climate change and on the sensitivity of the system. The response will often be non-linear, so it is probably sensible not to assume a linear response when predicting the impacts of future climate, unless there is some justification for doing so. I use the well studied Atlantic cod (*Gadus morhua*) to illustrate the response of a fish species to temperature change, but similar patterns of response can be expected for other species and for other environmental factors.

Sensitivity of growth to temperature change

The response of growth to temperature shows how sensitivity changes during the life history, being greatest for cod in early life. Growth experiments in which they were fed to satiation produced a family of response curves at different temperatures and fish sizes (Fig. 1). The growth rate of small fish (100 g) increased rapidly at low temperatures (<6 °C) and peaked at around 12°C. In larger fish the growth rate was lower and the temperature for maximum growth rate declined, so that for a 5 kg fish it was just over 6°C. Large fish are therefore less sensitive to temperature than small fish and the sensitivity (i.e. slope of the relationship) is greatest for all sizes at low temperatures. The experiments were carried out at temperatures of up to 15°C and should not be extrapolated above this level (Brander, 2008 a).

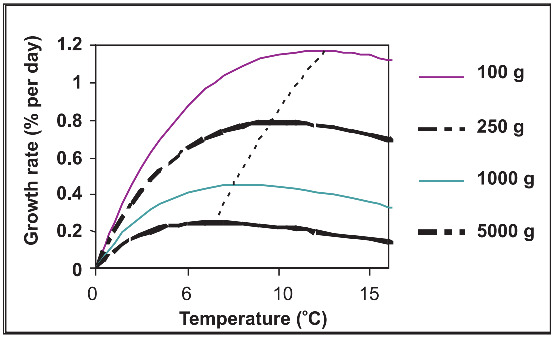

Fig. 1. Growth rate of four sizes of Atlantic cod (*Gadus morhua* L.) in rearing experiments at different temperatures in which they were provided unlimited food. The steep dashed line intersects the growth curves at their maximum values to show how the temperature for maximum growth rate declines as fish get bigger (Redrawn from Bjornsson and Steinarsson, 2002)

The information provided by these experiments about the actual response of cod to temperature changes is incomplete and a number of other factors need to be considered. One is that the seasonal pattern and variability of temperature will have a profound effect; growth will be faster if the temperature stays close to the optimum level throughout the year than if it varies from sub-optimally cold in winter to sub-optimally hot in summer. This means that it is not sufficient only to use information on annual mean temperature – the seasonal pattern is also required. A second factor is that food supply affects the optimum temperature. The optimum temperature for growth is reduced when food is in short supply because the basal metabolic requirement is higher at high temperatures leaving less energy for growth. Of course if the food supply for cod is affected (either positively or negatively) by temperature, then this must also be taken into account. Finally we know that fish, including cod, are capable of sophisticated behavioral thermoregulation, either by altering their depth distribution in thermally stratified water columns or by migratory behavior (Neat *et al*., 2006). This means that any assumptions concerning the actual temperature which fish experience (e.g. that it follows the regional or local pattern of interannual variability) are liable to be wrong. Analysis of variability in regional patterns of cod migration under different temperature conditions and of data storage tags on individual fish shows how poor the relationship between ambient temperature (*i.e.* the temperature actually experienced) and local or regional temperature can be.

Sensitivity of early life survival to temperature change

The response of cod survival in early life to temperature exhibits a similar domed pattern and is also most sensitive at low temperatures (<6°C) (Brander, 2008 a) (Fig. 2). The joint effect on growth and survival is therefore that cod populations at low temperatures (which include all the NW Atlantic stocks except that south of the Scotian Shelf) would be expected to be most sensitive to changes in temperature. Information on processes occurring at the warm end of the range for cod (above 15°C) is poor, but such high temperatures can probably only sustain growth if food is abundant. The proportion of cod in the total demersal fish biomass certainly declines in warm areas, even though their individual growth rate and condition there are higher than in any other areas. It may be that they are unable to compete with other species and also suffer from increased natural mortality rates.

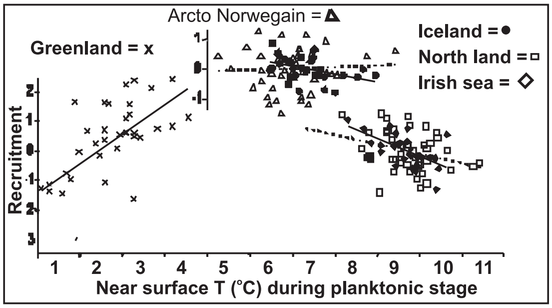

Fig. 2. Composite pattern of recruitment for five Atlantic cod stocks to illustrate the effect of temperature during the planktonic stage of early life on the number of recruiting fish. The scales are log e (number of 1-year-old fish), with the means adjusted to zero. The axes for the Arcto-Norwegian and Iceland stocks have been displaced vertically

Sensitivity to environmental change may increase due to other stresses such as fishing

Theoretical and field studies show that populations and systems become more sensitive to climate impacts when they are heavily exploited (Brander, 2005; Hsieh *et al*., 2006). This is due to reduced age structure (Ottersen *et al*., 2006), constriction of geographic distributions ((Hilborn *et al*., 2003) and other kinds of loss of diversity (Perry *et al*., 2008; Planque *et al*., 2008). The consequence is that heavily exploited species are more strongly affected by climate change than less exploited or unexploited species. A key adaptation for reducing the impact of climate change is therefore to reduce fishing pressure (Brander, 2007).

Distribution shifts and how they relate to rates of change in physical variables

Climate change is only one of a number of stresses that fish stocks experience (Fig. 3). Fishing was the earliest anthropogenic pressure on fish stocks and marine ecosystems, beginning hundreds or even thousands of years ago (Jackson *et al*., 2001; Ojaveer and MacKenzie, 2007). Climate change, whose impact has been detected over the past few decades, is the most recent. Management of fisheries, and of marine ecosystems has not yet succeeded in dealing adequately with the old pressures and some of them, particularly overfishing, are of greater immediate concern than the effects of climate change (Beddington *et al*., 2007). Nevertheless, climate change over the coming decades to centuries will

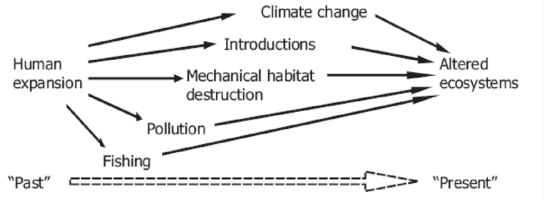

Fig. 3. The historic development of pressures on fisheries and marine ecosystems due to human expansion (Redrawn from Jackson *et al*., 2001)

have progressively greater impacts on marine ecosystems and fisheries. Anticipating and adapting to such changes will help to minimize the disruption to marine ecosystems and to human food supplies.

Attributing causes and predicting changes in distribution

Changes in fish distribution (and in abundance) can occur due to a number of factors, not all of which are climate-related or due to human activity (anthropogenic) (Table 3).

The factors may interact with each other and may act at all timescales from short-term (hours – days) to long-term (years to centuries). The changes in climate factors shown in Table 3 can be due to natural variability or to anthropogenic effects as part of the changes brought about by rising greenhouse gas emissions.

When considering climate impacts a number of distinct questions can be addressed. Are we interested in past effects or future effects? Do we only want to determine whether there has been an effect of climate or do we also want to know how big the effect has been and whether the relationship is linear or non-linear? Can we distinguish between the effects of climate and the effects of other factors such as fishing, habitat degradation, and pollution? Can we distinguish between the impact of the anthropogenic component of climate change and "natural" climate variability? Do we want to evaluate changes in abundance and productivity or only changes in distribution?

In the case of non-climate factors the division between natural and anthropogenic causes is fairly clear, but for climate the factors are the same in both cases and it is not easy to partition them in order to attribute a proportion of the observed changes in biota to anthropogenic climate change. The partitioning of causes shown in the table is not complete and interactions between causes should not be ignored, in particular the effect which fishing has on the sensitivity of marine systems to climate impacts.

Testing, credibility and critical assumptions

Information about present-day species distributions in relation to environmental factors can be used to predict changes that will take place under possible future climate scenarios and the demand for such predictions is rising. However the reliability of predictions from such "climate matching" on a small number of environmental variables (often only temperature) is questionable. For example, Gaston (2003) concludes that "…simple models based on climate matching approaches are likely to prove misleading" because "a number of critical assumptions of climate matching approaches to predicting the response of a species geographic range to climate change are likely to be severely violated." The assumptions underlying such predictions include:

1. Correlations between climate and distribution are due to causal relationships.
2. Factors which are not included in the prediction do not influence the outcome.
3. The metrics and spatial-temporal averaging of factors used to define the envelope of present distribution are appropriate for predicting the future distribution. This assumption conceals a large array of problems in defining sensitive periods in the life history, local effects, seasonal effects, effects of extreme events and general difficulties in defining and measuring ambient conditions which organisms actually experience.

Table 3. Two-way tabulation of factors which may cause changes in distribution of fish species

Causes of change	Natural	Anthropogenic
Non-climate	Competition, predation, disease, internal dynamics	Fishing, eutrophication, pollution, habitat destruction, introduction
Climate	Temperature, salinity, vertical mixing, circulation. pH	Temperature, salinity, vertical mixing, circulation, pH

4. Predictions are not affected by interactions which are not occurring at present, but may occur in future (*e.g.* new combinations of temperature and pH).

5. There is no physiological capacity to withstand environmental conditions which are outside those found in the current distribution area.

6. Range shifts do not cause physiological changes, other than local non-genetic acclimatization. (The question whether the rates of climate change are too rapid for genetic adaptation is still open).

7. Dispersal limitation does not determine present distribution or ability to respond to climate change. (If present distribution is affected by dispersal e.g. "retention areas", then this must be included when making predictions).

Prediction of distribution change is far more difficult than simple climate matching might suggest and we should probably concentrate more on how to improve our methods for making predictions and less on applying methods which rely on many assumptions and which produce results that cannot be tested. Studies which give us greater insight into the underlying problems identify the sources of uncertainty and show how these can be addressed should have priority.

The dangers of simple climate matching models are well illustrated by the history of a number of introduced species. For example *Crassostrea gigas* was introduced for aquaculture in Europe in the 1960 and was not expected to spread because average temperatures are below those at which it occurs in its native areas in Japan and Taiwan. In some cases (but probably not *C. gigas*) the native range may be limited by a "lurking variable" (e.g. a competitor, parasite or physical or chemical constraint). A "lurking variable" will cause the realized range to be more restricted than the potential range. If a species whose distribution is in fact restricted by a parasite is introduced in another area, but the parasite does not establish itself in the new area (perhaps because an intermediate host is absent) then the introduced species may spread far beyond the range predicted by climate matching.

Evaluating studies of climate induced changes

Five criteria can be used to judge the quality of predictions of distribution changes and also to identify ways of improving such predictions:

1. *Do they provide additional information beyond what can be concluded from first principles?*

   A simple global "null model" of distribution change in relation to temperature change can be constructed as follows – the difference in SST between the equator and the poles (or at least to 80°) is about 30°C, so the geographic rate of temperature change is about 300 km per °C, assuming isotropy, no lags and a direct relationship between SST and biological distribution. Thus for example, the warming of the European continental shelf by ~1°C since 1985 would be expected to cause northward distribution shifts of ~300 km.

   300 km in 20 years is probably quite a reasonable average for the observed rates, with some components (e.g. plankton, some shelf edge fish species) moving faster and others (e.g. North Sea fish species) more slowly. Differences between observed and expected rates can be due to the simplifications of the underlying assumptions (e.g. temperature fields which are anisotropic in horizontal and vertical directions). Other models can be compared with the null model in order to determine whether they improve the match between observed and expected. A good fit may indicate that important processes are better represented and that the models are therefore more credible.

2. *Will it be possible to test whether their prediction are correct (in principle or in practice)?*

   Making testable predictions of distribution change is not easy. The specific information and detail of the prediction have to match that of the observations against which they are to be compared. For fish our knowledge of distributions is seasonally and geographically very patchy and is mainly derived from highly selective gears which only sample a small fraction of the total sea area. It is therefore difficult to compare predictions with observation.

Another pitfall in testing is that predictions are often conditional (e.g. …if the distribution and level of fishing remains the same then…). Such predictions are inherently un-testable and are also prone to confirmatory biases (where match between observed and predicted is regarded as confirmation, but mismatch is ascribed to violation of the assumptions).

3. *Are they credible and do they specify what level of confidence is attached to them and what uncertainties or confounding factors may affect them?*

   Credibility depends on how well the model fits, but also on uncertainties and confounding factors that may not have been included in the model. Few studies fit more than one model, with different factors or parameters, to the same data in order to test whether alternative explanations are equally likely. I discuss some of the problems with niche and bioclimate envelope models later and also the need for explanation and knowledge of processes.

4. *Are they capable of predicting past distribution changes?*

   A credible model-based prediction of future changes in distribution should also be able to represent past changes in distribution. This is a weak test if the structure and parameters of the model are derived from the past distribution; nevertheless it is surprising how often such models fail to capture past distribution changes. There may be periods in the past when temperature and other environmental conditions were similar to those predicted for the next decades and if the predicted future biological distributions do not correspond to those past analogue periods then this indicates that the model is in some way wrong or incomplete.

5. *Are they based on knowledge of physical, physiological and ecological structures, processes and limits?*

   The most credible predictions of future distribution changes are based on knowledge of the biological process affected by changing environmental conditions. For example we know from field and experimental studies that cod are unable to reproduce at salinities below 11 because their sperm become immobile and their eggs sink, therefore we can predict with confidence that cod will cease to reproduce in areas where salinity falls below these levels.

Using meta-analysis for attributing observed changes to climate

Simple statistics and signal detection theory tell us that it is easier to detect climate impacts which are big in relation to other factors (such as those in Table 3) and to "noise". The smaller the signal to noise ratio the more data are required to detect an impact with confidence and to attribute the cause correctly. The principal long time series available for marine fish species come from research surveys and sampling, but commercial fisheries can sometimes also provide acceptable data. Programmes for monitoring fish, plankton and other taxa are essential for following the course of climate impacts over time, but take many years to establish a pattern against which changes can be assessed; however it is sometimes possible to carry out data mining, in which old datasets are rescued from archives and historic sources. Time series can also be constructed from sediment cores, stratigraphic analysis of archaeological sites and annual ring formation in mollusc shells and fish otoliths (the marine equivalent of tree-ring analysis). Another means of increasing the volume of data for analysis is to bring together material from many time series or separate studies and carry out a collective meta-analysis.

Rosenzweig *et al.* (2008) compiled ~29,500 data series from ~80 studies to carry out a meta-analysis which concluded that anthropogenic climate change is having a significant impact on physical and biological systems globally and in some continents. Marine systems and regions other than Europe and North America were not well represented in the data compilation due partly to lack of monitoring programmes with the necessary longevity and consistency, but also due to the circumstances in which the data were compiled. (Agriculture and forestry were also very poorly represented even though they could probably supply an immense amount of relevant data if an effort was made to mine it out). Rosenzweig *et al.* (2008) commented that "Improved observation networks are urgently needed to enhance data sets and to document sensitivity of physical and biological systems to warming in tropical and subtropical regions, where many developing countries are located."

Efforts to compile data sets for marine systems which can be added to future regional or global analyses of climate impacts are underway. A meta-analysis for the NE Atlantic (ICES, 2008) shows that the changes in distribution, abundance, and other characteristics (particularly seasonality) of marine biota are consistent with expected climate effects. This does not mean that all changes are consistent with a climate change effect or that climate is the only cause, but it is undoubtedly a recognizably important factor in around ¾ of the 288 cases examined in the study. These cases include zooplankton (83 cases), benthos (85 cases), fish (100 cases), and seabirds (20 cases).

Impacts of climate change on fisheries

Trends in world fisheries and in Indian fisheries

Of the total of 156.3 million tonnes of global aquatic production in 2007 (not including China) (Fig. 4) 58% was from capture fisheries and the remaining 42% from aquaculture. For India the total aquatic production was 6.4 Mt of which 48% was from capture fisheries and the remaining 52% from aquaculture. The trends since 1950 for India and for the global total are similar, with little change in capture production since the mid 1990s but rapid increases in aquaculture. In India aquaculture production already exceeds capture production (*http://www.fao.org/fishery/countrysector/FI-CP_IN/3/en*).

Threats to future aquaculture due to climate change arise from (i) stress due to increased temperature and oxygen demand and decreased pH, (ii) uncertain future water supply, (iii) extreme weather events, (iv) increased frequency of diseases and toxic events, (v) sea level rise and conflict of interest with coastal defenses, and (vi) an uncertain future supply of fishmeal and oils from capture fisheries. Aquaculture poses some additional threats to capture fisheries, and the development of aquaculture could affect the resilience of capture fisheries in the face of climate change. There will also be some positive effects of climate change due to increased growth rates and food conversion efficiencies, longer growing season, range expansion, and the use of new areas as a result of decrease in ice cover.

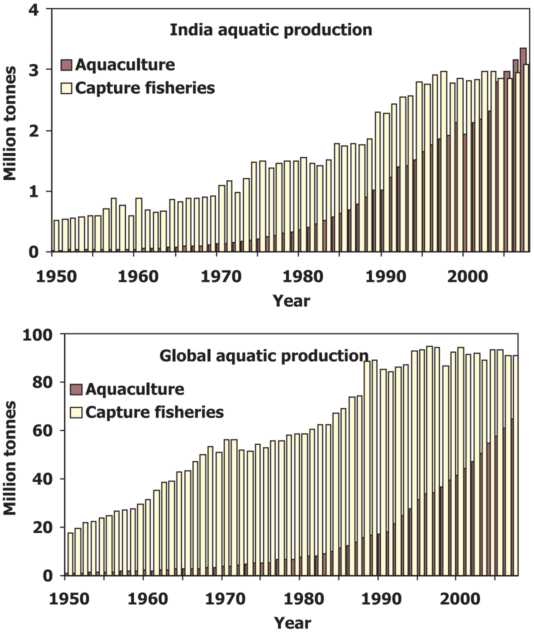

Fig. 4. Trends in aquatic production (freshwater and marine) from aquaculture and capturefisheries (1950-2007). Source: FAO Fisheries Global Information System (*http://www.fao.org/fishery/countrysector/FI-CP_IN/3/en*)

The effects of climate change on future trends in capture fisheries production are difficult to predict because they depend on changes in primary productivity and how this is transferred through one or more trophic steps in the food chain. Changes in ocean physics predicted by global circulation models indicate that the supply of nutrients to the upper mixed layer of the ocean (where light conditions are sufficient for primary production) may be reduced due to greater thermal stratification. This is expected to reduce primary production, particularly in low latitudes, but in higher latitudes primary production may increase, because the growing season may become longer. Changes in windfield will also affect mixing and upwelling, leading to altered seasonality and possible changes in production. The pattern of impacts of climate change on fisheries production is likely to be complex and will require detailed regional or local-scale analysis of the species, processes and biological interactions.

One of the best examples linking processes and scales from climate related upwelling and primary production to the impact on fish is for the tuna species skipjack (*Katsuwonus pelamis)* and yellowfin (*Thunnus albacares).* These are among the top predators of tropical pelagic ecosystem and produced a catch of 3.6 million tonnes 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 Nino-La Nina 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 species (*Thunnus alalunga*) 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. 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).

Identifying vulnerable countries, species and marine ecosystems

On a global scale, it is not easy to identify the main losers and winners from changes in fisheries as a result of climate change. There are obvious advantages to being well informed, well capitalized and able to shift to alternative areas or kinds of fishing activity (or other non-fishery activities) as circumstances change. Modeling studies have assessed country vulnerability on the basis of exposure of its fisheries to climate change, high dependence on fisheries production, and low capacity to respond (Allison *et al*., 2009). The studies show that climate will have the greatest economic impact on the fisheries sectors of central and northern Asian countries, the Western Sahel in Africa, and coastal tropical regions of South America as well as on some small- and medium-sized island states (Aaheim and Sygna, 2000). Indirect economic impacts will depend on the extent to which local economies are able to adapt to new conditions in terms of labour and capital mobility. Change in natural fisheries production is often compounded by decreased harvest capacity and reduced access to markets.

Some of the most vulnerable systems may be in the megadeltas 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 (IPCC, 2007). Thus, the impact of climate change is just one of a number of pressures that require integrated international solutions if the fisheries are to be maintained.

Although processes affecting future fisheries production are expected to act progressively (*i.e*., a linear response) and to interact with each other, marine ecosystems can also respond to changes in physical or biological forces in a nonlinear way (Hsieh *et al*., 2005), for example, when a threshold value is exceeded and a major change in species composition, production, and dynamics takes place. We know that such nonlinear responses occur (often described as regime shifts) but do not yet understand how or under what conditions. This is a key limitation in our ability to forecast future states of marine ecosystems.

Robust and adaptive management strategies

Given the evidence that climate change is beginning to affect the distribution, abundance and productivity of exploited marine resources and the expectation that further changes will occur as conditions move beyond what we have previously experienced, it is timely to review strategies for future management. Our ability to predict future regional climate and the impact that this will have on marine ecosystems is limited (Pearce and Le Page, 2008); therefore two kinds of strategy suggest themselves. The first is to devise robust management systems such as harvest control rules, which are designed to achieve their purpose even if climate causes changes in distribution, abundance and productivity (Mohn and Chouinard, 2007). This can be likened to adopting a strategy for driving a car safely even if conditions (*e.g.*, visibility, volume of traffic) change. The second strategy is to devise responsive management systems that rely on rapid updating about changes in conditions and respond accordingly. This is like an alert driver who immediately adjusts driving style as conditions change. The first strategy is more cautious, but both strategies can be followed at the same time with the more cautious approach being used when the incoming information about conditions is uncertain or is not available quickly enough. The second strategy requires constant monitoring and interpretation of new information which of course has a cost.

In the real world there are many institutional and technical problems in creating fisheries management systems that are well informed and flexible and can interpret and respond quickly to the kinds of change that climate may cause. A basic requirement for most fisheries management is accurate knowledge of how much fish is being caught, but in many parts of the world the quality of this information is poor and may even be deteriorating. Existing fisheries management often uses historic patterns of fish distribution to allocate fishing rights between different countries or communities which can create problems when fish distribution and productivity changes. Some flexibility in fisheries (gear switching, harvesting different species) is adaptive, and even within communities there may be advantages in allowing or encouraging diversity of alternative livelihoods. The benefits of being well informed and having sufficient resources to plan for changing conditions are obvious.

The problems that climate change poses for fisheries management are very serious in the long term and therefore warrant considerable attention. However, they should not be allowed to divert attention away from the urgent problems caused by overfishing, habitat degradation, and other existing pressures. Ignoring the effects of climate and continuing with existing strategies for fisheries management is not a sensible option. The possible consequences of climate change are being taken into account in planning most areas of human activity including sea defense, water supply, health, tourism, insurance, agriculture, and forestry, and it is timely to include them in planning fisheries management.

References

Aaheim, A. and L. Sygna. 2000. Economic Impacts of Climate Change on Tuna Fisheries in Fiji Islands and Kiribati. *Cicero* 4: 21 pp.

Allison, E. H., A. L. Perry, M.-C. Badjeck, W. N. Adger, K. Brown, D. Conway, A. S. Hall, G. M. Pilling, J. D. Reynolds, N. L. Andrew and N. K. Dulvy. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, 10: 173-196.

Barber, R. 2001. Upwelling ecosystems. *In:* J. H. Steele, S. A. Thorpe, and K. K. Turekian (Eds.), *Encyclopedia of Ocean Sciences*, Academic Press, London, 3128-3135.

Baumgartner, T. R., A. Soutar, and V. Ferreira-Bartrina. 1992. Reconstructions of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California. *Calif. Coop. Oceanic Fish. Invest. Rep.*, 33: 24-40.

Beddington, J. R., D. J. Agnew and C. W. Clark. 2007. Current problems in the management of marine fisheries. *Science*, 316: 1713-1716.

Bjornsson, B. and A. Steinarsson. 2002. The food-unlimited growth rate of Atlantic cod (*Gadus morhua*). *Can. J. Fish. Aquat. Sci.*, 59: 494-502.

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

Brander, K. M. 2007. Climate Change and Food Security Special Feature: Global fish production and climate change. *Proceedings of the National Academy of Sciences*, 104: 19709-19714.

Brander, K. M. 2008a. Fisheries and Climate. *In:* J. H. Steele, K. K. Turekian and S. A. Thorpe (Eds.), *Encyclopedia of Ocean Sciences*, Elsevier online edition (in press).

Brander, K. M. 2008 b. Tackling the old familiar problems of pollution, habitat alteration and overfishing will help with adapting to climate change. *Marine Pollution Bulletin*, 56: 1957-1958.

Brander, K. M. 2009. Impacts of climate change on fisheries. *Journal of Marine Systems* (in press).

De'Ath, G., J. M. Lough, and K. E. Fabricius. 2009. Declining coral calcification on the Great Barrier Reef. *Science*, 323: 116-119.

Drinkwater, K. F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES *Journal of Marine Science*, 62: 1327-1337.

Enghoff, I. B., B. R. MacKenzie, and E. E. Nielsen. 2007. The Danish fish fauna during the warm Atlantic period (ca. 7000-3900 bc): Forerunner of future changes? *Fisheries Research*, 87: 167-180.

Fernand, L. and P. Brewer. 2008. Changes in surface CO_2 and ocean pH in ICES shelf sea ecosystems. *ICES Cooperative Research Report,* 290: 35 pp.

Gaston, K. J. 2003. The Structure and Dynamics of Geographic Ranges. Oxford University Press 276 pp.

Hamilton, L. C., B. C. Brown, and R. O. Rasmussen. 2003. West Greenland's Cod-to-Shrimp Transition: Local Dimensions of Climatic Change. *ARCTIC*, 56: 271-282.

Hilborn, R., T. P. Quinn, D. E. Schindler and D. E. Rogers. 2003. Biocomplexity and fisheries sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, 100: 6564-6568.

Hsieh, C., S. M. Glaser, A. J. Lucas and G. Sugihara. 2005. Distinguishing random environmental fluctuations from ecological catastrophies for the North Pacific Ocean. *Nature*, 435: 336-340.

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

ICES, 2008. Report of the ICES Advisory Committee, 2008: An assessment of the changes in the distribution and abundance of marine species in the OSPAR maritime area in relation to changes in hydrodynamics and sea temperature. Book 1: 40 pp.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, 1009 pp.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner and R. R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science*, 293: 629-637.

Jacobson, L. D., J. A. A. De Oliveira, M. Barange, R. Félix-Uraga, J. R. Hunter, J. Y. Kim, M. Ñiquen, C. Porteiro, B. J. Rothschild, R. P. Sanchez, R. Serra, A. Uriarte and T. Wada. 2001. Surplus production, variability, and climate change in the great sardine and anchovy fisheries. *Can. J. of Fish. Aquat. Sci.*, 58: 1891-1903.

Jensen, A. S. 1939. Concerning a change of climate during recent decades in the Arctic and SubArctic regions, from Greenland in the west to Eurasia in the east, and contemporary biological and geophysical changes. Biologiske Meddelelser. Kongelige Danske Videnskabers Selskab. XIV: 75 pp.

Lehodey, P. 2001. The pelagic ecosystem of the tropical Pacific Ocean: dynamic spatial modelling and biological consequences of ENSO. *Progress in Oceanography*, 49: 439-469.

Lehodey, P., F. Chai and J. Hampton. 2003. Modelling climate-related variability of tuna populations from a coupled ocean biogeochemical-populations dynamics model. *Fisheries Oceanography*, 12: 483-494.

McPhaden, M. J. and D. Zhang. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature,* 415: 603-608.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, D.C., Chapter 3: p. 71-83.

Mohn, R. K. and G. A. Chouinard. 2007. Harvest control rules for stocks displaying dynamic production regimes. *ICES Journal of Marine Science*: *Journal du Conseil*, 64: 693-697.

Neat, F., P. Wright, A. Zuur, I. Gibb, F. Gibb, D. Tulett, D. Righton and R. Turner. 2006. Residency and depth movements of a coastal group of Atlantic cod (*Gadus morhua* L.). *Marine Biology*, 148: 643-654.

Ojaveer, H. and B. R. MacKenzie. 2007. Historical development of fisheries in northern Europe—Reconstructing chronology of interactions between nature and man. *Fisheries Research*, 87: 102-105.

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

Pearce, F. and M. Le Page. 2008. Climate change: The next ten years. *The New Scientist*, 199: 26-30.

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

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

Rosenberg, A. A., W. J. Bolster, K. E. Alexander, W. B. Leavenworth, A. B. Cooper and M. G. McKenzie. 2005. The history of ocean resources: modeling cod biomass using historical records. *Frontiers in Ecology and the Environment*, 3: 78-84.

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

Rozwadowski, H. M. 2002. The sea knows no boundaries: a century of marine science under ICES. ICES, Copenhagen. ISBN : 0-295-98250-4. 410 pp.

Shaffer, G., S. M. Olsen and J. O. P. Pedersen. 2009. Long-term ocean oxygen depletion in response to carbon dioxide emissions from fossil fuels. *Nature Geosci*., 2: 105-109.

Smith, D. M., S. Cusack, A. W. Colman, C. K. Folland, G. R. Harris and J. M. Murphy. 2007. Improved surface temperature prediction for the coming decade from a Global Climate Model. *Science*, 317: 796-799.

Received : 01/06/09
Accepted : 20/06/09