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# Climate and current anthropogenic impacts on fisheries

Keith Brander

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**Abstract** Human impacts on marine fisheries go back many centuries or even thousands of years in some coastal areas. Full global exploitation of the most productive fish stocks probably occurred around 1990. Many stocks have been overexploited and the assessment and management required to rein this in and to combat other human pressures, such as pollution, has been slow to mature, but is showing positive trends. The need to protect marine ecosystems for their intrinsic value and for the services they provide has also been recognised and is being embodied in legislation and turned into operational tools. As with terrestrial systems, it will not be easy to find acceptable balances between food production and conservation objectives. Climate change imposes a new set of pressures on marine ecosystems; increasing temperature, reduced salinity in some enclosed seas and coastal areas, changing windfields and seasonality, acidification, deoxygenation and rising sea level will all affect the productivity and distribution of marine life. We can detect some of the consequences already but prediction is very difficult for a variety of reasons. In spite of these difficulties it is possible to map out robust guidance on the kind of research that will help us to adapt and on the development of practices and management that will insure against future change.

## 1 Introduction

The rate of global warming, rising sea level, altered rainfall and falling pH in the oceans is becoming more apparent (IPCC 2007a). Evidence of impacts of anthropogenic climate change on all aspects of the natural world and on human activity is steadily increasing and has become an issue of pressing political and social concern. There has been an upsurge of scientific activity studying past and current rates of climate change (Burrows et al. 2011).

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

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strategies. The extent to which a particular fish stock is affected by climate depends on how much the climate changes in the area that the stock inhabits and how sensitive all life history stages of the species in question are to such changes in climate. However sensitivity also depends on the degree to which a stock is stressed (both demographically and physiologically) by pressures other than climate, such as overfishing, habitat damage, pollution, eutrophication, invasive species and other ecosystem changes.

The vulnerability of a fishery (enterprise, community, industry) to climate depends on changes in fish stocks, but also on the ability of the enterprise to prepare for and adapt to changes in their catch, which may include changes in location, species composition or abundance. The vulnerability of an enterprise, community or industry will be greatest where financial and social capital is lacking and where other pressures, particularly overfishing, are already stressing the social-ecological system (Miller et al. 2012).

Dealing with the continuing stresses from other human activities (pollution, habitat degradation, introduced species and overfishing) must become an integral part of planning for and adapting to climate change. Climate change is an additional stress; because of interactions between all the stresses, measures that reduce any of them will also benefit fish populations in adapting to climate change (Brander 2008a). The impacts of climate change present a growing strategic challenge that 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 tackle them.

## 2 Historical background and evidence of impacts of humans and climate

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 (Jensen 1939; Brander 2010), 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 Niño—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 (Jacobson et al. 2001; Barber 2001). Industrial fisheries also contributed greatly to the population decline, however such declines in pelagic fish species preceded the advent of industrial fishing (Baumgartner et al. 1992) and although fishing pressure can cause rapid population decline, the rapid population increases that are also a common feature of pelagic fish are not attributable to fishing, but to the intrinsic productivity of the species and improving ecosystem conditions (Jacobson et al. 2001; Barber 2001; FAO 2005). 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.

There are many examples of the impacts of past climate variability on marine ecosystems and fisheries (Brander 2010). 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, with widespread impacts on marine and terrestrial life. The range of Atlantic cod and other fish and invertebrate species extended far north along the west coast of Greenland and catches of cod rose from a few thousand tons to over 400,000 tons, 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 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 is sustainable during favourable climate conditions may cease to be sustainable if conditions change (iv) marine science requires good international cooperation because of the scale of distribution of marine ecosystems and of fish stocks.

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 are coming to realize that anthropogenic impacts can no longer be understood and dealt with as local issues. Recognition of the impacts of climate fluctuations at all time scales in earth history has resulted in increased research effort into past warm periods and how natural systems and human societies adapted during them (Rosenberg et al. 2005). The adaptive capacity of societies and communities can be judged from past responses and future impacts can be predicted by analogy with the past events. However, future climate will differ fundamentally from past experience, because the rate of change will be very rapid and the accompanying biogeochemical changes, such as acidification of the oceans, are novel.

### 3 Climate variables and rates of change

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 the consequence of 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<sub>2</sub> 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 (e.g. Hoegh-Guldberg et al. 2007). Our scientific basis for interpreting and predicting impacts is immature and changes in ocean climate affect many variables other than temperature. In addition to the variables shown in Table 1 others may be locally important (e.g. freshwater runoff, aeolian iron deposition) and not yet accounted for. Indices such as the Indian Ocean Dipole (IOD), El Nino Southern Oscillation (ENSO), La Nina, North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) have been devised to represent modes in atmosphere and ocean climate on regional to global scales.

Some of the climate variables shown in Table 1 are conservative, showing little geographic, seasonal or interannual variability (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 2007a). The rate of

**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	e.g. Monsoon timing

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). Global geographic variability in velocity of climate change ( $\text{km y}^{-1}$ ) over the past 50 years can be derived by dividing the temporal rate ( $^{\circ}\text{C y}^{-1}$ ) by the spatial rate ( $^{\circ}\text{C km}^{-1}$ ) (Burrows et al. 2011). The rate of change in seasonal timing can be derived and mapped in a similar way to compare the rates at which distributions of biota on land and in the sea are shifting with the rates at which isotherms have moved at the same locations (Polocznska et al., submitted). They also show the direction of isotherm movement, which is generally, but not always, poleward.

Temperature changes are not all due to anthropogenic climate change. Furthermore, the rate of warming due to anthropogenic climate change can seem very small (0.02 °C per year) compared with interannual variability (which is  $>1$  °C in many oceanic areas), however the anthropogenically driven trend is continuously upward and the effect is cumulative. 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 increasingly dominate.

#### 4 Impacts of climate change on marine ecosystems

Ecosystems, including marine ecosystems, provide a range of services (Table 2) on which we depend and many of these are already being affected by climate change. Within the marine realm the effects on fisheries production, carbon sequestration, coastal protection and loss of biodiversity are of greatest concern (TEEB 2010).

Climate change can be expected to result in increases in primary productivity in some areas and decreases in others. Changes in ocean physics predicted by global circulation models indicate that the supply of nutrients to the upper mixed layer of the ocean (where

**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° and 2° production Biodiversity

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, as growing seasons become longer (Sarmiento et al. 2005). Changes in windfield will also affect mixing and upwelling, leading to altered seasonality and possible changes in production.

Fresh examples of climate related threats to marine ecosystem services appear frequently in the popular press as well as in scientific journals. For example a decline by 13 % in calcification rates of massive porites coral heads on the Great Barrier Reef since 1990 has been reported, due to a combination of higher temperature and lower pH (De'Ath et al. 2009), however this may represent the response of corals at the upper end of the temperature range and not the wider pattern (Cooper et al. 2012). Some global biogeochemical models predict that oxygen levels will 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).

The scale 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 in question. 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. In many cases, particularly where the impact of climate is indirect (e.g. via an effect on the prey of the species in question), there may be a lag between the timing of the climate driver and the biological response.

The role that acclimation may play in enabling a species to maintain physiological and population performance under changing climate is little known, but recent studies (Donelson et al. 2012; Portner 2010) suggest that it may be far from rare .

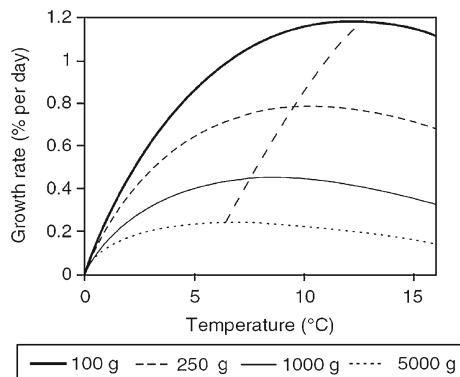
The well studied Atlantic cod (*Gadus morhua*) can be used to illustrate some of the response of a fish species to temperature change and similar responses can be expected for other species and for other environmental factors. Growth experiments in which cod were

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. The growth rate of larger fish was lower and the temperature for maximum growth rate declined; 5 kg fish grew fastest at just over 6 °C. Large fish are 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 2008b).

The information provided by such 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. An analysis of over 100,000 juvenile cod caught in 91 year trawl survey of cod on the Norwegian Skagerrak coast (Rogers et al. 2011) showed that warmer springs result in faster growth, but warmer summer result in slower growth. There were also density-dependent effects, but only at the highest population levels. This shows that it is not sufficient only to use information on annual mean temperature—the seasonal pattern is also required. Food supply affects the optimum temperature and growth rate is reduced when food is in short supply, because the basal metabolic requirement is higher at high temperatures leaving less energy for growth (Pörtner et al. 2007). If the food supply for cod is affected (either positively or negatively) by temperature or other factors, such as density dependence in the Skagerrak study, then this must also be taken into account. Finally we know that fish, including cod, are capable of sophisticated behavioural thermoregulation, either by altering their depth distribution in thermally stratified water columns or by migratory behaviour (Righton et al. 2010). 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 (Neat et al. 2006).

Like growth, the response of cod survival in early life to temperature exhibits a domed pattern and is also most sensitive at low temperatures (<6 °C) (Brander 2008b). As with growth, survival is also affected by food as well as climate (Beaugrand et al. 2003; Olsen et al. 2010). The joint effect on growth and survival is therefore that cod populations at low

**Fig. 1** Growth rates of satiation fed cod. Dashed line joins the loci of maximum growth rate for cod of different sizes (100 g to 5000 g) and shows how both growth rate and temperature for maximum growth decline as fish increase in size (refitted from data in Björnsson et al. 2001)



temperatures would be expected to be most sensitive to changes in temperature. The optimum temperature for both growth and survival lies at intermediate values (between about 4–12 °C). At high temperatures performance declines due to higher metabolic costs (Pörtner et al. 2007).

## 5 Sensitivity to environmental change and 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 (Planque et al. 2010; Perry et al. 2010). 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).

Climate change is only one of a number of stresses that fish stocks experience. 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 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.

## 6 Attribution and prediction

The development of policies for adapting to climate change requires that the causes of observed biological impacts are correctly identified. An understanding of the causes and processes is essential for predicting likely future biological impacts and evaluating the effectiveness of different adaptation strategies. If the causes of observed biological impacts are mis-identified (e.g. a decline in a fish stock is attributed to climate when it is in fact due to overfishing) then an ineffective strategy is likely to result (Plaganyi et al. 2011). Intense public and political awareness of climate change as a force for all kinds of global change has unfortunately resulted in over-attribution of many adverse trends (e.g. declining fish stocks) to climate.

Given the complexity of direct and indirect biological responses to climate change it is not surprising that prediction of future responses is highly uncertain. 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. They also depend on changes in predators, parasites, diseases and other ecosystem components. 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. A detailed critique of the reliability of predictions and a list of attributes that predictions should be tested against is given in Brander 2009. A basic test of any prediction methodology is whether it can reproduce past



observed changes (although for some parameters e.g. pH there may be no analogous periods in the historic past, making such a test difficult or impossible).

Changes in fish distribution and 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 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 Table 3 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.

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 tons in 2003, which represents approximately 5.5 % of total world capture fisheries in weight and a great deal more in value (FAO 2011). 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 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

**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, natural invasion	Fishing, eutrophication, pollution, habitat destruction, assisted invasion, introduced species
Climate	Temperature, salinity, vertical mixing, circulation, pH	Temperature, salinity, vertical mixing, circulation, pH

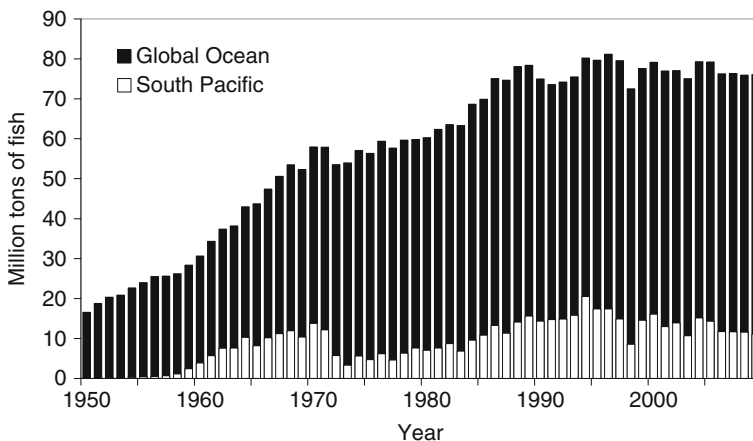
primary production and biomass to decrease by about 10 % since 1976–77 in the equatorial Pacific (McPhaden and Zhang 2002).

## 7 Current state of global fisheries and fish stocks

Of the total of 142 million tonnes of global aquatic production in 2008, 115 million tonnes was used for human food, of which 54 % was from capture fisheries and the remaining 46 % from aquaculture (FAO 2011). The total fish catch in the Southern Pacific was only 14 % of the total global catch over the past 50 years (11 million of the total 76 million tons in 2009), but the Southern Pacific accounts for half of the variability in global fish catch (Fig. 2) due mainly to the effect of fluctuating ocean conditions on the catches of small pelagic fish off the west coast of South America.

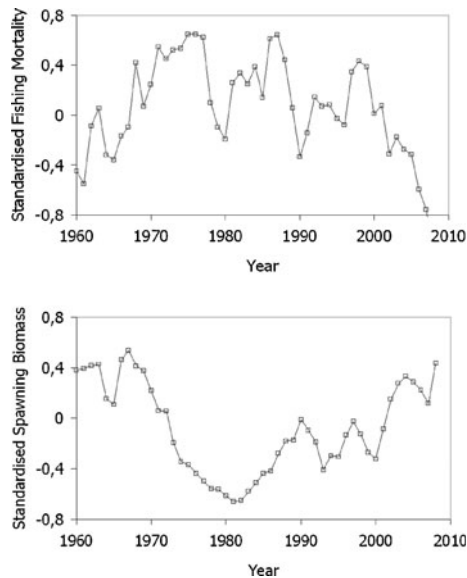
Global fish catches from capture fisheries increased steadily until about 1990 and have since then remained around 77 million tons per year. The proportion of fully exploited stocks has remained at around 50 % since 1970, but the proportion of underexploited or moderately exploited stocks has fallen from 40 % to 18 % in 2008, while the proportion of overexploited, depleted or recovering stocks has increased from 10 % to 32 %. In their most recent review of fisheries and aquaculture FAO report that “of the 23 tuna stocks, most are more or less fully exploited (possibly up to 60 percent), some are overexploited or depleted (possibly up to 35 percent) and only a few appear to be underexploited (mainly skipjack). In the long term, because of the substantial demand for tuna and the significant overcapacity of tuna fishing fleets, the status of tuna stocks may deteriorate further if there is no improvement in their management.” (FAO 2011)

There is clearly still a long way to go in improving the state of exploitation of fish stocks globally, in order to maintain catches, protect species that are at risk and minimize further damage to the marine environment (Worm et al. 2009; Hutchings et al. 2010). However there is also accumulating evidence of improvement in a number of areas and the processes that are bringing about such improvements need to be studied, encouraged and copied in other areas (Hilborn 2012). Even in the North Atlantic, where some areas have been overfished for centuries, there are signs that the battle to rein in excessive fishing pressure is gradually turning (Fig. 3).



**Fig. 2** Global trends in capture fishery production. Source FAO Fisheries Global Information System

**Fig. 3** Standardised average fishing mortality and spawning stock biomass for eleven NE Atlantic stocks that have been assessed continuously since 1960. They include Barents Sea and Icelandic stocks of Atlantic cod (*Gadus morhua*), Barents Sea and Faroese haddock (*Melanogrammus aeglefinus*), northern stock of saithe (*Pollachius virens*), North Sea plaice (*Pleuronectes platessa*), sole (*Solea solea*) and herring (*Clupea harengus*), Norwegian spring spawning herring, North Sea herring, Irish Sea herring and W. Scotland herring. (derived from data in the ICES Fish Stock Assessment Summary Database, 2012 <http://ices.dk/datacentre/StdGraphDB.asp>)



## 8 Adaptation to climate change

Fishing communities and enterprises have coped more or less successfully with the consequences of past climate changes and for most of human history they did so without government support or scientific knowledge. Future climate change will of course be very different (persistent, unidirectional change that goes beyond previously experienced conditions), but we can learn from past experience of successful adaptation.

Considerable scientific effort is now going into making predictions and projections of future climate impacts on living marine resources and marine ecosystems in general (e.g. Hollowed et al. 2009). A forecast describes a future state (e.g. it will rain tomorrow) whereas a projection gives a probabilistic description of a range of possible future states, given an assumed set of climate conditions (see Appendix 1 of IPCC 2007b). Projections incorporate uncertainties and provide a basis for evaluating risks associated with different strategies. The uncertainties in projections of living marine resources arise partly from the climate model projection (coarse resolution of global models, biases and inter-model spread at regional to local scales) and partly from the complexity and incomplete understanding of coupled physical-biological processes (Stock et al. 2011). In spite of the difficulty and uncertainty of making forecasts or projections it is possible to propose robust, no-regret strategies that rely little or not at all on the quality of predictions.

Robust management systems, such as harvest control rules, are designed to work in spite of alterations in distribution, abundance, and productivity that may be caused by climate. This can be likened to driving a car slowly and carefully in order to be safe in changing conditions (e.g., visibility, ice, volume of traffic). A second strategy is to design the management system to be responsive, with rapid updating to take account of changes in conditions and to respond accordingly. This is like an alert driver who immediately adjusts driving style as conditions change. The first, robust 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.

The design and implementation of robust and responsive management strategies and systems is an urgent task for all those with an interest in ensuring that fisheries are able to adapt to climate change. However this task must be set in the context of dealing with overfishing, habitat degradation, pollution, eutrophication, invasive species and other ecosystem changes. Any progress that is made in dealing with these pre-existing stresses will ease the task of adapting to climate change.

One of the requirements for effective fisheries management is accurate and timely information about fish catches, but in many parts of the world the quality of this information is poor and may even be deteriorating. The allocation of fishing rights between different communities or countries is often based on historic patterns of catch, but changes in fish distribution and productivity can render such patterns obsolete. 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.

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## References

- Barber R (2001) Upwelling ecosystems. In: Steele JH, Thorpe SA, Turekian KK (eds) Encyclopedia of ocean sciences. Academic, London, pp 3128–3135
- Baumgartner TR, Soutar A, Ferreira-Bartrina V (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
- Beaugrand G et al (2003) Plankton effect on cod recruitment in the North Sea. Nature 426:661–664
- Beddington JR, Agnew DJ, Clark CW (2007) Current problems in the management of marine fisheries. Science 316:1713–1716
- Björnsson B, Steinarrsson A, Oddgeirsson M (2001) Optimal temperature for growth and feed conversion of immature cod (*Gadus morhua* L). ICES J Mar Sci 58:29–38
- Brander KM (2005) Cod recruitment is strongly affected by climate when stock biomass is low. ICES J Mar Sci 62:339–343
- Brander KM (2007) Climate change and food security special feature: global fish production and climate change. Proc Natl Acad Sci 104:19709–19714
- Brander KM (2008a) Tackling the old familiar problems of pollution, habitat alteration and overfishing will help with adapting to climate change. Mar Pollut Bull 56:1957–1958
- Brander KM (2008b) Fisheries and climate. In: Steele JH, Turekian KK, Thorpe SA (eds) Encyclopedia of ocean sciences, online edition. Elsevier.
- Brander KM (2009) Impacts of climate change on marine ecosystems and fisheries. J Mar Biol Assoc India 51:1–13
- Brander KM (2010) Impacts of climate change on fisheries. J Mar Syst 79:389–402
- Burrows MT et al (2011) The pace of shifting climate in marine and terrestrial ecosystems. Science 334:652–655
- Cooper TF, O’Leary RA, Lough JM (2012) Growth of Western Australian Corals in the Anthropocene. Science 335: 593–596
- De’Ath G, Lough JM, Fabricius KE (2009) Declining coral calcification on the Great Barrier Reef. Science 323:116–119
- Donelson JM et al (2012) Rapid transgenerational acclimation of a tropical reef fish to climate change. Nat Clim Chang 2:30–32

- Enghoff IB, MacKenzie BR, Nielsen EE (2007) The Danish fish fauna during the warm Atlantic period (ca. 7000–3900 bc): Forerunner of future changes? *Fish Res* 87:167–180
- FAO (2005) Fishery Resources Division. Review of the state of world marine fishery resources. FAO Fisheries Technical Paper. No. 457. Rome, p. 235
- FAO (2011) Fisheries Department. Review of World Fisheries and Aquaculture 2010. Rome, p. 88
- Fernand L, Brewer P (2008) Changes in surface CO<sub>2</sub> and ocean pH in ICES shelf sea ecosystems. ICES Cooperative Research Report 290
- Hamilton LC, Brown BC, Rasmussen RO (2003) West Greenland's cod-to-shrimp transition: local dimensions of climatic change. *ARCTIC* 56:271–282
- Hilborn R (2012) The evolution of quantitative marine fisheries management 1985–2010. *Nat Resour Model* 25:122–144
- Hilborn R, Quinn TP, Schindler DE, Rogers DE (2003) Biocomplexity and fisheries sustainability. *Proc Natl Acad Sci* 100:6564–6568
- Hoegh-Guldberg O et al (2007) Coral reefs under rapid climate change and ocean acidification. *Science* 318:1737–1742
- Hollowed AB, Bond NA, Wilderbuer TK, Stockhausen WT, A'mar ZT, Beamish RJ, Overland JE, Schirripa MJ (2009) A framework for modelling fish and shellfish responses to future climate change. *ICES J Mar Sci* 66:1584–1594
- Hsieh C, Reiss CS, Hunter JR, Beddington JR, May RM, Suguhara G (2006) Fishing elevates variability in the abundance of exploited species. *Nature* 443:859–862
- Hutchings et al (2010) Trends in abundance of marine fishes. *Can. J Fish Aquat Sci* 67:1205–1210
- IPCC (2007a) 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, p. 1009
- IPCC (2007b) Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, p. 976
- Jackson JBC et al (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293:629–637
- Jacobson LD, De Oliveira JAA, Barange M, Félix-Uraga R, Hunter JR, Kim JY, Ñiquen M, Porteiro C, Rothschild BJ, Sanchez RP, Serra R, Uriarte A, Wada T (2001) Surplus production, variability, and climate change in the great sardine and anchovy fisheries. *Can J Fish Aquat Sci* 58:1891–1903
- Jensen AS (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. *Det Kgl Danske Videnskabernes Selskab. Biologiske Medd XIV*, p. 75
- Lehodey P (2001) The pelagic ecosystem of the tropical Pacific Ocean: dynamic spatial modelling and biological consequences of ENSO. *Progr Oceanogr* 49:439–469
- Lehodey P, Chai F, Hampton J (2003) Modelling climate-related variability of tuna populations from a coupled ocean biogeochemical-populations dynamics model. *Fish Oceanogr* 12:483–494
- McPhaden MJ, Zhang D (2002) Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature* 603–608
- Miller K et al (2012) Climate change, uncertainty, and resilient fisheries: institutional responses through integrative science. *Progr Oceanogr* 87:338–346
- Neat F, Wright P, Zuur A, Gibb I, Gibb F, Tulett D, Righton D, Turner R (2006) Residency and depth movements of a coastal group of Atlantic cod (*Gadus morhua* L.). *Marine Biol* 148:643–654
- Ojaveer H, MacKenzie BR (2007) Historical development of fisheries in northern Europe—Reconstructing chronology of interactions between nature and man. *Fish Res* 87:102–105
- Olsen EM et al (2010) Spawning stock and recruitment in North Sea cod shaped by food and climate. *Proc R Soc B* 278:504–510
- Ottersen G, Hjermmann DØ, Stenseth NC (2006) Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (*Gadus morhua*) stock. *Fish Oceanogr* 15:230–243
- Perry RI, Cury P, Brander K, Jennings S, Möllmann C, Planque B (2010) Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. *J Mar Syst* 79:427–435
- Plaganyi E et al (2011) Assessing the adequacy of current fisheries management under changing climate: a southern synopsis. *ICES J Mar Sci* 68:1305–1317
- Planque B, Fromentin J-M, Cury P, Drinkwater KF, Jennings S, Perry RI, Kifani S (2010) How does fishing alter marine populations and ecosystems sensitivity to climate? *J Mar Syst* 68:403–417
- Pörtner H-O (2010) Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. *J Exp Biol* 213:881–893

- Pörtner H-O et al (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* 315:95–97
- Righton DA et al (2010) Thermal niche of Atlantic cod *Gadus morhua*: limits, tolerance and optima. *Mar Ecol Prog Ser* 420:1–13
- Rogers LA et al (2011) Climate and population density drive changes in cod body size throughout a century on the Norwegian coast. *Proc Natl Acad Sci* 108:1961–1966
- Rosenberg AA, Bolster WJ, Alexander KE, Leavenworth WB, Cooper AB, McKenzie MG (2005) The history of ocean resources: modeling cod biomass using historical records. *Front Ecol Environ* 3:78–84
- Sarmiento JL, Slater R, Barber R et al (2005) Response of ocean ecosystems to climate warming. *Global Biogeochem Cycles* 18. doi:10.1029/2003GB002134 23 pp
- Shaffer G, Olsen SM, Pedersen JOP (2009) Long-term ocean oxygen depletion in response to carbon dioxide emissions from fossil fuels. *Nat Geosci* 2:105–109
- Smith DM, Cusack S, Colman AW, Folland CK, Harris GR, Murphy JM (2007) Improved surface temperature prediction for the coming decade from a global climate model. *Science* 317:796–799
- Stock CA et al (2011) On the use of IPCC-class models to assess the impact of climate on Living Marine Resources. *Progr Oceanogr* 88(2011):1–27
- TEEB (2010) The economics of ecosystems and biodiversity: mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB
- Worm B et al (2009) Rebuilding global fisheries. *Science* 325:578–585