# Chapter 1

# Fisheries management and governance challenges in a climate change

*Nicholas K. Dulvy and John D. Reynolds,*
*Simon Fraser University, Burnaby, Canada*

*Graham M. Pilling, John K. Pinnegar and Joe Scutt Phillips*
*The Centre for Environment, Fisheries and Aquaculture Science, Suffolk , UK*

*Edward H. Allison and Marie-Caroline Badjeck*
*The WorldFish Center, Penang, Malaysia*

*Most (84%) of the warming due anthropogenic climate change has been transferred to the oceans. This chapter outlines the causes and consequences of climate change and summarise future projections for ocean temperature rise, coral bleaching events and ocean acidification, and the associated uncertainties. This review largely focuses on marine ecosystems, as three quarters of capture fisheries landings come from the seas. However, it also presents key issues and examples from freshwater fisheries, as these fisheries provide important livelihoods and fish protein for some of the world's poorest people. While the physical and biological effects of climate change are increasingly well understood, particularly for well-studied temperate shelf ecosystems, relatively little is known of the likely impacts for ecosystems elsewhere and their associated fisheries. Overall, on balance, climate change appears to have impacts on fish ecology and fisheries, but the strength and direction (positive or negative) of the effects vary from place to place. The social and economic effects are less clear; however it is likely that the economies of countries with the lowest levels of adaptive capacity will be most vulnerable to the effects of climate change on capture fisheries and less able to anticipate and capitalise on any advantages of climate impacts. Despite the uncertainty surrounding the direction and degree of the impact of climate change on marine and freshwater ecosystems, and the associated fisheries and fishing communities, the options for policy makers are relatively clear. Policy makers can respond by pursuing mitigation strategies (reducing $CO^2$ emissions), building socio-ecological resilience and capacity to enable fishing communities to cope with and adapt to the opportunities, challenges and potential dangers presented by climate change, and by integrating the management of natural resource sectors in a portfolio approach.*

# Overview of global warming relevant to fisheries

## *Climate change causes, observations and projections*

We briefly summarise the technical background to climate change including its causes, against the recent historic patterns of climate variation, and outline the wider changes in physiochemical and oceanographic processes, namely: carbon dioxide (CO2) concentrations, temperature increase, sea level rise, rainfall and runoff, hazards and storms, ocean upwelling, primary production, oxygen depletion, acidification, and coral reef degradation. We highlight the areas of consensus and where possible, highlight areas of uncertainty and debate.

### *Carbon dioxide concentrations*

Atmospheric CO2 concentrations oscillated between 200 and 280 parts per million (ppm) over the 400 000 years before the industrial revolution. Current atmospheric concentrations are now approaching 380 ppm, representing a 33% increase on recent historic levels, largely as a result of emissions from industry and changes in land use practices. Estimates of future atmospheric and oceanic CO2 concentrations, based on the Intergovernmental Panel on Climate Change emission scenarios and general circulation models, suggest that by the end of the century CO2 levels could be over 800 ppm (Prentice *et al*., 2001).

### *Atmospheric and oceanic temperature rise*

Climate model simulations show that the estimated temperature variations during the past two millennia prior to the Industrial Revolution can be explained plausibly by estimated variations in solar radiation and volcanic activity during the same period (National Research Council, 2006). It is widely accepted that at least part of the earth's 0.6 °C warming during the last 100 years is due to emissions of greenhouse gases caused by human activities (IPCC, 2001; National Research Council, 2006). It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries (Mann *et al*., 1998, 1999; National Research Council, 2006).

The temperature rise over the last 50 years is broadly accounted for by anthropogenic forcing due to increases in greenhouse gases (mainly CO2 and methane), with some minor cooling caused by sulphate particles in the atmosphere from a concurrent increase in sulphur dioxide emissions, and some natural forcing from volcanoes (Houghton *et al*., 2002). The scientific consensus is that most of the observed warming over this period was due to human activities (Houghton *et al*., 2002). During the present century, the world is expected to continue warming, by between 1.4 and 5.8 °C (Houghton *et al*., 2002). The range in values reflects the range of different climate models and emission scenarios used to provide projections. There is strong consensus that warming will be no less than 1.4 oC over the next century, but there is greater uncertainty in the upper boundary of the projected temperature increase (Kerr, 2004). Land masses are projected to warm more than oceans, with high latitudes being most affected (Royal Society, 2002).

The oceans are warming as a result of human-induced climate change (Barnett *et al*., 2005b). Observations show approximately 84% of the change in energy content of the Earth system (oceans, atmosphere, continents and cryosphere) over the last 40 years has gone into warming the oceans (Levitus *et al*., 2005). There is considerable variation in the penetration of warming among ocean basins, with greatest penetration in the deeply convecting North Atlantic Ocean, and less heat penetration occurring in North Pacific and south Indian Oceans (Barnett *et al*., 2005b). Importantly, these findings are relatively robust, the uncertainties in the models used are too small to affect the conclusion attributing the historic ocean warming signal to anthropogenic forcing, at least for the temperature-driven part of the signal (Barnett *et al*., 2005b).

### *Sea level rise*

Sea-level has already risen by 10 to 20 cm during the 20th century, largely due to thermal expansion, and is predicted to rise by between 9 and 88 cm by 2100 based on the Intergovernmental Panel on Climate Change's full range of 35 climate projection scenarios (Church *et al*., 2001). The largest contributions to sea level rise are estimated to come from thermal expansion of ocean water (288 cm) and the melting of mountain glaciers and icecaps (106 cm), with smaller inputs from Greenland (24 cm) and a negative sea level lowering contribution from Antarctica (-74 cm) (Church *et al*., 2001; Raper and Braithwaite, 2006). There is a high degree of uncertainty in projected sea level rise, particularly in the strength of positive feedback which might accelerate the loss of glaciers which might result in sea level rise of several meters by 2100 (Hansen, 2007). Rising sea levels could lead to inundation of low-lying countries and many islands.

### *Precipitation, glacial melt and run-off*

Model projections generally show increased precipitation and water availability in the high latitudes and in the tropics and less precipitation in the sub-tropics (southern Africa and Mediterranean) (Scholze *et al*., 2006). In other subtropical regions there is little consistency among model projections. The predicted precipitation changes will significantly affect surface water access across 25% of Africa by the end of this century (de Wit and Stankiewicz, 2006). Climate change will cause earlier season peak flows and reductions in flow overall, due to reduced snowfall and melting glaciers (Barnett *et al*., 2005a). In a warmer world, less winter precipitation falls as snow and the melting of winter snow occurs earlier in spring (Arnell, 1999). Even without any changes in precipitation intensity, both of these effects lead to a shift in peak river runoff to winter and early spring, away from summer and autumn when demand is highest. Where storage capacities are not sufficient, much of the winter runoff will immediately be lost to the oceans (Barnett *et al*., 2005a). All of these physical changes in timing and volume of flows will have potential consequences for fish and fisheries production.

### *Hazards, storms and El Niño Southern Oscillation (ENSO)*

The frequency of extreme events is likely to increase with climate change. These may have a greater impact than expected changes in the mean conditions. Extreme events include more intense precipitation events, increased frequency and severity of flooding and increased frequency and severity of El Niño Southern Oscillation events and extreme weather such as hurricanes and droughts (Goldenberg *et al*., 2001, Timmerman *et al*., 1999). Theory, observations and modelling provide evidence of a direct link between changes in sea surface temperatures and hurricane intensity (Emanuel, 2005). Globally, there is little sign that the frequency of hurricanes has increased with increasing sea surface temperatures, however there is a correlation between sea surface temperature and power dissipation due to both longer storm lifetimes and greater storm intensities (Emanuel, 2005). There has been debate about the link between hurricanes and climate change (Pielke Jr. *et al.*, 2005). However, a recent study shows that the observed increase in sea surface temperatures in hurricane-forming regions of the Atlantic and Pacific Ocean are a result of human-caused global warming (Santer *et al.*, 2006). In 2010 a study published by US government researchers predicted an 18% decline in the number of hurricanes in a warmer world, but that future hurricanes will be fiercer and more destructive (Bender *et al.*, 2010).

### *Ocean upwelling*

The relationship between climate and the production of upwelling systems remains uncertain. On one hand stronger wind fields might lead to enhanced upwelling in eastern boundary currents, which could increase nutrient availability at the surface (Bakun, 1990). For example, upwelling in the California current system is positively correlated to temperature and has increased over the last 30 years (Pisias *et al.*, 2001, Snyder *et al.*, 2003). On the other hand, however, stronger thermal stratification and deepening of the thermocline in some areas could prevent upwelling of the cool nutrient waters associated with plankton production (Roemmich and McGowan, 1995).

### *Ocean primary production*

The relationship between climate change and future ocean primary production is likely to be a key constrain on fish and fisheries production (Cushing, 1982; Dulvy *et al.*, 2009; Chassot *et al.*, 2010). Metabolic scaling theory suggests that the balance between primary production and respiration will be profoundly affected by temperature increase (López-Urrutia *et al.*, 2006). While both production and respiration will increase with temperature, respiration will increase relatively more than production. These models predict that the epipelagic1 ocean biota will capture 4 gigatonnes less of C per year by 2100. This equates to 21% less CO2 being captured (López-Urrutia *et al.*, 2006). At present there is considerable uncertainty in empirical measures of the effects of climate change on global primary production and in regional variation in these effects.

The declines in primary production predicted by metabolic theory are consistent with global observation datasets. Recent comparisons of two satellite datasets - Coastal Zone Color Scanner (CZCS, 1979-1986) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) ocean colour observations (1998-2002) suggest that global ocean annual primary production has declined more than 6% since the early 1980s. Nearly 70% of the global decadal decline occurred in high latitudes (Gregg and Conkright, 2002). In northern high latitudes, these reductions in primary production have corresponded with increases in sea surface temperature and decreases in atmospheric iron deposition to the oceans (Gregg *et al.*, 2003). Satellite estimates indicate chlorophyll concentrations decreased in the northern high latitudes while chlorophyll in the low latitudes increased. Mid-ocean gyres exhibited limited changes (Gregg and Conkright, 2002) or declining concentrations (Antoine *et al.*, 2005). There is further heterogeneity among regions. Sea surface warming in the North-east Atlantic is accompanied by increasing phytoplankton abundance in cooler regions and decreasing phytoplankton abundance in warmer regions (Richardson and Schoeman, 2004). Sea temperature increases have led to an 80% decrease in macrozooplankton biomass since 1951 in waters off southern California (Roemmich and McGowan, 1995). Global chlorophyll concentration increased following a strong El Niño year in 1998, until a La Niña in 2000 whereupon global chlorophyll concentration decreased. These changes are largely attributed to changes in surface temperatures and stratification associated with the ENSO cycle and multivariate ENSO index (Behrenfeld *et al.*, 2006).

An analysis of six coupled Atmosphere-Ocean Global Circulation Models (AOGCMs) indicates that primary production may increase in the future by very little, no more than 10% by 2050 relative to a pre-industrial state (Sarmiento *et al.*, 2004). However, the level of confidence in this prediction is low, primarily due to large increases in the inter-tropical areas (Antoine *et al.*, 2005). The AOGCMs predict a reduced area of permanently stratified low productivity waters in subtropical gyres (Sarmiento *et al.*, 2004), which has already been observed in ocean colour estimates. At the same time this study suggested that there will be a 15% increase in the size of the ocean's most oligotrophic waters (that have chlorophyll concentrations <0.07 mg chl m-3) and this has been confirmed through analyses of satellite-derived ocean colour estimates (Polovina *et al.*, 2008). Coupled ocean biogeochemical and GCM models predict climate change to lead to more nutrient-depleted conditions in the ocean surface favouring small phytoplankton at the expense of diatoms (Bopp *et al.*, 2005).

### *Oxygen depletion*

Hypoxia (low oxygen) is starting to become an issue of major concern for coastal waters around the world (Weston *et al.*, 2008). However, little is understood of the possible impact of low oxygen zones on fish and fisheries. Dead zones in the coastal oceans have spread exponentially since the 1960s and have serious consequences for ecosystem functioning. The formation of dead zones has been exacerbated by the increase in primary production and consequent worldwide coastal eutrophication fuelled by riverine runoff of fertilisers. Enhanced primary production results in an accumulation of particulate organic matter, which encourages microbial activity and the consumption of dissolved oxygen in bottom waters. Dead zones have now been reported from more than 400 systems, affecting a total area of more than 245 000 square kilometres, and are probably a key stressor on marine ecosystems (Diaz and Rosenberg, 2008). Low oxygen is predicted to occur more regularly in the future as a result of climate change. In the North Sea, for example, waters are 2-3 ºC warmer and therefore contain less dissolved oxygen by 0.4 mg l-1; the period of stratification will last for longer, and summer storms that normally dissipate areas of hypoxia will likely decrease in the future (Weston *et al.*, 2008). In the Kattegat, the Baltic Sea, and the Gulf of St. Lawrence, fish such as cod completely avoid low oxygen waters (Chabot and Claireaux, 2008). Furthermore, in the Baltic Sea cod eggs do not survive low oxygen conditions, and years with extensive hypoxia have been related to very poor stock recruitment for this species (Koster *et al.*, 2005).

### *Ocean acidification*

Rising atmospheric CO2 concentrations over the past two centuries have led to greater CO2 uptake by the oceans. In the past few decades, only half of the CO2 released by human activity has remained in the atmosphere; of the remainder, about 30% has been taken up by the ocean and 20% by the terrestrial biosphere. Based on the Intergovernmental Panel on Climate Change estimates of future atmospheric and oceanic CO2 concentrations, corresponding models for the oceans indicate that surface-water dissolved inorganic carbon (DIC) could probably increase by more than 12%, and the carbonate ion concentration would decrease by almost 60%, resulting in a corresponding pH drop of about 0.3-0.5 pH units in surface waters by 2100 (Caldeira and Wickett, 2003). Ocean pH was around 8.3 after the last ice age, and 8.2 before CO2 emissions took-off in the industrial era (when CO2 in the atmosphere amounted to around 280 parts per million). Ocean pH is now 8.1, with an atmospheric CO2 concentration of around 380 parts-per-million (ppm). This is more acidic than the ocean has been for hundreds of millennia, and the rate of pH change is estimated to be 100 times faster than at any other time during the past 100 000 years. A key consequence is that the degree of saturation of seawater with aragonite2 and calcite, which is largely governed by bicarbonate concentration (CO3-2).

Undersaturation, particularly of aragonite, is predicted in near surface waters between 200-1000 m in the North Pacific, north Indian and east Atlantic Oceans within the next few decades (Feeley *et al.*, 2004). The calcification rate of organisms across multiple taxa – from single-celled protists to reef-building corals – is expected to decrease in response to a decreased CaCO3 saturation state (Feeley *et al.*, 2004). Coral reef calcification depends on the aragonite saturation state of surface waters. By the middle of the next century, an increased concentration of carbon dioxide will decrease the aragonite saturation state in the tropics by 30% (Kleypas *et al.*, 1999). Acidification is likely to favour some phytoplankton species over others, particularly in the Southern Ocean, which may in turn influence the community structure of the higher trophic levels that are reliant upon phytoplankton as food and will also influence the cycling of elements, since processes and mechanisms differ between phytoplankton species (Hays *et al.*, 2005). High pCO2 and lower pH will also affect the growth and reproduction of many benthic invertebrate species (see Fabry *et al.* 2008), including echinoderms, bivalve molluscs and some crustaceans. While understanding the effects of acidification on components of the life history of organisms has been the focus of laboratory scientists, the real question is: what are the population and community effects of acidification? Whole ecosystems already exist in the acidified deep water below the aragonite saturation horizon; the question is who will be the winners and losers as the undersaturated acidic waters shoal and influence shallower water ecosystems that support commercial fisheries and aquaculture.

### *Coral reef degradation*

Rising sea temperatures are likely to have the greatest effects in the tropics, particularly on coral reef habitats. Tropical oceans have already warmed by 0.5-1 °C over the past 100 years (Hoegh-Gulburg, 1999). Elevated carbon dioxide levels and temperatures are likely to increase coral mortality through bleaching, ocean acidification and changing frequency and intensity of hurricanes (Hughes *et al.*, 2003).

Coral growth and reef building processes occur only under conditions of low nutrients, warm waters >18°C, high light, and stable full salinity (Veron, 1993). Corals can be found in conditions other than these but do not form massive atoll and barrier reef structures. The temperature range under which reef building corals survive is wide (18-34 °C) but the variance is low, suggesting that coral are highly adapted to live within narrow temperature tolerances (Hoegh-Gulburg, 1999; Hughes *et al.*, 2003). Overheated corals expel their symbiotic microalgae (zooxanthellae) and become pale or white. If the stress is prolonged the coral will die. Temperature elevation by 1 °C above the summer seasonal average is likely to cause coral mortality (Hoegh-Gulburg, 1999), accentuated by calm conditions in which coral receive more light (Sheppard *et al.*, 2009). Temperature rises of this magnitude and greater are associated with ENSO events, which have occurred with increasing frequency in the last two decades resulting in widespread coral bleaching and mortality (Glynn, 1996).

Bleaching could become an annual or biannual event for the vast majority of the world's coral reefs in the next 30-50 years without an increase in thermal tolerance of 0.2-1.0 °C per decade (Donner *et al.*, 2005). In the western Indian Ocean the probability of repeated episodes of mass bleaching similar to that observed in 1998 will increase to a 50% chance of recurrence for the warmer months within 25-35 years (Sheppard, 2003).

Thermal bleaching along with fisheries exploitation, pollution and disease are the greatest threats to coral reefs (Newton *et al.*, 2007; Hughes *et al.*, 2003; Pandolfi *et al.*, 2003). In 1998 the biggest ENSO-driven bleaching event killed between 10-16% of the world's corals (Goreau *et al.*, 2000; Wilkinson, 2000). Mortality in some areas was higher: western Indian Ocean reefs lost as much as 46% of reef-building coral cover (Wilkinson, 2000). The degree of degradation has been higher on Caribbean reefs; it is estimated that fishing, hurricanes, bleaching and disease have resulted in a loss of 80% of Caribbean hard coral cover over the last three decades (Gardner *et al.*, 2003). Even relatively pristine, well-managed reefs such as the Great Barrier Reef, Australia have been severely degraded; hard coral cover has halved from ~38% cover in 1964 to the current cover of ~21% in 2004 (Bellwood *et al.*, 2004). Overall, it has been estimated that 30% of coral reefs have been severely damaged and close to 60% may be lost by 2030 (Wilkinson, 2000). The current annual rate of loss of coral cover is approximately 0.5-1.5% per year, based on estimates from the Caribbean (1.3% year-1) (Gardner *et al.*, 2003) and the Great Barrier Reef, Australia (0.56% year-1) (Bellwood *et al.*, 2004).

Ocean acidification poses a major threat to the world's coral reefs. A high profile paper in 2009 highlighted the deleterious effects of falling pH on corals across a huge swath of the Great Barrier Reef in Australia (De'ath *et al.*, 2009). Reading the rate of growth recorded in coral skeletons, the authors found that calcification rates had declined by 14.2% since 1990, and they demonstrated that no equivalent phenomenon had been recorded within the past 400 years. Laboratory experiments have revealed that high CO2 is also a bleaching agent for corals (Anthony *et al.*, 2008), and projections suggest that under the current rate of increase in CO2 emissions, (>1 ppm y-1) carbonate ion concentrations will drop below 200 µmol kg-1 and reef erosion will exceed calcification by the year 2040 (expected to occur at 450-500 ppm). The density and diversity of corals on reefs are likely to decline, leading to vastly reduced habitat complexity and loss of biodiversity, including commercially important fish and invertebrates (Hoegh-Guldberg *et al.*, 2007). Added to this, a recent study on coral reef fish (Munday *et al.*, 2009) has shown that larval fish reared in control seawater (pH 8.15) discriminated between a range of cues that could help them locate reef habitat and suitable settlement sites. This discriminatory ability was disrupted when larvae were reared in high CO2 waters. Larvae became strongly attracted to olfactory stimuli they normally avoided when reared at levels of ocean pH that could occur ca. 2100 (pH 7.8) and they no longer responded to any olfactory cues when reared at pH levels (pH 7.6) that might be attained later next century on a business-as-usual carbon-dioxide emissions trajectory. If acidification continues unabated, the impairment of sensory ability may reduce population sustainability of many reef fish species, with potentially profound consequences for marine diversity.

### *What are the latest projections and associated uncertainties?*

Global surface temperature has been observed to have increased by 0.6 °C and global average sea level has already risen by 10-20 cm. Precipitation has increased in the northern hemisphere by 1% per decade, and the frequency of heavy precipitation events increased by 2-4% over the century. Arctic sea-ice thickness during late summer-early autumn has decreased by up to 40% and global snow cover has decreased by about 10% since 1960 (IPCC, 2001; Barange, 2002). In the past 200 years ocean uptake of CO2 has led to a reduction of the pH of surface seawater of 0.1 units, equivalent to a 30% increase in the concentration of hydrogen ions (Royal Society, 2005).

The predictions for the twenty-first century include an increase in the rate of global warming. Mean global surface temperature is predicted to increase by 1.4-5.8 °C by 2100. Warming will be most pronounced over land areas, particularly in high latitudes and in the cold season. Most models predict a weakening, but not shutdown, of the thermohaline circulation by 2100. Shutdown may occur beyond 2100. Sea level will rise by 9-88 cm by 2100. The Antarctic ice sheet will gain mass due to greater precipitation, but the Greenland ice mass will decrease significantly because of increased run-off and glacial melt. There is relatively high certainty that ocean pH will decrease (acidify) by 0.3-0.5 pH units over the next century (Royal Society, 2005).

There are some aspects of future climate change with which we have greater confidence than others. For example, we are more confident about increases in greenhouse gas concentrations and rises in sea-level than we are about increases in storminess, winds and waves, and the behaviour of the El Niño-Southern Oscillation (ENSO) (Allison *et al.*, 2005). The main sources of uncertainty in the physical effects of climate change result from:

- Uncertainty over future $CO_2$ emissions (a consequence of human demography and development) and consequently atmospheric concentrations of greenhouse gases, as these will depend on societal choices.
- Incomplete knowledge about how the global climate system will respond to greenhouse gas forcing.
- Inherent variability because climate models are non-linear and thus tend to be sensitive to the starting conditions, which can create uncertainty at a later time.
- Variation in feedbacks among models associated with not knowing how the climate system reacts to unprecedented rates of greenhouse gas emissions or in knowing how clouds, forest, grasslands or particularly the world's oceans react to climate perturbations and how they feed back into the system.
- Reduced confidence in Global Circulation Model (GCM) results at the detailed spatial and temporal scales often required by planners and managers. One outcome of this uncertainty is that different climate models sometimes yield different regional climate responses to the same greenhouse gas emissions, producing an additional measure of uncertainty in future climate scenarios. This is particularly acute for precipitation, wind and storminess. While there is high certainty that precipitation will increase, particularly in the northern hemisphere, the effect will be less certain at smaller spatial scales.
- A key uncertainty is the degree to which short-lived mobile calcifying organisms will be able to respond to ocean acidification and higher pCO2 by altering their

distribution or adapting to lower saturation states. There is relatively low certainty of how complex second-order climate phenomena and extreme events, such as hurricanes, upwelling, ENSO are affected by climate change.

- The detailed response of ecological and socio-economic systems to the observed and predicted physical and chemical changes is less certain. While there is relatively high certainty that elements of climate change, such as temperature, have changed the growth, phenology, productivity and geographic distribution of some populations and species, it is less clear how climate change will affect ecological interactions such as the "match-mismatch" of consumers and resources. The greatest area of uncertainty is in the our understanding of the degree to which effects of climate change on physical and biological systems have translated into positive or negative effects on social and economic systems, such as fisheries.

## How and where does global warming potentially impact on fisheries?

There are many different potential pathways through which climate change may influence fisheries and their contribution to local community livelihoods, national economies and global trade-flows and supplies of fishery products to consumers. Notwithstanding this complexity and uncertainty, it is increasingly recognised that climate change can impact local human communities through two broad pathways.

- Climate change, including ocean acidification, modifies the structure and function of the aquatic ecosystem, which in turn influences the productivity and spatial and temporal distribution of fisheries resources. This is likely to reduce access to livelihood opportunities and natural capital through changes in the fisheries productivity in some areas, but may well enhance opportunities elsewhere (especially at higher latitudes).
- The increasing frequency and severity of extreme events such as floods, storms and hurricanes will increase the vulnerability of fishing communities through damage to infrastructure, reduced opportunities to go to sea, and increasing threats to human health (Kovats *et al.*, 2003; Adger *et al.*, 2005b; Pascual *et al.*, 2000).

While it is clear that both of these climate change pathways tend to result in generally negative impacts, Cheung *et al.* (2009b) suggests that climate change may lead to large-scale redistribution of global catch potential, with an average of 30-70% increase in yield of high-latitude regions, but a drop of up to 40% in the tropics. Changes in fish productivity will result in the larger, macro-scale impacts such as reduced contribution of fisheries to the national economy in some areas and reduced availability of fish as a source of dietary protein. These potential impacts are examined further below.

### *Climate effects on fisheries-relevant populations, species and ecosystems*

Climatic variation has wide-ranging effects on the ecology of aquatic systems, by acting across ecosystems and propagating through trophic webs, over broad spatial and temporal scales (Harley *et al.*, 2006; Stenseth *et al.*, 2005). For exploited species, the various impacts of climate change include direct and indirect effects on individuals (Wood and McDonald, 1997), populations (Cushing, 1982; Beaugrand *et al.*, 2002; Edwards and Richardson, 2004; Perry *et al.*, 2005) and ecosystems (Feeley *et al.*, 2004; Harvell *et al.*, 2002; Schindler *et al.*, 1996). These effects are likely to coincide with more general warming-related changes in habitat quality and productivity which are likely to affect fished species and fisheries, e.g. coral reef loss (Hoegh-Gulberg, 2005; Graham *et al.*, 2006). Recent reviews provide strong circumstantial evidence to suggest that ocean climate will have far-reaching effects on the dynamics of fish populations. However, knowledge of the underlying mechanisms and likely future trajectories is rather limited (see Rijnsdorp *et al.* 2009; Drinkwater *et al.*, 2010). First, there is uncertainty about the future development of the ocean climate itself, as various aspects will be influenced such as circulation patterns, air and sea surface temperatures, frequency and intensity of storm events, precipitation patterns, pH and river run off. Second, fish have complex life cycles comprising several life history stages, differing in their sensitivity to climate effects (Graham and Harrod, 2009). We summarise the known effects of climate change at the individual and population scale on fish physiology, growth, reproduction, distribution and abundance, and known effects on assemblages, communities and ecosystems.

### *Physiology and metabolism: the acute response to thermal stress*

Changes in temperature will have a direct impact on the physiology and metabolic processes of fish, which will in turn influence energy allocation, and consequently the life histories and demography of populations and species (Atkinson, 1994; Charnov and Gillooly, 2004). When faced with physiological stress, such as temperature change, individuals have four options: tolerate the stress, move or migrate, adapt physiologically or die (Schmidt-Nielson, 1973; Pörtner and Knust, 2007). Individuals are characterised by relatively narrow temperature and salinity tolerances, limiting their ecological habits and distribution (Wood and McDonald, 1997). Tolerances, such as to temperature variation, may change with season and age. A review of the upper and lower lethal temperatures of various marine fish species indicated that thermal tolerance changed markedly with latitude (Rijnsdorp *et al.*, 2009). The range of tolerable temperatures was narrower in fish inhabiting high and low latitudes and wider for fish inhabiting intermediate latitudes. Furthermore in some species, egg and larval stages have been observed to have a narrower range of tolerable temperatures than other life-history stages (specifically juveniles) making these early life stages more vulnerable to changes in temperature (Portner and Farrell, 2008). Increases in temperature, changes in precipitation, and atmospheric gas concentrations resulting from climate change may benefit some species (e.g. in temperate regions) by increasing growth, reproductive capacity and metabolic efficiency. However, these benefits will only occur up to a point. As temperature increases beyond an individual's thermal optimum, the ability to extract oxygen from the water decreases, and energy is more likely to be diverted away from movement, growth and reproduction into maintenance metabolism, ultimately constraining the tolerance of individuals (e.g. Björnsson and Steinarsson, 2002).

### *Migration, movement, invasion and distribution changes*

Individual fish that are unable to tolerate ambient conditions may migrate to locations with more thermally optimal habitats (e.g. MacCall, 1990; Blanchard *et al.*, 2005b). Such individual-based decisions, combined with changing habitat size and quality, may result in geographic range expansion and invasions of new coastlines and sea areas and reductions in abundance and range size of others (Francour *et al.*, 1994). Adult fish in particular may adjust their migratory patterns following food availability and become the targets of new fisheries as a result (Reid *et al.*, 2001). In Europe, offshore fishes with southerly distributions are increasing in abundance and expanding their range into the North Sea and other northerly waters. Examples include John Dory (Zeus faber), red mullet (Mullus surmeletus), anchovy (Engraulis encrasicolus), sardine (Sardina pilchardus) (Quero, 1998; Beare *et al*., 2004; MacKenzie *et al*., 2007) many of these are subject to new and emerging fisheries.

Considerable shifts in the geographic and depth distribution of Northeast Atlantic fish species have already been identified and linked to climate change (Perry *et al*., 2005). Southerly species increased their depth range, e.g. plaice (Pleuronectes platessa), or extended their range centres or range boundaries northwards. Northerly species contracted and retracted northwards. The rate of distribution change was greatest for species with faster life histories and smaller body sizes. Species and assemblages are deepening coherently as their preferred thermal habitat (isotherms) deepen (Dulvy *et al*., 2008). Similarly, the distribution of intertidal invertebrates is changing, with southerly limpets, topshells and barnacles increasing their range around UK coastlines (Mieszkowska *et al*., 2006). Northward range shifts associated with coastal warming were observed in Californian coastline invertebrates, with eight out of nine southern species increasing in abundance and five out of eight northerly species becoming less abundant since the 1930s (Barry *et al*., 1995; Sagarin *et al*., 1999). These changes reflect the impacts of both climate and fishing. For individual fish, tolerance to temperature change can vary significantly; indeed individual North Sea cod may tolerate temperatures considered too warm for optimal growth (Neat and Righton, 2007). This reflects the complexity of the impacts of future climate on species distribution.

Cheung *et al*. (2009) investigated the global patterns of climate impacts on marine biodiversity by projecting the distributional ranges of a sample of 1066 exploited marine fish and invertebrates up to the year 2050 using a dynamic bioclimate envelope model. These projections showed that climate change could lead to numerous local extinctions in the sub-polar regions, the tropics and semi-enclosed seas. Localised extinctions have also been projected at the edges of current ranges, including in freshwater and diadromous species (Brander, 2007; Drinkwater, 2005), and within the Mediterranean Sea (Lasram *et al*., 2010). Simultaneously, species invasion was projected to be most intense in the Arctic and the Southern Ocean. The authors suggested species turnovers of over 60% of the present biodiversity, with the potential for these ecological disturbances to disrupt ecosystem services and fisheries.

Building on this work Cheung *et al*. (2009) attempted to predict changes in catch potential of exploited marine fish and invertebrates under various climate change scenarios. Maximum catch potential declines considerably in the southward margins of semi-enclosed seas while it increases in poleward tips of continental shelf margins. Such changes are most apparent in the Pacific Ocean. Among the 20 most important fishing exclusive economic zone (EEZ) regions in terms of their total landings, EEZ regions with the highest increase in catch potential by 2055 include Norway, Greenland, the United States (Alaska) and Russia (Asia). On the contrary, EEZ regions with the biggest loss in maximum catch potential include Indonesia, the United States (excluding Alaska and Hawaii), Chile and China. Many highly-impacted regions, particularly those in the tropics, are socio-economically vulnerable to these changes.

### *Changing timing of ecological events*

On land, increases in temperature are bringing forward the onset of springtime and delaying the onset of autumn. Similarly, in the sea biological events are happening earlier in the seasonal cycle, and there have been marked changes in the seasonal distribution and abundance of plankton (Richardson and Schoeman, 2004) and in the maturation of fish (Morgan *et al.*, 2010), their spawning (Sundby and Nakken, 2008) and fish larval abundance (Greve *et al.*, 2005), for example. The timing of migrations and peak abundance of squid and fishes varies with the North Atlantic Oscillation (Sims *et al.*, 2001, 2004). Change in migration phenology has been described for the flounder Platichthys flesus, which has been shown to undertake a spawning migration 1-2 months earlier when conditions are cooler. This may seem paradoxical at first, given our usual expectation that organisms will migrate earlier during warmer years. In the English Channel region however, freshwaters, estuaries and shallow marine environments are colder in winter than the deep offshore waters. Flounder make their annual winter migration to these warmer deep waters to breed, and the timing of migration appears to be triggered by the onset of low temperatures. Recently published evidence from ichthyoplankton sampling suggests that other winter breeding species in the English Channel region also spawn earlier in cooler years, while summer spawning fish tend to spawn later (Genner *et al.*, 2010; Greve *et al.*, 2005). Together this evidence suggests that fish spawning and migration phenology may be spatially variable and highly dependent on local differences in thermal regimes. For example, veined squid (Loligo forbesi) migrate eastwards in the English Channel earlier when water in the preceding months is warmer. Higher temperatures and early arrival correspond with warm (positive) phases of the North Atlantic Oscillation (NAO). The timing of squid peak abundance advanced by 120-150 days in the warmest years ("early" years) compared with the coldest ("late" years).

A key concern with changing timing of annual recurring life cycle events is that is will lead to a decoupling or mismatch between consumers and their prey resource. The degree of spatial and temporal overlap of the spring phytoplankton bloom with the timing and spatial distribution of the spawning of eggs into the surface waters strongly influences larval fish survival, and hence recruitment success (year class strength) of important fish species (Platt *et al.*, 2003). The North Atlantic Oscillation (NAO) influences sea temperature and the timing of phytoplankton blooms and other ecological processes in the North Atlantic (Reid *et al.*, 1998; Irigoien *et al.*, 2000). Temperature-driven acceleration of egg development times may result in fish and zooplankton eggs hatching prior to the peak in abundance of their main food source - phytoplankton - resulting in a mismatch between trophic levels and functional groups (Edwards and Richardson, 2004). In the North Sea, phytoplankton blooms have generally advanced more in response to warming than have their zooplankton grazers (Hays *et al.*, 2005).

### *Assemblage, community and ecosystem effects of climate change*

The changing distribution and abundance of species is likely to affect the structure and function of communities and ecosystems. Recent analyses of changing fish distributions indicate that temperate fish communities are likely to be composed of increasing numbers of smaller-bodied species of southerly biogeographic affinity, with less contribution from larger-bodied species with boreal, northerly affinity (Blanchard *et al.*, 2005a; Drinkwater, 2005; Perry *et al.*, 2005). The change in relative contribution of southern and northern species to fish communities has been observed in the North Sea and the Bering Sea (Perry *et al.*, 2005; Wang *et al.*, 2006; Dulvy *et al.*, 2008). This simplified summary of community and ecosystem change is relatively conservative; little is known of the effects of changing phenology on predator-prey relationships, and there is also uncertainty about overall effects of temperature and the other variables describing climate change on ecosystem properties such as production and turnover. Specific modelling studies for Australian waters (Brown *et al.*, 2010) suggest increases in primary production and hence ecosystem biomass. Overall, however, predicting the resulting response of populations to primary production change is complicated by predation and competition interactions.

Even though commercial finfishes may be less impacted by ocean acidification than is the case with commercial shellfish, in terms of direct physiological effects, they may be impacted by changes in the marine food-web. Larvae and juveniles of most fish are reliant on planktonic crustaceans which may or may not be impacted by future ocean acidification. As adults, many commercial fish species (e.g. haddock and plaice) are also reliant on bivalve molluscs or echinoderms which are predicted to decline in the future as a result of ocean acidification (Fabry *et al*., 2008).

### *Effects of changing aquatic ecosystems and fish ecology on fisheries*

Climate change can affect fisheries ecosystems in complex and sometimes contradictory ways. This makes it difficult to assess net impacts. For example, freshwater lakes have been predicted to increase in productivity across trophic levels as a consequence of the effect of warming on metabolism and production (Regier and Meisner, 1990). However, the warming effect is often associated with other physical changes which can have countervailing effects, such as thermal stratification resulting from lighter winds. These may result in anoxic conditions or less intense upwelling and/or seasonal mixing, which may cause fish mortality or reduced primary productivity. This is not a comprehensive review and we have not considered open ocean ecosystems, but for a fuller treatment see Stenseth *et al.* (2005), Barange (2002), Brander (2006) and Lehodey *et al.* (2006).

#### *Upwelling systems*

Climate-sensitive upwellings of nutrient-rich waters support huge catches of sardines (Sardinops sagax) and anchovy (Engraulis mordax), primarily off Peru and Chile. Catches of small pelagic fishes have been as high as 11 million tonnes per year, representing more than 10% of world capture fish production (FAO, 2004). However, these show pronounced fluctuations often associated with ENSO effects on upwelling dynamics and productivity (Lehodey *et al*., 2006). The strength of upwelling off the South American coastline is strongly determined by the ENSO phase, with warm phases associated with a lower thermocline, which reduces phytoplankton production through inhibited upwelling of nutrients. As a result sardine move southward. However, anchovies are more constrained and become more accessible to fisheries as they aggregate in dense coastal pockets of colder water. During the 1972 El Niño, anchovies were so highly concentrated on the coast that 170 000 tonnes were caught on one day (Lehodey *et al*., 2006).

In coastal western Africa fisheries, catches of small pelagic fishes also track the strength of the upwelling pulses, which are largely driven by El Niño-like effects on eastern boundary current circulation and local wind stress (Binet *et al*., 2001; Binet, 1997). The frequency of ENSO events is projected to increase with global warming (Bakun, 1990). This has obvious implications not just for coastal fishers whose fishing range is constrained by technology and conditions, but also major industrial fisheries and export-derived incomes (see the sections below on the social and economic impacts of climate change).

### *Temperate shelf waters*

Climate change is shifting target species northwards in the northern hemisphere (southwards in the southern hemisphere) and at the southerly extent of their range reducing the productivity and recovery capacity of some species. For example Atlantic cod (Gadus morhua) growth, recruitment, abundance and distribution are all strongly influenced by climate (Brander, 2000). Some important stocks, including those in the North Sea cod produce fewer recruits in years when winter sea surface temperature is warm (Planque and Fredou, 1999), whereas those at the northerly limit benefit from warm conditions and exhibit enhanced recruitment. During the late 1960s and early 1970s in the North Sea, cold conditions were correlated with a sequence of positive recruitment years in cod, haddock and whiting (Brander and Mohn, 2004) and subsequently high fisheries catches for a number of years to come. However, in more recent years, a warming climate has prevailed and year class strength has been weaker than average.

Extensive fishing may cause fish populations to be more vulnerable to short-term natural climate variability (O'Brien *et al.*, 2000; Walther *et al.*, 2002; Beaugrand *et al.*, 2003), by making such populations less able to "buffer" against the effects of the occasional poor year classes. Conversely, long-term climate change may make stocks more vulnerable to fishing, by reducing the overall "carrying capacity" of the stock, such that it might not be sustained at, or expected to recover to, levels observed in the past (Jennings and Blanchard, 2004). Cook and Heath (2005) concluded that if the recent warming period were to continue, as suggested by climate models, stocks which express a negative relationship with temperature (including cod) might be expected to support much smaller fisheries in the future. In the case of cod, climate change has been estimated to have been eroding the maximum sustainable yield at a rate of 32 000 t per decade since 1980.

Older and larger cod have lower optimal temperatures for growth (Bjornsson *et al.*, 2001) and the local distribution of cod is known to depend on depth and temperature (Ottersen *et al.*, 1998; Swain *et al.*, 2003). Blanchard *et al.* (2005b) used information on optimal temperatures for growth and suggested that in years when stock size is low, catches are largely confined to regions with near-optimal bottom temperatures. Conversely, when population size is high, catches are spread across a larger area including regions with suboptimal temperatures. The authors demonstrated that spatial extent of optimal habitat appears to have decreased from 1977 to 2002, reflecting a gradual warming of the North Sea. This is particularly worrying given that the remaining, highly aggregated, stocks would be especially vulnerable to over-harvesting.

Cod are known to be capable of moving large distances (approximately 1000 km), and hence could theoretically relocate to anywhere in the North Sea. However, a study by Neat and Righton (2007), based on observations of the temperature experienced by 129 individual cod (using data storage tags), suggested that in the summer most of the individuals in the south experienced temperatures considered suboptimal for growth. Cooler waters were easily within the reach of these cod and a small number of individuals migrated to areas that allowed them to experience lower temperatures, indicating that the cod had the capacity to find cooler water. Most however, did not, suggesting that cod could be trading between thermally optimal habitats and requirements for prey, shelter and reproduction.

Climate change-induced warming is expected to have adverse effects on some exploited invertebrates such as abalone (Haliotis spp.). Warm temperatures are known to increase the onset of withering syndrome, a fatal abalone disease, and to halt growth and reproduction of red abalone (Vilchis *et al.*, 2005). By contrast, year-class-strength in scallops around the Isle of Man are, on average, positively related to seawater temperature in the spring (Shephard *et al.*, 2010). The gonads of adult scallops are also larger, indicating higher egg production, in warmer years.

Historic studies can be used to provide some information on the possible effect of climate change on fish stocks. Cod and halibut (Hippoglossus hippoglossus and Reinhardtius hippoglossoides) catch records in the Barents and White Sea from the 17th and 18th centuries suggests catches were much lower in cooler periods (Lajus *et al.*, 2005). Similarly, Southward *et al.* (1988) suggested that sardine were more abundant in south-east England when climate was warmer (e.g. 1590 to 1640), whereas herrings were more abundant in cooler times (e.g. the "little ice age" of the late 17th century).

Despite all these expected direct effects of climate change on fisheries, Harley *et al.* (2006) note that abiotic changes and subsequent biological responses will be complex. They note that changes in ocean chemistry may be more important than changes in temperature for the performance and survival of many organisms. Furthermore, climatic impacts on one or a few "leverage species" may result in sweeping community-level changes. In turn, synergistic effects between climate and other anthropogenic variables, particularly fishing pressure, will likely exacerbate climate-induced changes. Indeed, in the short term, it is often effective management of fish stocks that is needed, to return the populations to relative health in the short term (Kell *et al.*, 2005). A diversity of healthy stocks may then provide a greater buffer against the impacts of climate change on fish recruitment success and other direct and indirect impacts (Hilborn *et al.*, 2003).

### *Coral reefs*

Coral reef coasts provide diverse, productive and accessible open livelihoods centred on fisheries and aquaculture resources, which are particularly attractive and important for poor and migrant people (Whittingham *et al.*, 2003). Variation in natural resource systems are expected to occur with increased frequency and increased intensity of shocks, such as bleaching events and hurricanes, and the degradation and loss of resilience of coral reefs e.g. associated with ocean acidification (Hughes *et al.*, 2003; Bellwood *et al.*, 2004). The diversity and abundance of reef fishes is correlated with the extent and architectural complexity of coral reefs (Friedlander and Parrish, 1998). The loss and degradation of coral reefs through climate change can be expected to reduce the abundance and diversity of fishes, with negative impacts for subsistence and artisanal fisheries that provide important livelihoods and a source of protein and micronutrients for coastal and island populations.

The acute short-term impacts of coral bleaching mortality have had a relatively minor impact on fish assemblages to date. Events such as the 1998 mass coral bleaching in the Indian Ocean have not been accompanied by obvious negative short-term bio-economic impacts for coastal reef fisheries (Grandcourt and Cesar, 2003; Spalding and Jarvis, 2002; Bellwood *et al.*, 2006). However, a longer term study of Seychelles fish assemblages has indicated that responses may lag long after the coral mortality event, due to the loss in complex substrate that smaller fishes depend upon. Fish assemblage structure appears to be determined by the degree of bio-erosion and collapse of the dead reef architecture (Graham *et al.*, 2006). The collapse of reef skeletons resulted in local extinctions, particularly of obligate corralivores, substantial reductions in species richness, reduced taxonomic distinctness, and a loss of species within key functional groups of reef fish, particularly planktivores, corralivores and herbivores (Graham *et al.*, 2006), with reduced recruitment success and potential population collapse (Graham *et al.*, 2007). Following the loss of Caribbean coral cover there has been region-wide collapse in the complexity of reefs, due to disease-induced die-off of structure-forming Acropora corals in the later 1970s and the subsequent renewed phase of collapse following the 1998 ENSO bleaching event (Alvarez-Filip *et al.*, 2009). This renewed phase of collapse coincides with the region-wide decline in reef fishes (Paddack *et al.*, 2009). Coral reefs are already suffering from overfishing in many parts of the world (Newton *et al.*, 2007), which, when combined with the effects of coral mortality and reef architecture collapse, can only further diminish coral reef fish productivity (Sadovy, 2005; Warren-Rhodes *et al.*, 2003). The loss of fish productivity is anticipated to have substantial negative consequences for island and coastal communities (Whittingham *et al.*, 2003).

### *Freshwater lakes*

Freshwater lakes act as microcosms for the impacts of climate change in marine waters. At the most extreme, lakes such as Lake Chad can dry up in particular years. Impacts of climate change have been found in Lake Baikal, with significant warming of surface waters and long-term changes in the lake's foodweb, and corresponding increases in chlorophyll a and some zooplankton grazers (Hampton *et al.*, 2008). In the deep African Rift Valley lakes, such as Lake Tanganyika, climate change has been associated with increases in surface water temperature, reduced vertical mixing of water, reduced primary productivity and reduced fish catch per unit effort, which has driven fishers to other lakes (Verburg *et al.*, 2003; O'Reilly *et al.*, 2003; Allison and Ellis, 2001). In Lake Tanganyika, the surface water temperature has risen over the last century. This has increased the stability of the water column, which along with a regional decrease in wind velocity has contributed to reduced mixing, decreasing deep-water nutrient upwelling and entrainment into surface waters. This has decreased primary productivity by about 20%, and decreased fish yields as a result (Verburg *et al.*, 2003; O'Reilly *et al.*, 2003). Water levels and surface areas of some large, shallow African lakes (such as Lakes Chilwa, Bangweulu and Chad) fluctuate with changes in ENSO (Jul-Larson *et al.*, 2003). These fluctuations are mirrored by changes in fishing activity and catches (Allison and Mvula, 2002).

### *Rivers and estuaries*

The impact of climate change on river fisheries and fisher livelihoods will vary among river basins according to regional differences in the forecasted effects on the water temperature, and on the hydrological regimes of rivers and their floodplains.

Increased temperatures have been shown to negatively affect the survival of juvenile summer chinook salmon (Oncorhynchus tshawytscha) in wide and warm streams, and positively affect survival in narrow cool streams of the Salmon River basin, Idaho (Crozier and Zabel, 2006). Stream temperatures in this basin have been increasing steadily since 1992. It has been argued that few North Atlantic fish species will be as intensely affected by climate change as Atlantic salmon (Stenseth *et al.*, 2005; Jonsson and Jonsson, 2009). Whalen *et al.* (1999) reported that peak migration of salmon occurs later in spring for tributaries with lower temperature. Also, annual variation in the timing of peak migration of Atlantic salmon is related to variation in annual temperatures (McCormick *et al.*, 1998). Low water flow in rivers can also have a deleterious effect on upstream migration of salmon returning from the sea to spawn (Solomon and Sambrook, 2004). Studying radio tagged salmon in four English rivers, they noted that when water flows were relatively high, the majority of migrating adult salmon passed through estuaries and into the rivers with a minimum of delay. However, when river flow was low (drought years), most fish arriving from the sea did not pass quickly into freshwater but remained in the estuary or returned to sea for several months. Many fish subsequently failed to enter the river even when favourable flow conditions returned, possibly as a result of lost physiological opportunity (Solomon and Sambrook, 2004). Jonsson and Jonsson (2009) provided a detailed review of the likely effects of climate change on salmon and sea-trout, with particular reference to water temperature and river flow.

The effects on river hydrology, driven largely by changing patterns of precipitation and run-off, are currently difficult to predict with certainty at the river basin scale (McCarthy *et al.*, 2001; Conway *et al.*, 2005). This uncertainty propagates to our predictions of the impacts on river fisheries. In addition to the direct effects of climate change (e.g. increased atmospheric and water temperatures), climate change will have indirect impacts. Increased precipitation and evapotranspiration will change the hydrology of inland waters and rivers. In turn, anthropogenic impacts on water use and extraction will further impact downstream processes (see below).

Fisheries production in many Asian countries relies on rivers that arise in the Himalayan Mountains, such as the Indus, Brahmaputra, Ganga and Mekong. The effect of changes in the hydrological regime will vary amongst river basins, according to regional differences, although forecasts of these changes are often lacking. Climate change will cause earlier season peak flows and reductions in flow overall, attributable to reduced snowfall and melting glaciers (Barnett *et al.*, 2005a). Changing timing of peak flows, higher summer temperatures and lower oxygen concentration are likely to reduce larval fish survival (Gibson *et al.*, 2005) and thermally optimal habitat by 15-30%, particularly for cool and cold-adapted species (Mohseni *et al.*, 2003).

Reductions in river discharge (water availability) stemming from climate change or increased water withdrawal tends to reduce freshwater biodiversity. In rivers with reduced discharge, up to 75% (quartile range 4-22%) of local fish biodiversity would be headed toward extinction by 2070 because of combined changes in climate and water consumption. This effect would be disproportionately high for the world's poorest countries (Xenopoulos *et al.*, 2005). The consequences for river fisheries are uncertain and depend on the interaction of local rainfall and glacier melt profiles and the importance of dry versus wet season water levels for fish productivity.

Increased run-off and discharge rates might increase fish yield through more extensive and prolonged inundation of floodplains, such as in the Ganges Basin (Welcomme, 1985). Fish abundance and catches tend to be higher depending on the depth and duration of floodplain inundation in the wet season. In Bangladesh a 20-40% increase in flooded area could raise total annual yields by 60 000-130 000 t (Halls *et al.*, 2006; Mirza *et al.*, 2003). These elevated yields may not be realised as a key bottleneck to river fish populations is the amount of water remaining in the dry season, when the area of water remaining can be as low as 5% of the floodplain area (Halls *et al.*, 2001; Halls and Welcomme, 2004). According to the available models, benefits may arise during the flood season, but these must be offset by reductions to yield predicted during the dry season. Increased peak flows associated with increased inland precipitation due to climate change is likely to increase the run-off of fertiliser and sewage into coastal waters. Increased nutrient loading may trigger algal blooms, leading to potential poisoning of fish and humans, and directly affect those countries farming fish in coastal waters (Anderson, 1997).

Estuaries and wetlands are productive and rapidly changing environments, but are less resilient to climate change because many native species currently live near their tolerance limits (Roessig *et al.*, 2004). Global warming-induced changes in ocean circulation and river flows are anticipated to increase marine intrusion or freshwater plumes, increase eutrophication and lower oxygen levels and are predicted to destroy saltmarsh and intertidal habitats resulting in declines in native species and increases in invasive species (Roessig *et al.*, 2004).

### *Climate hazard effects on coastal communities*

Climate change has the potential to affect coastal and inland fisheries systems through increased risk of disaster and health problems. Over one third (37%) of the global human population lived within 100 km of the coast in 1994 and this proportion is expected to increase over time (Cohen *et al.*, 1997). Globally, the number of fishers has increased considerably over the last two decades. Fisheries have emerged as one of the last refuges of the impoverished. With reduced opportunities and incomes in other sectors of the economy (often associated with climatic changes inland), fishing has been viewed as an attractive option, and this has contributed significantly to the overexploitation of marine resources and the deterioration of the coastal environment (Tietze *et al.*, 2000). For example, in the 1970s and 1980s difficulties in the agriculture sector led to increases in small-scale fisheries in the Philippines and in Senegal during this period (Tietze *et al.*, 2000). As more and more people enter fisheries, so they are faced with declining catches.

Sea level rise resulting from thermal expansion of the oceans and melting ice caps and glaciers may inundate almost 1 million km2 of coastal land, dependent upon the climate projection (Liu, 2000). This may destroy coastal habitats by inundating them faster than the ability of accretion and plant colonisation to create wetland habitats (Daniels *et al.*, 1993). Sea level rise may reduce intertidal habitats, while the increased water column depth will also alter hydrodynamic coastal processes, affecting shoreline configuration and sedimentation patterns. This may be particularly severe in countries such as Bangladesh, Guyana, and low-lying coral islands in the Pacific and Indian Oceans (Dickson, 1989). The effects of sea level rise may be exacerbated by other anthropogenic activities, such as coastal development and mangrove forest clearance. These activities, which are done to support high export value shrimp farming in Asia, are reducing coastal defences, biodiversity and food security options of vulnerable countries and people (Adger, 2000; Danielson *et al.*, 2005). As a result, new approaches to the design of aquaculture farms that utilise the protection provided by mangroves have been developed to reduce these impacts.

Sea level rise will interact with other climatic changes including changes in storm surge heights, resulting from increasingly strong winds and low pressure events, and increased frequency and severity of storms, flooding and hurricanes or cyclones. These events are likely to result in tragically increased loss of life among fishermen, lost fishing days, damage to the fishing gears and boats of coastal communities, and increased damage to infrastructure (Adger *et al.*, 2005b). For instance, during Hurricane Gilbert in 1988, Jamaican fisherfolk lost 90% of their fish traps resulting in a huge loss of revenue and high cost of repairs, as well as resulting in the inability to resume fishing activities promptly after the disturbance (Aiken *et al.*, 1992).

Increased flooding resulting from climate change is anticipated to increase the risks of water-borne infectious diseases. For example, ENSO events are often followed by an upsurge in cholera cases in Bangladesh coastal communities and malaria epidemics in parts of South Asia and South America (Kovats *et al.*, 2003; Pascual *et al.*, 2000). Marine bacterial and fungal growth rates are positively correlated with temperature, increasing human, coral and fish disease risk (Harvell *et al.*, 2002). Shifts in the range and impacts of diseases are likely to be exacerbated by other impacts of climate change on organisms whose metabolic resources are being diverted to deal with the stresses of increased temperatures. In tropical areas, the increased bleaching and disturbance of coral reef systems is likely to increase the risk of ciguatera poisoning - a tropical disease caused by ingesting a poison found in certain marine fishes (Wilkinson *et al.*, 1999). These effects are often exacerbated in small coastal and riparian rural communities where systems for potable water, sewage and drainage may be limited (Badjeck *et al.*, 2010).

Peperzak (2003) attempted to evaluate whether harmful algal blooms (HABs) are likely to occur more or less often over the next 100 years in the North Sea as a consequence of future climate change. Climate change is expected to lead to an increase in extreme precipitation events (intense rainfall), and this will result in sudden pulses of freshwater being released at the coast and hence intermittent salinity stratification. During such conditions, surface phytoplankton benefit from a decrease in salinity, greater availability of terrestrial nutrients, rapid increases in daily irradiance and higher water temperature, all of which are conducive to bloom formation. During recent years there has been an apparent increase in the occurrence of HABs in many marine and coastal regions around the world (Anderson *et al.*, 2008). Increase in the prevalence and distribution of HABs may have a substantial human health impact, and serious economic effects due to closure of commercial fisheries, losses of fish in aquaculture facilities, public health sector costs, and related environmental and socio-economic disruption.

### *Identification of regions vulnerable to the economic impact of climate change on fisheries systems*

The observed and anticipated impacts of climate change on biophysical systems will have significant potential impacts that themselves represent opportunities, challenges and potential dangers for societies and economies. Current scientific knowledge of impacts and vulnerabilities is based on models that rely on future socio-economic scenarios and interpretative reviews of location-specific case studies (Arnell, 2004; Smit and Pilifosova, 2001). A major recent advance is the development of a quantitative indicator-based implementation of the vulnerability assessment frameworks outlined in the Intergovernmental Panel on Climate Change and the Millennium Ecosystem Assessment (Kasperson *et al.*, 2005; McCarthy *et al.*, 2001; Turner *et al.*, 2003). Allison *et al.* (2009) used such an indicator-based framework to assess the vulnerability of national economies of OECD and non-OECD countries to the impacts of climate change on fisheries systems.

Vulnerability can be defined as a combination of the extrinsic exposure of groups or individuals to a hazard, such as climate change, their intrinsic sensitivity to the hazard, and their capacity to modify exposure to, absorb, and recover from losses stemming from the hazard, and to exploit new opportunities that arise in the process of adaptation (Adger *et al.*, 2005a; Brooks *et al.*, 2005; Kasperson *et al.*, 2005; O'Brien *et al.*, 2005; Smit and Wandel, 2006). At sub-national and regional scales, vulnerability is regarded as a context-specific local property that varies by socio-economic grouping and geographically within and among countries (O'Brien *et al.*, 2005; Metzger *et al.*, 2005). However, vulnerability can be influenced by national policies within the context of larger (regional and global) and smaller scale (individual, community and district) processes.

Allison *et al.*'s approach to measuring vulnerability was used to identify those countries that have the greatest predicted exposure to climate change, high dependence on fisheries and low capacity to respond to social and economic change. Given the complex of inter-related climate variables through which fisheries may be affected (including water temperature, precipitation, evaporation, extreme events, changes to ocean currents), the underlying driver of all these changes – projected surface air temperatures for 2050 – was used as a proxy measure of climate change risk exposure. The approach assumes that warming-related impacts upon physical and biological variables affecting fisheries production and fishery operations will be greater in areas where projected surface air temperature increases above the landmass are greater. Sensitivity of the national economy to climate risk exposure was assessed as a composite index of dependence upon fisheries, calculated on the basis of national fishery landings and the contribution of fisheries to employment, production, dietary protein and export income. The index of the adaptive capacity combined human development indices (HDIs: health, education and governance) with size of economy (total gross domestic product), based on the assumption that countries with high levels of economic and human development have the resources and institutions necessary to permit adaptation.

Warming will be greatest for high latitudes, but overall the most vulnerable countries lay in the tropics. Surface temperature changes were predicted to be highest in northern parts of North America, Europe and Asia (Table 1.A1.1 in the annex). The OECD countries that would experience the highest land surface temperature changes included: Canada, Finland, Hungary, Japan, Korea, Portugal, Sweden, Turkey and the USA (Table 1.A1.1). Overall the most fisheries-dependent countries were found throughout Africa, Asia and the Americas. The most fisheries-dependent OECD countries included Iceland, which falls within the upper quartile, followed by Canada, Japan, Mexico, Norway, Portugal and Spain (Table 1.A1.1). OECD countries had the highest adaptive capacity with almost all countries falling within the upper quartile, apart from Turkey, Hungary and Mexico (Table 1.A1.1). The countries with the lowest adaptive capacity were concentrated almost exclusively in Africa and tropical Asia. Virtually all Saharan and sub-Saharan African countries, except Namibia, Botswana and South Africa, had low adaptive capacity. The Asian countries with lowest adaptive capacity were Pakistan, Bangladesh, Laos PDR and Nepal (Table 1.A1.1). As a result of the high adaptive capacity of OECD countries, almost all were among the least vulnerable to the socio-economic effects of climate change on their fisheries sectors. The most vulnerable OECD country was Turkey, due to relatively low adaptive capacity, high exposure to climate change and moderate fisheries dependence derived from a relatively high fisheries catches and number of fishers in the economically active population (Table 1.A1.1; Figure 1.A1.1). Those regions most vulnerable to climate-induced changes in fisheries were in the Western Sahel and Central Africa, north-western South America, and, in Asia, Yemen, Pakistan, Bangladesh and Cambodia.

The national economies of OECD countries appeared to have relatively low vulnerability to the effect of climate change on the fisheries sector. This was largely due to the relatively high capacity to cope with and respond to the future challenges and opportunities presented by climate change. It should be emphasised that this indicator-based analysis does not suggest that there will not be significant effects of climate to fish, fisheries and aquatic ecosystems among OECD countries (both positive and negative). Much of our knowledge of the impact of climate variability on fish, fisheries and aquatic ecosystems comes from OECD countries and suggest the environmental, economic and social impacts are potentially large. However, compared to many other parts of the world, these countries have large, diverse economies and functioning social service provision that can help to reduce the social and economic disruption caused by climate-induced changes in employment and profitability in the fisheries. This analysis highlights the importance of building and maintaining social, economic and ecological resilience to ensure societies have the greatest opportunity to both cope with and take advantage of climate change.

## Social, economic and environmental consequences of the impact of climate change on the fisheries sector

The effects of climate change on the environment have been considered in detail above. Climate change also has the potential to affect the food security and livelihoods of the world's 36 million fisherfolk and 1.5 billion consumers who rely on fish for more than 20% of their dietary protein and as a source of key micronutrients (see Badjeck *et al.*, 2010). Here we highlight some examples of how global climate change and climatic variation are associated with changes in the social and economic factors associated with fishers and fishing communities.

### *Social impacts of climate change*

The impact of global warming on the fisheries sector in socio-economic terms is difficult to assess, not only because of the great uncertainty regarding the extent and rate of climate change, but also due to the uncertainty surrounding the impacts on bio-physical processes and how these propagate upwards through ecosystems to harvest or use ecosystem services. In addition to the effect of climate on natural resource systems, Arnason (2003) proposed that climate change may impact fisheries in at least two different ways: by altering the availability of fish to fishermen (direct impact) and by changing the price of fish products and fisheries inputs (indirect impact). This section focuses on the direct impact and the next section will provide examples of the indirect impact.

Changes in the availability of fish to fishers can occur through impacts of climate change and climate variability on stock distribution and abundance (Roessig *et al.*, 2004). Changes in the availability of fish products can affect total revenues and harvesting costs (net revenues) of fishermen, thus influencing the choice of target species. For example, the anticipated increased travel costs due to increased sea surface temperatures disproportionately caused a decrease in the number of boats targeting squid in a fishery off Monterey Bay, California (Dalton, 2001).

West Greenland's transition from a cod-fishing to a shrimp-fishing economy, *ca.* 1960-90, provides a case study in the human dimensions of climatic change. The southern town (Paamiut) was more specialised in cod fishing, with one of the largest fish processing plants in the North Atlantic. However, as the cod collapsed the human population declined due to out-migration. The climate- and overexploitation-driven declines in predatory cod resulted in increases in shrimp abundance (Worm and Myers, 2003). The more northerly town (Sisimiut) had less specialised fisheries pursuing multiple species, and once cod declined the fisheries focused on shrimp and the town grew rapidly in size as a result (Hamilton *et al.*, 2003). By contrast in Paamiut the small shrimp catches were insufficient to replace the large cod catches and support the large-scale industrial processing plant (Hamilton *et al.*, 2003). Two lessons were drawn from this example. First, socially important environmental changes result not simply from climatic change, but from interactions between climate, ecosystem and resource usage. Second, environmental changes affect people differentially and through interactions with social factors. Social networks and cohesion (social capital) are important, in addition to skills (human capital), investments (physical capital), and alternative resources (natural capital): all shape how the benefits and costs are distributed. (Hamilton *et al.*, 2003)

Fish distribution shifts may have "knock-on" impacts upon commercial fisheries catches because changes in migration or spawning location affect the "catchability" of individual fish to fishing gears. Fish populations may move away from (or towards) the area where particular fishing fleets operate and/or where spatial restrictions on fishing are in place. Also species distributions may migrate across the boundaries where quotas belong to different nations. A notable example might arise as a result of quota allocations between a non EU country and the EU. If, for example, species such as mackerel or herring move away from the EU sector, then EU fisheries may no longer be able to catch their full quota within indigenous waters, and hence there will be difficult political negotiations between nations with regard to future access to key fish stocks (*e.g.* Sissener and Bjørndal, 2005). The converse happened in October 2009 when North Sea mackerel appeared to have moved away from the Norwegian Sector, resulting in disagreements over permissible catches by Norwegian boats in EU waters. Norwegian vessels were forcibly evicted from Scottish waters by UK fishery patrol vessels once they had caught their allotted quota (see Fishing News, 9th October 2009). At the same time Iceland and the Faeroe Islands unilaterally claimed quota for mackerel, since the species had migrated westwards and had attained high abundance in their indigenous waters. International law provides that coastal states have sovereign rights to manage fisheries in waters under their jurisdiction. More than 90% of the global fish catch is estimated to be taken within waters under the jurisdiction of particular coastal states. With climate change in the future, we might anticipate more territorial disagreements of this type.

### *Economic impacts of climate change*

Here we address the second of Arnason's (2003) proposed impacts of climate change on fisheries sectors, *i.e.* indirect impacts on fishers due to changes in fisheries economics. Much of our knowledge of the economic impacts of climate change can be drawn from the effect of ENSO-induced climatic variability on fisheries targeting small pelagic plankton-feeding fishes.

The 1997/98 *El Niño* was the strongest in the last century. Chilean and Peruvian pelagic marine fish landings fell by 50% and 52%, respectively, and the value of their fish meal exports dropped by USD 8.2 billion. The share of world fish meal export market of these two countries decreased from 70% in 1997 to 49% in 1998. The pelagic marine fisheries were essential to both the Chilean and Peruvian economies. As almost 90% of the Peruvian and Chilean anchovy harvest was processed into fish meal, the huge reduction in exports caused a great deal of hardship in the already strained fishing industries and generated adverse long-term economic consequences (Caviedas and Fik, 1992).

A reduction in financial capital, for instance access to credits and loans, can also be observed as a consequence of climatic variability. In Peru, at the time of the 1997/98 *El Niño* event, a percentage of the catch was put into a recently privatised social security and health organisation for the industrial fishermen (Broad *et al.*, 1999). As a result of decreasing catches the agency's coffer quickly ran dry, leaving fishermen without a safety net and access to financial resources to cope with the difficult economic situation (Broad *et al.*, 1999). While infrastructure damages are recoverable, the time necessary for such endeavour can be critical for the fisheries sector and in countries where state assistance is minimal and financial capital limited the impact of extreme events could be damaging in the longer term.

Such patterns are not restricted to Peruvian-Chilean anchovy/sardine fisheries but co-occur throughout the world. Landings of the SE Asian mackerel purse-seine fishery experienced a dramatic decrease of 47.75% following the 1997/98 *El Niño*, due to changes in sea surface temperatures in the area between Chinese Taipei and Japan (Sun *et al.*, 2006). Based on comprehensive daily logbook records during 1982–99 and a fishing cost survey, the loss to the fishery was estimated to be USD 6.22 million for 1998 (Sun *et al.*, 2006).

Changes in migration routes and fish distribution can also affect fishermen; for instance increased travel time can lead to increased fuel and ice costs. Fluctuations in sea surface temperatures, such as driven by *El Niño* events, have significant effects on fishing effort in the albacore tuna, chinook salmon, sablefish and squid fisheries in Monterey Bay, California (Dalton, 2001). Fishing effort was defined by Dalton as the number of vessels or boats landing an individual species. Under a scenario of a 1.2 °C sea surface temperature increase corresponding to the ENSO events of 1983, the number of vessels or boats landing each species decreased. Decreases in effort ranged from 60% for the sablefish fishery to 400% for the squid fishery (Dalton, 2001). The anticipated increased travel costs due to increased sea surface temperature disproportionately decreased the number of boats targeting squid (Dalton, 2001). Decreased revenues for fishermen due to decline in total catch and stock abundance are commonly cited as a consequence of climate variability and change (Callaway *et al.*, 1998).

In Belize, Hurricane Mitch (1998) destroyed the main lobster and finfish fishing grounds of the northern part of the country in 1998. This translated into a loss in production of 65 000 lbs that year (Gillet, 2003). Direct losses to fishers in relation to the loss of fishing tackle and associated infrastructures as a consequence of the hurricane has been estimated at USD 1.2 million (Gillet, 2003).

Climate variability and increased sea-level rise, storminess and floods can lead to decreased fishing capacity and decreased access to markets. Storm and severe weather events can destroy or severely damage infrastructures and equipments such as port, landing sites and boats (Jallow *et al.*, 1999). For instance, during hurricane Gilbert in 1998, Jamaican fishermen lost 90% of their traps, resulting in a loss of revenue and high cost of repairs, as well as the inability to resume fishing activities promptly (Aiken *et al.*, 1992). In Antigua and Barbuda 16% of the fishing fleet was destroyed or lost, while 18% was damaged due to Hurricane Luis in 1995 (Mahon, 2002). The overall loss of the industry was estimated at 24% of the annual mean revenue.

In less developed countries, and particularly in the Least Developed Countries in West Africa, the mainstay of both artisanal and industrial fisheries is small pelagic fishes, such as sardines (*Sardinella* spp.) and mackerels (*Scomber* and *Trachurus* spp.). These species have relatively short life cycles and feed on plankton and consequently their dynamics and productivity are strongly influenced by climate-forced upwelling of nutrients from eastern boundary currents (Binet *et al.*, 2001; Binet, 1997). These fisheries are subject to exploitation by foreign fleets, mainly from the European Union, but also from Russia and Asia. Despite increasing catches by foreign fishing fleets, the economic growth and social benefits from marine resources have not been met for many western

African countries that host these fleets (Atta-Mills *et al.*, 2004; Alder and Sumaila, 2004). Further climate change-induced changes in fish catches may deepen these problems.

In developing Asian countries, small pelagic fisheries make a prominent contribution to the livelihoods of inshore fishers, as well as to protein consumption of poor households. However, decades of overexploitation have dramatically reduced small pelagic fish stocks in the region, and have increased the vulnerability of these stocks to adverse climate change (Briones *et al.*, 2005). Artisanal fishers in India, Thailand and the Philippines rely on the simplest gears and vessels and are highly dependent on small pelagic fisheries. A simulation analysis of the effects of a climate-induced reduction in small pelagic fish landings upon catch values suggests that modest gains in freshwater capture and culture and marine culture sectors will be massively overshadowed by the decline in producer income from the marine sector. This results in a substantial total economic loss to society, which varies in degree from country to country. The loss ranges in value from USD 53-210 million (India), USD 165-700 million (Philippines), USD 1-300 million (Thailand) depending on the level of decline in small pelagic fish catches, which ranges from 5% -20% (Briones *et al.*, 2005).

The warm *El Niño* event of 1997/98 resulted in nearly USD 15 million worth of damages to infrastructures in the Peruvian fishing sector (CAF, 2000). Rural fishing villages in the northern part of the country were damaged from heavy rains and were unable to get their products to markets due to washed out roads and bridges (Broad *et al.*, 1999). Macroeconomic consequences of climate variability and changes in the fisheries sector range from impacts to the labour market, industry reorganisation, to loss of export earnings to national economies due to declines of catches (Glantz and Thompson, 1981). Chile and Peru produce almost half of the world's fishmeal supply (Merino *et al.*, 2010; Mullon *et al.*, 2009). In Chile, the *El Niño* event of 1972/73 resulted in a decrease in catches of anchovies and cool-water species like sardines and hake which created an inflated demand for fish derivates (fish meal and fish oil). This led to an increase in world market prices (USD 325 per ton in 1975 compared with USD 90 per ton in 1965). It is worth noting that while some communities were adversely affected by the reduced stock of anchovies and sardines in the eastern pacific upwelling areas, fishermen in Denmark received near record prices for Baltic sprat and North Sea sand eel, a competing species for fishmeal production (MacKenzie and Visser, 2001). Modelling the future climatic and market forces on fishmeal production, Merino *et al.* (2010) note that the way society responds to climatic and fishing effects will define the sustainability of stocks, while market demand and the development of fishmeal substitutes will influence market dynamics within the system.

In addition to the effects of climate variability and change on fisheries systems there are likely to be considerable costs associated with other aspects of climate change. The likely ecological effects of ocean acidification are poorly understood, however there is convincing evidence for significant negative impacts on marine ecosystems, particularly for coral reefs and calcifying organisms in the southern ocean. The socio-economic effects are hard to determine but could amount to many billions of dollars. The vast majority of the studies that have been published on the impacts of ocean acidification so far have tended to focus on benthic or planktonic species that are of limited importance for fisheries and aquaculture. However, it is clear that commercial species of shellfish may be impacted in the future. At high pCO2 (low pH) the growth and shell formation of oysters and mussels seems to be impaired (Gazeau *et al.*, 2007) and in the north-west Pacific commercial oyster hatcheries are already reporting reduced survival of juveniles and hence reduced viability of aquaculture operations attributable to low pH in coastal waters. With an average annual increase of 7.9% over the last 30 years, global shellfish production reached 11.7 million tonnes in 2002, corresponding to a commercial value of USD 10.5 billion (Gazeau *et al.*, 2007). In a case study of US commercial fishery revenues, Cooley and Doney (2009) attempted to provide a first estimate of the economic effects of ocean acidification over the next 50 years using atmospheric CO2 trajectories and laboratory studies focusing especially on molluscs. In 2007, the USD 3.8 billion annual domestic ex-vessel commercial harvest contributed USD 34 billion to the US gross national product of which molluscs contributed 19% (USD 748 million). Assuming harvest decreases of 6%-25% accompany 0.1-0.2-unit pH decreases over 50 years (2010–60) results in losses of USD 0.6-2.6 billion through to 2060. Shellfish fisheries have grown in importance in many OECD countries in recent years (e.g. Canada, the UK and US) as finfish populations have dwindled; consequently ocean acidification represents a growing threat to fishing communities and economies in these countries.

The potential economic effects of climate change on coral reefs have been explored for the Great Barrier Reef, Australia. The contribution of reef-interested tourism was 68% of the regional Queensland economy, totalling AUD 1.4 billion (GBP 0.58 billion, May 2005 exchange rate) (Royal Society, 2005). Reduced Caribbean coral cover linked to climate-related disease outbreaks, more frequent and severe hurricanes and sea temperature increases are predicted to decrease annual fish production by up to 40% by 2015, a net revenue loss of between USD 95 million and USD 140 million for more than 100 000 fishers (Trotman *et al.*, 2009).

Arnason (2007) estimated the economic impact of climate change on fisheries and on the national economies of Iceland and Greenland. The author assumed that fisheries yields would increase by around 20% for the most important fish stocks (in particular cod and Atlanto-Scandian herring) in Iceland and up to 200% in Greenland over the next 50 years (based on projections from ACIA, 2004). The analysis then used econometric techniques based on economic growth theory to estimate the role of the future fisheries sector in the wider economy of each country. Somewhat surprisingly the dramatic increase in fisheries yields assumed for Iceland resulted in only miniscule increases in national GDP, despite the fishing industry currently accounting around 10% of GDP and 40% of export earnings. The accumulative impact of climatic warming on Icelandic GDP was only 4% by 2054, and given economic volatility and measurement errors, this level of economic growth is considered hardly detectable at the 95% significance level. Benefits for the national economy of Greenland were greater (a 40% increase in GDP by 2054) but this assumed an enormous increase in the fish stock (by 200%) and it should be remembered that the fishing industry in Greenland is the main source of non-government employment and local economic activity (over 90% of all exports).

## How can policy makers respond?

Policy makers can respond along three broad lines: pursue mitigation strategies, build social and economic capacity to adapt, and pursue a portfolio management approach across natural resource sectors (Dulvy and Allison, 2009).

### *Pursue mitigation*

Reducing carbon dioxide emissions to the atmosphere appears to be the only practical approach to mitigate against the degree of impact from anthropogenic climate change, with the aim of minimizing the probability of “dangerous” climate change and the risk of large-scale and long-term changes to ecosystems (Royal Society, 2005; Scholze *et al.*, 2006). Ocean acidification is a powerful reason, in addition to climate change, for reducing global $CO_2$ emissions. There appears to be no practical way to remove this additional $CO_2$ from the oceans after it has been absorbed, nor any realistic way to reverse its widespread chemical and probable biological effects (see the recent Royal Society report on *"Geoengineering the climate: science, governance and uncertainty"*; 2009). It will take many thousands of years for natural processes to remove this excess $CO_2$ and return the oceans to a level close to their pre-industrial state. Thus, it appears that the only practical way to minimise long-term consequences for the oceans is to reduce $CO_2$ emissions to the atmosphere (Royal Society, 2005).

The fisheries sector itself can only play a small part in reducing $CO_2$ emissions to mitigate against future climate change; the world's marine fishing fleets are estimated to burn 1.2% of global fuel oil used per year, equivalent to that consumed annually by The Netherlands (Tyedmers *et al.*, 2005). However, there may be synergies between emissions reductions, energy savings and responsible fisheries. For example, policy support for the following measures could contribute to all three of these goals:

- Raising awareness of the impacts of climate change, to ensure that the special risks to the fishery sector are understood and used to plan national responses to climate change, including the setting of mitigation targets through mechanisms such as the Kyoto Protocol.
- Reducing fuel subsidies granted to fishing fleets, to encourage energy efficiency and assist towards reducing overcapitalisation in fisheries.
- Supporting the use of static-gear – pots, traps, longlines and gillnets, which uses less fuel than active gear such as trawls and seines – and therefore emits less $CO_2$.
- Supporting the use of alternative fishing gears (*e.g.* semi-pelagic trawls rather than demersal trawls) that are more fuel efficient.
- Restoring mangroves and protecting coral reefs, which will contribute to $CO_2$ absorption, coastal protection, fisheries and livelihoods.

### *Maintain and build socio-ecological resilience, or adaptive capacity*

The effects of climate change are already apparent and foreshadow what is to come (McCarthy *et al.*, 2001; Parmesan and Yohe, 2003). Cutting $CO_2$ emissions tomorrow cannot immediately eliminate the effects of anthropogenic climate change, since it will take many decades to turn around changes that are already "locked in". Since climate change cannot be locally mitigated, minimisation of the impacts of climate change requires adaptation and the development of socio-ecological resilience (Adger *et al.*, 2005a). Societies, organisations and individuals have adjusted their behaviour in response to past climatic changes, and many are now contemplating adapting to altered future climatic conditions. Much of this adaptation is reactive, in the sense that it is triggered by past or recent events, but it is also anticipatory in the sense that it is based on some assessment of conditions in the future.

Adaptation to climate change can be defined as an adjustment in ecological, social or economic systems in response to observed or expected changes in climatic stimuli and their effects, in order to alleviate adverse impacts of change or take advantage of new opportunities (IPCC, 2001). Adaptation can involve both building adaptive capacity thereby increasing the ability of individuals, groups, or organisations to adapt to changes, and implementing adaptation decisions, i.e. transforming that capacity into action. Adaptation can be manifested in myriad ways: through market exchanges or through extension of social networks, or through actions of individuals and organisations to meet their own individual or collective goals. It can be undertaken by an individual or by governments and public bodies to protect their citizens.

In December 2009 Rashid Sumaila and William Cheung (writing in a report for the World Bank) attempted to establish the costs of adaptation to climate change in the fisheries sector worldwide. The analysis began by detailing the likely impact of climate change on the productivity of marine fisheries (more than 1 000 species) and, through that, on landed catch values and household incomes. Adaptation costs were then estimated based on the costs of restoring these revenue indicators to levels that would have prevailed in the absence of climate change. The impact of climate change on marine fisheries was assumed to primarily occur through changes in primary productivity, shifts in species distribution and through acidification of the oceans. The authors considered three scenarios that reflect these impacts. Climate change was predicted to lead to losses in gross fisheries revenues world-wide of USD 10-31 billion by 2050. In Europe (including the UK) the estimated annual cost of adaptation was between USD 0.03 and 0.15 billion which is relatively minor, compared to USD 1.05-1.7 billion of anticipated annual adaptation costs in East Asia and Pacific.

Options for adaptation can be considered at local and regional (national and international) scales. At local scales, action can be undertaken to promote diversity in ecological and local livelihood systems and to build legitimate and inclusive governance structures and social capital. Diversity in ecological systems and functionality can be maintained or enhanced through promoting sustainable use (Hilborn *et al.*, 2003). The same is true of diversified rural livelihood systems that have evolved in response to variations and uncertainties in fishery production systems (Allison and Ellis, 2001). As such any local or regional activity that seeks to achieve the World Summit on Sustainable Development goals; "to achieve a significant reduction in the current rate of loss of biological diversity by 2010", and "to maintain or restore stocks to levels that can produce the maximum sustainable yield, and on an urgent basis where possible for depleted stocks not later than 2015", thus will also contribute to adaptation to potential effects of climate change (WSSD, 2002).

At regional (national and international) scales, appropriate adaptation actions include pursuance of a mitigation strategy (see above), avoidance of perverse or harmful incentives for ecosystem degradation that increase sensitivity to hazards, promotion of early warning networks and structures and enhancement of disaster recovery through appropriate donor responses (Adger *et al.*, 2005b). The impacts of climate change events must be recognised by fisheries management agencies and the fishing industry and factored into management plans (Allison *et al.*, 2005). Actions that are likely to enhance adaptive capacity include a move toward sustainability, removal of harmful subsidies, increasing management adaptability, and promotion of diverse, less capital intensive fisheries. Below we briefly highlight some actions that can enhance local and regional capacity to adapt.

### *Move toward sustainable fisheries*

Many stocks are managed to hover around the "limit" (*i.e.* lowest permissible) reference levels, although improvements have been seen in recent years (Rosenberg *et al.*, 2006; Pitcher, 2001). The recovery and maintenance of fisheries resources closer to the larger stock sizes implied by target reference points will provide greater robustness to uncertainty in fishing mortality and the direct and indirect effects of climatic variability (Cabinet Office, 2004). This will also benefit fishers through sustainable and less uncertain catches and potentially greater profitability (Pauly *et al.*, 2003).

### *Reduce harmful subsidies*

Governments pay out some USD 6 billion a year to support the fisheries sector in OECD countries. This money, variously called subsidies, support and/or financial transfers, is used to help manage fish stocks, to modernise fishing fleets, and to help communities and regions that can no longer make a living out of fishing to develop other economic activities. The money is also intended to assist in resolving problems of overfishing and over-capacity that affect many parts of the OECD fishing industry. However questions have been raised as to the true benefit of some forms of subsidies, as they may encourage fishers to remain in an industry incapable of supporting them in the medium to long term (OECD, 2005).

Sustainability and profitability can be enhanced by the removal of harmful subsidies. For example in many European and other developed country fisheries this will involve the removal of subsidies for vessel construction (OECD, 2005). Raising the efficiency of fishing effort through improved boat designs, subsidising credit for purchases will only increase incomes if the resource remains relatively under-exploited compared to the long-run sustainable catch. As soon as the catch rate approaches or exceeds this sustainable long-run level, increased efficiency must result in a reduced number of individuals or families involved in fishing. The alternative is that the same number of people stay in fishing but under-utilise their enhanced capacity to catch fish, thus making no gains in income, and incurring a social waste of resources in the idle capacity represented by their improved assets (Bailey and Jentoft, 1990).

### *Enable mobility of large-scale fishing fleets*

Given that fish stock production, distribution and species composition may all change under future climate change, it is important for economic efficiency and sustainability that national fishery legislation and investment programmes do not lock fleets, processing capacity and marketing chains into exploiting particular species caught within national boundaries. The current hostility towards the “roving bandits” (Berkes *et al.*, 2006) of the global fishing fleet and the questions raised around fairness of EU-West African nation bilateral fishing agreements (Kaczynski and Fluharty, 2002) – although see Witbooi (2008) for recent changes – make the current legislative climate hostile towards the notion of enabling global mobility of capital and labour in fisheries. Nevertheless, from the point of view of adapting to climate change, such mobility has always been important. Fishing fleets have to retain some flexibility in where they fish and what they catch. Thus, it is necessary to establish institutional mechanisms to enhance the capacity of fishing interests (fleets, processing capacity, and quota ownership) to move within and across national boundaries to respond to changes in resource distribution. This implies developing bilateral and multilateral agreements. This can only be recommended in the context of functional transboundary fishery governance regimes and effective systems to control illegal, unreported and unregulated fishing. Thus, the key link remains the promotion of sustainable fisheries (see above).

As part of this, issues of trade must be considered. FAO figures suggest that 38% (live weight equivalent) of all fish production was exported in 2004, and total world exports of fish and fish products reached a record value of USD 71.5 billion (FAO, 2004). In turn, world fish imports rose 25.4% from 2000 to 2004, reaching the new record of more than USD 75 billion in 2004. Developed countries accounted for about 81% of the total value of imports. The fishery net exports of developing countries (*i.e.* the total value of their exports less the total value of their imports) were USD 20.4 billion in 2004. These figures were significantly higher than those for other agricultural commodities such as rice, coffee and tea. In the future, a balance may be needed between gaining income from third country agreements and the international export of fish, and the protein and micronutrient needs of a tropical nation's population that are hardest hit by the impacts of climate change on fisheries (Alder and Sumaila, 2004).

### *Promote diverse, less capital-intensive fisheries*

Diversification of activities is a key factor in building adaptive capacity to climate change (Adger *et al.*, 2005a; Allison and Ellis, 2001). It reduces the risk of livelihood failure by spreading risk across more than one income source. It also helps to overcome the uneven use of assets (principally labour) caused by seasonality, to reduce vulnerability, and to generate financial resources in the absence of credit markets, and it confers a host of other advantages in the presence of widespread market failures and uncertainties. In Mexico, diversified multi-species multi-gear traditional fishers, in contrast to the highly specialised and technologically rigid industrial fishing fleet, see the measurement and quantification of climate variability at the core of their adaptation strategies (Vasquez-Leon, 2002). Danish small-scale fisheries, artisanal fisheries in Galicia (north-east Spain) and some Icelandic fishing towns show similar flexibility, where fishers switch between different target species, gear types and fishing areas on a seasonal or annual basis (Hamilton *et al.*, 2003; Vestergaard, 1996; Freire and Garcia-Allut, 2000). In Denmark, income uncertainties are buffered by supplier credits, while families are willing to reduce their levels of spending or to earn supplementary incomes outside fishing. Furthermore, fishers are able to mobilise cheap or unpaid assistance within the fishing enterprise in times of need. Diversification of nutritional sources may reduce vulnerability in some areas strongly affected by climate change.

The promotion of increased specialisation through investment in more capital-intensive fishing technologies tends to reduce capacity to adapt and respond to change (Hamilton *et al.*, 2003). In Greenland heavy investment in a cod processing plant at the village of Paamiut contributed to socio-economic failure when climate change and overexploitation led to the demise of Greenland cod (Hamilton *et al.*, 2003). Investment can push part-time fishers into full-time operations simply to repay loans and to earn an adequate return on the increased investment. Increased dependency on fishing can mean that individuals find it harder to turn to non-fishing alternatives during periods of resource scarcity. This, in turn, can compromise resource sustainability (Allison and Ellis, 2001).

From an institutional perspective, system-wide adaptation can be supported through insurance, subsidies or other government aid. However, while small-scale diversified fishers may be better able to adapt to the uncertainties of fisheries, they are more vulnerable if governments withdraw support from that sector in favour of more industrial sectors. This is offset where fishers have diversified beyond pure fishing incomes to mixed livelihoods. In Indonesia, for example, South Java Coast individuals switch between rice-farming, tree-crop farming and fishing in response to seasonal and interannual variations in fish availability (Musa *et al.*, 2001). Elsewhere (*e.g.* in Europe and Canada) inshore fishermen switch between fishing and tourism (whale watching, recreational fishing or dive charter). Migration allows fishers to move to areas with greater resources, where access is unlimited. An example is the flexible access rights around shallow African lakes, whereby landowners allow access by large numbers of migrant fishers to exploit fisheries resources that fluctuate with climatically driven lake water levels (Allison and Mvula, 2002; Jul-Larson *et al.*, 2003). Outsiders can access village-based fishing territories in times of their need, or when there are local surpluses, often in exchange for an access fee. Reciprocal access agreements, rather than exclusive territoriality, seem to be common features of indigenous "community-based" management systems. Flexible financial mechanisms at local level recognise the inherent variability of fishing. Permeable barriers to entry allow those in need of a "safety net" access to the fishery, while there is recognition of the importance of ease of exit from the fishery in times of resource scarcity.

In many developed countries with industrial fisheries, this flexibility does not exist and can be less easily negotiated within the strict management regimes that operate. To adjust to the multiple potential impacts of climate change, management measures need to be flexible, adapting to changes identified, and transparent in the use of information and in governance (Brander, 2007). Adaptation may involve the abandonment of previous livelihood options. Low-lying atoll and coastal nations may be forced into adaptation strategies that involve long-term migration of human populations due to sea level rise and other factors (Barnett and Adger, 2003). Whether fishing remains a viable option in new locations will be a case-specific question.

In fisheries with excess fishing effort the use of financial incentives to promote reduction of fleet capacity through vessel decommissioning coupled with a promotion of alternative land-based jobs is one approach to moving toward more sustainable resilient marine ecosystems and coastal communities (OECD, 2006).

### *Manage an adaptation "portfolio" across natural resource sectors*

It is worth considering whether fisheries and aquatic environmental management systems can function effectively in isolation of other natural resource industries. Many natural resource sectors overlap both geographically and socially, with many of the poorest people relying on two or more natural resource sectors to provide for the bulk of their livelihood, e.g. water resources, forestry, farming, aquaculture, and capture fisheries. This pattern may be particularly acute in river catchments where capture fisheries exist downstream of other natural resource sectors and ecosystem services, such as water abstraction, forestry and agriculture, themselves acutely affected by climate change (Badjeck *et al.*, 2010). Other upstream activities, such as damming for hydroelectric power generation, will obviously affect downstream ecosystem services (e.g. Dugan *et al.*, 2010). An example is for Lake Chilwa, where the combination of a series of droughts and the expansion of rice cultivation to the fringing wetlands have put severe pressures on water resources and fisheries (Allison *et al*., 2007).

Climate change is expected to result in increased summer continental drying and associated risks of drought (IPCC, 2001). Adaptation in other sectors may result in increased water offtake to support increased irrigation demands of climatically stressed crops, as well as increased damming of rivers. Increased upstream water use as a result of climate change adaptation activities may therefore reduce outflows from rivers, affecting salinity levels, nutrient levels, reproductive success and other physical and biological factors, which will compromise fisheries and associated livelihoods. For example, in Bangladesh by 2050 the negative impacts of climate change on water availability are predicted to lead to declines in rice (8%) and wheat (32%) yields. Maintenance of food self-sufficiency would require about 40% to 50% of the dry season water availability. Meeting such a high agricultural water demand can be expected to cause significant negative impacts on the domestic and commercial water supply, fisheries, and ecosystems (Faisal and Parveen, 2004).

A cross-sectorial view of adaptive activities to climate change needs to be taken not only in the fisheries sector. For example, in water management there is a prevailing perception that it is wasteful to allow freshwater to reach the sea. This is a fallacy: the concept of an ecosystem take should be paramount to ensure sufficient water in the lower river to support riverine and coastal fisheries and other ecosystem services critical to the local communities. When the production of one kilogram of beef requires 16 thousand litres of water, the benefits of wild fish capture and aquaculture for protein, as well as the provision of micronutrients, becomes clear. In turn, aquaculture can be integrated with other livestock farming as a strategy for small farmers in many developing countries to increase farm returns from per unit area of land. This portfolio approach helps a farmer insure himself against the risk of falling into crises of subsistence by spreading the risk of production over several activities.

The key message is that interactions between natural resource sectors are often poorly characterised and the interactions are rarely considered by sectorially-focussed planners. Any improvements to cross-sectoral planning and adaptation, such as the development of the ecosystem approach to fisheries management, or attainment of WSSD goals, concurrently will improve the socioecological resilience of fisheries systems.

### *Mainstream fisheries in wider development processes*

Climate change is not the only stress facing fishing communities. Many fishing communities are poorly served by infrastructure, markets and social services and are thus economically, socially and politically marginalised (FAO, 2005). Building adaptive capacity to address these multiple stressors will require cross-sectoral approaches implemented through newly decentralised governance approaches. The thrust of current fisheries development policy in non-OECD countries is to ensure that, in countries where fisheries are important to the economy, the sector is adequately represented in national-level planning processes related to poverty reduction and maintenance or enhancement of food security (Béné and Heck, 2005; FAO, 2005). In the case of the highly indebted poor countries, incorporation of the fisheries sector in the national poverty reduction strategy process (PRSP) is critical for allocation of funds for building adaptive capacity in the sector (Thorpe, 2005).

The least developed countries (LDCs) are also eligible for UN funding to engage in long-term adaptation planning through the national adaptation programmes of action (NAPAs; *www.undp.org/cc/napa.htm*). Again, in countries where fisheries are important, sector-specific adaptation needs should be planned and budgeted for in this process.

## Concluding remarks

Human-induced climate change has occurred and the effects are predicted to increase over this century. There is high certainty of increasing $CO_2$, temperature, sea level, ocean acidity and extreme events. There is high certainty for climate-induced biological change; however the detail of change is less certain at larger ecological scales. Overall, it appears that climate change has strongly negative consequences for a variety of aquatic ecosystems, especially those in the tropics and developing world. The social and economic impacts of climate change on fisheries are less well-understood. Notwithstanding this limitation, the impacts of climate variability on fish availability, fish prices and the hazard impacts on coastal communities are substantial and can have profound social and economic consequences at local, national and international scales. The degree to which national economies are vulnerable to the impacts of climate change on fisheries depends upon their degree of exposure to climate change, dependence on fisheries, and the capacity to adapt and response to the opportunities, challenges and dangers. The countries with national economies most vulnerable to the impacts of climate change on fisheries sectors are primarily in Africa and Asia and include many of the world's least developed nations. This is a consequence of high social and economic dependence on fisheries for livelihoods and food. Most OECD countries are likely to be least vulnerable to climate change impacts on their fisheries sectors (some may even benefit, *e.g.* Iceland and Norway), due to the increased adaptive capacity of these nations. However, some OECD countries may have a role to play as they have fishing access agreements and strong fish trade links with the most fisheries-dependent vulnerable least developed nations.

Policy makers can respond by pursuing a mitigation strategy to limit $CO_2$ emissions, maintaining and building adaptive capacity or "socio-ecological resilience", and by managing natural resources as a portfolio to ensure adaptation in one sector will not have adverse effects on other "downstream" sectors.

## Notes

1. The oceanic zone where enough light is present for photosynthesis to occur.
2. Aragonite and calcite are the two crystalline mineral forms of calcium carbonate, caco3.

# Annex 1.A1

## Table 1.A1.1. Vulnerability of national economies to the impacts of climate change on fisheries[1]

| Country | Fisheries dependence | Climate change exposure | | Adaptive capacity | Vulnerability | |
|---|---|---|---|---|---|---|
| **OECD countries** | | A1F1 | B2 | | A1F1 | B2 |
| Australia | 2 | 2 | 2 | 4 | 1 | 1 |
| Austria | 1 | 3 | 3 | 4 | 1 | 1 |
| Belgium | 1 | 2 | 2 | 4 | 1 | 1 |
| Canada | 4 | 4 | 4 | 4 | 2 | 2 |
| Czech Rep | 1 | 3 | 2 | 4 | 1 | 1 |
| Denmark | 3 | 2 | 2 | 4 | 1 | 1 |
| Finland | 2 | 4 | 4 | 4 | 2 | 2 |
| France | 2 | 3 | 2 | 4 | 1 | 1 |
| Germany | 1 | 2 | 2 | 4 | 1 | 1 |
| Greece | 3 | 3 | 3 | 4 | 2 | 2 |
| Hungary | 1 | 4 | 4 | 3 | 1 | 1 |
| Iceland | 4 | 1 | 2 | 4 | 1 | 2 |
| Ireland | 2 | 1 | 1 | 4 | 1 | 1 |
| Italy | 2 | 3 | 2 | 4 | 1 | 1 |
| Japan | 4 | 4 | 3 | 4 | 2 | 2 |
| Korea | NA | 4 | 4 | NA | NA | NA |
| Mexico | 4 | 3 | 3 | 3 | 3 | 3 |
| Netherlands | 2 | 2 | 1 | 4 | 1 | 1 |
| New Zealand | 3 | 1 | 1 | 4 | 1 | 1 |
| Norway | 4 | 3 | 3 | 4 | 2 | 2 |
| Poland | 2 | 3 | 3 | 4 | 2 | 2 |
| Portugal | 4 | 4 | 3 | 4 | 2 | 2 |
| Spain | 4 | 3 | 3 | 4 | 2 | 2 |
| Sweden | 2 | 3 | 4 | 4 | 1 | 1 |
| Switzerland | 1 | 3 | 3 | 4 | 1 | 1 |
| Turkey | 2 | 4 | 4 | 2 | 3 | 4 |
| UnitedKingdom | 2 | 1 | 1 | 4 | 1 | 1 |
| United States | 3 | 4 | 4 | 4 | 1 | 1 |

## Table 1.A1.1. Vulnerability of national economies to the impacts of climate change on fisheries (*cont.*)

| Country | Fisheries dependence | Climate change exposure | | Adaptive capacity | Vulnerability | |
|---|---|---|---|---|---|---|
| **Non-OECD countries** | | A1F1 | B2 | | A1F1 | B2 |
| Afghanistan | NA | 4 | 3 | NA | NA | NA |
| Albania | 1 | 3 | 3 | 2 | 2 | 2 |
| Algeria | 2 | 4 | 4 | 2 | 3 | 4 |
| Angola | 3 | 3 | 3 | 1 | 4 | 4 |
| Antigua & Barbuda | NA | 1 | 1 | NA | NA | NA |
| Argentina | 2 | 2 | 2 | 3 | 1 | 1 |
| Armenia | 1 | 4 | 4 | 2 | 2 | 2 |
| Aruba | NA | 1 | 1 | NA | NA | NA |
| Azerbaijan | 1 | 4 | 4 | 2 | 2 | 2 |
| Bahamas | NA | 1 | 1 | NA | NA | NA |
| Bahrain | NA | 2 | 3 | NA | NA | NA |
| Bangladesh | 4 | 2 | 2 | 1 | 4 | 4 |
| Barbados | NA | 1 | 1 | NA | NA | NA |
| Belarus | 1 | 4 | 4 | 3 | 3 | 3 |
| Belize | 3 | 3 | 3 | 3 | 2 | 2 |
| Benin | NA | 2 | 2 | NA | NA | NA |
| Bermuda | NA | 2 | 1 | NA | NA | NA |
| Bhutan | NA | 2 | 2 | NA | NA | NA |
| Bolivia | 1 | 4 | 4 | 2 | 3 | 3 |
| Bosnia & Herzegovina | 1 | 4 | 4 | 3 | 2 | 2 |
| Botswana | 1 | 4 | 4 | 2 | 2 | 3 |
| Brazil | 3 | 4 | 4 | 3 | 3 | 3 |
| Brunei Darussalam | NA | 2 | 1 | NA | NA | NA |
| Bulgaria | 1 | 4 | 4 | 3 | 2 | 2 |
| Burkina Faso | 1 | 3 | 2 | 1 | 4 | 3 |
| Burundi | 2 | 3 | 2 | 1 | 4 | 4 |
| Cambodia | 4 | 2 | 2 | 2 | 4 | 4 |
| Cameroon | 3 | 2 | 2 | 1 | 3 | 3 |
| Cape Verde | NA | 1 | 1 | NA | NA | NA |
| Central African Rep. | NA | 3 | 3 | NA | NA | NA |
| Chad | NA | 3 | 3 | NA | NA | NA |
| Chile | 4 | 1 | 1 | 4 | 1 | 1 |
| China | 4 | 3 | 3 | 4 | 3 | 3 |
| China, Hong Kong | NA | 2 | 2 | NA | NA | NA |
| China, Macao | NA | 2 | 2 | NA | NA | NA |
| Colombia | 3 | 4 | 4 | 2 | 4 | 4 |
| Comoros | NA | 1 | 1 | NA | NA | NA |
| Congo | 1 | 2 | 2 | 1 | 3 | 2 |
| Congo, Dem. Rep. | 4 | 3 | 3 | 1 | 4 | 4 |
| Cook Islands | NA | 1 | 1 | NA | NA | NA |
| Costa Rica | 2 | 2 | 2 | 4 | 1 | 1 |
| Côte d'Ivoire | 3 | 2 | 2 | 1 | 4 | 4 |
| Croatia | 3 | 4 | 4 | 3 | 3 | 3 |

| Country | Fisheries dependence | Climate change exposure | Adaptive capacity | Vulnerability | Country | Fisheries dependence |
|---|---|---|---|---|---|---|
| **Non-OECD countries** |  | A1F1 | B2 |  |  |  |
| Cuba | NA | 2 | 2 | NA | NA | NA |
| Cyprus | 2 | 1 | 1 | 4 | 1 | 1 |
| Djibouti | NA | 4 | 3 | NA | NA | NA |
| Dominica | NA | 1 | 1 | NA | NA | NA |
| Dominican Rep. | 2 | 1 | 2 | 3 | 1 | 1 |
| Ecuador | 3 | 3 | 3 | 2 | 3 | 3 |
| Egypt | 3 | 3 | 3 | 2 | 3 | 3 |
| El Salvador | 2 | 3 | 3 | 2 | 3 | 3 |
| Equatorial Guinea | NA | 2 | 2 | NA | NA | NA |
| Eritrea | NA | 3 | 3 | NA | NA | NA |
| Estonia | 3 | 4 | 4 | 4 | 3 | 3 |
| Ethiopia | 1 | 2 | 2 | 1 | 2 | 2 |
| Fiji | 4 | 1 | 1 | 3 | 1 | 1 |
| French Guiana | NA | 2 | 2 | NA | NA | NA |
| French Polynesia | NA | 1 | 1 | NA | NA | NA |
| Gabon | 3 | 2 | 2 | 2 | 3 | 2 |
| Gambia | 2 | 2 | 3 | 1 | 4 | 4 |
| Georgia | 1 | 4 | 4 | 3 | 2 | 2 |
| Ghana | 4 | 2 | 2 | 2 | 4 | 4 |
| Grenada | NA | 1 | 1 | NA | NA | NA |
| Guadeloupe | NA | 1 | 1 | NA | NA | NA |
| Guatemala | 2 | 4 | 3 | 2 | 3 | 3 |
| Guinea | 3 | 2 | 2 | 1 | 4 | 4 |
| Guinea-Bissau | 2 | 2 | 2 | 1 | 4 | 4 |
| Guyana | 3 | 3 | 3 | 3 | 3 | 3 |
| Haiti | 2 | 2 | 2 | 1 | 3 | 2 |
| Honduras | 2 | 2 | 3 | 2 | 2 | 3 |
| India | 4 | 2 | 2 | 2 | 3 | 3 |
| Indonesia | 4 | 1 | 1 | 2 | 3 | 3 |
| Iran | 3 | 3 | 3 | 2 | 3 | 3 |
| Iraq | NA | 4 | 4 | NA | NA | NA |
| Israel | 1 | 2 | 2 | 4 | 1 | 1 |
| Jamaica | 2 | 1 | 1 | 3 | 1 | 1 |
| Jordan | 1 | 3 | 3 | 3 | 1 | 1 |
| Kazakhstan | 1 | 4 | 4 | 2 | 3 | 3 |
| Kenya | 3 | 2 | 2 | 1 | 3 | 3 |
| Kiribati | NA | 1 | 1 | NA | NA | NA |
| Korea | NA | 3 | 3 | NA | NA | NA |
| Kuwait | 1 | 2 | 2 | 3 | 1 | 1 |
| Kyrgyzstan | NA | 4 | 4 | NA | NA | NA |
| Lao | 2 | 2 | 2 | 1 | 3 | 3 |
| Latvia | 2 | 4 | 4 | 3 | 3 | 3 |
| Lebanon | 1 | 3 | 3 | 3 | 2 | 2 |
| Lesotho | NA | 3 | 2 | NA | NA | NA |
| Liberia | NA | 2 | 2 | NA | NA | NA |
| Libya | 2 | 3 | 3 | 2 | 3 | 3 |

| **Country** | **Fisheries dependence** | **Climate change exposure** | | **Adaptive capacity** | **Vulnerability** | |
|---|---|---|---|---|---|---|
| **Non-OECD countries** | | A1F1 | B2 | | A1F1 | B2 |
| Lithuania | 2 | 4 | 4 | 3 | 3 | 2 |
| Macedonia | 1 | 4 | 4 | 3 | 2 | 3 |
| Madagascar | 4 | 1 | 1 | 1 | 3 | 3 |
| Malawi | 3 | 3 | 3 | 1 | 4 | 4 |
| Malaysia | 4 | 2 | 2 | 3 | 2 | 2 |
| Maldives | NA | 1 | 1 | NA | NA | NA |
| Mali | 3 | 4 | 3 | 1 | 4 | 4 |
| Malta | 1 | 1 | 1 | 4 | 1 | 1 |
| Marshall Islands | NA | 1 | 1 | NA | NA | NA |
| Martinique | NA | 1 | 1 | NA | NA | NA |
| Mauritania | 3 | 4 | 4 | 1 | 4 | 4 |
| Mauritius | 3 | 1 | 1 | 3 | 1 | 1 |
| Micronesia, Fed. States | NA | 1 | 1 | NA | NA | NA |
| Morocco | 4 | 4 | 3 | 2 | 4 | 4 |
| Mozambique | 3 | 3 | 3 | 1 | 4 | 4 |
| Myanmar | NA | 2 | 2 | NA | NA | NA |
| Namibia | 3 | 3 | 3 | 2 | 3 | 3 |
| Nauru | NA | 1 | 1 | NA | NA | NA |
| Nepal | 2 | 2 | 2 | 1 | 3 | 3 |
| Netherlands Antilles | NA | 1 | 1 | NA | NA | NA |
| New Caledonia | NA | 1 | 1 | NA | NA | NA |
| Nicaragua | 3 | 2 | 3 | 2 | 3 | 3 |
| Niger | 2 | 3 | 3 | 1 | 4 | 4 |
| Nigeria | 4 | 2 | 2 | 1 | 4 | 4 |
| Oman | NA | 2 | 2 | NA | NA | NA |
| Pakistan | 4 | 3 | 3 | 1 | 4 | 4 |
| Palau | NA | 1 | 1 | NA | NA | NA |
| Panama | 3 | 2 | 2 | 3 | 2 | 2 |
| Papua New Guinea | 4 | 1 | 1 | 2 | 2 | 2 |
| Paraguay | 1 | 4 | 4 | 2 | 2 | 2 |
| Peru | 4 | 4 | 4 | 3 | 4 | 4 |
| Philippines | 4 | 1 | 1 | 3 | 2 | 2 |
| Puerto Rico | NA | 1 | 1 | NA | NA | NA |
| Qatar | NA | 3 | 3 | NA | NA | NA |
| Réunion | NA | 1 | 1 | NA | NA | NA |
| Romania | 1 | 4 | 4 | 3 | 2 | 2 |
| Russian Federation | 4 | 4 | 4 | 3 | 4 | 4 |
| Rwanda | NA | 3 | 2 | NA | NA | NA |
| Saint Kitts and Nevis | NA | 1 | 1 | NA | NA | NA |
| Saint Lucia | NA | 1 | 1 | NA | NA | NA |
| St. Vincent/Grenadines | NA | 1 | 1 | NA | NA | NA |
| Samoa | NA | 1 | 1 | NA | NA | NA |
| Sao Tome & Principe | NA | 1 | 1 | NA | NA | NA |
| Saudi Arabia | 2 | 3 | 4 | 2 | 2 | 3 |
| Senegal | 4 | 3 | 3 | 1 | 4 | 4 |
| Serbia & Montenegro | NA | 4 | 4 | NA | NA | NA |
| Seychelles | NA | 1 | 1 | NA | NA | NA |

| Country | Fisheries dependence | Climate change exposure | | Adaptive capacity | Vulnerability | |
|---|---|---|---|---|---|---|
| **Non-OECD countries** | | A1F1 | B2 | | A1F1 | B2 |
| Sierra Leone | 4 | 2 | 2 | 1 | 4 | 4 |
| Singapore | NA | 1 | 1 | NA | NA | NA |
| Slovenia | 1 | 4 | 3 | 4 | 1 | 1 |
| Solomon Islands | NA | 1 | 1 | NA | NA | NA |
| Somalia | NA | 2 | 2 | NA | NA | NA |
| South Africa | 2 | 2 | 3 | 2 | 2 | 2 |
| Sri Lanka | 4 | 1 | 1 | 2 | 2 | 2 |
| Sudan | 1 | 3 | 3 | 1 | 3 | 3 |
| Suriname | 3 | 2 | 3 | 3 | 2 | 3 |
| Syria | 1 | 4 | 4 | 2 | 2 | 2 |
| Tajikistan | NA | 4 | 4 | NA | NA | NA |
| Tanzania | 4 | 2 | 2 | 1 | 4 | 4 |
| Thailand | 4 | 2 | 2 | 3 | 3 | 2 |
| Togo | 3 | 2 | 2 | 1 | 4 | 3 |
| Tonga | NA | 1 | 1 | NA | NA | NA |
| Trinidad & Tobago | 2 | 1 | 1 | 3 | 1 | 1 |
| Tunisia | 4 | 2 | 2 | 3 | 2 | 2 |
| Turkmenistan | 1 | 3 | 3 | 2 | 2 | 1 |
| Tuvalu | NA | 1 | 1 | NA | NA | NA |
| Uganda | 4 | 3 | 3 | 1 | 4 | 4 |
| Ukraine | 3 | 4 | 4 | 3 | 4 | 4 |
| United Arab Emirates | NA | 3 | 3 | NA | NA | NA |
| Uruguay | 2 | 2 | 2 | 4 | 1 | 1 |
| Uzbekistan | 1 | 4 | 3 | 2 | 1 | 1 |
| Vanuatu | NA | 1 | 1 | NA | NA | NA |
| Venezuela | 3 | 4 | 4 | 3 | 4 | 4 |
| Vietnam | 4 | 2 | 2 | 2 | 4 | 4 |
| Yemen | 3 | 3 | 3 | 1 | 4 | 4 |
| Zambia | 3 | 3 | 3 | 1 | 4 | 4 |
| Zimbabwe | 1 | 4 | 4 | 1 | 4 | 4 |

NA indicates that no data were available.

1. Ranked scores of fisheries dependence, exposure to climate change (A1F1 & B2 scenarios), adaptive capacity and vulnerability for 27 OECD and 166 non-OECD countries. A rank score of 1 indicates countries in the upper quartile for fisheries dependence or vulnerability (see Annex 1.A2 for further details of the methods).

### Figure 1.A1.1. Vulnerability of OECD national economies to the impacts of climate change on fisheries under A1F1 and B2 emission scenarios*

OECD national vulnerability presented as ranked quartiles within the overall global analysis (see Table 1.A1.1)

# Annex 1.A2

## Further details on the calculation of an index of vulnerability of national economies to the impacts of climate change on fisheries

Vulnerability is usually defined as a combination of the extrinsic exposure of groups or individuals to a hazard, such as climate change, their intrinsic sensitivity to the hazard, and their capacity to modify exposure to, absorb, and recover from losses stemming from the hazard, and to exploit new opportunities that arise in the process of adaptation (Smit and Wandel, 2006; Turner *et al.*, 2003). At sub-national and regional scales, vulnerability is regarded as a context-specific local property that varies by socio-economic grouping and geographically within and among countries (Brooks *et al.*, 2005). However, vulnerability can be influenced by national policies within the context of larger (regional and global) and smaller scale (individual, community and district) processes. There are no objective, independently derived measures of vulnerability, exposure, sensitivity, or adaptive capacity. The usual approach is to select proxy measures that capture the properties of interest (Turner *et al.*, 2003). Vulnerability was calculated simply by averaging the three indicators of exposure, fisheries dependence and adaptive capacity as $V = f(E, D, AC)$. Further details on the calculation of this vulnerability index can be found in Allison *et al.* (2005).

## An index of exposure to climate change

The aim was to create an exposure index representing the degree to which fisheries will be subject to climate change. Climatic change influences fisheries production through a range of both direct and indirect pathways (Allison *et al.*, 2005). The direct effects include changes in the abundance and distribution of exploited species and increases in the frequency and severity of extreme events, such as floods and storms, which affect fishing operations and infrastructure. The indirect effects include: (i) impacts on aquatic habitat quantity and quality, ecosystem productivity, and the distribution and abundance of aquatic competitors and predators; (ii) impacts on other food production sectors that might affect people's livelihoods and food security; and (iii) other climate change impacts on aspects of people's lives unrelated to their fishing activities, such as diseases or damage to their homes (see above, "How and where does global warming potentially impact on fisheries?"). We focused on projected land surface temperature change, because it is the most direct, best understood, and most readily available measure of future warming. We used projected annual mean temperature change by 2050 as a proxy variable of climate change exposure. Mean temperature changes at 1.5 m above the surface was calculated for 2050 by rescaling the 2080 values from the TYN CY 3.0 dataset, which provides country-specific projections based on gridded values from HadCM3 climate model outputs (Table 1.A2.1).

The model results used here are from the UK Hadley Centre model (HadCM3), with two IPCC emissions scenarios (B2 and A1F1) (Gordon *et al.*, 2000). The two IPCC climate change scenarios were selected because they represent two contrasting potential futures. The A1FI world is characterised by a high dependence on fossil fuels, reflected in higher temperatures than in the B2 world, in which economic development is more moderate.

## An index of fisheries dependence

We calculated an index of fisheries dependence to represent the national role and importance of fisheries for the economy. Dependence upon fisheries was measured using national fishery landings, and the contributions of fisheries to employment, production, export income and dietary protein (Table A1.2.1). This assumed that countries with greater landings and higher contributions of fisheries to employment, export income, and dietary protein were more likely to be impacted (positively or negatively) by warming-related changes in fishery production. We calculated two measures of the contribution of fisheries to national employment: total numbers of fishers and the number of fishers expressed as a proportion of the economically active population. Fisheries production was measured as capture fisheries landings for coastal and inland waters, summed across edible fish, crustaceans and molluscs (FAOSTAT, 2004). Annual fishery-related export value (USD) was the sum of exports and re-exports of products fit for human consumption for each country, averaged over the four-year period 1998-2001 (FAOSTAT, 2004). Total fish and animal protein available for consumption was estimated as annual total supply (production + imports - exports) from FAO food balance sheets (FAOSTAT, 2004).

## An index of adaptive capacity

We calculated an adaptive capacity index from four variables: healthy life expectancy, education, governance and gross domestic product (GDP) using the Climate Analysis Indicator Tool (CAIT) of the World Resources Institute (CAIT, 2005) (Table 1.A2.1). Healthy life expectancy was the number of years a newborn child can expect to live in full health based on current mortality rates and the distribution of health states in the population (WHO, 2002). The link between health and climate change involves opportunity cost, such that countries with significant health costs are likely to find it socially and politically difficult to allocate resources to mitigate and to adapt to climate change. Education levels were measured as a weighted combination of adult literacy and school enrolment rates (UNDP, 2003). The World Bank governance index combines six components of governance: political stability (*e.g.* perceptions of likelihood of armed conflict); government effectiveness (*e.g.* bureaucratic quality); regulatory quality (*e.g.* regulatory burden, market-friendliness); rule of law (*e.g.* black markets, enforceability of contracts); voice and accountability (*e.g.* free and fair elections, political rights); and corruption (*e.g.* its prevalence among local officials) (Kaufmann *et al.*, 2002). GDP was the sum of gross value added by all resident producers in the economy, plus any product taxes, less any subsidies not already included in product values. We used the total GDP, converted from local currency to 2000 US dollar value using purchasing power parity, as a measure of the size of the economy.

Where appropriate, variables were normalised and standardised to a range between 0 and 1. For exposure and fisheries dependence, the country with the lowest value scored 0, and the country with the highest value scored 1. For adaptive capacity, the converse applied.

### Table 1.A2.1. Summary of variables used to calculate exposure, fisheries dependence and adaptive capacity, and their interpretation

Years shown indicate periods over which data were available

| Component | Interpretation | Variable | Reference |
|---|---|---|---|
| Exposure | Gross measure of projected levels of climate change | Mean projected surface temperature increase (°C at 1.5m) by 2050 | (Mitchell *et al.,* 2004) |
| Fisheries-dependency | | Number of fishers (most recent year 1990-96) | (FAO, 1999) |
| | Index of employment and economic dependence on the fisheries sector | Fisheries export value as proportion (%) of total export value (averaged over 1998-2001) | (FAOSTAT, 2004, World Bank, 2003) |
| | | Proportion (%) of economically active population (1990) involved in the fishery sector | |
| | | Total fisheries landings (tonnes, averaged over 1998-2001) | |
| | Index of nutritional dependence | Fish protein as proportion of all animal protein (% g person$^{-1}$ day$^{-1}$, averaged over 1998-2001) | (FAOSTAT, 2004) |
| Adaptive Capacity | Health | Healthy life expectancy (years, 2000) | (CAIT, 2005) |
| | Education | Literacy rates (% of people ≥ 15 years, 2000-01) | (CAIT, 2005) |
| | | School enrolment ratios (% in primary, secondary and tertiary education, 2000-01) | |
| | Governance (2000-1) | Political stability | (CAIT, 2005, Kaufmann *et al.*, 2002) |
| | | Government effectiveness | |
| | | Regulatory quality | |
| | | Rule of law | |
| | | Voice and accountability | |
| | | Corruption | |
| | Size of economy | Total GDP (2000) | (CAIT, 2005) |

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# PART II
# CLIMATE CHANGE IMPACTS ON FISHERIES AND ADAPTATION FISHERIES