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Climate change implications for fisheries and aquaculture

Overview of current scientific knowledge

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FAO FISHERIES AND AQUACULTURE TECHNICAL PAPER

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Preparation of this document

This document was prepared in response to the request from the twenty-seventh session of the Committee on Fisheries (COFI) that the FAO Fisheries and Aquaculture Department (FI) should undertake a scoping study to identify the key issues on climate change and fisheries. It contains the three comprehensive technical papers that formed the basis for the technical discussions during the Expert Workshop on Climate Change Implications for Fisheries and Aquaculture held from 7 to 9 April 2008 at FAO headquarters. The conclusions and recommendation of this Expert Workshop are available in the 2008 FAO Fisheries Report No. 870.

The three papers in this document intend to provide an overview of the current available knowledge on the possible impacts of climate change on fisheries and aquaculture. The first addresses climate variability and change and their physical and ecological consequences on marine and freshwater environments. The second tackles the consequences of climate change impacts on fishers and their communities and reviews possible adaptation and mitigation measures that could be implemented. Finally, the third addresses specifically the impacts of climate change on aquaculture and reviews possible adaptation and mitigation measures that could be implemented.

All participants in the Expert Workshop are gratefully acknowledged for providing comments and helping to improve the three technical papers included in this publication.

Funding for the organization of the Expert Workshop and the publication of this Technical Paper was provided by the Governments of Italy and Norway through activities related to the FAO High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy (Rome, 3–5 June 2008).

Abstract

An overview of the current scientific knowledge available on climate change implications for fisheries and aquaculture is provided through three technical papers that were presented and discussed during the Expert Workshop on Climate Change Implications for Fisheries and Aquaculture (Rome, 7–9 April 2008). A summary of the workshop outcomes as well as key messages on impacts of climate change on aquatic ecosystems and on fisheries- and aquaculture-based livelihoods are provided in the introduction of this Technical Paper.

The first paper reviews the physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. The paper begins with a review of the physical impacts of climate change on marine and freshwater systems and then connects these changes with observed effects on fish production processes. It also outlines a series of scenarios of climate change impacts on fish production and ecosystems through case studies in different regions and ecosystems.

The second paper tackles the consequences of climate change impacts on fisheries and their dependent communities. It analyses the exposure, sensitivity and vulnerability of fisheries to climate change and presents examples of adaptive mechanisms currently used in the sector. The contribution of fisheries to greenhouse gas emissions is addressed and examples of mitigation strategies are given. The role of public policy and institutions in promoting climate change adaptation and mitigation is also explored.

Finally, the third paper addresses the impacts of climate change on aquaculture. It provides an overview of the current food fish and aquaculture production and a synthesis of existing studies on climate change effects on aquaculture and fisheries. The paper focuses on the direct and indirect impacts of climate change on aquaculture, in terms of biodiversity, fish disease and fishmeal. Contribution of aquaculture to climate change is addressed (carbon emission and carbon sequestration), as well as possible adaptation and mitigation measures that could be implemented.

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Introduction

GENERAL BACKGROUND ON CLIMATE CHANGE

The threats of climate change to human society and natural ecosystems have been elevated to a top priority since the release of the fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2007. While the importance of fisheries and aquaculture is often understated, the implications of climate change for these sectors and for coastal and riparian communities in general are difficult to ignore. At the same time, fisheries and aquaculture do contribute to greenhouse gas emissions, although in a relatively minor way, and present some opportunities for mitigation efforts.

From local to global levels, fisheries and aquaculture play important roles for food supply, food security and income generation. Some 43.5 million people work directly in the sector, with the great majority in developing countries. Adding those who work in associated processing, marketing, distribution and supply industries, the sector supports nearly 200 million livelihoods. Aquatic foods have high nutritional quality, contributing 20 percent or more of average per capita animal protein intake for more than 1.5 billion people, mostly from developing countries. They are also the most widely traded foodstuffs and are essential components of export earnings for many poorer countries. The sector has particular significance for small island States, who depend on fisheries and aquaculture for at least 50% of their animal protein.

Climate change is projected to impact broadly across ecosystems, societies and economies, increasing pressure on all livelihoods and food supplies, including those in the fisheries and aquaculture sector. Food quality will have a more pivotal role as food resources come under greater pressure and the availability and access to fish supplies will become an increasingly critical development issue.

The fisheries sector differs from mainstream agriculture and has distinct interactions and needs with respect to climate change. Capture fisheries has unique features of natural resource harvesting linked with global ecosystem processes. Aquaculture complements and increasingly adds to supply and, though more similar to agriculture in its interactions, has important links with capture fisheries.

The Food and Agriculture Organization of the United Nations (FAO), in recognizing the likely changes to come and the interactions between fisheries and aquaculture, agriculture and forestry and these changes, held a High-Level Conference on World Food Security: the Challenges of Climate Change and Bioenergy at FAO headquarters in Rome from 3 to 5 June 2008. This conference addressed food security and poverty reduction issues in the face of climate change and energy security.

The FAO Fisheries and Aquaculture Department (FI) held an Expert Workshop on Climate Change Implications for Fisheries and Aquaculture, from 7 to 9 April 2008[1], in order to provide the FAO Conference with a coherent and high quality understanding of the fisheries and aquaculture climate change issues. This Workshop provided inputs into the High-Level Conference and also constitutes a response to the request from the twenty-seventh session of the FAO Committee on Fisheries (COFI) that “FAO should undertake a scoping study to identify the key issues on climate change and fisheries, initiate a discussion on how the fishing industry can adapt to climate change,

[1] FAO. 2008. Report of the FAO Expert Workshop on Climate Change Implications for Fisheries and Aquaculture. Rome, Italy, 7–9 April 2008. *FAO Fisheries Report*. No. 870. Rome, FAO. 2008. 32p.

and for FAO to take a lead in informing fishers and policy-makers about the likely consequences of climate change for fisheries".

CONCLUSIONS OF THE FAO EXPERT WORKSHOP ON CLIMATE CHANGE IMPLICATIONS FOR FISHERIES AND AQUACULTURE (ROME, 7–9 APRIL 2008)

This Expert Workshop was convened to identify and review the key issues of climate change in relation to fisheries and aquaculture, from the physical changes, the impacts of those changes on aquatic resources and ecosystems and how these ecological impacts translate into human dimensions of coping and adapting within fisheries and aquaculture. Three comprehensive background documents were developed to help to inform the technical discussions and are included in the present publication:

– *Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture* by Manuel Barange and Ian Perry;
– *Climate change and capture fisheries: potential impacts, adaptation and mitigation* by Tim Daw, Neil Adger, Katrina Brown and Marie-Caroline Badjeck;
– *Climate change and aquaculture: potential impacts, adaptation and mitigation* by Sena De Silva and Doris Soto.

One of the key messages that came out of the discussions after analysing the three documents is that climate change is a compounding threat to the sustainability of capture fisheries and aquaculture development. Impacts occur as a result of both gradual warming and associated physical changes as well as from frequency, intensity and location of extreme events, and take place in the context of other global socio-economic pressures on natural resources. An outline of the main impacts on ecosystems and livelihoods and their implications for food security was produced by the workshop. Urgent adaptation measures are required in response to opportunities and threats to food and livelihood provision due to climatic variations.

Ecosystem impacts

The workshop concluded that in terms of physical and biological impacts, climate change is modifying the distribution of marine and freshwater species. In general, warm-water species are being displaced towards the poles and are experiencing changes in the size and productivity of their habitats. In a warmed world, ecosystem productivity is likely to be reduced in most tropical and subtropical oceans, seas and lakes and increased in high latitudes. Increased temperatures will also affect fish physiological processes; resulting in both positive and negative effects on fisheries and aquaculture systems depending on the region and latitude.

Climate change is already affecting the seasonality of particular biological processes, altering marine and freshwater food webs, with unpredictable consequences for fish production. Increased risks of species invasions and spreading of vector-borne diseases provide additional concerns.

Differential warming between land and oceans and between polar and tropical regions will affect the intensity, frequency and seasonality of climate patterns (e.g. El Niño) and extreme weather events (e.g. floods, droughts and storms). These events will impact the stability of related marine and freshwater resources.

Sea level rise, glacier melting, ocean acidification and changes in precipitation, groundwater and river flows will significantly affect coral reefs, wetlands, rivers, lakes and estuaries; requiring adaptive measures to exploit opportunities and minimise impacts on fisheries and aquaculture systems.

Impacts on livelihoods

The workshop noted that changes in distribution, species composition and habitats will require changes in fishing practices and aquaculture operations, as well as in the location of landing, farming and processing facilities.

Extreme events will also impact on infrastructure, ranging from landing and farming sites to post-harvest facilities and transport routes. They will also affect safety at sea and settlements, with communities living in low-lying areas at particular risk.

Water stress and competition for water resources will affect aquaculture operations and inland fisheries production, and are likely to increase conflicts among water-dependent activities.

Livelihood strategies will have to be modified, for example, with changes in fishers migration patterns due to changes in timing of fishing activities.

Reduced livelihood options inside and outside the fishery sector will force occupational changes and may increase social pressures. Livelihood diversification is an established means of risk transfer and reduction in the face of shocks, but reduced options for diversification will negatively affect livelihood outcomes.

There are particular gender dimensions, including competition for resource access, risk from extreme events and occupational change in areas such as markets, distribution and processing, in which women currently play a significant role.

The implications of climate change affect the four dimensions of food security:

– ***availability*** of aquatic foods will vary through changes in habitats, stocks and species distribution;
– s***tability*** of supply will be impacted by changes in seasonality, increased variance in ecosystem productivity and increased supply variability and risks;
– ***access*** to aquatic foods will be affected by changes in livelihoods and catching or farming opportunities; and
– ***utilization*** of aquatic products will also be impacted and, for example, some societies and communities will need to adjust to species not traditionally consumed.

Carbon footprints of fisheries and aquaculture

The workshop agreed that fisheries and aquaculture activities make a minor but still significant contribution to greenhouse gas (GHG) emissions during production operations and the transport, processing and storage of fish. There are significant differences in the emissions associated with the sub-sectors and with the species targeted or cultured. The primary mitigation route for the sector lies in its energy consumption, through fuel and raw material use, though as with other food sectors, management of distribution, packaging and other supply chain components will also contribute to decreasing the sector's carbon footprint.

Greenhouse gas contributions of fisheries, aquaculture and related supply chain features are small when compared with other sectors but, nevertheless can be improved, with identifiable measures already available. In many instances, climate change mitigation could be complementary to and reinforce existing efforts to improve fisheries and aquaculture sustainability (e.g. reducing fishing effort and fleet capacity in order to reduce energy consumption and carbon emissions and reducing fishmeal reliance in aquaculture).

Technological innovations could include energy reduction in fishing practices and aquaculture production and more efficient post-harvest and distribution systems. There may also be important interactions for the sector with respect to environmental services (e.g. maintaining the quality and function of coral reefs, coastal margins, inland watersheds), and potential carbon sequestration and other nutrient management options, but these will need further research and development (R&D). The sustainable use of genetic diversity, including through biotechnologies, could have particular efficiency impacts (e.g. through widening production scope of low-impact aquaculture species, aquaculture systems, or making agricultural crop materials or waste products usable for growing carnivorous aquatic species) but would need to be evaluated on wider social, ecological and political criteria.

Mitigation R&D expenditure will need to be justified clearly by comparison with other sectors whose impacts could be much greater, but policy influence could already be used to support more efficient practices using available approaches.

Possible negative impacts of mitigation on food security and livelihoods would have to be better understood, justified where relevant, and minimized.

Adapting to change

Although resource-dependent communities have adapted to change throughout history, projected climate change poses multiple additional risks to fishery dependent communities that might limit the effectiveness of past adaptive strategies. The workshop concluded that adaptation strategies will require to be context and location specific and to consider impacts both short-term (e.g. increased frequency of severe events) and long-term (e.g. reduced productivity of aquatic ecosystems). All three levels of adaptation (community, national and regional) will clearly require and benefit from stronger capacity building, through awareness raising on climate change impacts on fisheries and aquaculture, promotion of general education and targeted initiatives in and outside the sector.

Options to increase resilience and adaptability through improved fisheries and aquaculture management include the adoption as standard practice of adaptive and precautionary management. The ecosystem approaches to fisheries (EAF) and to aquaculture (EAA) should be adopted to increase the resilience of aquatic resources ecosystems, fisheries and aquaculture production systems, and aquatic resource-dependent communities.

Aquaculture systems, which are less or non-reliant on fishmeal and fish oil inputs (e.g. bivalves and macroalgae), have better scope for expansion than production systems dependent on capture fisheries commodities.

Adaptation options also encompass diversification of livelihoods and promotion of aquaculture crop insurance in the face of potentially reduced or more variable yields.

In the face of more frequent severe weather events, strategies for reducing vulnerabilities of fishing and fish farming communities have to address measures including: investment and capacity building on improved forecasting; early warning systems; safer harbours and landings; and safety at sea. More generally, adaptation strategies should promote disaster risk management, including disaster preparedness, and integrated coastal area management.

National climate change adaptation and food security policies and programmes would need to fully integrate the fisheries and aquaculture sector (and, if non-existent, should be drafted and enacted immediately). This will help ensure that potential climate change impacts will be integrated into broader national development (including infrastructure) planning.

Adaptations by other sectors will have impacts on fisheries, in particular inland fisheries and aquaculture (e.g. irrigation infrastructure, dams, fertilizer use runoff), and will require carefully considered trade-offs or compromises.

Interactions between food production systems could compound the effects of climate change on fisheries production systems but also offer opportunities. Aquaculture based livelihoods could for example be promoted in the case of salination of deltaic areas leading to loss of agricultural land.

Options for enabling change

The workshop considered policy options and activities at the international, regional and national levels that can help to minimize negative impacts of climate change, improve on mitigation and prevention, and maintain and build adaptive capacity to climate change. These were as follows:

Developing the knowledge base. In the future, planning for uncertainty will need to take into account the greater possibility of unforeseen events, such as the increasing frequency of extreme weather events and other "surprises". However, examples of past management practices under variability and extreme events can still provide useful lessons to design robust and responsive adaptation systems. Improved knowledge in a number of areas will be valuable, e.g. projections of future fish production level, detailed impact predictions on specific fisheries and aquaculture systems, improved tools for decision-making under uncertainty, and improved knowledge of who is or will be vulnerable with respect to climate change and food security impacts and how they can be addressed.

Policy, legal and implementation frameworks. Addressing the potential complexities of climate change interactions and their possible impacts requires mainstreaming of cross-sectoral responses into governance frameworks. Action plans at the national level can have as their bases the Code of Conduct for Responsible Fisheries (CCRF) and related International Plans of Action (IPOAs), as well as appropriately linked policy and legal frameworks and management plans. Links will be required among national climate change adaptation policies and programmes as well as cross-sectoral policy frameworks such as those for food security, poverty reduction, emergency preparedness and others. The potential for spatial displacement of aquatic resources and people as a result of climate change impacts will require existing regional structures and processes to be strengthened or given more specific focus. Internationally, sectoral trade and competition issues are also likely to be impacted by climate change.

Capacity building: technical and organizational structures. Policy-making and action planning in response to climate change involves not only the technically concerned agencies, such as departments responsible for fisheries, interior affairs, science, and education, but also those for national development planning and finance. These institutions, as well as community or political representatives at subnational and national level should also be identified to receive targeted information and capacity building. Partnerships would also need to be built and strengthened among the public, private, civil society and non-governmental organization (NGO) sectors.

Enabling financial mechanisms: embodying food security concerns in existing and new financial mechanisms. The full potential of existing financial mechanisms, such as insurance, at national and international levels will be needed to tackle the issue of climate change. Innovative approaches may also be needed to target financial instruments and to create effective incentives and disincentives. The public sector will have an important role in levering and integrating private sector investment, interacting through market mechanisms to meet sectoral aims for climate change response and food security. Many of these approaches are new and will need to be tested in the sector.

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

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ABSTRACT

This chapter reviews the physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. It is noted that the oceans are warming but that this warming is not geographically homogeneous. The combined effect of temperature and salinity changes due to climate warming are expected to reduce the density of the surface ocean, increase vertical stratification and change surface mixing. There is evidence that inland waters are also warming, with differential impacts on river run off. Increased vertical stratification and water column stability in oceans and lakes is likely to reduce nutrient availability to the euphotic zone and thus primary and secondary production in a warmed world. However, in high latitudes the residence time of particles in the euphotic zone will increase, extending the growing season and thus increasing primary production. While there is some evidence of increased coastal upwelling intensity in recent decades, global circulation models do not show clear pattern of upwelling response to global warming at the global scale. However, current climate models are not yet sufficiently developed to resolve coastal upwelling and so the impacts of climate change on upwelling processes require further work. There is also evidence that upwelling seasonality may be affected by climate change. Sea level has been rising globally at an increasing rate, risking particularly the Atlantic and Gulf of Mexico coasts

of the Americas, the Mediterranean, the Baltic, small-island regions, Asian megadeltas and other low-lying coastal urban areas. Ocean acidification has decreased seawater pH by 0.1 units in the last 200 years and models predict a further reduction of 0.3-0.5 pH units over the next 100 years. The impacts of ocean acidification will be particularly severe for shell-borne organisms, tropical coral reefs and cold water corals. Climate change effects marine and inland ecosystems are in addition to changes in land-use, including changes in sediment loads, water flows and physical-chemical consequences (hypoxia, stratification, salinity changes). The consequences of these processes are complex and will impact community composition, production and seasonality processes in plankton and fish populations. This will put additional pressure on inland fish and land-based, water intensive, food production systems, particularly in developing countries.

Many effects of climate change on ecosystem and fish production processes have been observed. While a slight reduction in global ocean primary production has been observed in recent decades, a small increase in global primary production is expected over this century, but with very large regional differences. Changes in the dominant phytoplankton group appear possible. In general terms, high-latitude/altitude lakes will experience reduced ice cover, warmer water temperatures, a longer growing season and, as a consequence, increased algal abundance and productivity. In contrast, some deep tropical lakes will experience reduced algal abundance and declines in productivity, likely due to reduced resupply of nutrients. The intensification of hydrological cycles is expected to influence substantially limnological processes, with increased runoff, discharge rates, flooding area and dry season water level boosting productivity at all levels (plankton to fish). Climate change is expected to drive most terrestrial and marine species ranges toward the poles, expanding the range of warmer-water species and contracting that of colder-water species. The most rapid changes in fish communities will occur with pelagic species, and include vertical movements to counteract surface warming. Timing of many animal migrations has followed decadal trends in ocean temperature, being later in cool decades and up to 1–2 months earlier in warm years. Populations at the poleward extents of their ranges will increase in abundance with warmer temperatures, whereas populations in more equatorward parts of their range will decline in abundance as temperatures warm. More than half of all terrestrial, freshwater or marine species studied have exhibited measurable changes in their phenologies over the past 20 to 140 years, and these were systematically and predominantly in the direction expected from regional changes in the climate. Differential responses between plankton components (some responding to temperature change and others to light intensity) suggest that marine and freshwater trophodynamics may be altered by ocean warming through predator-prey mismatch. There is little evidence in support of an increase in outbreaks of disease linked to global warming, although spread of pathogens to higher latitudes has been observed. The paper summarises the consequences of climate change along temporal scales. At "rapid" time scales (a few years) there is high confidence that increasing temperatures will have negative impacts on the physiology of fish, causing significant limitations for aquaculture, changes in species distributions, and likely changes in abundance as recruitment processes are impacted. Changes in the timing of life history events are expected, particularly affecting short lived species, such as plankton, squid, and small pelagic fishes. At intermediate time scales (a few years to a decade), temperature-mediated physiological stresses and phenology changes will impact the recruitment success and therefore the abundances of many marine and aquatic populations, particularly at the extremes of species' ranges, and for shorter-lived species. At long time scales (multi-decadal), predicted impacts depend upon changes in net primary production in the oceans and its transfer to higher trophic levels, for which information is lacking. Considerable uncertainties and research gaps remain, in particular the effects of synergistic interactions among stressors (e.g. fishing, pollution), the occurrences and roles of critical thresholds, and the abilities of marine and aquatic organisms to adapt and evolve to the changes. Regarding freshwater systems, there are specific concerns over changes in timing, intensity and duration of floods, to which many fish species are adapted in terms of migration, spawning, and transport of spawning products, as a result of climate change. The chapter concludes with specific anticipated responses of regional marine ecosystems (Arctic, North Atlantic, North Pacific, coastal upwelling, tropical and subtropical regions, coral reefs, freshwater systems and aquaculture systems) to climate change.

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We thank Kevern Cochrane and Cassandra de Young for the opportunity and invitation to write this report, and for their constructive comments on an earlier draft. We thank Iddya Karunasagar for his contribution of information on the potential effects of climate change on human pathogens in the marine environment. We also thank all our colleagues who participated in the FAO Expert Workshop on Climate Change Implications for Fisheries and Aquaculture (Rome, 7–9 April 2008), for their comments and suggestions.

CONTENTS

1. CLIMATE CHANGE: THE PHYSICAL BASIS IN MARINE AND FRESHWATER SYSTEMS

In recent years numerous long-term changes in physical forcing have been observed at global, regional and basin scales as a result of climate and other anthropogenic changes. Impacts of these on biological processes supporting fish and fisheries production in marine and freshwater ecosystems have already been observed and may be used as proxies to estimate further global climate change impacts. These physical factors include atmospheric circulation, intensity and variability patterns, ocean currents and mixing, stratification, hydrological cycles and seasonal patterns.

1.1 Heat content and temperature

1.1.1 Ocean ecosystems

The ocean plays an important role in regulating the climate. Its heat capacity (and thus net heat uptake) is about 1 000 times larger than that of the atmosphere. Biological activity interacts substantially with physical processes, creating several feedback loops. For example, heat absorption by phytoplankton influences both the mean and transient state of the equatorial climate (e.g. Murtugudde *et al*., 2002; Timmermann and Jin, 2002; Miller *et al*., 2003), and the global mean sea surface temperature field (Frouin and Lacobellis, 2002).

There is significant consensus to conclude that the world ocean has warmed substantially since 1955 and that the warming accounts for over 80 percent of changes in the energy content of the Earth's climate system during this period (Levitus, Antonov and Boyer, 2005; Domingues *et al.,* 2008, Figure 1)*.* Studies have attributed anthropogenic contributions to these changes (Bindoff *et al.,* 2007), and it has been suggested that climate change models underestimate the amount of ocean heat uptake in the last 40 years (Domingues *et al*., 2008). While the global trend is one of warming, significant decadal variations have been observed in the global time series (Figure 2), and there are large regions where the oceans are cooling (Bindoff *et al*., 2007). For example, Harrison and Carson (2007) observed large spatial variability of 51-year trends in the upper ocean, with some regions showing cooling in excess of 3 °C, and others warming of similar magnitude. They concluded that additional attention should be given to uncertainty estimates for basin average and World Ocean average thermal trends.

Observations indicate that warming is widespread over the upper 700 m of the global ocean, but has penetrated deeper in the Atlantic Ocean (up to 3 000 m) than in the Pacific, Indian and Southern Oceans, because of the deep overturning circulation that occurs in the North Atlantic (Levitus, Antonov and Boyer, 2005). At least two seas at subtropical latitudes (Mediterranean and Japan/East China Sea) are also warming.

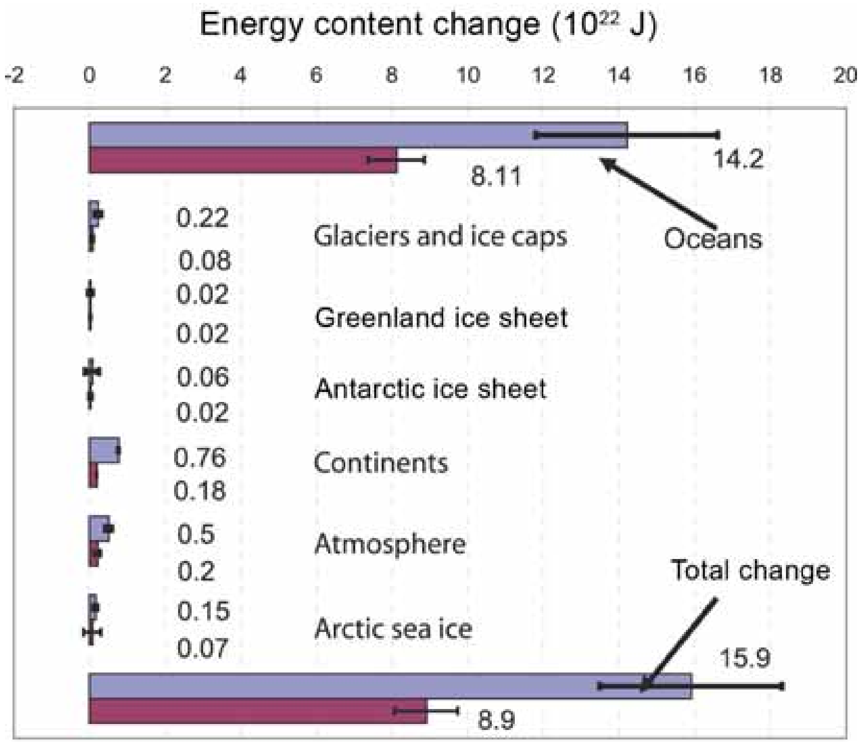
It is predicted that even if all radiative forcing agents were held constant at year 2000 levels, atmospheric warming would continue at a rate of about 0.1 °C per decade due to the slow response of the oceans. Geographical patterns of projected atmospheric warming show greatest temperature increases over land (roughly twice the global average temperature increase) and at high northern latitudes, and less warming over the southern oceans and North Atlantic (Meehl *et al*., 2007).

1.1.2 Inland waters

The International Panel on Climate Change (IPCC) has examined the implications of projected climate change for freshwater systems. Overall, it concludes that freshwater resources are vulnerable to, and have the potential to be strongly impacted by climate change (Bates *et al*., 2008). Expected changes include (Kundzewicz *et al*., 2008): decreases of between 10 and 30 percent of average river runoff at mid-latitudes and in the dry tropics by mid-century, but increases of 10–40 percent at high latitudes and in the wet tropics (Milly, Dunne and Vecchia, 2005); shifts in the form of precipitation

FIGURE 1

Energy content changes in different components of the Earth system for two periods (1961–2003, blue, and 1993–2003, burgundy). The ocean heat content change is from Levitus, Antonov and Boyer (2005); continental heat content from Beltrami *et al.* (2002); atmospheric energy content based on Trenberth *et al.* (2001); and arctic sea ice release from Hilmer and Lemke (2000); rest from IPCC (2007). Positive energy content change means an increase in stored energy. All error estimates are 90 percent confidence intervals. No estimate of confidence is available for the continental heat gain. Some of the results have been scaled from published results for the two respective periods. Ocean heat content change for the period 1961 to 2003 is for the 0 to 3 000 m layer. The period 1993 to 2003 is for the 0 to 700 m (or 750 m) layer and is computed as an average of the trends from Ishii *et al.* (2006), Levitus, Antonov and Boyer (2005) and Willis, Roemmrich and Cornuelle (2004)



Source: Bindoff *et al.*, 2007.

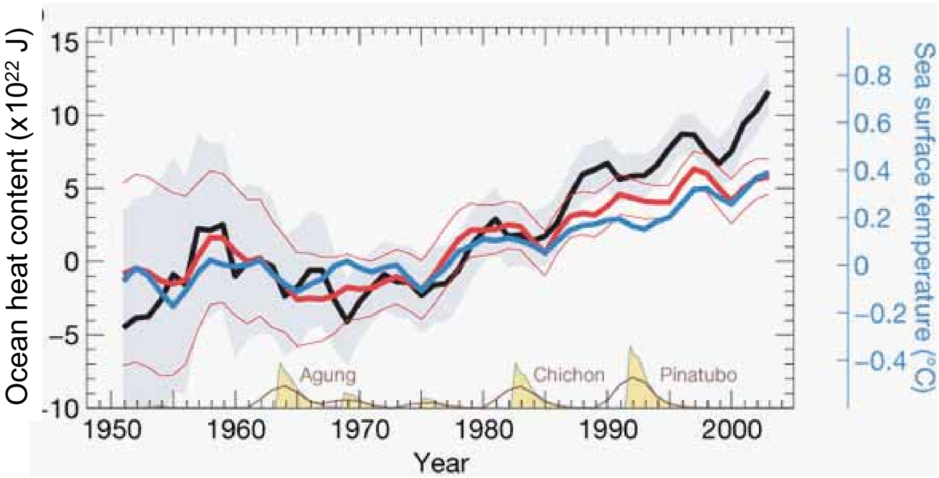
from snow to rain and a consequent change in the timing of peak river flows; and changes in flood and drought frequency and intensity. The IPCC assessment also concluded that the impacts of climate change and effective adaptations will depend on local conditions, including socio-economic conditions and other pressures on water resources (Kundzewicz *et al*., 2008). Patterns of temperature change for inland waters are expected to follow the changes over land areas which are warming at greater than global atmospheric annual means because there is less water available for evaporative cooling and a smaller thermal inertia as compared to the oceans (Christensen *et al*., 2007).

Since the 1960s, surface water temperatures have warmed by 0.2 ºC to 2 °C in lakes and rivers in Europe, North America and Asia (Rosenzweig *et al.,* 2007). Increased water temperature and longer ice free seasons influence thermal stratification. In several lakes in Europe and North America, the stratified period has advanced by up to 20 days and lengthened by two to three weeks as a result of increased thermal stability (Rosenzweig *et al.,* 2007; O'Reilly *et al*., 2003).

Ninety percent of inland fisheries occur in Africa and Asia (FAO, 2006).Therefore, a brief summary of likely physical impacts of climate change in these regions follows.

FIGURE 2

Time series of global annual ocean heat content (1022 J for the 0-700 m layer (black) and 0-100 m layer (thick red line; thin red lines indicate estimates of one standard deviation error), and equivalent sea surface temperature (blue; right-hand scale). All time series were smoothed with a three-year running average and are relative to 1961



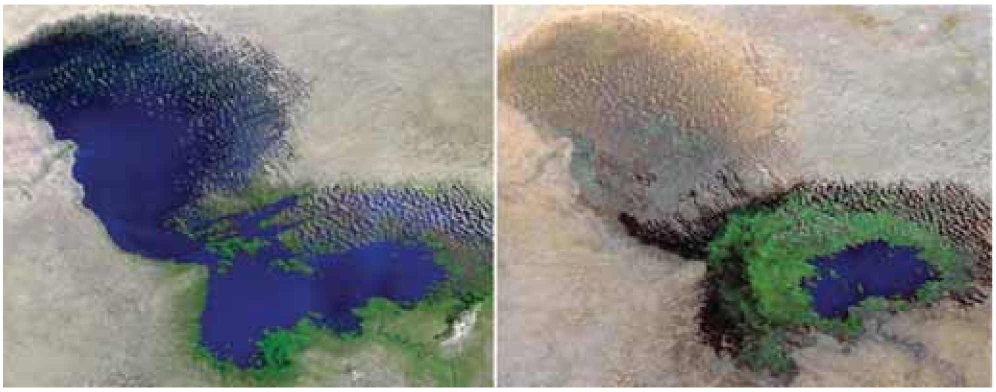
Source: modified from Domingues *et al*., 2008.

Warming in Africa is very likely to be larger than the global annual mean warming throughout the continent and in all seasons, with drier subtropical regions warming more than the wetter tropics. Annual rainfall is likely to decrease in much of Mediterranean Africa and the northern Sahara, with a greater likelihood of decreasing rainfall as the Mediterranean coast is approached. Rainfall in southern Africa is likely to decrease in much of the winter rainfall region and western margins. There is likely to be an increase in annual mean rainfall in East Africa. It is unclear how rainfall in the Sahel, the Guinea coast and the southern Sahara will evolve (Christensen *et al*., 2007).

Warming is likely to be well above the global mean in central Asia, the Tibetan Plateau and northern Asia, above the global mean in eastern Asia and South Asia, and similar to the global mean in Southeast Asia. Precipitation in boreal winter is very likely to increase in northern Asia and the Tibetan Plateau, and likely to increase in eastern Asia and the southern parts of Southeast Asia. Precipitation in summer is likely to increase in northern Asia, East Asia, South Asia and most of Southeast Asia, but is likely to decrease in central Asia. It is very likely that heat waves/hot spells in summer will be of longer duration, more intense and more frequent in East Asia. Fewer very cold days are very likely in East Asia and South Asia. There is very likely to be an increase in the frequency of intense precipitation events in parts of South Asia, and in East Asia. Extreme rainfall and winds associated with tropical cyclones are likely to increase in East Asia, Southeast Asia and South Asia. There is a tendency for monsoonal circulations to result in increased precipitation because of enhanced moisture convergence, in spite of a tendency towards weakening of the monsoonal flows themselves. However, many aspects of tropical climatic responses remain uncertain (Christensen *et al*., 2007).

Inland water temperatures are strongly linked to the dynamics of the hydrological cycle. Overall, there were many studies on trends in river flows and lake levels during the twentieth century at scales ranging from catchment to global. Some of these studies detected significant trends, such as rising levels in response to increased snow and ice melt, or declines because of the combined effects of drought, warming and human activities (Rosenzweig *et al*., 2007). Overall, no globally homogeneous trend has been reported (Rosenzweig *et al*., 2007). Variation in river flows from year to year is very

FIGURE 3
Comparison of the area and volume of Lake Chad in 1973 and 1987. Lake Chad, which supplies water to Chad, Cameroon, Niger and Nigeria, was once one of the largest lakes in Africa. Extensive irrigation projects, encroaching desert and an increasingly dry climate have caused it to shrink to 5 percent its former size



Source: NASA Goddard Space Flight Centre, www.gsfc.nasa/gov.)

strongly influenced in some regions by large scale atmospheric circulation patterns associated with *El Niño* Southern Oscillation (ENSO) North Atlantic Oscillation (NAO) and other decadal variability systems. On a global scale, there is evidence of a broadly coherent pattern of change in annual runoff, with some regions experiencing an increase at higher latitudes and a decrease in parts of West Africa, southern Europe and southern Latin America (Milly, Dunne and Vecchia, 2005). Labat *et al.* (2004) claimed a 4 percent increase in global total runoff per 1 °C rise in temperature during the twentieth century, with regional variation around this trend, but this has been challenged (Legates, Lins and McCabe, 2005) because of the effects of non climatic drivers on runoff and bias due to the small number of data points.

Worldwide a number of lakes have decreased in size during the last decades, mainly because of human water use. For some, declining precipitation was also a significant cause; e.g. Lake Chad (Coe and Foley, 2001; Figure 3). In general, atmospheric warming is contributing to a reduction of rainfall in the subtropics and an increase at higher latitudes and in parts of the tropics. However, human water use and drainage is the main reason for inland water shrinkages (Christensen *et al.*, 2007).

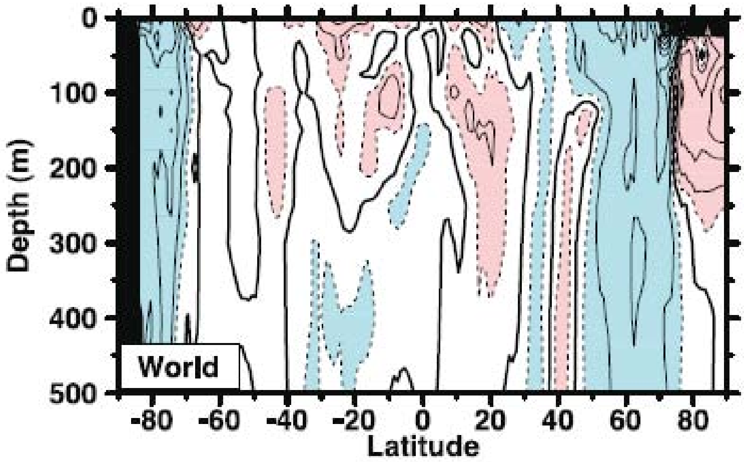
Predictions suggest that significant negative impacts will be felt across 25 percent of Africa's inland aquatic ecosystems by 2100 (SRES B1 emissions scenario, De Wit and Stankiewicz, 2006) with both water quality and ecosystem goods and services deteriorating. Because it is generally difficult and costly to control hydrological regimes, the interdependence between catchments across national borders often leaves little scope for adaptation.

1.2 Ocean salinity, density and stratification

Ocean salinity changes are an indirect but potentially sensitive indicator of a number of climate change processes such as precipitation, evaporation, river runoff and ice melt, although data are much more limited than those for temperature. Figure 4 shows linear trends of zonally averaged salinity in the upper 500 m of the World Ocean for five-year periods from 1955 to 1998 (Boyer *et al.*, 2005). In summary, changes in ocean salinity at gyre and basin scales in the past half century have been observed, with near surface waters in the more evaporative regions increasing in salinity in almost all ocean basins, and high latitudes showing a decreasing trend due to greater precipitation, higher runoff, ice melting and advection. Overall indications are that the global ocean

FIGURE 4

Linear trends (1955–1998) of zonally averaged salinity (psu) in the upper 500 m of the World Oceans. The contour interval is 0.01 psu per decade and dashed contours are ±0.005 psu per decade. The dark solid line is the zero contour. Red shading indicates values equal to or greater than 0.005 psu per decade and blue shading indicates values equal to or less than –0.005 psu per decade



Source: Boyer *et al.,* 2005.

is freshening (Antonov, Levitus and Boyer, 2002), but with large regional differences. Salinity is increasing in the surface of the subtropical North Atlantic Ocean (15-42 °N), while further north there is a freshening trend. In the Southern Ocean there is a weak freshening signal. Freshening also occurs in the Pacific, except in the upper 300 m and in the subtropical gyre, where salinity is increasing. The Indian Ocean is generally increasing its salinity in the upper layers (Bindoff *et al*., 2007). Although the low volume of available data precludes us from reaching stronger conclusions, the apparent freshening of the World Ocean seems to be due to an enhanced hydrological cycle (Bindoff *et al*., 2007).

Predictions of salinity patterns in a warmer ocean are consistent with observations. Sarmiento *et al.* (2004) expected salinity changes as a result of an enhancement of the hydrologic cycle that occurs due to the increased moisture bearing capacity of warmer air. The combined effect of the temperature and salinity changes would be an overall reduction of the surface density, resulting in an expected increase in vertical stratification and changes in surface mixing (Sarmiento *et al*., 2004). In most of the Pacific Ocean, surface warming and freshening act in the same direction and contribute to reduced mixing, which is consistent with regional observations (Freeland *et al*., 1997; Watanabe *et al*., 2005). In the Atlantic and Indian Oceans, temperature and salinity trends generally act in opposite directions, but changes in mixing have not been adequately quantified.

Sea ice changes are one of the major factors involved in the above mentioned salinity patterns in a warmer ocean. Sea ice is projected to shrink in both the Arctic and Antarctic over the twenty-first century, under all emission scenarios, but with a large range of model responses (Meehl *et al*., 2007). In some projections, arctic late summer sea ice disappears by 2030 (Stroeve *et al*., 2007).

Large salinity changes have been historically observed in the North Atlantic in association with sporadic changes in fresh water inputs and the NAO. These Great Salinity Anomalies (Dickson *et al*., 1988) result from strengthening of the subpolar gyre during positive NAO phases, and cause lower surface salinity in the central subpolar region. Three such anomalies have been documented in 1968 to 1978, the 1980s and 1990s (Houghton and Visbeck, 2002).

1.3 Ocean circulation and coastal upwelling

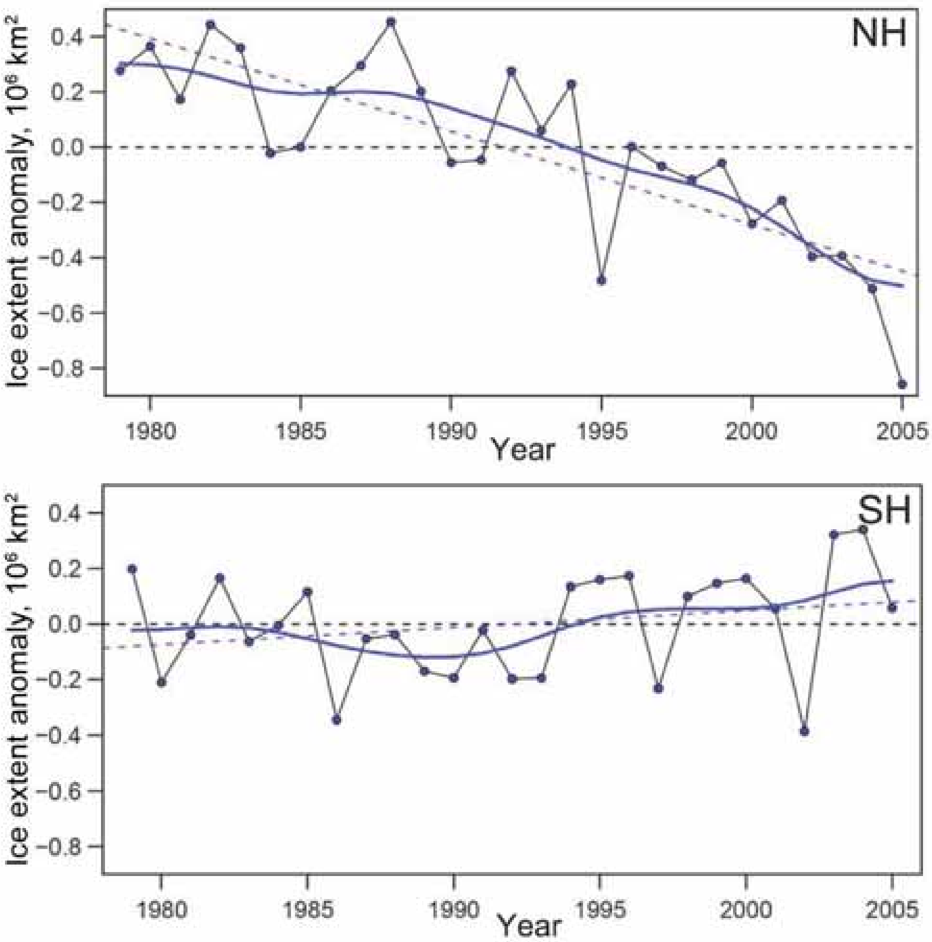
Observed and predicted changes in the ocean's heat content and salinity are and will continue to affect circulation patterns. A full description of existing and potential impacts is beyond the scope of this review, and readers are directed to the relevant IPCC 4AR for details (Bindoff *et al.*, 2007). We will however, discuss two specific circulation issues: possible changes in the North Atlantic Meridional Overturning Circulation (MOC), as impacts could be extreme; and long-term patterns in coastal upwelling, because of its implication to biological production in eastern boundary currents. In addition, it is worth noting that there is evidence that mid-latitude westerly winds have strengthened in both hemispheres since the 1960s (Gillett, Allan and Ansell, 2005) and this is predicted to be enhanced under global warming conditions, with concomitant ocean circulation changes.

1.3.1 Meridional Overturning Circulation (MOC)

The Atlantic MOC carries warm upper waters into far-northern latitudes. In the process it cools, sinks and returns southwards at depth. Changes in the hydrological cycle (including sea ice dynamics, as freezing water releases salt) have the potential to influence the strength of the MOC. The heat transport of the MOC makes a substantial contribution to the climate of continental Europe and any slowdown would have important atmospheric climate consequences (up to 4 °C lower than present for a total shutdown, Velinga and Wood, 2002). Observations and model predictions indicate increased freshwater input in the Arctic and sub Arctic (both through precipitation reduced sea ice, Schrank, 2007; Figure 5), potentially increasing stratification, with increased stability of the surface mixed layer, reduction in salt flux, reduced ocean convection, and less deepwater formation (e.g. Stenevik and Sundby, 2007), which could lead to a prolonged reduction in thermohaline circulation and ocean ventilation in the Atlantic. A reduction of about 30 percent in the MOC has already been observed between 1957 and 2004 (Bryden, Longworth and Cunningham, 2005). Model simulations indicate that the MOC will slow further during the twenty-first century (up to a further 25 percent by 2100 for SRES emission scenario A1B, Meehl *et al.*, 2007). Whereas a positive NAO trend might delay this response by a few decades, it will not prevent it (Delworth and Dixon, 2000). Currently, none of the available climate models predict a complete shutdown of the MOC, but such an event cannot be excluded if the amount of warming and its rate exceed certain thresholds (Stocker and Schmittner, 1997). Schmittner (2005) suggested that a disruption of the thermohaline circulation (THC) would collapse North Atlantic zooplankton stocks to less than half of their original biomass. Kuhlbrodt *et al.* (2005), conducted an in-depth study of the physical, biological and economic consequences of a THC change for northern Europe. They concluded that a major THC change might increase sea level by more than 50 cm. They further suggested strong impacts on the whole marine food web in the northern North Atlantic, from algae to plankton, shrimp and fish. In one specific study, Vikebo *et al.* (2005) investigated the consequences of a 35 percent reduction in the THC on Norwegian seas. The main results were a drop in sea surface temperature (SST) in the Barents Sea of up to 3 °C, because of reduced inflow of Atlantic Water to the Barents and an increased flow west of Svalbard. Simulations of the transport of larvae and juvenile cod under the new scenario indicate a possible southward and westward shift in the distribution of cod year classes from the Barents Sea onto the narrow shelves of Norway and Svalbard and reduced individual growth of the pelagic juveniles with subsequent poorer year classes (probably <10 percent of the strong year classes of today). An increasing number of larvae and juveniles would be advected towards the western parts of Svalbard and possibly further into the Arctic Ocean where they would be unable to survive (under present conditions).

FIGURE 5

Sea ice extent anomalies (computed relative to the mean of the entire period) for (a) the Northern Hemisphere and (b) the Southern Hemisphere, based on passive microwave satellite data. Symbols indicate annual mean values while the smooth blue curves show decadal variations. Linear trend lines are indicated for each hemisphere. For the Arctic, the trend is equivalent to approximately –2.7 percent per decade, whereas the Antarctic results show a small positive trend. The negative trend in the NH is significant at the 90 percent confidence level whereas the small positive trend in the SH is not significant.



Source: Lemke *et al.,* 2007.

1.3.2 Coastal upwelling

Wind driven Ekman pumping drives the four major eastern boundary upwelling systems of the world: the Humboldt, Benguela, California and Canary currents, supplemented by a region off North East Africa in the Arabian Sea that is driven by monsoonal wind forcing. There is contradicting evidence and differing predictions with regard to impacts of climate change on upwelling processes. Bakun (1990) predicted that differential warming between oceans and land masses would, by intensifying the alongshore wind stress on the ocean surface, lead to acceleration of coastal upwelling. He suggested that this effect was already evident in the Iberian margin, California and Humboldt currents. This hypothesis was later supported by Snyder *et al*. (2003) who observed a 30-year trend in increased wind driven upwelling off California, corroborated by regional climate forced modelling outputs. In support of the above, Auad, Miller and Di Lorenzo (2006) concluded that increased stratification of warmed waters was overcome by increased upwelling caused by the intensification of alongshore wind stress off California. Positive correlations between upwelling and atmospheric temperature in paleo records in the California Current have also been observed (Pisias, Mix and Heusser, 2001). SST records obtained from sediment cores off Morocco indicate anomalous and unprecedented cooling during the twentieth century, which would be consistent with increased climate change driven upwelling (McGregor *et al*., 2007). Increased twentieth century Arabian Sea upwelling, attributed to global warming-related heating of the Eurasian landmass, has also been observed (Goes *et al*., 2005). The conclusion was arrived at through paleo records linking declining winter and spring snow cover over Eurasia with stronger southwest (summer) monsoon winds, and thus coastal upwelling (Anderson, Overpeck and Gupta, 2002), suggesting that further increases in southwest monsoon and upwelling strength during the coming century are possible as a result of greenhouse gas concentrations.

In contrast to the above observations, Vecchi *et al*. (2006) suggest that because the poles will warm more dramatically than the tropics, the trade wind system which also drives upwelling favourable winds should weaken. Simulations conducted by Hsieh and Boer (1992) indicated that the mid-latitude continents do not all follow Bakun's (1990) scenario in developing anomalous low pressure in summer and enhancing coastal winds favourable to upwelling. In the open ocean the equatorial and subpolar zonal upwelling bands and the subtropical downwelling bands would weaken as winds diminish because of the weakening of the equator-to-pole temperature gradient in the lower troposphere under global warming. With a weakening of open ocean upwelling and an absence of enhanced coastal upwelling, the overall effect of global warming could be to decrease global biological productivity. In fact, most recent contributions agree that global warming would strengthen thermal stratification and cause a deepening of the thermocline, both reducing upwelling and decreasing nutrient supply into the sunlit regions of oceans, thus reducing productivity (Cox *et al*., 2000; Loukos *et al*., 2003; Lehodey, Chai and Hampton, 2003; Roemmich and McGowan, 1995; Bopp *et al*., 2005).

On the basis of global circulation model (GCM) studies, Sarmiento *et al.* (2004) conclude that there is no clear pattern of upwelling response to global warming at the global scale, except within a couple of degrees of the equator, where all but one atmosphere-ocean general circulation models show a reduction (Sarmiento *et al*., 2004). Overall, the equatorial and coastal upwelling within 15 ° of the equator drops by 6 percent. However, it must be noted that current climate models are not yet sufficiently developed to resolve coastal upwelling (Mote and Mantua, 2002) and so the results of large scale GCM simulations have to be treated with caution. The consequences of generic increases or decreases in coastal upwelling as a result of climate change can be dramatic and not limited to biological production. Bakun and Weeks (2004) suggested that, should upwelling intensify in coming decades, it could lead to switches to undesirable states dominated by unchecked phytoplankton growth by rapidly exported herbivorous zooplankton, sea floor biomass depositions and eruption of noxious greenhouse gases.

Overall, the response of coastal upwelling to climate warming is likely to be more complex than a simple increase or decrease. Focusing on the California Current, Diffenbaugh, Snyder and Sloan (2004) showed that biophysical land-cover–atmosphere feedbacks induced by CO_2 radiative forcing enhance the land–sea thermal contrast, resulting in changes in total seasonal upwelling and upwelling seasonality. Specifically, land-cover–atmosphere feedbacks lead to a stronger increase in peak- and late-season near-shore upwelling in the northern limb of the California Current and a stronger decrease in peak- and late-season near-shore upwelling in the southern limb. Barth *et al*. (2007) show how a one month delay in the 2005 spring transition to upwelling-favourable wind stress off northern California resulted in numerous anomalies: nearshore surface waters averaged 2 °C warmer than normal, surf-zone chlorophyll-*a* and nutrients were 50 percent and 30 percent less than normal – respectively – and densities of recruits of mussels and barnacles were reduced by 83 percent and 66 percent respectively. The delay was associated with 20-to-40-day wind oscillations accompanying a southward shift of the jet stream resulting in the lowest cumulative upwelling-favourable wind stress for 20 years. They concluded that delayed early-season upwelling and stronger late-season upwelling are consistent with predictions of the influence of global warming on coastal upwelling regions. Because upwelling is of fundamental importance in coastal marine systems, further elucidation of the relationship between climate and upwelling is a high research priority.

1.4 Sea level rise

Global average sea level has been rising at an average rate of 1.8 mm per year since 1961 (Douglas, 2001; Miller and Douglas, 2004; Church *et al*., 2004), threatening many low altitude regions. The rate has accelerated since 1993 to about 3.1 mm per year as a result of declines in mountain glaciers and snow cover in both hemispheres and losses from the ice sheets of Greenland and Antarctica (Bindoff *et al*., 2007; Figure 5). Ice loss from Greenland has been aggravated by melting having exceeded accumulation due to snowfall. Sea ice extent in the Antarctic however, shows no statistically significant average trends, consistent with the lack of warming reflected in atmospheric temperatures (Lemke *et al*., 2007; Figure 5).

There is evidence of increased variability in sea level in recent decades, which may be consistent with the trend towards more frequent, persistent and intense El Niños (Folland *et al*., 2001). Model-based projections of global average sea level rise at the end of the twenty-first century (2090 to 2099) relative to 1980 to 1999 range between 0.18 m (minimum under B1 scenario, world convergent to global sustainability principles) and 0.59 m (maximum under A1F1 scenario, very rapid, fossil-intensive world economic growth, Meehl *et al*., 2007), although empirical projections of up to 1.4 m have been estimated (Rahmstorf, 2007). IPCC models used to date do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. In particular, contraction of the Greenland ice sheet is projected to continue to contribute to sea level rise after 2100. Revised estimates of upper ocean heat content (Domingues *et al*., 2008) imply a significant ocean thermal expansion contribution to sea level rise of 0.5 to 0.8 mm per year in water below 700 m depth. Since the start of the IPCC projections in 1990, sea level has actually risen at near the upper end of the third (and equivalent to the upper end of the fourth) assessment report, including an estimated additional allowance of 20 cm rise for potential ice sheet contributions. It is important to note that sea level change is not geographically uniform because it is controlled by regional ocean circulation processes.

All coastal ecosystems are vulnerable to sea level rise and more direct anthropogenic impacts, especially coral reefs and coastal wetlands (including salt marshes and mangroves). Long-term ecological studies of rocky shore communities indicate adjustments apparently coinciding with climatic trends (Hawkins, Southward and Genner, 2003). Global losses of 33 percent in coastal wetland areas are projected given a 36 cm rise in sea level from 2000 to 2080. The largest losses are likely to be on the Atlantic and Gulf of Mexico coasts of the Americas, the Mediterranean, the Baltic, and small island regions (Nicholls *et al*., 2007). Sea level rise may reduce intertidal habitat area in ecologically important North American bays by 20 to 70 percent over the next hundred years, where steep topography and anthropogenic structures (e.g. sea walls) prevent the inland migration of mudflats and sandy beaches (Galbraith *et al*., 2002).

Key human vulnerabilities to climate change and sea level rise exist where the stresses on natural low-lying coastal systems coincide with low human adaptive capacity and/

or high exposure and include: deltas, especially Asian megadeltas (e.g. the Ganges-Brahmaputra in Bangladesh and West Bengal); low-lying coastal urban areas, especially areas prone to natural or human-induced subsidence and tropical storm landfall (e.g. New Orleans, Shanghai); small islands, especially low-lying atolls (e.g. the Maldives) (Nicholls *et al*., 2007).

1.5 Acidification and other chemical properties

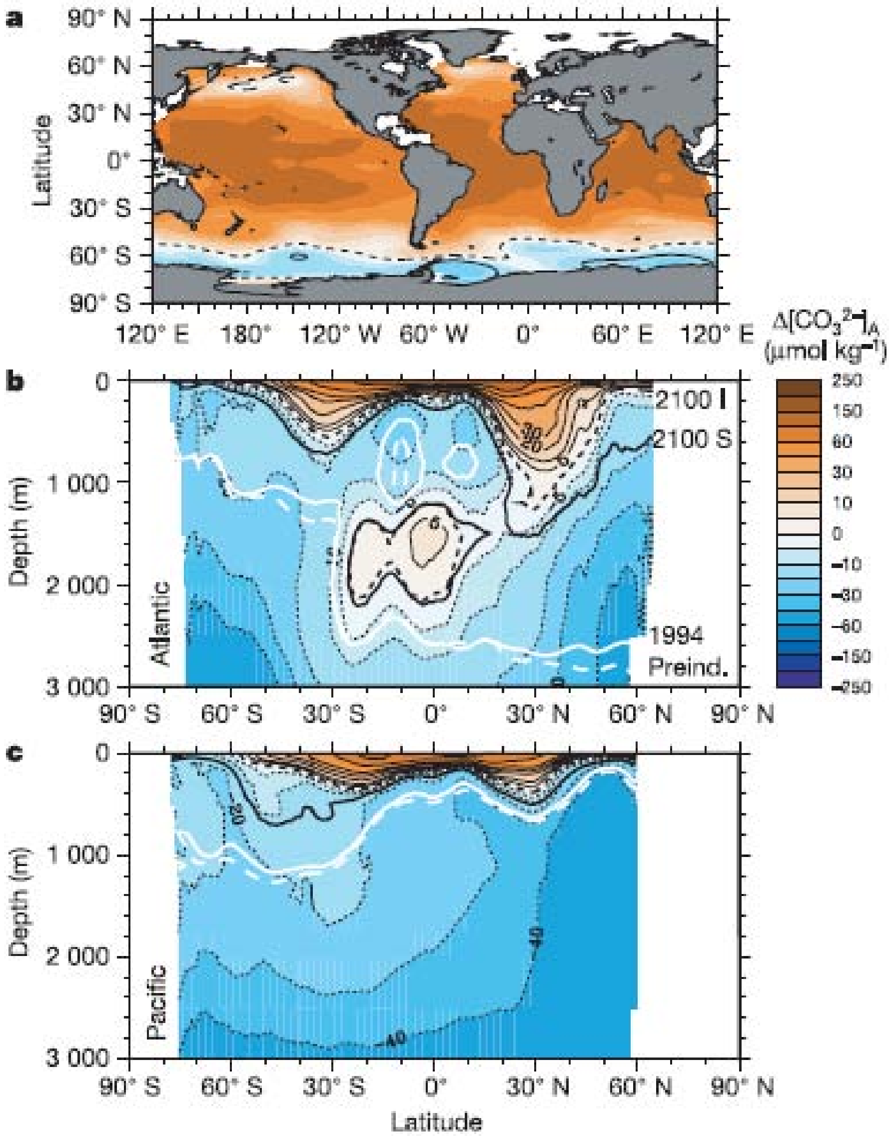
Roughly half the CO_2 released by human activities between 1800 and 1994 is stored in the ocean (Sabine *et al*., 2004), and about 30 percent of modern CO_2 emissions are taken up by oceans today (Feely *et al*., 2004). Continued uptake of atmospheric CO_2 has decreased the pH of surface seawater by 0.1 units in the last two hundred years. Model estimates of further pH reduction in the surface ocean range from 0.3 to 0.5 units over the next hundred years and from 0.3 to 1.4 units over the next three hundred years, depending on the CO_2 emission scenario used (Caldeira and Wickett, 2005). The impacts of these changes will be greater for some regions and ecosystems and will be most severe for shell-borne organisms, tropical coral reefs and cold water corals in the Southern Ocean (Orr *et al*., 2005, Figure 6). Recent modelling results of Feely *et al*. (2008) suggest that by the end of the century the entire water column in some regions of the subarctic North Pacific will become undersaturated with respect to aragonite. Warmer tropical and sub tropical waters will likely remain supersaturated over the range of IPCC-projected atmospheric CO_2 concentration increases (Feely *et al*., 2008).

Impacts on other marine organisms and ecosystems are much less certain than the physical changes because the mechanisms shaping sensitivity to long-term moderate CO_2 exposures are insufficiently understood. It is expected that pH reduction will change the depth below which calcium carbonate dissolves, increasing the volume of ocean that is undersaturated with respect to aragonite and calcite, which are used by marine organisms to build their shells (Kleypas *et al*., 1999; Feely *et al*., 2004). Changes in pH may affect marine species in ways other than through calcification. Havenhand *et al*. (2008) report that expected near-future levels of ocean acidification reduce sperm motility and fertilization success of the sea urchin *Heliocidaris erythrogamma*, and suggest that other broadcast spawning marine species may be at similar risk. Impacts on oxygen transport and respiration systems of oceanic squid make them particularly at risk of reduced pH (Pörtner, Langenbuch and Michaelidis, 2005). However, the degree of species adaptability and the rate of change of seawater pH relative to its natural variability are unknown. Aragonite undersaturation is expected to affect corals and pteropods (Hughes *et al*., 2003; Orr *et al*., 2005), as well as other organisms such as coccolitophores (Riebesell *et al*., 2000; Zondervan *et al*., 2001). In contrast to experiments where no adaptation is possible, Pelejero *et al*. (2005) observed that ~three hundred-year-old massive Porites corals from the southwestern Pacific had adapted to ~fifty-year cycles of large variations in pH, covarying with the Pacific Decadal Oscillation. This would suggest that adaptation to long-term pH change may be possible in coral reef ecosystems. Research into the impacts of high concentrations of CO_2 in the oceans is in its infancy and needs to be developed rapidly.

Other chemical properties subject to climate change driven trends include oxygen and inorganic nutrients. The oxygen concentration of the ventilated thermocline (about 100 to 1000 m) has been decreasing in most ocean basins since 1970 (Emerson *et al*., 2004), ranging from 0.1 to 6 $\mu mol\ kg^{-1}\ yr^{-1}$, superposed on decadal variations of $\pm 2\ \mu mol\ kg^{-1}\ yr^{-1}$ (Ono *et al*., 2001; Andreev and Watanabe, 2002). The observed O_2 decrease appears to be driven primarily by a reduced rate of renewal of intermediate waters (Bindoff *et al*., 2007), and less by changes in the rate of O_2 demand from downward settling of organic matter. As mentioned above, global warming is likely to strengthen thermal stratification, deepen the thermocline, and as a result decrease nutrient supply

FIGURE 6

The global ocean aragonite saturation state in the year 2100 as indicated by $\Delta[CO^{2-}_{3}]_A$. The $\Delta[CO^{2-}_{3}]_A$ is the *in situ* $[CO^{2-}_{3}]$ minus that for aragonite-equilibrated sea water at the same salinity, temperature and pressure. Shown are modelled median concentrations in the year 2100 under scenario IS92a: a, surface map; b, Atlantic; and c, Pacific zonal averages. Thick lines indicate the aragonite saturation horizon in 1765 (Preind.; white dashed line), 1994 (white solid line) and 2100 (black solid line for S650; black dashed line for IS92a). Positive $\Delta[CO^{2-}_{3}]_A$ indicates supersaturation; negative $\Delta[CO^{2-}_{3}]_A$ indicates undersaturation



Source: Orr *et al.*, 2005.

to surface waters. Only a few studies have reported decadal changes in inorganic nutrient concentrations. In the North Pacific, the concentration of nitrate plus nitrite (N) and phosphate decreased at the surface (Freeland *et al*., 1997; Watanabe *et al*., 2005) and increased below the surface (Emerson *et al*., 2004) in the past two decades. There are no clear patterns in nutrient changes in the deep ocean (Bindoff *et al*., 2007).

1.6 Atmosphere-ocean and land-ocean exchanges

In the period 2000-2005, CO_2 uptake by the oceans amounted to 2.2±0.5 $GtCy^{-1}$ (out of 7.2 $GtCy^{-1}$ fossil CO_2 emissions). These values are at least double the terrestrial biosphere intake (Denman *et al*., 2007). Increasing CO_2 levels in the atmosphere have been postulated to deplete the ozone layer (Austin, Butchart and Shine, 1992), potentially leading to enhanced levels of ultraviolet radiation at the earth's surface, with possible indirect effects on ocean processes (see Section 2.7).

Land-use change, particularly deforestation and hydrological modifications, has had downstream impacts, particularly erosion in catchment areas. Suspended sediment loads in the Huanghe (Yellow) River, for example, have increased two to ten times over the past two thousand years (Jiongxin, 2003). In contrast, damming and channelization have greatly reduced the supply of sediments to the coast from other rivers through retention of sediment by dams (Syvitski *et al*., 2005). Changes in fresh water flows will affect coastal wetlands by altering salinity, sediment inputs and nutrient loadings (Schallenberg, Friedrich and Burns, 2001; Flöder and Burns, 2004). Changed fresh water inflows into the ocean will lead to changes in turbidity, salinity, stratification, and nutrient availability, all of which affect estuarine and coastal ecosystems (Justic, Rabalais and Turner, 2005), but consequences may vary locally. For example, increased river discharge of the Mississippi would increase the frequency of hypoxia events in the Gulf of Mexico, while increased river discharge into the Hudson Bay would lead to the opposite (Justic, Rabalais and Turner, 2005). Halls and Welcomme (2004) conducted simulation studies to develop criteria for the management of hydrological regimes for fish and fisheries in large floodplain–river systems. They concluded that, in general, fish production was maximized by minimizing the rate of drawdown and maximizing the flood duration and flood and dry season areas or volumes.

Little attention has been paid to trade offs between land use and inland capture production, such as dry season trade off between rice and inland fish production on the floodplains of Bangladesh. Shankar, Halls and Barr (2004) noted that floodplain land and water in Bangladesh are coming under ever-increasing pressure during the dry winter months, which are critical to the survival and propagation of the floodplain resident fish. River floodplain systems, particularly in the developing world, need to consider the trade offs between fish and rice production in the context of climate change effects on hydrological systems (Shankar, Halls and Barr, 2004).

Mangroves are adapted for coastal areas with waterlogged and often anoxic soils but their tolerance of salinity stress varies among species. Freshwater influx not only reduces the salinity of coastal waters but also enhances the stratification of the water column, thereby decreasing nutrient resupply from below. Flood events are associated with an increase in productivity as nutrients are washed into the sea (McKinnon *et al*., 2008). While diatoms seem to be negatively affected by increases in river discharge, dinoflagellates have been observed to profit from the increase in stratification and availability of humic substances associated with riverine freshwater input (Carlsson *et al*., 1995; Edwards *et al*., 2006). Regardless of the direction of change, modifications in rain water runoff and accompanying changes in salinity and resource supply should therefore affect the composition and, potentially, the productivity of the phytoplankton community in coastal waters.

1.7 Low frequency climate variability patterns

Atmospheric circulation patterns arise primarily as a consequence of heating contrasts between the poles and the equator, modulated by seasonality, and because land and water absorb and release heat at different rates. The result is a patchwork of warmer and cooler regions characterized by a number of patterns of atmospheric circulation with different persistence. The extent to which preferred patterns of variability can be considered true modes of the climate system is debatable, but certainly these patterns are used to explain physical and biological variability in the ocean, particularly at decadal scale (e.g. Lehodey *et al*., 2006). Because of the long time scales of some natural climate patterns, it is difficult to discern if observed decadal oceanic variability is natural or a climate change signal, and have to be treated separately from the gradual, linear, long-term warming expected as a result of greenhouse gas emissions. Furthermore, there may be impacts of gradual climate change on the intensity, duration and frequency of these climate patterns and on their teleconnections.

Overland *et al*. (2008) concluded that most climate variability in the Atlantic and Pacific Oceans is accounted for by the combination of intermittent one to two-year duration events (e.g. ENSO), plus broad-band "red noise" (large signals are only visible when a number of otherwise random contributions add together in the same phase) and intrinsic variability operating at decadal and longer timescales. ENSO predictability has had some degree of success. However, although heat storage and ocean time lags provide some multi-year memory to the climate system, basic understanding of the mechanisms resulting in observed large decadal variability is lacking. Decadal events with rapid shifts and major departures from climatic means will occur, but their timing cannot yet be forecast (Overland *et al*., 2008). In this section we describe the main patterns of climate variability relevant to fish production and their observed impacts on biological processes. Impacts at the ecosystem level, which often take the form of regime shifts, are discussed in more detail in Section 2.9 (Regime shifts).

The most obvious driver of interannual variability is the El Niño Southern Oscillation (ENSO). Climate scientists have arbitrarily chosen definitions for what is and what is not an "ENSO event" (Trenberth, 1997), and today, warm phases of ENSO are called "El Niño" and cool phases "La Niña". ENSO is an irregular oscillation of three to seven years involving a warm and a cold state that evolves under the influence of the dynamic interaction between atmosphere and ocean. Although ENSO effects are felt globally (Glynn 1988; Bakun 1996), the major signal occurs in the equatorial Pacific with an intensity that can vary considerably from one event to another. El Niño events are associated with many atmospheric and oceanic patterns, including abnormal patterns of rainfall over the tropics, Australia, southern Africa and India and parts of the Americas, easterly winds across the entire tropical Pacific, air pressure patterns throughout the tropics and sea surface temperatures (Nicholls 1991; Reaser, Pomerance and Thomas, 2000; Kirov and Georgieva, 2002). Coincident ecological changes are both vast and global and include influences over plankton (MacLean 1989), macrophytes (Murray and Horn 1989), crustaceans (Childers, Day and Muller, 1990) fish (Mysak, 1986; Sharp and McLain, 1993), marine mammals (Testa *et al.*, 1991; Vergani, Stanganelli and Bilenca, 2004), seabirds (Anderson, 1989; Cruz and Cruz, 1990; Testa *et al.*, 1991) and marine reptiles (Molles and Dahm, 1990).

El Niño events have three major impacts in coastal upwelling systems: they increase coastal temperatures, reduce plankton production by lowering the thermocline (which inhibits upwelling of nutrients) and change trophodynamic relationships (Lehodey *et al.*, 2006). In non-upwelling areas they change the vertical structure of the water column, increasing and decreasing available habitats (Lehodey, 2004). The warm-water phase of ENSO is associated with large-scale changes in plankton abundance and associated impacts on food webs (Hays, Richardson and Robinson, 2005), and changes to behaviour (Lusseau *et al*., 2004), sex ratio (Vergani *et al*., 2004) and feeding and diet (Piatkowski, Vergani and Stanganelli, 2002) of marine mammals. The strong 1997 ENSO caused bleaching in every ocean (up to 95 percent of corals in the Indian Ocean), ultimately resulting in 16 percent of corals destroyed globally (Hoegh-Guldberg, 1999, 2005; Wilkinson, 2000). Evidence for genetic variation in temperature thresholds among the obligate algal symbionts suggests that some evolutionary response to higher water temperatures may be possible (Baker, 2001; Rowan, 2004). However, other studies indicate that many entire reefs are already at their thermal tolerance limits (Hoegh-Guldberg, 1999).

Some studies expect stronger and more frequent El Niño as a result of global warming (e.g. Timmerman *et al*., 1999; Hansen *et al*., 2006). Others suggest that the evidence is still inconclusive (Cane, 2005) because ENSO is not well enough simulated in climate models to have full confidence in these projected changes (Overland *et al*., 2008). ENSO events are connected to weather changes outside the Pacific Ocean that are linked by remote atmospheric associations or teleconnections (Mann and Lazier, 1996). This means that changes in the position and intensity of atmospheric convection in one area will result in adjustments in pressure cells in adjacent areas and can lead to altered wind and ocean current patterns on a global scale. Teleconnected shifts could occur if they are linked to the Earth nutation (wobbling motion of the earth's axis, Yndestad, 1999) or changes in the Earth's rotational speed (Beamish, McFarlane and King, 2000).

The most prominent teleconnections over the Northern Hemisphere are the North Atlantic Oscillation (NAO) and the Pacific-North American (PNA) patterns (Barnston and Livezey, 1987). Both patterns are of largest amplitude during the winter months. The NAO is an index that captures north-south differences in pressure between temperate and high latitudes over the Atlantic sector (Hurrell *et al.,* 2003). Thus, swings in the NAO index from positive to negative (and vice versa) correspond to large changes in the mean wind speed and direction over the Atlantic, the heat and moisture transport between the Atlantic and the neighbouring continents and the intensity and number of Atlantic storms, their paths and their weather. It appears that the NAO does not owe its existence primarily to coupled ocean-atmosphere-land interactions: it arises from processes internal to the atmosphere, in which various scales of motion interact with one another to produce random and thus largely unpredictable variations with a fundamental time scale of ten days and longer (Overland *et al*., 2008).

Changes in the NAO index have occurred concurrently with changes in biological communities evident at multiple trophic levels, e.g. zooplankton community structure (Planque and Fromentin, 1996), timing of squid peak abundance (Sims *et al.*, 2001), gadoid recruitment and biomass (Hislop, 1996; Beaugrand *et al.*, 2003) and herring (*Clupea harengus*, Clupeidae) and sardine populations (Southward *et al.*,1988), and occasionally in the form of regime shifts (see Section 2.9). Observation and model predictions using General Circulation Models (GCMs) both seem to indicate that the NAO has been high (positive) over recent decades (Cohen and Barlow, 2005) and despite fluctuations is likely to remain high during the twenty-first century because of climate change effects (Palmer, 1999; Gillet, Graf and Osborn, 2003; Taylor, 2005). There is some indication as well, that some of the upward trend in the NAO index over the last half of the twentieth century arose from tropical SST forcing or/and freshening at high latitudes and increased evaporation at subtropical latitudes. It is not unreasonable to claim that part of the North Atlantic climate change, forced by the imposed slow warming of tropical SSTs, constitutes an anthropogenic signal that has just begun to emerge (Overland *et al*., 2008). Moreover, as both ENSO and the NAO are key determinants of regional climate, our ability to detect and distinguish between natural and anthropogenic regional climate change is limited.

The PNA teleconnection pattern relates to four centres of high and low pressure in a roughly great circle route from the central Pacific, through the Gulf of Alaska and western Canada to the southeastern United States. Over the North Pacific Ocean pressures near the Aleutian Islands vary out-of-phase with those to the south, forming a seesaw pivoted along the mean position of the Pacific subtropical jet stream, the centre of the main westerly (coming from the west) winds in the atmosphere. Over North America, variations over western Canada and the northwestern United States are negatively correlated with those over the southeastern United States but are positively correlated with the subtropical Pacific centre. At the surface, the signature of the PNA is mostly confined to the Pacific. Like the NAO, the PNA is an internal mode of atmospheric variability. The PNA is closely related to an index consisting of variability in North Pacific sea surface temperatures (SST), called the Pacific Decadal

Oscillation (PDO). The NAO and PNA explain about 35 percent of the climate variability during the twentieth century (Quadrelli and Wallace, 2004).

Changes in climate variability patterns in the North Pacific are often referred to as regime changes (see Section 2.9). The index generally used to identify the shifts is based on the Pacific Decadal Oscillation (PDO), which is defined as the first empirical orthogonal function of sea surface temperature in the North Pacific (Mantua *et al*., 1997). The 1977 regime change led to changes in surface wind stress (Trenberth, 1991), cooling of the central Pacific, warming along the west coast of North America and decreases in Bering Sea ice cover (Miller *et al.,* 1994; Manak and Misak, 1987). There are indications of other shifts in 1925, 1947 (Mantua *et al*., 1997) and 1989 (Beamish *et al*., 1999) and possibly 1998 (McFarlane, King and Beamish, 2000). Around the time of the 1977 regime shift, total chlorophyll *a* nearly doubled in the central North Pacific owing to a deepening of the mixed layer (Venrick, 1994), while the mixed layer in the Gulf of Alaska was shallower (but also more productive, Polovina, Mitchum and Evans, 1995). These changes resulted in a dramatic decrease in zooplankton biomass off California caused by increased stratification and reduced upwelling of nutrient-rich water (Roemmich and McGowan, 1995). However, zooplankton responses were far from linear, and have been largely attributed to salps and doliolids (Rebstock, 2001).

There is evidence that the existence of these climate patterns can lead to larger-amplitude regional responses to forcing than would otherwise be expected. It is therefore important to test the ability of climate models to simulate them and to consider the extent to which observed changes related to these patterns are linked to internal variability or to anthropogenic climate change. In general, a primary response in the IPCC climate models to climate patterns is a rather spatially uniform warming trend throughout the ocean basins combined with the continued presence of decadal variability similar to that of the twentieth century, NAO, PDO, etc. (Overland and Wang, 2007).

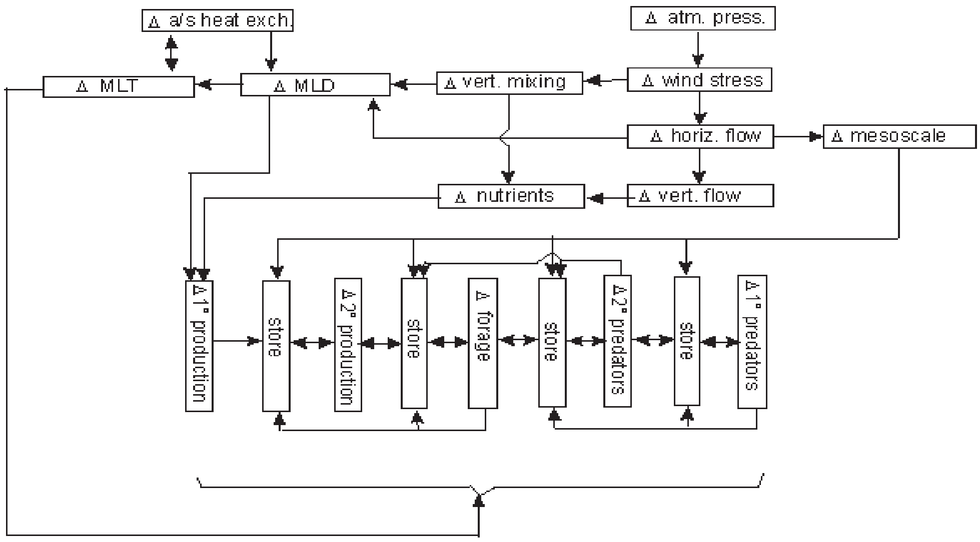
Climate variables such as temperature and wind can have strong teleconnections (large spatial covariability) within individual ocean basins, but between-basin teleconnections, and potential climate-driven biological synchrony over several decades, are usually much weaker (Overland *et al*., 2008).

2. OBSERVED EFFECTS OF CLIMATE VARIABILITY AND CHANGE ON ECOSYSTEM AND FISH PRODUCTION PROCESSES

Direct effects of climate change impact the performance of individual organisms at various stages in their life history via changes in physiology, morphology and behaviour. Climate impacts also occur at the population level via changes in transport processes that influence dispersal and recruitment. Community-level effects are mediated by interacting species (e.g. predators, competitors, etc.), and include climate-driven changes in both the abundance and the strength of interactions among these species. The combination of these proximate impacts results in emergent ecological responses, which include alterations in species distributions, biodiversity, productivity and microevolutionary processes (Harley *et al*., 2006).

In general, there is limited observational information on climate change impacts on marine ecosystems. For example, only 0.1 percent of the time series examined in the IPCC reports were marine (Richardson and Poloczanska, 2008). Generalizations are thus difficult to make, compounded by the fact that impacts are likely to manifest differently in different parts of the world's oceans. For example, observed patterns of sea surface variability in the Pacific and Indian oceans exceed those in the Atlantic Ocean (Enfield and Mestas-Nunez, 2000), mostly because the western Pacific and eastern Indian Oceans have the largest area of warm surface water in the world. The effects that this warm-water pool exerts on interannual and multi-decadal time scales can result in significant variations in primary production, fish abundance and ecosystem structure at basin scales (Chavez *et al*., 2003).

FIGURE 7
A model illustrating potential pathways by which climate change effects can be mechanistically transmitted to marine biota. a/s, atmosphere/ sea; MLD, mixed layer depth; MLT, mixed layer temperature; Store boxes in the trophic ladder inserted between levels indicate that the effects of climate variation may be felt differently by the actual production process and by storage and dispersal of accumulated biomass



Source: Francis *et al.*, 1998.

In spite of this scarcity of data, there is now significant evidence of observed changes in physical and biological systems in every continent, including Antarctica, as well as from most oceans in response to climate change, although the majority of studies come from mid and high latitudes in the Northern Hemisphere. Documentation of observed changes in tropical regions and the Southern Hemisphere is particularly sparse (Parry *et al*., 2007).

Marine and freshwater systems respond to the combined and synergistic effects of physical and chemical changes acting directly and indirectly on all biological processes (see Figure 7). We begin with a brief summary of the physiological, spawning, and recruitment processes by which marine and freshwater populations respond to environmental and climate variability. These are also the processes and responses that individuals and populations must use to adjust to climate change. We then provide examples of how marine and freshwater populations, communities, and ecosystems have responded to observed climate variability as proxies for their potential responses to climate change.

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

2.1.1 Physiological effects of climate change on fish

Most marine and aquatic animals are cold-blooded (poikilotherms) and therefore their metabolic rates are strongly affected by external environmental conditions, in particular temperature. The thermal tolerances of fish have been described by Fry (1971) as consisting of lethal, controlling, and directive responses, which indicate that fish will respond to temperature long before it reaches their lethal limits. Magnuson, Crowder and Medvick, (1979) proposed the concept of a thermal niche similar to niches for other resources such as food or space. For North American freshwater fishes they found that fish spent all of their time within ± 5 °C of their preferred temperature, and that three thermal guilds could be recognised: cold, cool, and warm water-adapted species. Moderate temperature increases may increase growth rates and food conversion efficiency, up to the tolerance limits of each species.

Marine species are also strongly affected by temperature and have thermal tolerances of often similar ranges to those of freshwater fishes (e.g. Rose, 2005, lists distributional temperature limits for 145 fish species in the subarctic North Atlantic). Thermal tolerance of marine organisms is non-linear, with optimum conditions at mid-range and poorer growth at temperatures which are too high or too low. Pörtner *et al*. (2001) found, for both Atlantic cod (*Gadus morhua*) and common eelpout (*Zoarces viviparus*) that temperature-specific growth rates and fecundity declined at higher latitudes. Takasuka, Oozeki and Aoki, (2007) suggested that differences in optimal temperatures for growth during the early life stages of Japanese anchovy (*Engraulis japonicus*; 22 °C) and Japanese sardine (*Sardinops melanostictus*; 16.2 °C) could explain the shifts between the warm "anchovy" regimes and cool "sardine" regimes in the western North Pacific Ocean.

Many macrophysiological studies have found that organisms transferred into conditions different from those to which they have been adapted, function poorly compared with related organisms previously adapted to these new conditions (Osovitz and Hofmann, 2007). Pörtner (2002) describes an interaction of thermal preference and oxygen supply, such that the capacity to deliver oxygen to the cells is just sufficient to meet the maximum oxygen demand of the animal between the high and low environmental temperatures to be expected. When fish are exposed to conditions warmer than those to which they have been adapted their physiologies are incapable of supplying the increased tissue demand for oxygen over extended periods. This restricts the exposure of whole-animal tolerances to temperature extremes (Pörtner and Knust, 2007). According to Pörtner and Knust (2007), it is the lack of oxygen supply to tissues as conditions warm and metabolic demands increase that lead to altered distributions or extinction of fish from cooler conditions. Larger individuals may be at greater risk of this effect as they may reach their thermal aerobic limits sooner than smaller individuals (Pörtner and Knust, 2007).

In many cases, such changes in thermal conditions are also accompanied by changes in other characteristics, such as changes in sea levels (and therefore exposure regimes, e.g. Harley *et al*., 2006) and lake levels (e.g. Schindler, 2001); changes in the composition and amount of food; and changes in acidity and other chemical characteristics. In a study of the effects of temperature changes on rainbow trout (*Oncorhynchus mykiss*) in the presence of low pH and high nitrogen, Morgan, McDonald and Wood (2001) found improved growth during winter with a 2 °C temperature increase but decreased growth in summer when the 2 °C increase was added to the already high temperatures. Therefore, seasonal influences and instances when such changes occur may be equally (or more) important than changes expressed on an annual basis. The term "bioclimate envelope" has been used to define the interacting effects and limits of temperature, salinity, oxygen, etc. on the performance and survival of species (e.g. Pearson and Dawson, 2003). Such bioclimate envelopes could be used to model changes in species' distributions and abundance patterns as a result of climate change. The increasing experimentation in culture operations for a wide variety of marine and freshwater vertebrate and invertebrate species should provide opportunities to learn more about their responses to environmental conditions and which conditions lead to optimal (and suboptimal) growth.

2.1.2 Spawning

The characteristics of spawning and successful reproduction of marine and freshwater organisms are largely under evolutionary control; organisms adapt to the prevailing conditions, and possibly the variability of these conditions, so that they can complete their life cycle and reproduce. In this context, the influences of climate variability and change on the characteristics of spawning and reproduction are also closely related to their influences on growth and successful recruitment to the mature population. Spawning times and locations have evolved to match prevailing physical (such as temperature, salinity, currents) and biological (such as food) conditions that maximize the chances for a larva to survive to become a reproducing adult; or at the very least to minimize potential disruptions caused by unpredictable climate events. Whereas evolution is responsible for the type of spawning, environmental features such as temperature have significant influences on specific characteristics of spawning. These include its timing (e.g. Atlantic cod; Hutchings and Myers, 1994), and the size of eggs and consequent size of larvae at hatch (e.g. Atlantic cod; Pepin, Orr and Anderson, 1997). Crozier *et al*. (2008) concluded that climate change is likely to induce strong selection on the date of spawning of Pacific salmon in the Columbia River system. Temperature has also been demonstrated to influence the age of sexual maturity, e.g. Atlantic salmon (*Salmo salar*; Jonsson and Jonsson, 2004) and Atlantic cod (Brander, 1994). For these cold water species, warmer conditions lead to earlier (younger) age-at-maturity.

2.1.3 Fish recruitment processes and climate change

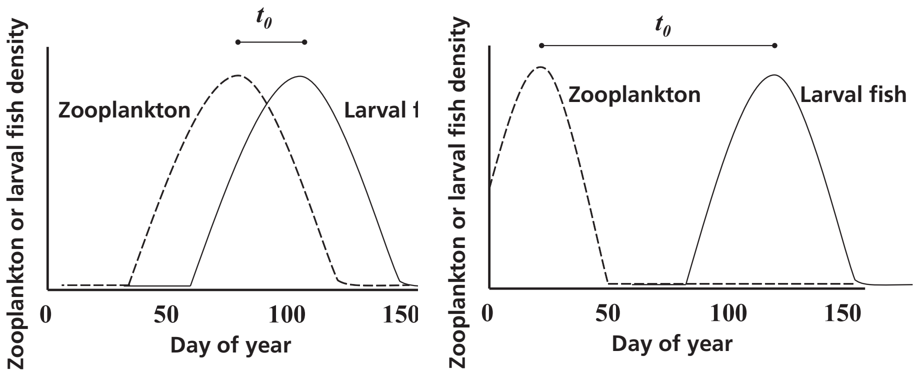
The issue of recruitment variability and its causes and consequences to commercial fish populations, in particular, has been the single most important problem in fisheries science over the past hundred years. Great advances have been achieved, but it is still rare for quantitative recruitment forecasts to be used to provide fisheries management advice. Such forecasts, often based on relationships with environmental variables, tend to be used for species with short life spans (e.g. California sardine, Jacobson *et al*., 2005; squid, Rodhouse, 2001) because the abundances of species with long life spans can usually be assessed more accurately using directed surveys of the later age classes.

Many theories and processes have been proposed to explain the huge reduction in the numbers of most marine and aquatic species as they develop from egg to larva to juvenile and finally the adult (e.g. see Ottersen *et al*., 2008, for a recent synthesis). These hypotheses can be grouped into three general categories: starvation and predation, physical dispersal and synthesis processes.

One of the principal hypotheses proposed to relate the impact of starvation on recruitment, which has clear connections with climate variability and change is the match-mismatch hypothesis of Cushing (1969; 1990; see also Durant *et al*., 2007). It recognises that fish, particularly in the early stages, need food to survive and grow. It also recognises that periods of strong food production in the ocean can be variable and are often under climate control (strength of winds, frequency of storms, amount of heating or fresh water supplied to the surface layers). The hypothesis proposes, therefore, that the timing match or mismatch between when food is available and when and where fish (particularly in the early stages) are able to encounter and consume this food (Figure 8), is a principle determinant of recruitment and the subsequent abundance of marine and freshwater species. Winder and Schindler (2004a) have shown how increasingly warmer springs in a temperate lake have advanced thermal stratification and the spring diatom bloom, thereby disrupting trophic linkages and causing a decline in a keystone predator (*Daphnia* spp.) populations. Mackas, Batten and Trudel (2007) observed similar responses of earlier zooplankton blooms and their consequences for the growth and survival of pelagic fish as a result of warming in the North East Pacific. Predation is an alternative to starvation as a source of mortality, and the two may be related in that slower growing larvae are more susceptible to predators. The vulnerability to predation of larval fish depends on the encounter rate of predators and prey (a function of abundances, sizes and their relative swimming speeds and turbulent environments) and the susceptibility to capture (Houde, 2001).

FIGURE 8

Cushing's (1969, 1990) match-mismatch hypothesis for recruitment variations of marine species. Left panel represents a match between zooplankton prey and larval fish abundance, resulting in good recruitment. The right panel represents a mismatch between predator and prey, resulting in poor fish recruitment. The separation time between peaks of prey and predators is represented by t_0



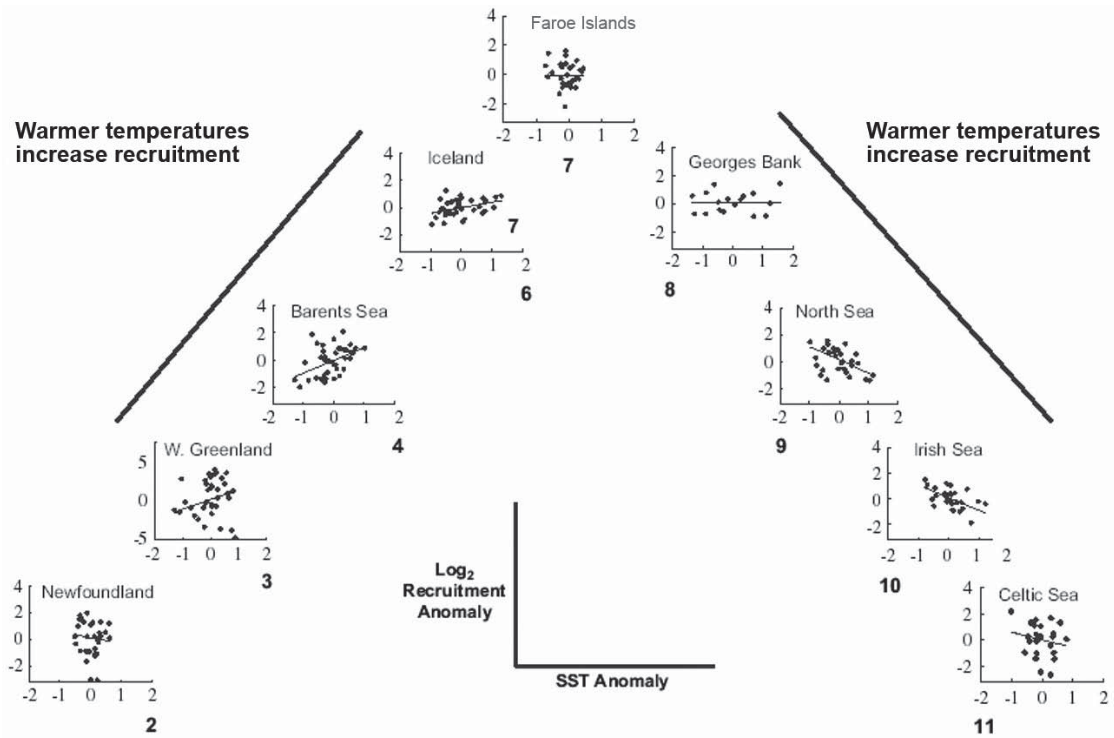
Source: Modified from Cushing, 1990.

Physical dispersal is largely concerned with the effects of physical processes, in particular the circulation, on the distributions of marine and aquatic species, and their abilities to grow, survive, and spawn to successfully close the life cycle. Since physical processes play a direct role in these processes, they are likely to be susceptible to climate variability and change. Three hypotheses relate climate effects directly to the recruitment and abundance of marine fish populations. These are the optimal environmental window hypothesis of Cury and Roy (1989), the Triad hypothesis of Bakun (1996), and the oscillating control hypothesis of Hunt *et al.* (2002).

Cury and Roy's (1989) optimal environmental window hypothesis assumes that species are adapted to the typical ("optimal") conditions within their preferred habitats. This implies that better recruitment success should be expected with "mean" rather than with "extreme", either high or low, conditions, i.e. a non-linear relationship. The concept of an optimal environmental window for recruitment success has subsequently been proposed for a variety of species including Pacific salmon (Gargett, 1997). The concept can also be applied in a spatial context, such that stocks living at the edges of the adapted range should be expected to experience more marginal conditions and greater environmental influences on recruitment success than stocks in the middle of their range (Figure 9). This has been verified for 62 marine fish populations of 17 species in the Northeast Atlantic (Brunel and Boucher, 2006).

Bakun's (1996) Triad hypothesis posits that optimal conditions of enrichment processes (upwelling, mixing, etc.) concentration processes (convergences, fronts, water column stability) and retention within appropriate habitats is necessary for good recruitment. Locations in which these three elements exist to support favourable fish habitats are called "ocean triads". Since the processes of enrichment, concentration and retention are in opposition, the Triad hypothesis also requires non-linear dynamics, with optimal conditions for each component located at some mid-point of the potential range. Bakun (1996) proposed the Triad hypothesis for Atlantic bluefin tuna (*Thunnus thynnus*), Japanese sardine (*Sardinops melanostictus*), albacore tuna (*Thunnus alalunga*) and various groundfish species in the North Pacific, and anchovy (*Engraulis* spp.) in the Southwest Atlantic. It has subsequently been described for anchovy (*Engraulis ringens*) in the Humboldt upwelling system off Peru (Lett *et al.*, 2007), sardine (*Sardinops sagax*) in the southern Benguela ecosystem (Miller *et al.*, 2006), and anchovy

FIGURE 9
The relationship between the $\log_2$ recruitment anomaly and sea surface temperature anomaly (in °C) for various cod stocks in the North Atlantic. The large axis in the bottom centre of the diagram shows the axis legends for all of the plots. The numerical value at the bottom of each plot represents the mean annual bottom temperatures for the stocks. For the cold-water stocks, the SST-recruitment relationship is generally positive whereas for the warm-water stocks it is negative. There is no relationship in the mid-temperature range



Source: Drinkwater, 2005, modified from Planque and Frédou,1999.

in the Mediterranean Sea (Agostini and Bakun, 2002). Since such systems are based on optimal conditions across these otherwise opposing processes, they are likely to be sensitive to disruptions or systematic alterations in these processes that may occur with climate change.

The oscillating control hypothesis (Hunt *et al*., 2002) was developed for the southern Bering Sea. It posits that the pelagic ecosystem is driven by plankton production processes in cold years but predominately by predation in warm periods. During cold years, production of walleye pollock (*Theragra chalcogramma*) is limited by cold temperatures and low food reserves. Early in the warm period, strong plankton production promotes good fish recruitment but as the abundance of adult pollock increases, their recruitment is reduced by cannibalism and other predators. A comparable impact of climate on oscillating trophic control has also been found for Pacific cod (*Gadus macrocephalus*) and five prey species in the North Pacific (Litzow and Ciannelli, 2007).

2.2 Primary production

2.2.1 Global ocean

In general, observations and model outputs suggest that climate change is likely to lead to increased vertical stratification and water column stability in oceans and lakes, reducing nutrient availability to the euphotic zone and thus reducing primary (Falkowski, Barber and Smetacek, 1998; Behrenfeld *et al*., 2006) and secondary (Roemmich and McGowan, 1995) production. The climate–plankton link in the ocean is found most strongly in the tropics and mid latitudes, where there is limited vertical mixing because the water column is stabilized by thermal stratification (that is, when light, warm waters overlie dense, cold waters). In these areas, the typically low levels of surface nutrients limit phytoplankton growth. Climate warming further inhibits mixing, reducing the upward nutrient supply and lowering productivity (Doney 2006). However, in certain regions (e.g. high latitudes) a compensation mechanism has been proposed through which the residence time of particles in the euphotic zone will increase, assuming the nutrient supply remains the same (Doney 2006).

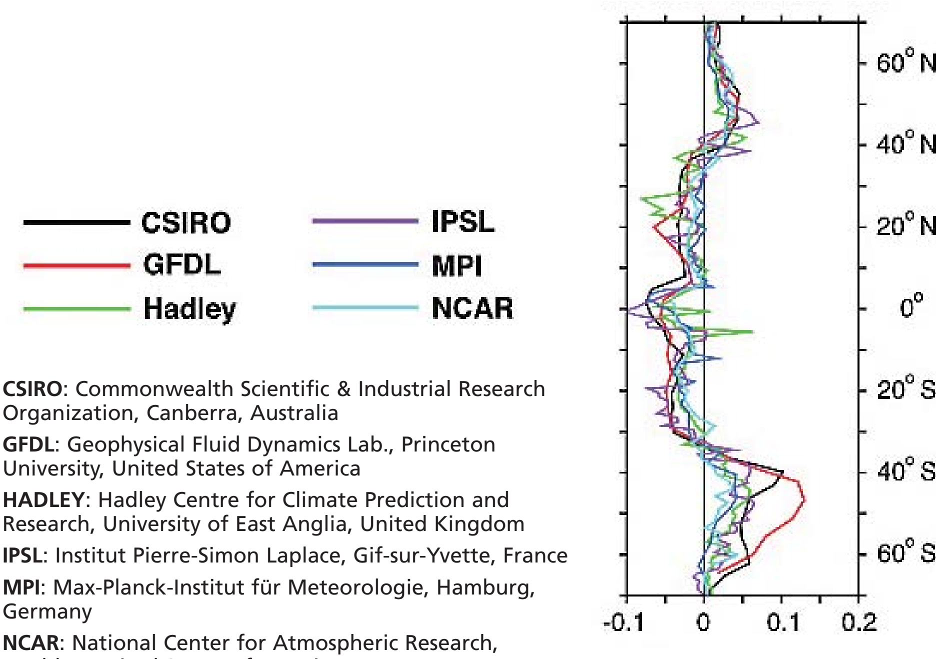
Observations in support of the above include a 6 percent reduction in global oceanic primary production between the early 1980s and the late 1990s, based on the comparison of chlorophyll data from two satellites (Gregg *et al*., 2003). Extrapolating the satellite observations into the future suggests that marine biological productivity in the tropics and mid latitudes will decline substantially. Observations in higher latitudes may reflect the compensation mechanism mentioned above, as chlorophyll in the Northeast Atlantic for example, has increased since the mid-1980s (Raitsos *et al*., 2005; Reid *et al.,* 1998; Richardson and Schoeman, 2004).

Predicting climate change impacts on primary and secondary production is subject to uncertainties in the parameterization of biogeochemical models. In a major comparative study Sarmiento *et al. (*2004) simulated the effect of greenhouse gas emissions using six Atmosphere-Ocean General Circulation Models (AOGCMs), comparing emission scenarios for the period from pre-industrial to 2050 and 2090 with a control in which emissions remained at pre-industrial levels. The models assessed chlorophyll and primary production distribution changes using temperature, salinity and density at the sea surface, upwelling, stratification and sea ice cover. Predicted climate-induced alterations in nutrient supply and production are predominantly negative, due to reduced vertical mixing. However, in high latitude regions the resultant increased stability of the water column and increased growing season will have a positive effect on production (Figure 10). Primary production was estimated for a set of seven biomes, further subdivided into biogeographical provinces. Global estimates predicted a small global increase in primary production of between 0.7 percent and 8.1 percent, with very large regional differences (Table 1). For example, decreases in the North Pacific and the area adjacent to the Antarctic continent are slightly more than offset by increases in the North Atlantic and the open Southern Ocean.

Bopp *et al*. (2005) used a multinutrient and multiplankton community model to predict a 15 percent decrease of global primary production at 4xCO_2 levels, balanced between an increase in high latitudes due to a longer growing season and a decrease in lower latitudes due to a decrease in nutrient supply. Their model results suggest that climate change leads to more nutrient-depleted conditions in the surface ocean, favouring small phytoplankton at the expense of diatoms, whose relative abundance is reduced by more than 10 percent at the global scale and by up to 60 percent in the North Atlantic and in the sub Antarctic Pacific (Figure 11). It is worth noting that this simulated change in the ecosystem structure impacts oceanic carbon uptake by reducing the efficiency of the biological pump, thus contributing to the positive feedback between climate change and the ocean carbon cycle. Similarly, Boyd and Doney (2002) used a complex ecosystem model incorporating multi-nutrient limitation (N, P, Si, Fe) and a community structure with planktonic geochemical functional groups, i.e. diatoms (export flux and ballast), diazotrophs (nitrogen fixation) and calcifiers (alkalinity and ballast), to predict a 5.5 percent decrease of the global primary production and an 8 percent decrease of the global new production due to enhanced stratification and slowed thermohaline overturning. They conclude that regional floristic shifts can be as important as changes in bulk productivity (see also Leterme *et al*., 2005).

It must be noted, however, that the above global predictions are based on large scale simulation work at resolutions that do not to resolve coastal upwelling processes, as

FIGURE 10
Zonally integrated response of the global ocean's primary production (PgC deg^{-1} yr^{1}, in response to the combined effect of the chlorophyll change and temperature increase) shown as the difference between the warming and the control simulation for each of the six Atmosphere-Ocean GCMs averaged over the period 2040 to 2060 (except for MPI, which is for the period 2040 to 2049)



CSIRO: Commonwealth Scientific & Industrial Research Organization, Canberra, Australia

GFDL: Geophysical Fluid Dynamics Lab., Princeton University, United States of America

HADLEY: Hadley Centre for Climate Prediction and Research, University of East Anglia, United Kingdom

IPSL: Institut Pierre-Simon Laplace, Gif-sur-Yvette, France

MPI: Max-Planck-Institut für Meteorologie, Hamburg, Germany

NCAR: National Center for Atmospheric Research, Boulder, United States of America

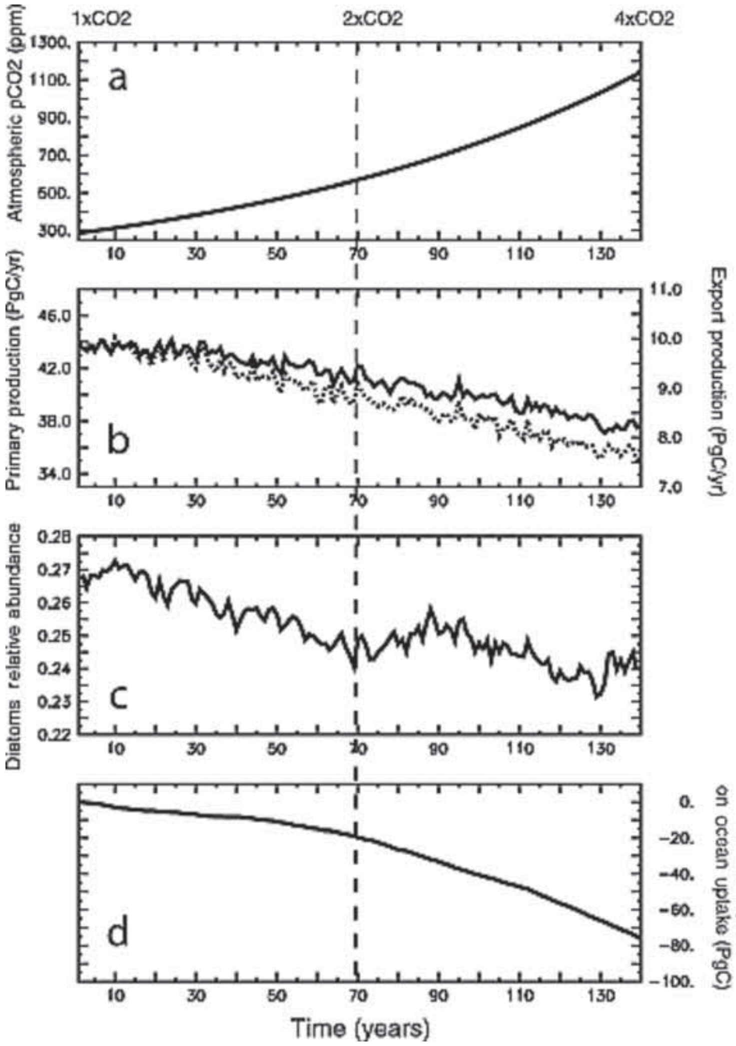
Source: modified from Sarmiento *et al.,* 2004.

discussed in section 1.3.2. Should climate change significantly impact coastal upwelling processes, plankton production predictions would have to be revised.

Vazquez-Dominguez, Vaque and Gasol (2007) determined experimentally the effects of a 2.5 °C sea temperature increase on bacterial production and respiration throughout a seasonal cycle in a coastal Mediterranean site. These results indicate an increase of nearly 20 percent in the total carbon demand of coastal microbial plankton without any effect on their growth efficiency, which could generate a positive feedback between coastal warming and CO_2 production.

Another recent study which combines modelling with empirical evidence looks at the consequences for global primary productivity of disruption of the Atlantic Meridional Overturning (AMO) circulation and concludes that a 50 percent reduction in North Atlantic primary production and a 20 percent reduction in global carbon export production is possible and was a feature of previous ice ages (Schmittner, 2005). Although the conclusions from these two studies appear to be very different, the results are probably compatible with each other when differences in time scales and processes are taken into account. In the Schmittner model, the spindown in AMO is relatively slow, occurring over a period of 500 years, but there is evidence that changes can be more rapid (Cubash *et al.*, 2001) and that reduction in meridional overturning may have begun in both the North Atlantic (Curry and Mauritzen, 2005) and the North Pacific (McPhaden and Zhang, 2002). Since even partial shutdown of the AMO may result in substantial reduction of productivity, it is evident that the causes, likelihood and consequences merit close scrutiny (Kuhlbrodt *et al.*, 2005).

FIGURE 11
Time series of (a) atmospheric CO_2 (ppm) which increases at a rate of 1 percent y^{-1}, (b) global oceanic primary productivity (full line) in PgC y^{-1} (left axis) and global ocean particulate export production at 100 m (dotted line) in PgC y^{-1} (right axis), (c) global mean contribution of diatoms to total ocean chlorophyll and (d) climate change cumulative effect on oceanic carbon uptake (PgC)



Source: Bopp *et al.*, 2005.

2.2.2 *Regional impacts*

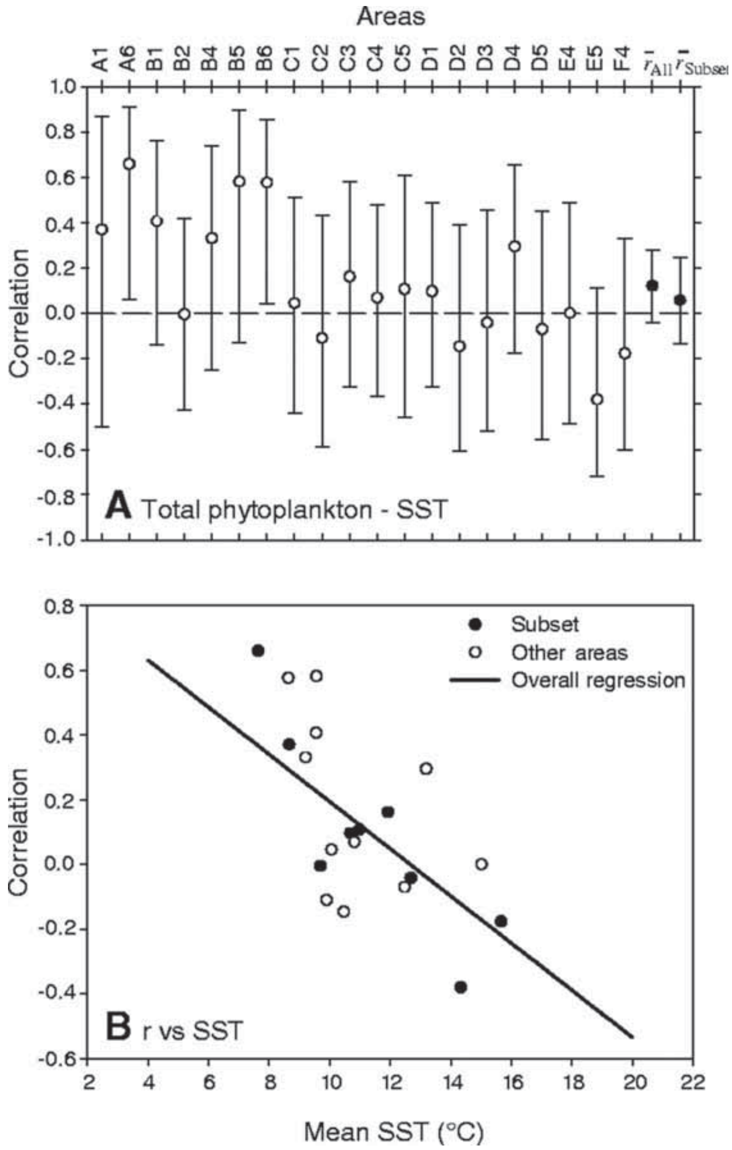
Projections of ocean biological response to climate warming by 2050 show contraction of the highly productive marginal sea ice biome by 42 percent and 17 percent in Northern and Southern Hemispheres (Sarmiento *et al*., 2004; see also Meehl *et al*., 2007; Christensen *et al*., 2007). The sea ice biome accounts for a large proportion of primary production in polar waters and supports a substantial food web. As timing of the spring phytoplankton bloom is linked to the sea ice edge, loss of sea ice (Walsh and Timlin, 2003) and large reductions of the total primary production in the marginal sea ice biome in the Northern Hemisphere (Behrenfeld and Falkowski, 1997; Marra, Ho and Trees, 2003) would have strong effects, for example, on the productivity of the Bering Sea (Stabeno *et al*., 2001). Climate warming would also lead to an expansion of the low productivity permanently stratified subtropical gyre biome by 4.0 percent in the Northern Hemisphere and 9.4 percent in the Southern Hemisphere. In between these, the subpolar gyre biome expands by 16 percent in the Northern Hemisphere and

TABLE 1

Average response of biogeographical province areas to global warming averaged over the period 2040 to 2060 (from Sarmiento *et al.* 2004). Areas are in 1012 m². "Chg" is the difference between the model average warming minus the control; "%Chg" is the percent change

	Indian Ocean			Pacific Ocean			Atlantic Ocean			Global		
	Control	Chg	% Chg	Control	Chg	% Chg	Control	Chg	% Chg	Control	Chg	% Chg
Northern Hemisphere												
Marginal sea ice				3.8	-1.7	-45.3	3.2	-1.2	-37.5	7.0	-2.9	-41.7
Subpolar				8.5	1.2	13.9	5.5	1.1	19.7	14.0	2.3	16.2
Subtropical seasonal				4.9	-0.7	-13.4	8.8	-0.8	-9.4	13.6	-1.5	-10.9
Subtropical permanent	3.3	0.1	2.3	35.4	1.0	2.9	12.5	0.9	7.4	51.2	2.0	4.0
Low latitude upwelling	2.1	-0.1	-6.8	10.9	0.2	1.6	4.4	0.0	0.8	17.3	0.1	0.4
5 °S to 5 °N												
Upwelling	4.5	0.5	10.1	14.6	0.2	1.3	4.6	0.1	2.4	23.7	0.7	3.2
Downwelling	2.3	-0.5	-19.5	4.4	-0.2	-4.3	1.3	-0.1	-10.9	7.7	-0.8	-9.7
Southern Hemisphere												
Low latitude upwelling	7.9	-0.1	-0.7	8.7	-0.6	-7.3	3.8	0.2	4.8	20.4	-0.5	2.5
Subtropical permanent	15.0	1.1	7.3	37.4	3.6	9.7	13.9	1.5	10.8	66.3	6.2	9.4
Subtropical seasonal	13.8	-0.5	-3.3	12.1	-1.8	-14.7	6.4	-1.2	-18.4	32.3	-3.4	-10.6
Subpolar	8.2	1.5	18.7	12.5	0.4	3.3	7.1	0.2	3.4	27.8	2.2	7.9
Marginal sea ice	8.8	-2.1	-23.7	8.8	-1.5	-16.9	7.8	-0.8	-10.3	25.3	-4.4	-17.2
TOTAL	65.8			161.9			79.3			306.7		

FIGURE 12
(A) Meta-analysis of the relation between marine phytoplankton abundance and sea surface temperature, showing no overall relation. Weighted mean correlations (circles) are shown with 99 percent confidence limits (bars) calculated using the random-effects model B for the entire study area (r_{All}) and a subset of nine non contiguous regions ($\bar{r}_{Subset}$). Bars not overlapping zero are significant. (B) The inverse relation between marine phytoplankton abundance–SST correlations and mean SST (°C) in each region. Points represent individual regions



Source: Richardson and Schoeman, 2004.

7 percent in the Southern Hemisphere, and the seasonally stratified subtropical gyre contracts by 11 percent in both hemispheres. The expansion of the subtropical gyre biomes has already been observed in the North Pacific and Atlantic (McClain, Feldman and Hooker, 2004; Sarmiento *et al.*, 2004; Polovina, Howell and Abecassis, 2008).

At smaller scales warming may either increase or decrease productivity based on what specific atmospheric-ocean processes dominate. For example, global warming is increasing the intensity of monsoon winds and, through increased upwelling, has resulted in over 350 percent increase in average summertime phytoplankton biomass along the Arabian Sea coast and 300 percent offshore (Goes *et al.*, 2005). It is therefore likely that warming may make the Arabian Sea more productive.

Hashioka and Yamanaka (2007) modelled the Northwest Pacific region under a global warming scenario and predicted increases in vertical stratification and decreases in nutrient and chlorophyll-*a* concentrations in the surface water by the end of the twenty-first century. Significantly with global warming, the onset of the diatom spring bloom is predicted to take place one half-month earlier than in the present-day simulation, because of stronger stratification. The maximum biomass in the spring bloom is also predicted to decrease significantly compared to present conditions. In contrast, the biomass maximum of the other small phytoplankton at the end of the diatom spring bloom is the same as the present, because of their ability to adapt to low nutrient conditions (as a result of their small half-saturation constant). Therefore a change in the dominant phytoplankton group appears noticeably at the end of spring bloom. Hashioka and Yamanaka (2007) find that changes, due to warming are not predicted to occur uniformly in all seasons, but that they may occur most noticeably at the end of the spring and in the fall bloom.

A study based on over 100 000 plankton samples collected between 1958 and 2002 with the Continuous Plankton Recorder (CPR) (Richardson and Schoeman, 2004) showed an increase in phytoplankton abundance in the cooler regions of the Northeast Atlantic (north of 55 °N) and a decrease in warmer regions (south of 50 °N; Figure 12). The likely explanation for this apparently contradictory result is that although both areas have undergone warming over this period, with consequent reduction of vertical mixing the nutrient supply in the cooler, more turbulent regions remains sufficient and plankton metabolic rates benefit from the increased temperature. Another study based on the CPR data attributed the observed decadal variability in phytoplankton biomass in the Northeast Atlantic to hydroclimatic forcing, as expressed by the NAO (Edwards *et al.,* 2006). In the North Sea this resulted in a shift in seasonal timing of the peak in phytoplankton colour from April to June which may have been accompanied by a taxonomic shift from diatoms to dinoflagellates (Leterme *et al*., 2005).

In the tropical Pacific, models have been developed to understand the links between climate, primary and secondary production, forage fish and, ultimately, skipjack (*Katsuwonus pelamis)* and yellowfin (*Thunnus albacares)* tuna. Key to these models is the definition of suitable tuna habitat which is linked to varying regimes of the principal climate indices El Niño-La Niña Southern Oscillation Index (SOI), and the related Pacific Decadal Oscillation (PDO). Both statistical and coupled biogeochemical models (Lehodey, 2001; Lehodey, Chai and Hampton, 2003) capture the slowdown of Pacific meridional overturning circulation and decrease of equatorial upwelling, which has caused primary production and biomass to decrease by about 10 percent since 1976 to 1977 (McPhaden and Zhang, 2002).

In the southeastern Bering Sea, the spring bloom is affected by the timing of the ice retreat (Hunt *et al*., 2002). During warm years when sea ice retreats early there is insufficient light to support a phytoplankton bloom and there is little stratification due to strong winter winds. The bloom is thus delayed until light and stratification increase. In contrast, when the ice retreat is late, there tends to be ice-melt induced stratification and sufficient light to support a bloom.

Coral reefs provide habitat for a highly diverse ecosystem and short-term extreme water temperatures can cause the symbiotic algae in corals to leave, resulting in coral "bleaching". When bleached corals do not recover, algae may grow over the corals resulting in an algal-dominated ecosystem. Bleaching usually occurs when temperatures exceed a "threshold" of about 0.8 to 1 °C above mean summer maximum levels for at least four weeks (Hoegh-Guldberg, 1999). Many reef-building corals live very close to their upper thermal tolerances and are thus extremely vulnerable to warming (Hughes *et al*., 2003; McWilliams *et al*., 2005). Numerous reports of coral bleaching due to recent warming have been reported (e.g. Hoegh-Guldberg, 1999; Sheppard, 2003; Reaser, Pomerance and Thomas, 2000). Coral destruction can lead to declines in reef community biodiversity and the abundance of a significant number of individual species (Jones *et al*., 2004). In addition, one of the most obvious expected consequences of sea level rise will be a poleward shift in species distributions. However, contrary to most other species, many corals are not expected to be able to keep pace with predicted rates of sea level rise (see Knowlton, 2001).

2.2.3 Inland waters

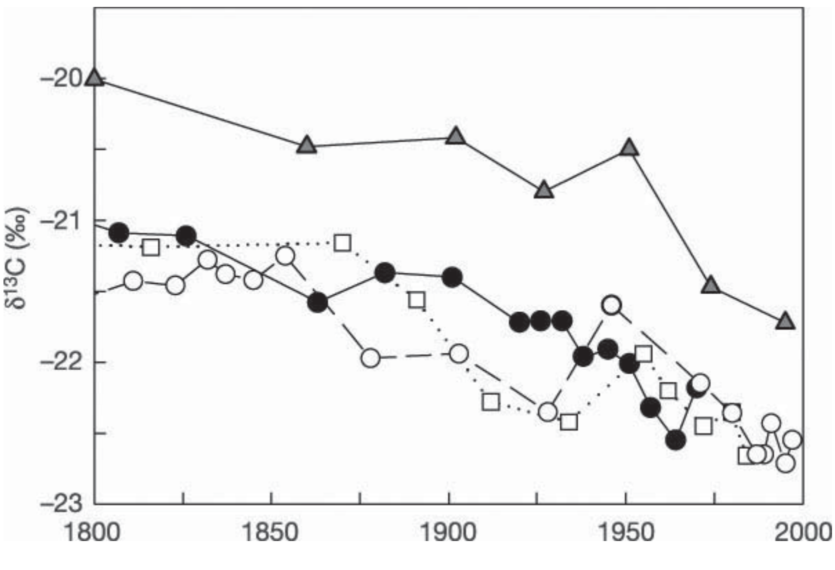
As in oceanic environments, the impacts of global warming on biological production in inland waters depends strongly on the combination of contrasting processes such as ice cover, water flows, stratification and nitrification, with the additional impact of human water and land use.

In high-latitude or high-altitude lakes, atmospheric warming has already led to reduced ice cover, warmer water temperatures, longer growing seasons and, as a consequence, increased algal abundance and productivity (e.g. Battarbee *et al.*, 2002; Korhola *et al.*, 2002; Karst-Riddoch, Pisaric and Smol, 2005). There have been similar increases in the abundance of zooplankton, correlated with warmer water temperatures and longer growing seasons (e.g. Battarbee *et al.*, 2002; Gerten and Adrian, 2002; Carvalho and Kirika, 2003; Winder and Schindler, 2004b; Hampton, 2005; Schindler *et al.*, 2005). For upper trophic levels, rapid increases in water temperature after ice break-up have enhanced fish recruitment in oligotrophic lakes (Nyberg *et al.*, 2001). Studies along an altitudinal gradient in Sweden show that net primary productivity (NPP) can increase by an order of magnitude for a 6 °C air temperature increase (Karlsson, Jonsson and Jansson, 2005).

In contrast, some lakes, such as deep tropical lakes, are experiencing reduced algal abundance and declines in productivity because stronger stratification reduces upwelling of nutrient-rich deep water (Verburg, Hecky and Kling, 2003; Hecky, Bootsma and Odada, 2006). Primary productivity in Lake Tanganyika may have decreased by up to 20 percent over the past two hundred years (O'Reilly *et al.*, 2003, Figure 13). Vollmer *et al.* (2005) have also documented rising temperatures over the last

FIGURE 13

Lake Tanganyika, Africa. Carbon isotope records in sediment cores indicating a post- 1950s trend towards more negative $\delta^{13}C$ values (lower phytoplankton productivity) in both relatively undisturbed (filled symbols), as well as developed (open symbols) watersheds



Source: O'Reilly *et al.*, 2003.

60 years in Lake Malawi, as well as measured reduced ventilation of the deep waters since 1980 (Vollmer, Weiss and Bootsma, 2002), leading to reduced nutrient loading and, presumably, reduced productivity.

Enhanced UV-B radiation and increased summer precipitation will significantly increase dissolved organic carbon (DOC) concentrations, altering major biogeochemical cycles (Zepp, Callaghan and Erickson, 2003; Phoenix and Lee, 2004; Frey and Smith, 2005).

2.3 Secondary production

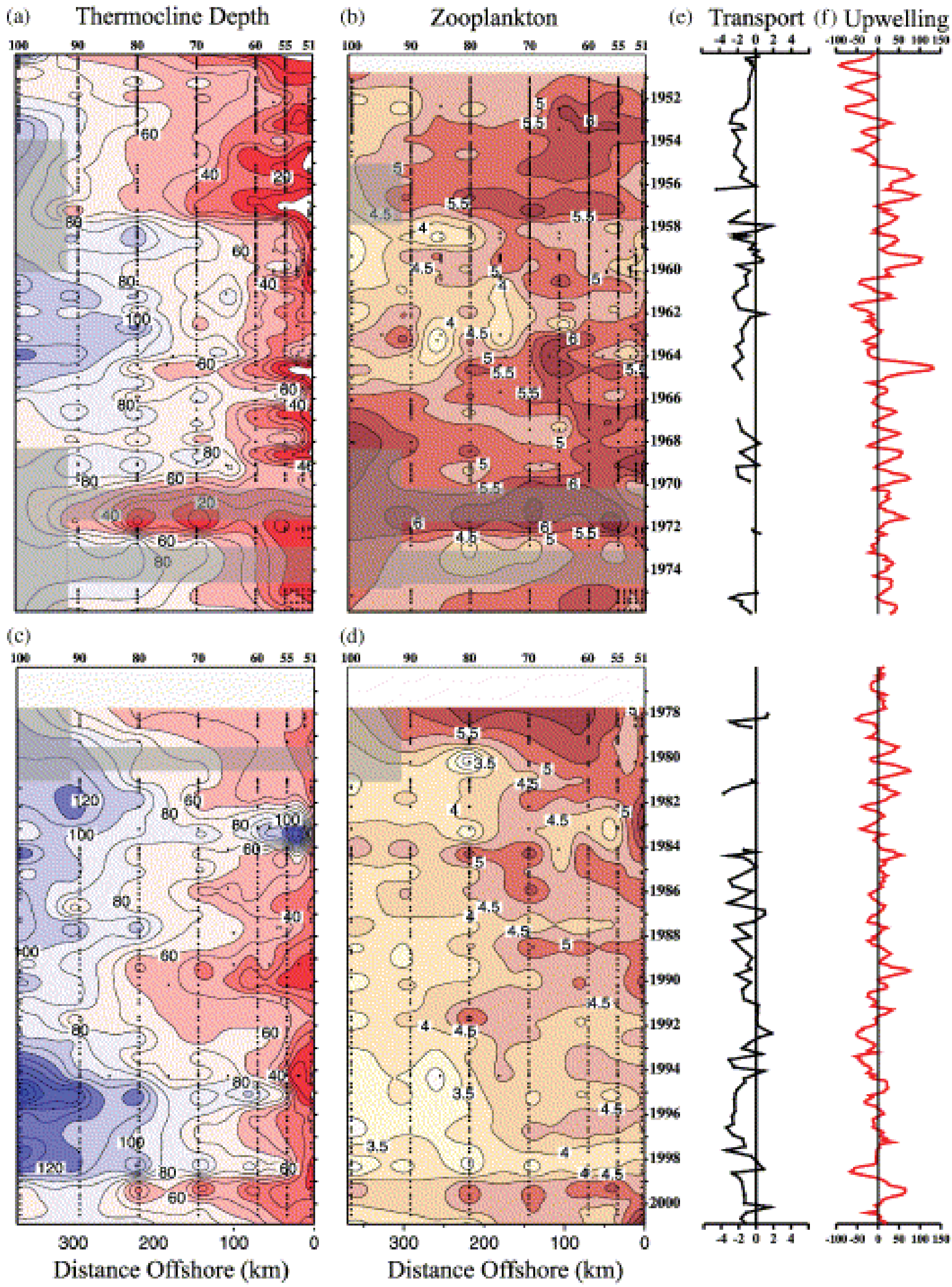
There is currently no global assessment of secondary productivity impacts of climate change, although Richardson (2008) provides a general review of the potential climate warming impacts to zooplankton. Demographic characteristics of marine zooplankton should make them good candidates for assessing the rapid impacts of climate change because of their lifespan (often annual) and the fact that they are rarely fished commercially, facilitating comparative analyses to separate "environment" from fishing' impacts (Mackas and Beaugrand, 2008). Some patterns can be deduced from recent observations at regional scales. Shifts and trends in plankton biomass have been observed in the North Atlantic (Beaugrand and Reid, 2003), the North Pacific (Karl, 1999; Chavez *et al*., 2003) and in the southern Indian Ocean (Hirawake, Odate and Fukuchi, 2005), among others, but the spatial and temporal coverage of these is limited. One of the complications in estimating warming effects on secondary producers is that different ontogenetic stages are differentially susceptible to environmental stress (Pechenik, 1989). Surprisingly, the more eurythermal and specifically heat-tolerant, mid- to high-intertidal species might actually be more vulnerable to climate change than less heat-tolerant species, because they may live closer to their physiological limits (Harley *et al*., 2006). This pattern may also hold at the latitudinal scale as low-latitude species may live nearer to their thermal limits than higher-latitude species (Tomanek and Somero, 1999; Stillman, 2002).

McGowan *et al*. (2003) show that significant ecosystem changes have taken place in the California Current system including a large, decadal decline in zooplankton biomass, along with a rise in upper-ocean temperature (Figure 14). Specifically, they note the abrupt temperature change that occurred around 1976 to 1977, concurrent with other Pacific basin-wide changes associated with an intensification of the Aleutian low pressure system. McGowan *et al*.'s (2003) results are consistent with the "optimal stability window" hypothesis (Gargett, 1997), wherein increased water column stability along the eastern boundary of the North Pacific would reduce (enhance) biological production at southern (northern) latitudes, where productivity is nutrient (light) limited. Trends in total biological production may however mask complex impacts of climate change. Investigating 15-year anomalies in zooplankton abundances in British Columbia, Mackas, Thompson and Galbraith (2001) noted that species-specific biomass anomalies are much larger than anomalies in total annual biomass, recognizing that there was more variability in the structure of the zooplankton community than would be implied by trends in its total biomass.

One of the better studied impacts of climate variability and change on marine zooplankton is the North Atlantic copepod community, which contributes up to 90 percent of the zooplankton biomass in the region. This community is dominated by the congeneric calanoid copepod species *Calanus finmarchicus* and *C. helgolandicus. C. finmarchicus* is mainly located north of the Oceanic Polar Front (Beaugrand and Ibanez, 2004) while the pseudooceanic species *C. helgolandicus* occurs in more temperate waters south of the Oceanic Polar Front, mostly between 40 and 60 °N (Beaugrand and Ibanez, 2004; Bonnet *et al*., 2005). In regions where they occur together (e.g. the North Sea), the two species generally have different seasonal timing (Beaugrand, 2003). *C. finmarchicus* abundance has declined throughout most of the North Atlantic since the 1950s and has collapse in the North Sea to the benefit of *C. helgolandicus*

FIGURE 14

Time-distance plots of depth of the 12°C isotherm (m; a proxy for thermocline depth and nutricline depth) off California (~34°N) for (a) 1950–75 and (c) 1976–2000, and $\log_e$ of macrozooplankton volume (cm^3 1000 m^{-3}) for (b) 1950–75 and (d) 1976–2000. Regions requiring significant interpolation or extrapolation are shaded gray, and nearshore areas in white are where the 12°C isotherm outcrops. Stations are marked by a dot and their labels are given on the top axis of each plot. Time series of (e) alongshore volume transport (10^6 m^3 s^{-1}), calculated between stations 80.55 and 80.90 for each cruise, and (f) monthly upwelling index anomalies (m^3 s^{-1} 1000 m^{-1}; base period 1946–1997), which are estimates of offshore Ekman transport driven by the alongshore geostrophic wind stress at 34°N, 120°W, are shown to the right of the time-distance plots



Source: McGowan *et al.*, 2003.

(Beaugrand *et al*., 2002). Transport processes from their deep overwintering basins to shelf regions determines *C. finmarchicus* distribution and abundance (Speirs *et al*., 2005) and high abundances are generally associated with increased presence of higher nutrient Atlantic waters, either through increased levels of primary production, direct transport or a combination (Astthorsson and Gislason, 1995). Recently, Helaouet and Beaugrad (2007) proposed that temperature change alone could be sufficient to have affected the ecological niche of both species (*C. finmarchicus* reflecting the fate of Atlantic Polar biome and *C. helgolandicus* that of the Atlantic westerly winds biome), suggesting that impacts of climate change at the biome level are responsible for the fate of these species. These changes in species dominance have also resulted in substantial changes in phenology, which affect trophic interactions, foodweb structure and ecosystem functioning (Edwards and Richardson, 2004).

Antarctic krill (*Euphausia superba),* one of the most abundant animal species on earth, have declined (from 38 percent to 75 percent per decade) since 1976 in the high latitude southwest Atlantic sector, probably due to reduction in winter sea ice around the western Antarctic Peninsula (Atkinson *et al.*, 2004). Krill are dependent on the highly productive summer phytoplankton blooms in the area east of the Antarctic Peninsula and south of the Polar Front. Salps, by contrast, which occupy the extensive lower-productivity regions of the Southern Ocean and tolerate warmer water than krill, have increased in abundance. This change has significant implications for the Southern Ocean food web because krill, not salps, are the primary food for penguins, seals, and whales in this system.

It is particularly important to ascertain impacts in regions where secondary producers are directly linked to fisheries production. For example, a decline in the relative importance of *Pseudocalanus* sp. in the Baltic Sea, driven by warming effects on the hydrographic conditions (MacKenzie and Schiedek, 2007), has been linked to fish stock size and condition (Möllmann, *et al*., 2005). Under laboratory conditions, Isla, Lengfellner and Sommer (2008) investigated the physiological response of *Pseudocalanus* sp. under different degrees of warming above decadal averages of the western Baltic Sea, and detected an increase in instantaneous mortality rates and a reduction in the net growth efficiency with temperature. They anticipate that temperature rise will negatively affect *Pseudocalanus* sp. and, as a result, fish stocks in the Baltic Sea.

Perhaps the most comprehensive study on the impacts of climate variability on marine ecosystem production, from zooplankton to fish and from intertidal to open waters, is that of Southward, Hawkins and Burrows (1995), which demonstrated many changes in the abundance of Northeast Atlantic taxa. Finally, Schmittner (2005) estimated that a disruption of the Atlantic meridional overturning circulation would lead to a collapse of the plankton stocks to less than half of their current biomass (see Section 1.3.1).

2.4 Distribution changes

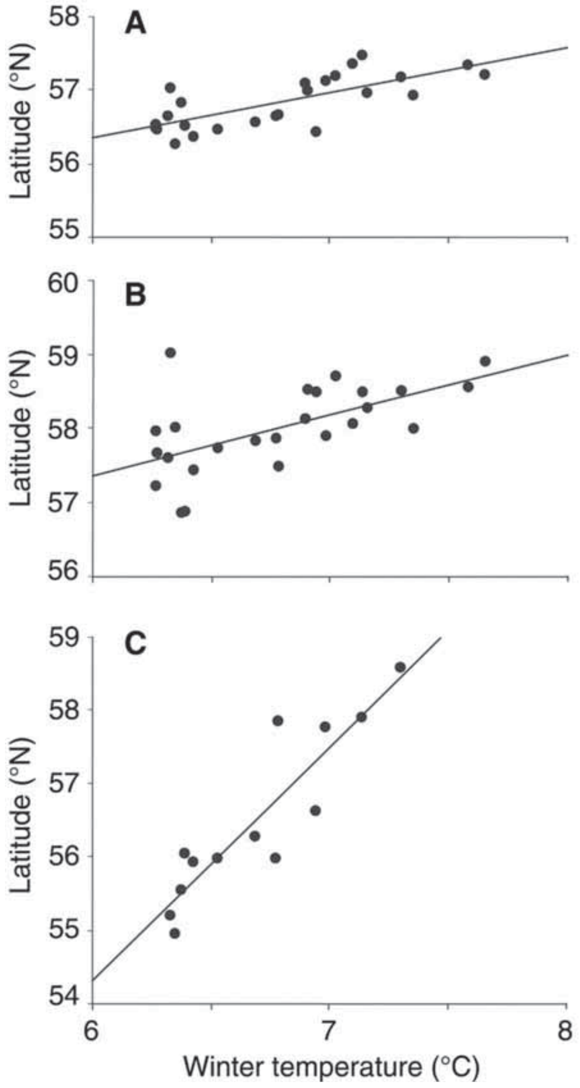
Climate change plays a major role in defining the habitat and distribution of marine and aquatic fishes through its influences on the physical properties of marine and aquatic environments. These include temperature, salinity, vertical mixing rates and thermohaline and wind-driven circulations. The environmental tolerances (bio-climate envelopes) to which populations have evolved (e.g. see Section 2.1.1), then interact with these climate-controlled environmental conditions to determine the preferred or suitable habitats and distributions of marine and aquatic organisms.

Decades of ecological and physiological research document that climatic variables are primary drivers of distributions and dynamics of marine plankton and fish (Hays, Richardson and Robinson, 2005; Roessig *et al*., 2004). Globally distributed planktonic records show strong shifts of phytoplankton and zooplankton communities in concert with regional oceanic climate regime shifts, as well as expected poleward range shifts and changes in timing of peak biomass (Beaugrand *et al*., 2002; deYoung *et al*., 2004; Hays, Richardson and Robinson, 2005; Richardson and Schoeman, 2004). Some copepod communities have shifted as much as 1 000 km northward. Beaugrand *et al*. (2002) documented a major large-scale reorganization of the plankton communities, especially the calanoid copepod crustaceans, in the eastern North Atlantic Ocean and European shelf seas. A northward extension of more than 10° in latitude occurred for warm-water species over the last four decades associated with a decrease in the number of colder water species and were related to both the increasing trend in Northern Hemisphere temperature and the North Atlantic Oscillation. Beaugrand *et al*. (2003) showed that, in addition to the effects of overfishing, these fluctuations in plankton abundance have resulted in long-term changes in cod recruitment in the North Sea through three bottom-up control processes (changes in mean size of prey, seasonal timing and abundance).

Climate change is expected to drive most terrestrial and marine species ranges toward the poles (Southward, Hawkins and Burrows, 1995; Parmesan and Yohe, 2003), as was the case in the Pleistocene–Holocene transition (reviewed in Fields *et al*., 1993) although the amplitude might be different. Shifts in marine fish and invertebrate communities have been particularly well documented off the coasts of western North America and the United Kingdom. These two systems make an interesting contrast (see below) because the west coast of North America has experienced a 60-year period of significant warming in nearshore sea temperatures, whereas much of the United Kingdom coast experienced substantial cooling in the 1950s and 1960s, with warming only beginning in the 1970s (Holbrook, Schmitt and Stephens, 1997; Sagarin *et al*., 1999; Southward *et al*., 2005). Species with greater mobility and migratory characteristics, such as smaller pelagic species with habitat requirements defined primarily by hydrographic characteristics such as temperature and salinity, are predicted to respond most quickly to such climate-driven interannual variability in habitat and distributions (Perry *et al*., 2005; Figure 15). Much of the data from the North Atlantic, North Sea, and coastal United Kingdom have exceptionally high resolution and long time series, so they provide detailed information on annual variability and long-term trends. Over 90 years, the timing of animal migration (e.g. veined squid, *Loligo forbesi*, and flounder *Platichthys flesus*) followed decadal trends in ocean temperature, being later in cool decades and up to one to two months earlier in warm years (Southward *et al*., 2005). Pilchard (*Sardina pilchardus)* increased egg abundances by two to three orders of magnitude during recent warming. In the North Sea, warm-adapted species (e.g. anchovy *Engraulis encrasicolus* and pilchard) have increased in abundance since 1925 (Beare *et al*., 2004), and seven out of eight species have shifted their ranges northward (e.g. bib, *Trisopterus luscus*) by as much as 100 km per decade (Perry *et al*., 2005). Some of these shifts are extremely fast, averaging over 2 km.y^{-1} (Perry *et a*l., 2005). The snake pipefish (*Entelurus aequoreus*), for example, moved its upper latitude from southern England in 2003 to the Spitzbergen in 2007 (Harris *et al*., 2007). In the pelagic environment, shifts are not only horizontal but also vertical, with species responding to warming trends by moving towards deeper cooler waters (Perry *et al*., 2005; Dulvy *et al*., 2008). Records dating back to 1934 for intertidal invertebrates show equivalent shifts between warm- and cold-adapted species (e.g. the barnacles *Semibalanus balanoides* and *Chthamalus* spp., respectively), mirroring decadal shifts in coastal temperatures (Southward, Hawkins and Burrows, 1995; Southward *et al.*, 2005).

Sagarin *et al*. (1999) related a 2 °C rise of SST in Monterey Bay, California, between 1931 and 1996 to a significant increase in southern-ranged species and decrease of northern-ranged species. Holbrook, Schmitt and Stephens (1997) found similar shifts over the past 25 years in fish communities in kelp habitat off California. There are also many examples of changes in distributions resulting from inter-annual climate

FIGURE 15
Examples of North Sea fish distributions that have shifted north with climatic warming. Relationships between mean latitude and 5-year running mean winter bottom temperature for (A) cod, (B) anglerfish, and (C) snake blenny are shown



Source: Perry *et al.*, 2005.

variability, in particular relating to ENSO events. Off California, anchovy spawning expands northwards during El Niño events (Checkley *et al*., 2009). Likewise, the northern limit of California sardines in Canadian waters is broadly related to sea surface temperature, expanding north during the months of June through August and returning south when sea temperatures begin to cool (McFarlane *et al.*, 2005). Rodriquez-Sánchez *et al*. (2002) have described how Pacific sardine (*Sardinops caeruleus*) in the California Current System changed its core habitat locations from the central to the southern and then back to the central parts of its full distributional range over the period 1931 to 1997 as the prevailing climate regimes shifted. Cross-shelf habitat is also affected by productivity conditions. California sardine shows significant interannual variation in the geographic extent of spawning, extending further offshore during La Niña and being compressed shoreward during El Niño (e.g. Lynn, 2003).

In the California Current upwelling system, the extent of the northwards migrations by Pacific hake (*Merluccius productus*) is positively correlated with increasing water temperatures (Ware and McFarlane, 1995). Philips *et al.* (2007) have also observed a northward expansion of the spawning areas for Pacific hake in the California Current system. Distributions of other species in the southern parts of the California Current System in relation to ENSO variations are provided by Lluch-Belda, Lluch-Cota and Lluch-Cota (2005). Variations in Peruvian anchoveta have been explained by changes in carrying capacity (Csirke *et al.,* 1996), based on habitat productivity regimes (Chavez *et al*., 2003). Skipjack tuna (*Katsuwonus pelamis*) in the western Pacific alter their distribution to follow the convergence zone between the tropical Pacific warm pool and the eastern Pacific cold tongue as it moves in response to ENSO cycles (Lehodey *et al*., 1997).

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

If changes in climate conditions persist, then demersal species will also alter their distributions and migration patterns. However, because habitat for demersal species often includes particular bottom features (such as kelp forests or coral reefs) and sediment types (rock or sand), they are likely to alter their distribution patterns more slowly than pelagic species. This suggests that changes in the distributions of such demersal species might be used as an index of persistent longer-term changes in habitat conditions. Such large-scale changes, persisting for at least a few decades, have occurred in the past. The effects of the warming event in the North Atlantic from the 1920s to 1940s and later, are particularly well-documented (Cushing, 1982; Brander *et al*., 2003; Rose, 2005; Drinkwater, 2006). Tåning (1949) and Fridriksson (1948) described how Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), redfish (*Sebastes* spp.) and Greenland halibut (*Reinhardtius hippoglossoides*) all expanded northwards, with cod spreading 1 200 km farther north along West Greenland that its previous distribution (Jensen, 1939, cited in Drinkwater, 2006). Such shifts involved benthic invertebrates as well as demersal finfish (Drinkwater, 2006). In general, species adapted to warmer waters expanded their distributions northwards, whereas species adapted to colder waters retracted their distributions northwards. More recently, major range extensions northwards of tropical and warm water marine species have been observed in the eastern North Atlantic (Quero, Du Buit and Vayne, 1998; Brander *et al*., 2003) and in the North Sea (Brander *et al*., 2003; Perry *et al*., 2005; Clemmensen, Potrykus and Schmidt, 2007; Dulvy *et al*., 2008).

It has been suggested (Harley *et al.*, 2006) that a warming-associated weakening of alongshore advection (Pisias, Mix and Heusser, 2001) could actually break down certain marine biogeographical barriers that currently prevent range expansions. For example, two particularly cold-sensitive coral species (staghorn coral, *Acropora cervicornis*, and elkhorn coral, *Acropora palmata*) have recently expanded their ranges into the northern Gulf of Mexico (first observation in 1998), concurrent with rising SST (Precht and Aronson, 2004). Although continued poleward shift will be limited by light availability at some point (Hoegh-Guldberg, 1999), small range shifts may aid in developing new refugia against extreme SST events in future.

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

2.5 Abundance changes

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

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

(1969) found low carbon to nitrogen ratios in zooplankton from the warmer tropical Pacific compared with those from the colder sub Arctic Pacific.

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

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

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

In freshwater ecosystems one of the most significant impacts of global warming would be a reduction in suitable habitat. In a simulation based on a doubling of the atmospheric CO_2 Mohseni, Stefan and Eaton (2003) estimated a reduction of 36 percent and 15 percent of the suitable thermal habitat for cold and cool water species, respectively, while the habitat for warm water species would increase by 31 percent. This study was based on the maximum and minimum temperature tolerances for 57 species in 764 stream stations in the United States of America.

2.6 Phenological changes

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

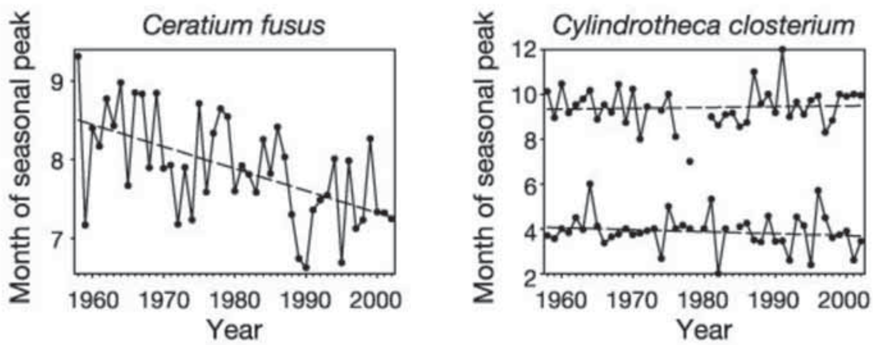
2.6.1 Ocean environments

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

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

FIGURE 16

Inter-annual variability of the seasonal peak for the dinoflagellate *Ceratium fusus* and the diatom *Cylindrotheca closterium*–used in the analysis for the periods 1958–1980 and 1981–2002 in the North Atlantic ocean

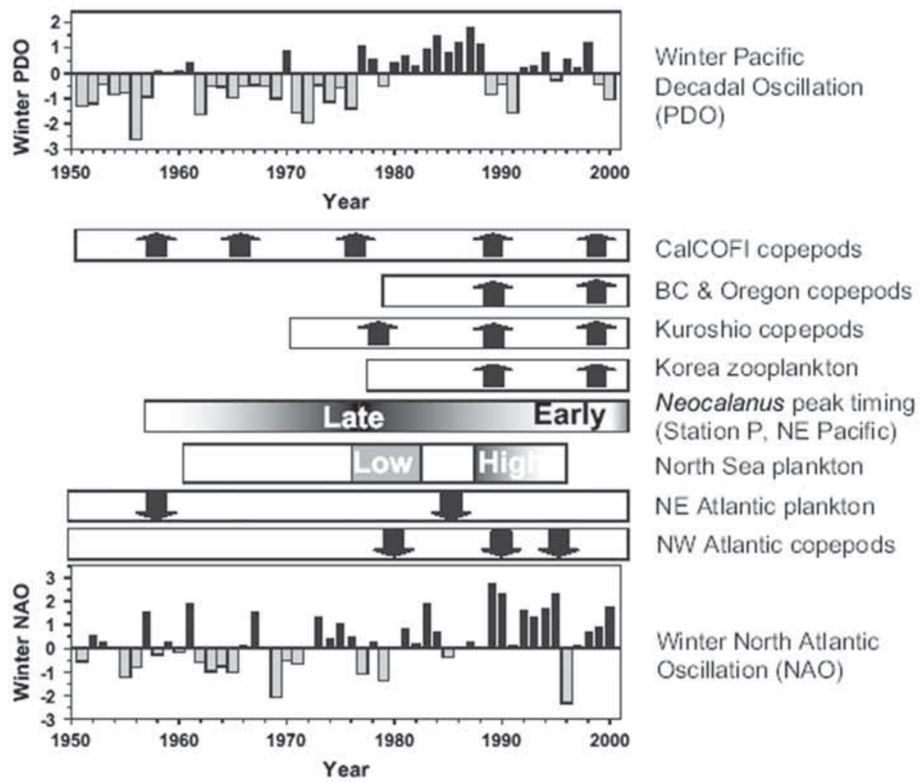


Source: Edwards and Richardson, 2004.

shifts in centres of abundance of many species (poleward under warm conditions), and changes in the life cycle timing of *Neocalanus plumchrus* (earlier by several weeks in warm years and at warmer locations). Observations of zooplankton and high trophic level indices (fish, birds) in the North Pacific showed consistent patterns that are strongly correlated with large scale year-to-year and decade-to-decade ocean climate fluctuations, as reflected by spring season temperature anomalies in the surface mixed layer. The change in zooplankton developmental timing cannot be explained solely by physiological acceleration, and thus differential mortality rates between cohorts are hypothesised (Mackas, Goldblatt and Lewis, 1998). Mackas, Batten and Trudel (2007) conclude that, in strongly seasonal environments, anomalously high temperature may provide misleading environmental cues that contribute to timing mismatch between life history events and the more-nearly-fixed seasonality of insolation, stratification and food supply. There are indications that such changes in timing may be coherent among different ocean basins (Figure 17; Perry *et al*., 2004). Edwards and Richardson (2004) also noted that water temperature affects the timing of ontogenetic transitions, which would decouple changes in the larval environment from the cues used by the adult population.

FIGURE 17

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



Source: Perry *et al.*, 2004.

2.6.2 Inland waters

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

2.7 Species invasions and diseases

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

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

There are also latitudinal shifts of diseases in terrestrial and marine environments, due either to direct response of the pathogen or to the response of its vector. Climate warming can increase pathogen development and survival rates, disease transmission and host vulnerability, although a subset of pathogens might decrease with warming, releasing hosts from disease (Harvell *et al*., 2002). Relatively little evidence exists in marine ecosystems except for marine mammals, marine invertebrates such as oysters, and eelgrass (although the mechanisms for pathogenesis are unknown for these last two groups) and most of all the growth rates of marine bacteria and fungi in coral ecosystems which could be positively correlated with temperature (Harvell *et al*., 1999). An exception is the northward spread of two protozoan parasites (*Perkinsus marinus* and *Haplosporidium nelsoni*) from the Gulf of Mexico to Delaware Bay and further north, where they have caused mass mortalities of Eastern oysters (*Crassostrea virginica*). Winter temperatures consistently lower than 3 °C limit the development of the Multinucleated Spore Unknown (MSX) disease caused by the protozoan pathogen, *Haplosporidium nelsoni* (Hofmann *et al.,* 2001) and the poleward spread of this and other pathogens can be expected to continue as such winter temperatures become rarer. This example also illustrates the relevance of seasonal information when considering the effects of climate change, since in this case it is winter temperature which controls the spread of the pathogen.

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

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

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

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

According to geological records taken from Atlantic and Pacific Canada when summer SST was much warmer during the late glacial–early Holocene (up to 58 °C), there was a period of sustained high production of red-tide blooms (Mudie, Rochon and Levac, 2002). This led the authors to suggest that global warming is strongly implicated in the historical increase in the frequency of red tides and other HABs (see also Dale, 2001).

A final impact, yet to be evaluated properly, involves the depletion of the ozone layer in response to the increase of CO_2 concentrations (Austin, Butchart and Shine, 1992). This process will result in an increase in ultraviolet radiation at the ocean surface, which is likely to affect biological processes. The response of a given species to UV exposure might depend on the presence of other species (Harley *et al*., 2006). For example, marine phytoplankton were protected from UVB damage when co-cultured with marine viruses (Jacquet and Bratbak, 2003).

2.8 Food web impacts from plankton to fish

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

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

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

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

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

2.9 Regime shifts and other extreme ecosystem events

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

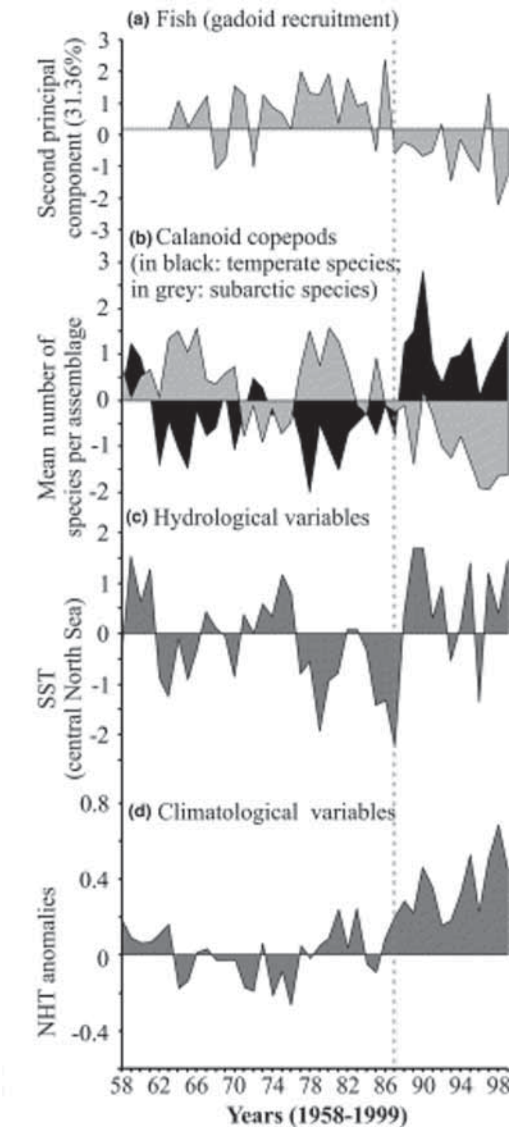
An important consideration highlighted by Hsieh *et al*. (2005) is that biological responses to shifting climatic conditions can be non-linear (e.g. a change in regime), even though the underlying abiotic changes may be linear and stochastic. This sensitivity of ecosystems to amplify climatic signals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

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

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

FIGURE 18

Long-term monthly changes (1958-1999) in fish, plankton and environment in the North Atlantic Ocean. (a) Long-term changes in fish recruitment (mainly gadoid species haddock and cod). (b) Long-term calanoid copepod species composition (temperate species in black, subarctic species in grey). (c) Changes in sea surface temperature. (d) Changes in northern hemisphere temperature anomalies



Source: modified from Beaugrand *et al.,* 2004.

from relatively high mean recruitment to relatively low mean recruitment around the late 1980s and were positively correlated with zooplankton biomass with time lags of two, five and six years, respectively (Lees *et al*., 2006). Cod spawning stock biomass appeared to shift from a high to low quasi-stable state in the late 1980s. Saithe and whiting SSB show evidence of a low quasi-stable state from the late 1970s and mid-1980s, respectively (Lees *et al*., 2006).

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

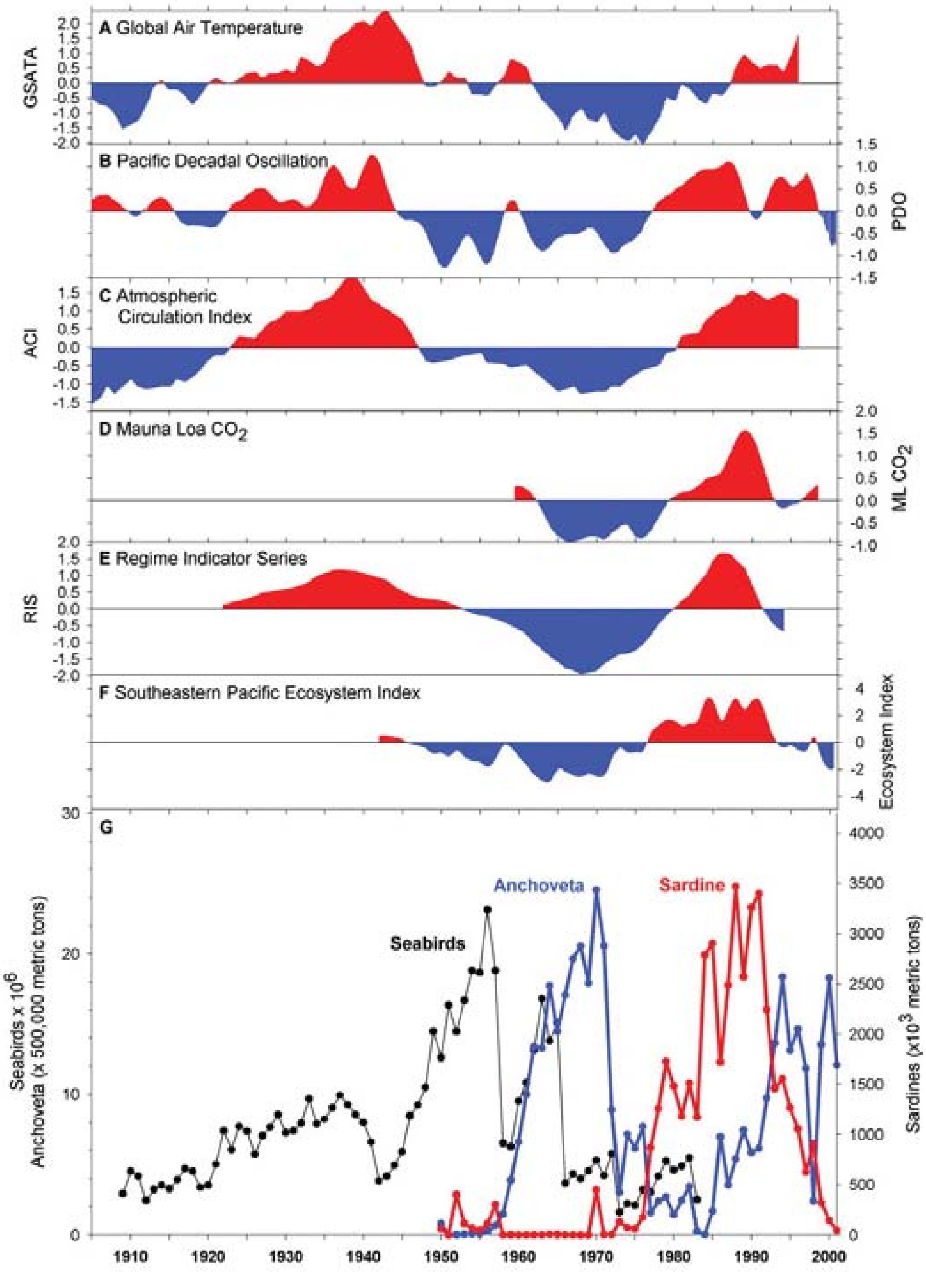
Chavez *et al.* (2003) noted that several characteristics of the entire North and South Pacific Ocean changed in the early 1950s and late 1970s (Figure 19). In the subtropical regions of both ocean basins, warmer conditions favoured sardine populations whereas cooler conditions favoured anchovy, although several other changes in nutrient supply, rockfish, salmon, tuna and seabirds also coincided with these warm and cool conditions. Chavez *et al*. (2003) attributed these changes to large spatial and long temporal scale alterations in the slope of the sea level, and therefore the proximity of the thermocline to the sea surface and subsequent supply of nutrients to the upper ocean layers.

Several authors have noted an apparent synchrony in fluctuations (or regimes) based on abundances of fish stocks from different parts of the same ocean basin, and even across ocean basins. This has been most apparent for small pelagic species (e.g. Kawasaki, 1992) although not exclusively (e.g. Bakun, 1996; Klyashtorin, 2001; Chavez *et al*., 2003; Weijerman, Lindeboom and Zuur, 2005). The implication would be that planetary-scale changes in atmospheric circulation patterns can induce seemingly related fluctuations in widely separated fish populations. These analyses have been criticized, however, based on statistical and mechanistic issues (Fréon, Mullon and Voisin, 2003; Stenseth *et al.*, 2003). Overland *et al*. (2008) concluded that while climate variables can have strong teleconnections within individual ocean basins, between-basin teleconnections and potential climate-driven biological synchrony over several decades are usually much weaker. Overland *et al*. (2008) also noted the cumulative effects of monthly weather anomalies, El Niño-type events, plus broad-band "red noise" variability at multi-decadal time scales. When transferring this variability to biological systems, the various time lag and feedback effects plus non-linearities, cause them to respond to climate changes with a mix of slow fluctuations, prolonged trends, and step-like changes that may be difficult to predict, and yet that cannot be avoided. Added to these natural system influences on possible large-scale synchrony of fish populations are human influences, such as the movement of fishing boats and expertise from California to South America following the collapse of the California sardine fishery in the 1940 and 1950s (Ueber and MacCall, 1992) and common trends in herring catches between Iceland and British Columbia, Canada, as a result of the development of similar technologies and markets (Hamilton, Otterstand and Ögmundardóttir, 2006).

De Young *et al*. (2008) present a conceptual framework to enhance the ability to detect, predict and manage regime shifts in the ocean and conclude that the ability to adapt to, or manage regime shifts, depends upon their uniqueness, our understanding

FIGURE 19

Representation of changes in several climate and Pacific biological indices, relating to global air temperature (A), the Pacific Decadal Oscillation (PDO; B), atmospheric circulation index (a measure of the "waviness" of the zonal atmospheric circulation, C), atmospheric CO_2 concentration (D), basin-wide index of sardine and anchovy catches (E), an index of seabird abundances and sardine and anchovy landings in the South East Pacific (F), seabird abundance and sardine and anchovy landings in Peru (G)



Source: Chavez *et al.*, 2003.

of their causes and linkages between ecosystem components and our observational capabilities. Because the likelihood of climate-driven regime shifts increases when humans reduce ecosystem resilience (understood as the disturbance an ecosystem can tolerate before it shifts into a different state, e.g. Scheffer *et al*., 2001a; Cropp and Gabrica, 2002; Folke *et al*., 2004), for example by removing key functional species, age groups, trophic levels, or adding waste and pollutants (Folke *et al*., 2004), a primary issue remains whether ecosystem resilience will be sufficient to tolerate future anthropogenic climate change.

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

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

3.1 General impacts

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

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

3.1.1 Rapid time scales

There is high confidence that increasing temperatures will have negative impacts on the physiology of fish because of limited oxygen transport to tissues at higher temperatures. Specifically, at some temperature the evolved circulatory system will be unable to deliver sufficient oxygen to meet tissue metabolic demands (Pörtner and

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

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

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

3.1.2 Intermediate time scales

At intermediate time scales of a few years to a decade, temperature-mediated physiological stresses and phenology changes will impact the recruitment success and therefore the abundances of many marine and aquatic populations (high confidence). The earliest impacted species are again likely to be those with shorter life-spans and faster turnover rates, since biomass of species with longer life-spans tends to be less dependent on annual recruitment. These impacts are also likely to be most acute at the extremes of species' ranges, and may manifest themselves as changes in fish distributions (e.g. loss of more southerly populations and stocks). Changes in abundance will alter the composition of marine and aquatic communities, with possible consequences to the structure and productivity of these marine ecosystems (Worm and Duffy, 2003) in particular if keystone or "high leverage" species are affected (Harley *et al*., 2006). Since these processes involve many unknowns, predicting impacts and directions for any specific case can only be done with low confidence. Predicting net community impacts such as total biomass or productivity may be done with intermediate confidence, however, because of compensatory dynamics among the members within the various functional groups that make up that community (Mackas, Thompson and Galbraith, 2001; Jennings and Brander, 2008).

Increasing vertical stratification is predicted for many marine areas (e.g. Houghton, 2001) and lakes (Ficke, Myrick and Hansen, 2007). It is expected to reduce vertical mixing and therefore reduce nutrient supply to the productive photic layers, thereby decreasing productivity (intermediate confidence). In addition, increasing stratification is predicted to alter the balance between pelagic and benthic recycling of nutrients, favouring the pelagic pathway and pelagic fishes at the expense of the benthos (Frank, Perry and Drinkwater, 1990). This will drive changes in species composition (e.g. in the Baltic, Mackenzie *et al.*, 2007) and affect the timing of life cycle processes (e.g. in the Pacific, Mackas, Batten and Trudel, 2007, and Atlantic, Greve *et al.*, 2005). Evidence of such increasing vertical stratification is available for the North Pacific Ocean (Freeland *et al.*, 1997) and the North Atlantic (Curry and Mauritzen, 2005; see also Section 1.2); its impacts on lower trophic levels of the Northwest Pacific (Chiba *et al.*, 2004) and fish productivity in East African lakes (O'Reilly *et al.*, 2003) have also been demonstrated.

3.1.3 Long time scales

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

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

3.2 Case studies

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

3.2.1 Arctic

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

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

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

3.2.2 North Atlantic

Large areas of the North Atlantic Ocean have already been impacted by climate warming-related changes, including phytoplankton (Edwards and Richardson, 2004), zooplankton (Beaugrand *et al.*, 2002) and fish (Quero, Du Buit and Vayne, 1998; Perry *et al.*, 2005; Dulvy *et al.,* 2008). Climate conditions in the North Atlantic are strongly modulated by the atmospheric pressure shifts that are indexed by the North Atlantic Oscillation. Details of future climate change impacts in the North Atlantic are therefore likely to continue to vary with the state of the NAO. If the warming trend with a high NAO index continues, then sea temperatures in the North Sea, Nordic seas and Barents Sea are likely to increase by 1 to 3 °C over the next 50 years, with the largest changes occurring in the northernmost regions (Stenevik and Sundby, 2007).

In addition, increased wind-induced fluxes of warm Atlantic waters into these regions can be expected, which will increase the vertical stratification (Stenevik and Sundby, 2007) and reduce ice cover (Ellingsen *et al*., 2008). Simulations suggest that primary production is likely to increase in the Barents Sea, although zooplankton production is likely to decrease as production by Arctic zooplankton declines (Ellingsen *et al*., 2008). These will cause northward shifts of the distributions of all species, increase biomass production of species in Arcto-boreal regions, but introduce southern invaders into the southern North Sea (Stenevik and Sundby, 2007). Spawning areas for capelin in the Barents Sea are predicted to shift eastwards and spawning is predicted to occur earlier because of warmer temperatures (Huse and Ellingsen, 2008). A significant change in the meridional overturning circulation would have substantial impact on the Barents Sea (see Section 1.3). The North Sea is likely to become dominated by pelagic species such as herring and mackerel in the north and sardine and anchovy in the south, although the total system productivity may not be too different than today (Stenevik and Sundby, 2007). The Baltic Sea is predicted to become warmer and fresher, with significant increases in its vertical stratification (Mackenzie *et al*., 2007). The biodiversity of the Baltic is particularly sensitive to salinity changes; decreased salinity is predicted to exclude many marine-tolerant species and to favour those more tolerant of low salinities (Mackenzie *et al*., 2007). Non-native species may enter the Baltic, but few are expected to be able to colonise because of the salinity stress (Mackenzie *et al*., 2007).

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

TABLE 2
Potential ("very likely to happen") long-term ecological changes in Arctic marine systems as a result of climate warming

	Phytoplankton	Zooplankton	Benthos	Fish	Marine mammals and seabirds
Distribution	Increased spatial extent of primary production in central Arctic Ocean.	Distribution limits move northwards.	Distribution limits move northwards.	Distribution limits move northwards. Altered timing and location of spawning/ feeding.	Poleward shift in species distributions.
Production	Increased production in Arctic Ocean, Barents and Bering Sea shelves.	Difficult to predict; depends on timing of phytoplankton blooms and water temperature.	Difficult to predict; depends on timing of plankton blooms and water temperature. Crab and shrimp production may decline.	Depends on timing of plankton blooms and drift patterns of eggs and larvae.	Declines in ice-associated species and increases by temperate species; seabird production dependent on changes in food availability.
Species composition and diversity	Depends on mixing depth: deep mixing favours flagellates.	Adaptable Arctic copepods favoured.	Cold water species decline in abundance; warm water species increase.	Cod, herring, pollock, some flatfish likely to move north and become more abundant; capelin, polar cod, Greenland halibut will have restricted range and decrease in abundance.	Declines of polar bears, ringed, harp, hooded, spotted, ribbon and possibly bearded seals. Increases of harbour and grey seals. Possible declines of several whale species. Ivory gulls, small auk species likely to decline.

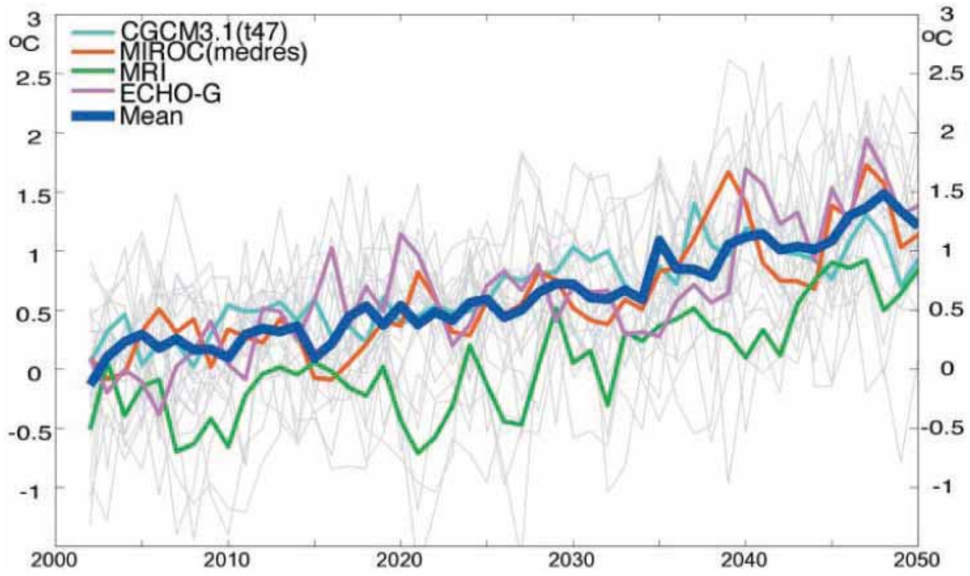
Source: Loeng, 2005.

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

3.2.3 North Pacific

Overland and Wang (2007) have examined the implications for the North Pacific Ocean of the results from ten models of atmospheric climate change. They conclude that anthropogenic impacts on the future North Pacific climate will be as large in 30 to 50 years as natural climate variability is today. This suggests that climate-ecosystem-fisheries relationships developed during the latter half of the twentieth century may not be robust in the twenty-first century. The implication is that relationships between fish production and indices of atmospheric state such as the Pacific Decadal Oscillation (PDO) may not be valid as the climate changes. As with the North Atlantic, the North Pacific is strongly influenced by variations in the strengths and positions of atmospheric pressures centres, which are indexed by east-west and north-south variations in sea surface temperature as captured in the PDO. Overland and Wang (2007) conclude that this pattern of decadal variability will continue into the twenty-first century, but it will occur on top of a persistent upward trend in sea surface temperature (Figure 20). Pierce (2004) modelled the impacts of increasing greenhouse gases to the plankton of the North Pacific and found the subpolar system changed from one with strong variability and winter lows to one with much more constant annual values and decreased yearly-averaged primary productivity. The productivity increased in other regions of the North Pacific as warmer temperatures enabled higher growth rates. Pierce (2004) found that his results were largely driven by changes in mixed layer depths (shoaling) and temperature (increasing). In contrast, the simulations by Hashioka and Yamanaka (2007) found that warmer conditions led to changes in the seasonal patterns of primary production in the North West Pacific. On the west coast of North America, northward shifts of fish populations are predicted (Overland and Wang, 2007) and have been observed (e.g. Okey, Wright and Brubaker, 2007). Welch, Ishida and Nagasawa (1998) predicted the restriction of suitable thermal habitat for sockeye salmon (*Oncorhynchus nerka*) in the North Pacific under a 2xCO_2 scenario to be reduced to the Bering Sea. The Bering Sea itself is predicted to be significantly impacted by climate change, including large-scale retreats of sea ice, losses of cold-water species and increasing abundances of species from the North Pacific (Overland and Stabeno, 2004). As noted above (Section 1.5), the sub-Arctic North Pacific is particularly sensitive to the effects of increasing acidification and by the the end of this century, some regions will become undersaturated in the aragonite form from surface to bottom (Feely, Fabry and Guinotte, 2008). Upwelling of aragonite undersaturated waters onto the continental shelf of western North America has already been reported (Feely *et al.*, 2008). Various vertebrate and invertebrate species have been shown to be negatively impacted by these low pH concentrations, including pteropods (common prey for many open ocean fish) and squid (Fabry *et al.*, 2008).

FIGURE 20
Projected winter sea surface temperature anomalies (SSTA,°C) relative to a 1980–1999 base period for the central North Pacific Ocean, showing a steady upward trend to 2050. Grey and thin coloured lines represent projected temperatures from 10 climate models; the bold blue line represents the trend of the all-model mean SSTA



Source: Overland and Wang, 2007.

3.2.4 Wind-driven coastal upwelling systems

Major coastal wind-driven upwelling systems tend to occur on the eastern boundaries of the world's oceans. The interaction of the wind-driven circulation with the bathymetry produces highly productive ecosystems, largely of pelagic species but which may also include demersal species. Predictions of the responses of coastal wind-driven upwelling systems are contradictory, however, partially because higher model resolution is required to resolve coastal upwelling at the global scale (see Section 1.3). Bakun (1990) proposed that with global warming the land-sea air pressure gradient would increase, thereby intensifying the alongshore wind stress and increasing coastal upwelling. This would have the effect of offsetting in these regions the global trend of increasing water temperatures and increasing vertical stratification, since such upwelled waters are cold and rich in nutrients. Synder *et al.* (2003) modelled wind-driven upwelling along the coast of California with increasing atmospheric CO_2 concentrations and found an intensified upwelling season with some change in seasonality. They concluded this effect should enhance the productivity of the system and possibly offset the local effects of increasing temperatures. McGregor *et al.* (2007) found that the upwelling system off North West Africa intensified during the twentieth century, and suggested it will continue to intensify with global warming. This should enable the system to retain its high productivity as the climate changes, although the composition of the predominant pelagic species may change (e.g. Zeeberg *et al.*, 2008). Predicted impacts of climate change to parts of the Benguela upwelling system are different, however. This system is very productive, often with phytoplankton settling on the sea floor where it decomposes, consuming oxygen and producing hydrogen sulphide. When these oxygen-depleted waters are upwelled towards the surface, significant species displacements and mortalities can result (Bakun and Weeks, 2004). With climate change, intensified Benguela upwelling may therefore further increase nutrient inputs, primary production and low-oxygen events (Clark, 2006). The emergence of increasing areas of hypoxia and anoxia in the California Current upwelling system (Chan *et al.*,

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

3.2.5 Tropical and subtropical seas

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

3.2.6 Coral reef systems

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

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

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

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

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

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

3.2.7 Freshwater systems

Freshwater lakes and their ecosystems are highly vulnerable to climate change. At very long time scales (greater than centennial) paleo records show that lakes have altered their shapes and distributions and have disappeared entirely, with the processes related to climate change as a result of the shifting dynamics among precipitation, evaporation and runoff (Poff, Brinson and Day, 2002). In general and at longer time scales (multiple decades) in North America, the anticipated response is for cold-water species to be negatively affected, warm-water species to be positively affected, and cool-water species to be positively affected in the northern but negatively affected in the southern parts of their range (Mohseni, Stefan and Eaton 2003; Field *et al*., 2007). A general shift of cool- and warm-water species northward is expected in North America and likely the rest of the Northern Hemisphere. However, the responses of particular lake ecosystems to climate change will depend strongly on the size, depth, and trophic status of the lake. In a modelling study of climate warming (2xCO_2) effects on lakes in central North America, Stefan *et al*. (1995) concluded that cold-water fish would be most affected because of losses of optimal habitats in shallow, eutrophic lakes. Growth conditions for cool- and warm-water fishes should improve in well-mixed lakes, small lakes and those with oligotrophic nutrient conditions. Since the production rates of invertebrate prey in lakes increases logarithmically with temperature (rates increase two to four times for each 10 °C increase in temperature; Watson *et al*., 1997) this should lead to long-term increases in fish production, although changes in prey species composition may offset this effect (Watson *et al*., 1997). In the short-term, however, lags between fish predators and their zooplankton prey may initially decrease fish production due to timing mismatches (Watson *et al*., 1997). Similar issues regarding productivity and timing mismatches have been proposed as likely in shallow lakes in the Netherlands (Mooij *et al*., 2005). The rates of change of freshwater systems to climate will depend on the ability of freshwater species to "move across the landscape", i.e. will depend on the existence of dispersal corridors; these can be strongly altered by human activities (Poff, Brinson and Day, 2002). Most affected are likely to be fish in lowland areas that lack northward dispersal corridors and cold-water species generally (Poff, Brinson and Day, 2002).

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

3.2.8 Aquaculture systems

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

- stress due to increased temperature and oxygen demands;
- uncertain supplies of freshwater;

- extreme weather events;
- sea level rise;
- increased frequency of diseases and toxic events;
- uncertain supplies of fishmeal from capture fisheries.

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

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

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

3.3 Uncertainties and research gaps

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

TABLE 3
Potential impacts of climate change on aquacuture systems (modified from Handisyde *et al.*, 2006)

Drivers of change	Impacts on culture systems	Operational impacts
Sea surface temperature changes	Increase in harmful alagal blooms Decreased dissolved O_2 Increased disease and parasites Longer growing seasons Changes in locations and ranges of suitable species Reduced winter natural mortality Enhanced growth and food converson rates Competition, parasitism and predation from altered local ecosystems, competitors, and exotic species	Changes in infrastructure and operation costs Increased fouling, pests, nuisance species and predators Expanded geographic ranges for species Changes in production levels
Changes in other oceanographic variables	Decreased flushing rates and food availability to shellfish Changes in abundnace of species used for food and fishmeal	Accumulation of wastes under nets Increased operating costs
Sea level rise	Loss of areas for aquaculture Loss of areas providing physical protection Greater flooding risks Salt intrusions into groundwater	Infrastructure damage Change in aquaculture zoning Increased insurance costs Reduced freshwater availability
Increased storm activity	Larger waves Higher storm surges Flooding from precipitation Salinity changes Structure damage	Loss of stock Facilty damage Higher costs for designing new facilities Increased insurance costs
Drought and water stress	Salinity changes Reduced water quality Increased diseases Uncertain water supplies	Loss of stock Facility damage Conflicts with outer water users Reduced production capacity Change in cultured species

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

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

Several research issues remain regarding the state of simulation models. These include model resolution (physical, biogeochemical and ecological), their integration across scales, levels of certainty of the projections and the lack of sufficient data to force and validate the models (e.g. Werner *et al.*, 2007). General Ocean Circulation Models (GCMs) used to make projections of future marine ecosystem states, in response to climate, are presently run at spatial resolutions of one degree (i.e. grids of 100x100 km; e.g. Sarmiento *et al.*, 2004). However, physical processes determining biogeochemical and biological responses require resolutions on the order of kilometres in the open ocean and finer in coastal regions. The use of regional climate models and methods for downscaling to regional models, e.g. through nesting (Hermann *et al.*, 2002; Snyder *et al*., 2003; Clark, 2006; Penven *et al*., 2006; Vikebø *et al*., 2007) are yielding new insights. Methodological approaches linking basin-scale models to coastal domains (e.g. Chassignet *et al*., 2006) and advances in adaptive and unstructured grid refinements appear to be promising (e.g. Pain *et al*., 2005). Development of Atmosphere-Ocean GCMs should include the specific kinds of information and output needed to evaluate climate change impacts on marine systems. The relationship between expected long-term changes and decadal (and shorter) variability is extremely important in considering climate impacts on fisheries. Downscaling and regional modelling of ocean climate change is also critical in making realistic regional forecasts of impacts. Present models of change in global marine primary production are very sensitive to the effect of temperature, which should therefore be a prominent topic for further field study and theoretical work.

Marine and aquatic systems have experienced warm conditions in the past, and have responded with significant changes of distributions and reorganizations of species community composition (e.g. Finney *et al*., 2002; Drinkwater, 2006). What marine systems have not experienced, at least as estimated from pre-industrial times, are acidification conditions as high as at present (Orr *et al*., 2005) and predicted to increase further. The large-scale impacts on marine systems of this interaction between increasing temperatures and increasing acidification are unknown. In contrast to experiments where no adaptation is possible, Pelejero *et al*. (2005) observed that 300-year-old massive Porites corals from the south western Pacific had adapted to 50-year cycles of large variations in pH, covarying with the Pacific Decadal Oscillation. This would suggest that adaptation to long-term pH change may be possible in some coral reef ecosystems. Research into the impacts of high concentrations of CO_2 in the oceans is in its infancy and needs to be developed rapidly.

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

Significant uncertainties in the responses of marine and aquatic individual animals, populations, communities, and ecosystems to climate change relate to the roles of feedbacks, critical thresholds and transition points to different stable states. Such thresholds clearly provide lethal tolerance limits, e.g. temperatures above which an organism will die of heat shock, but also occur at (initially) sublethal levels which overstress the physiological system (Pörtner and Knust, 2007) or disrupt commensal arrangements (coral bleaching). Significant shifts in the states of marine systems have already been observed (Scheffer *et al*., 2001a; de Young *et al*., 2008). The points at which such thresholds exist will differ for different species, systems and stressors, most of which are as yet unknown. When these thresholds are passed and significant changes occur, they are often called “surprises”.

The ability for marine organisms to adapt and evolve to climate change, on the relevant time scales is also generally unknown. There is some evidence that genetic differences in fish do occur between cohorts from warm and cold years (Smith, 1979). Rapid adaptation and evolution, at least to fishing-induced stresses, can occur on relatively rapid time scales of a few decades (de Roos, Boukal and Persson, 2006; Law, 2007). Berteaux *et al.* (2004), addressing the potential for evolutionary change in response to climate change in Arctic terrestrial animals, also concluded that evolutionary changes due to natural selection could occur on a time scale of a few decades, although they noted that all species may not have equal capacities for such changes. Species with longer generation times and clonal species (because of their low effective population size) may take longer to show an evolutionary response (Harley *et al*., 2006). Species with complex life histories, such as salmonids, may experience conflicting selection pressures due to the impacts of climate change on the various life stages (Crozier *et al*., 2008). As noted by Stockwell *et al*. (2003), evolutionary responses will be influenced by the strength of selection, population size, genetic variation and gene flow, making most species relatively unique.

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

4. SUMMARY OF FINDINGS

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

4.1.1 Heat content and temperature

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

4.1.2 Salinity and stratification

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

4.1.3 Ocean circulation and coastal upwelling

- A reduction of about 30 percent in the meridional overturning circulation was observed in the second half of the twentieth century. Further reductions are

expected as a result of increased freshwater input in the Arctic and subArctic, increased stability of the surface mixed layer, reduction in salt flux, reduced ocean convection and less deepwater formation. This would have important consequences on the physical and biological components of the North Atlantic ecosystem.
- There is some evidence of increased upwelling intensity in recent decades in several areas (California, North West Africa and Arabian Sea), consistent with the hypothesis that global warming would lead to increased upwelling activity through intensification of alongshore wind stress. However, an alternative hypothesis suggests that different pole-equator warming and increased stratification would counteract this effect. Low-resolution ecosystem simulations indicate that there is no clearly discernable pattern of upwelling response to warming at the global scale, except within a couple of degrees of the equator, where a small reduction is expected.
- There are indications that upwelling seasonality may be affected by climate change, with important food web consequences.

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

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

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

4.1.7 Low frequency climate variability patterns

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

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

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

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

4.2.2 Primary production

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

4.2.3 Secondary production

- There are no global assessments of the potential impacts of climate change on oceanic secondary production. Results tend to be dominated by local or regional conditions, although this is an area of active research (e.g. Mackas and Beaugrand, 2008).

- However, regional results suggest that climate change effects may be more evident in the structure of zooplankton communities than in its total biomass.

4.2.4 Distributional changes

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

4.2.5 Abundance changes

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

4.2.6 Phenological changes

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

4.2.7 Species invasions and diseases

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

4.2.8 Food web impacts from zooplankton to fish

- Climate change is likely to affect ecosystems and their species both directly and indirectly through food web processes. Whether direct or indirect processes predominate is likely to depend on whether they are structured from the top down, from the bottom up or from the middle. It is suggested that ecosystem control is correlated with species richness and temperature.

4.2.9 Regime shifts and other extreme ecosystem events

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

4.3 Scenarios of climate change impacts on fish production and ecosystems

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

- Regarding freshwater systems, there are specific concerns over changes in timing, intensity and duration of floods, to which many fish species are adapted in terms of migration, spawning and transport of spawning products as a result of climate change. It is important to develop management systems capable of addressing the needs for fresh water by fish and land-based food production systems (e.g. rice) in the context of climate change, particularly in developing countries.

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

Arctic

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

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

North Atlantic

Northeast Atlantic

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

Ecological changes:
- primary production likely to increase in the Barents Sea;
- zooplankton production likely to decrease as production by Arctic zooplankton declines;
- northward shifts in the distributions of all species;,
- increased biomass production of species in Arcto-boreal regions;
- fish species from south of the North Sea likely to appear in the North Sea;
- spawning areas for capelin in the Barents Sea likely to shift eastwards;
- North Sea dominated by pelagic species such as herring and mackerel in the north, and sardine and anchovy in the south, although the total system productivity may not be too different than today;
- Baltic Sea is predicted to become warmer and fresher, with significant increases in its vertical stratification;

- in the Baltic, exclusion of marine-tolerant species in favour of species more tolerant of low salinities;
- non-native species may enter the Baltic, but few are expected to be able to colonise because of the salinity stress.

Northwest Atlantic

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

Atlantic cod:

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

North Pacific

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

Wind-driven coastal upwelling systems

- responses to global warming of coastal wind systems that drive upwelling ecosystem are contradictory;

- if alongshore wind stress increases coastal upwelling, this would offset in these regions the global trend of increasing water temperatures and increasing vertical stratification;
- other model studies predict decreasing upwelling-favourable winds;
- global models of primary production responses to warmer conditions are contradictory. In the Pacific, the model of Sarmiento *et al*. (2004) showed no consistent global response of upwelling regions to climate change;
- intensified Benguela upwelling may increase nutrient inputs, primary production and low-oxygen events. Such may also occur in other upwelling systems;
- there is considerable local variability among systems which makes generalizations difficult.

Tropical and subtropical seas

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

Coral reef systems

- at risk from climate change impacts related to increasing temperatures, acidity, storm intensity and sea levels and non-climate factors such as overexploitation, non-native species introductions and increasing nutrient and sediment loads;
- risks to coral reefs not distributed equally: increasing temperatures significant issue for warm-water systems; increasing acidity and decalcification a significant issue for both warm- and cold-water systems; direct human impacts a significant issue in more populous regions;
- three different time scales can be identified for climate change-related impacts to coral reef systems:
  – years: increased temperature effects on coral bleaching;
  – decades: increasing acidification and dissolution of carbonate structures of reefs;

  – multidecades: weakening of structural integrity of reefs and increasing susceptibility to storms and erosion events.
- increasing acidity (decreasing pH) is a significant and pervasive longer-term threat to coral reefs. Potential for coral reef systems to adapt to these environmental stresses is uncertain: symbiotic zooxanthellae may adapt to be more tolerant of high temperatures. Migrations of corals to higher latitudes is unlikely;
- declines in corals had negative impacts on reef fish biodiversity in at least one study, however, to date there is little evidence for a link between climate warming and bleaching events with impacts on coastal fisheries.

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

Aquaculture systems
- direct impacts include changes in the availability of freshwater, changes in temperature, changes in sea level, and increased frequencies of extreme events (such as flooding and storm surges);
- indirect effects include economic impacts, e.g. costs and availability of feed;
- negative impacts include (Table 4):
  – stress due to increased temperature and oxygen demands;
  – uncertain supplies of freshwater;
  – extreme weather events;
  – sea level rise;
  – increased frequency of diseases and toxic events;
  – uncertain supplies of fishmeal from capture fisheries.

- positive impacts of climate change on aquaculture include increased food conversion efficiencies and growth rates in warmer waters, increased length of the growing season, and range expansions polewards due to decreases in ice;
- increased primary production would provide more food for filter-feeding invertebrates;
- may be problems with non-native species invasions, declining oxygen concentrations, and possibly increased blooms of harmful algae;
- local conditions in traditional rearing areas may become unsuitable for many traditional species;
- temperature stress will affect physiological processes such as oxygen demands and food requirements;
- increased food supplies are needed for aquaculture activities to realise benefits from increased temperatures;
- freshwater aquaculture activities will compete with changes in availability of freshwater due to agricultural, industrial, domestic and riverine requirements, as well as changes in precipitation regimes;
- increases in precipitation could also cause problems such as flooding;
- sea level rise also has the potential to flood coastal land areas, mangrove and sea grass regions which may supply seed stock for aquaculture species.

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Climate change and capture fisheries: potential impacts, adaptation and mitigation

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ABSTRACT

Climate change is predicted to have a range of direct and indirect impacts on marine and freshwater capture fisheries, with implications for fisheries-dependent economies, coastal communities and fisherfolk. This technical paper reviews these predicted impacts, and introduces and applies the concepts of vulnerability, adaptation and adaptive capacity.

Capture fisheries are largely driven by fossil fuels and so contribute to greenhouse gas emissions through fishing operations, estimated at 40-130 Tg CO_2. Transportation of catches is another source of emissions, which are uncertain due to modes and distances of transportation but may exceed those from fishing operations. Mitigation measures may impact on fisheries by increasing the cost of fossil fuel use.

Fisheries and fisherfolk may be impacted in a wide range of ways due to climate change. These include biophysical impacts on the distribution or productivity of marine and freshwater fish stocks through processes such as ocean acidification, habitat damage, changes in oceanography, disruption to precipitation and freshwater availability. Fisheries will also be exposed to a diverse range of direct and indirect climate impacts, including displacement and migration of human populations; impacts on coastal communities and infrastructure due to sea level rise; and changes in the frequency, distribution or intensity of tropical storms. Fisheries are dynamic social-ecological systems and are already experiencing rapid change in markets, exploitation and governance, ensuring a constantly developing context for future climate-related impacts. These existing socioeconomic trends and the indirect effects of climate change may interact with, amplify or even overwhelm biophysical impacts on fish ecology. The variety of different impact mechanisms, complex interactions between social, ecological and economic systems, and

the possibility of sudden and surprising changes make future effects of climate change on fisheries difficult to predict.

The vulnerability of fisheries and fishing communities depends on their exposure and sensitivity to change, but also on the ability of individuals or systems to anticipate and adapt. This adaptive capacity relies on various assets and can be constrained by culture or marginalization. Vulnerability varies between countries and communities, and between demographic groups within society. Generally, poorer and less empowered countries and individuals are more vulnerable to climate impacts, and the vulnerability of fisheries is likely to be higher where they already suffer from overexploitation or overcapacity.

Adaptation to climate impacts includes reactive or anticipatory actions by individuals or public institutions. These range from abandoning fisheries altogether for alternative occupations, to developing insurance and warning systems and changing fishing operations. Governance of fisheries affects the range of adaptation options available and will need to be flexible enough to account for changes in stock distribution and abundance. Governance aimed towards equitable and sustainable fisheries, accepting inherent uncertainty, and based on an ecosystem approach, as currently advocated, is thought to generally improve the adaptive capacity of fisheries. However, adaptation may be costly and limited in scope, so that mitigation of emissions to minimise climate change remain a key responsibility of governments.

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CONTENTS

KEY MESSAGES

1. Food security in fishing communities will be affected by climate change through multiple channels, including movement of people to coasts, impacts on coastal infrastructure and living space and through more readily observed biophysical pathways of altered fisheries productivity and availability. Indirect changes and trends may interact with, amplify or even overwhelm biophysical impacts on fish ecology.
2. Non-climate issues and trends, for example changes in markets, demographics, overexploitation and governance regimes, are likely to have a greater effect on fisheries in the short term than climate change.
3. The capacity to adapt to climate change is unevenly distributed across and within fishing communities. It is determined partly by material resources but also by networks, technologies and appropriate governance structures. Patterns of vulnerability of fisher folk to climate change are determined both by this capacity to adapt to change and by the observed and future changes to ecosystems and fisheries productivity.
4. Building adaptive capacity can reduce vulnerability to a wide variety of impacts, many of them unpredictable or unforeseen. The key role for government intervention is to facilitate adaptive capacity within vulnerable communities.
5. There is a wide range of potential adaptation options for fisheries, but considerable constraints on their implementation for the actors involved, even where the benefits are significant. For government interventions there may be trade-offs between efficiency, targeting the most vulnerable and building resilience of the system.

1. INTRODUCTION

1.1 Fisheries' contribution to food security

Fish is highly nutritious, so even small quantities can improve people's diets (FAO, 2007a). They can provide vital nutrients absent in typical starchy staples which dominate poor people's diets (FAO, 2005a). Fish provides about 20 percent of animal protein intake (Thorpe *et al*., 2006) in 127 developing countries and this can reach 90 percent in Small Island Developing States (SIDS) or coastal areas (FAO, 2005a). Although aquaculture has been contributing an increasingly significant proportion of fish over recent decades, approximately two-thirds of fish are still caught in capture fisheries.[1]

Fisheries can also contribute indirectly to food security by providing revenue for food-deficient countries to purchase food. Fish exports from low-income, food-deficient countries is equivalent to 50 percent of the cost of their food imports (FAO, 2005a).

1.2 Fisheries' contribution to livelihoods and economic development

The number of people directly employed in fisheries and aquaculture is conservatively estimated at 43.5 million, of which over 90 percent are small-scale fishers (FAO, 2005a). In addition to those directly employed in fishing, there are "forward linkages" to other economic activities generated by the supply of fish (trade, processing, transport, retail, etc.) and "backward linkages" to supporting activities (boat building, net making, engine manufacture and repair, supply of services to fishermen and fuel to fishing boats, etc.). Taking into account these other activities, over 200 million people are thought to be dependent on small-scale fishing in developing countries, in addition to millions for whom fisheries provide a supplemental income (FAO, 2005a). Fisheries are often available in remote and rural areas where other economic activities are limited and can thus be important engines for economic growth and livelihoods in rural areas with few other economic activities (FAO, 2005a). Some fishers are specialized and rely entirely on fisheries for their livelihood, while for many others, especially in inland fisheries and developing countries, fisheries form part of a diversified livelihood strategy (Allison and Ellis, 2001; Smith, Nguyen Khoa and Lorenzen, 2005). Fisheries may serve as a "safety net" to landless poor or in the event of other livelihoods failing (FAO 2005a).

Many small-scale fisher folk live in poverty, often understood as resulting from degradation of resources and/or from the safety net function of fisheries' for the poorest in society. This generalised understanding of the economic poverty of fishers in the developing world captures some of the situation of small scale fishers, but misses both the fact that they may earn more than peers in their communities and that their poverty is multidimensional and related to their vulnerability to a variety of stressors including HIV/AIDS, political marginalization and poor access to central services and healthcare (Bene, 2003; FAO, 2005a). Small-scale fisheries, and especially inland fisheries, have also often been marginalized and poorly recognized in terms of contribution to food security and poverty reduction.

1.3 Current trends and status of fisheries

Climate change impacts on fisheries will occur in the context of, and interact with existing drivers, trends and status of fisheries.

Following rapid increases in production since the 1950s, the yield of global fish has stagnated and may be declining. Many stocks have been, or are at risk of being, overexploited (Hilborn *et al*., 2003; FAO, 2005b). Statistics from the Food and

[1] Capture fisheries provide 50 percent of fish for food production and 58 percent of total fishery production, which includes marine mammals, crocodiles, corals, sponges, shells and aquatic plants (FAO, 2009).

Agriculture Organization of the United Nations (FAO) support this view, reporting that marine fisheries production peaked in the 1980s and that over recent years, approximately half of fisheries have been exploited to their maximum capacity, one quarter overexploited, collapsed or in decline and only one quarter have had potential for increased production (FAO, 2007a).

Inland fisheries have increased throughout the last half century reaching about nine million tonnes in 2002, although this trend has been accompanied in many lake and river systems by overfishing and the collapse of individual large, valuable species. “Ecosystem overfishing” has occurred as the species assemblage is fished down and fisheries use smaller nets to catch smaller and less valuable species (Allan *et al.,* 2005). Inland fish stocks have also been aversely affected by pollution, habitat alteration, infrastructure (dams and water management schemes) and introduction of alien species and cultured fish (Allan *et al.,* 2005).

In addition to stock collapses, overfishing in general has reduced revenues and economic efficiency, increased variability and reduced the resilience of stocks and catches (Hsieh *et al*., 2006). The aquatic ecosystems have been profoundly altered by fishing, with a generalised trend of “fishing down the food web” as fish from higher trophic levels decline, leading to lower trophic levels of harvests (Pauly *et al.,* 1998; Allan *et al.,* 2005) and a range of ecosystem effects, including disturbance of sensitive habitats by destructive gears such as explosives, poisons and heavy bottom trawling equipment. Extinctions of target fish species, even marine species with high reproductive outputs, are now thought to be possible (Sadovy and Cheung, 2003) while impacts on incidentally caught species and habitats also constitute a loss of aquatic biodiversity (Worm *et al.,* 2006; Allan, 2005) and can impact ecological processes like predation (Myers *et al.,* 2007), bioerosion (Bellwood, Hoey, and Choat, 2003), provision of food to seabirds (Jahncke, Checkley and Hunt, 2004) and transport of nutrients (Allan *et al.,* 2005). By introducing a new and dominant selection pressure, fishing probably also affects the genetic character of fish stocks (Hutchings, 2000).

Many industrialized fisheries suffer from over-investment and surplus fishing capacity (Hilborn *et al.,* 2003) making it economically and politically difficult to scale back fishing to match biological productivity (Ludwig, Hilborn and Walters, 1993). Thus, even without any changes attributable to climate change, there is a generally perceived need to reduce fishing capacity and fishing effort in most fisheries.

High profile collapses of Peruvian anchovy stocks, the Northwest Atlantic cod and sea cucumber fisheries throughout the tropical Indian and Pacific oceans are emblematic cases of the failure of fisheries management (in the former cases, in spite of considerable investments in scientific research) and the difficulty of sustainably exploiting many stocks. There is a growing awareness of the importance of understanding human aspects of fisheries and focusing on fisheries governance rather than purely management. Much more attention is now being paid to incentives created by management measures and institutional arrangements around fisheries, including the incorporation of local fishers and their knowledge through co-management and community-based management initiatives (Jentoft, 2006; Hilborn, 2003). This trend has been accompanied by a greater awareness of the importance of taking account of ecosystems within which fisheries are embedded. Both the involvement of stakeholders and the need to consider the wider ecosystem are incorporated in the Ecosystem Approach to Fisheries (FAO, 2003a).

Another key trend in the nature of fisheries is their increasing commercialization and globalization. Even small-scale fisheries are usually to some extent commercial, involving the sale of at least some of the catch (Berkes *et al.,* 2001). Meanwhile, international trade in fisheries products increased sharply until the 1990s. Forty percent of the total value and 33 percent of the total volume of fish produced is traded internationally. Of this, about half is exported from developing countries (Delgado *et al.,* 2003) earning them greater export revenues than any other food commodity (Thorpe *et al*., 2006). In the case of specific high value fisheries like sea urchins or live reef fish, demand from markets on the other side of the world can influence fishers in remote areas and result in rapid development, overexploitation and collapse of fisheries within a matter of years (Berkes *et al.,* 2006; Scales *et al.,* 2005).

1.4 The exposure and sensitivity of fisheries to climate change

Marine and freshwater fisheries are susceptible to a wide range of climate change impacts. The ecological systems which support fisheries are already known to be sensitive to climate variability. For example, in 2007, the International Panel on Climate Change (IPCC) highlighted various risks to aquatic systems from climate change, including loss of coastal wetlands, coral bleaching and changes in the distribution and timing of fresh water flows, and acknowledged the uncertain effect of acidification of oceanic waters which is predicted to have profound impacts on marine ecosystems (Orr *et al.,* 2005). Meanwhile, the human side of fisheries: fisher folk, fishing communities and related industries are concentrated in coastal or low lying zones which are increasingly at risk from sea level rise, extreme weather events and a wide range of human pressures (Nicholls *et al.,* 2007a). While poverty in fishing communities or other forms of marginalization reduces their ability to adapt and respond to change, increasingly globalized fish markets are creating new vulnerabilities to market disruptions which may result from climate change.

A key feature of the socio-economics of inland fisheries, which may influence how they interact with climate change, is the intense seasonality of many highly productive floodplain fisheries, for example those in Southeast Asia (SEA) and Bangladesh (Dixon *et al*., 2003). Somewhat related to this trend is the tendency for inland fisheries to be conducted by people who do not define themselves as fishers, but rather engage with seasonal fisheries alongside other livelihood options (Smith *et al.,* 2005).

The physical and ecological impacts of climate change and their relevance to the marine and freshwater environments are the focus of Barange and Perry in chapter one; this paper focuses on the impacts of those pathways on fishers and their communities. Allison *et al.* (2005) conducted a comprehensive review of potential climate change impacts on capture fisheries. This report draws on examples from Allison *et al. (*2005), but aims to focus on new findings, additional impact pathways and issues that have subsequently been raised.

2. CONCEPTUAL FRAMEWORKS

2.1 Fisheries categories

Fisheries demonstrate wide diversity in terms of scale, environment, species, technology, markets, fishers, management arrangements and political contexts (Berkes *et al.,* 2001; Jennings, Kaiser and Reynolds, 2001) and these factors will determine how each is affected by climate change. To simplify this diversity, a generalization will be made between large-scale/industrialized and small-scale/artisanal fisheries. Some of their characteristics relevant to the issue of climate change are illustrated in Table 1. Small-scale fisheries employ more than 99 percent of fishers but produce approximately 50 percent of global seafood catches.

Fisheries for reduction to fishmeal and fish oil are clearly distinguishable from fisheries for food production as they are subject to different market dynamics and have different implications for society.

Inland freshwater fisheries will be distinguished from marine fisheries. Inland fisheries are based on very different biophysical systems to marine fisheries, but in this paper, which focuses on the impacts of climate change on fisher folk rather than biophysical mechanisms, much of the discussion of vulnerability and poverty will be

TABLE 1
Some generalized differences between large-scale and small-scale fisheries

Characteristic	Large-scale, industrial fisheries	Small-scale, artisanal fisheries
Perpetrated by	Mostly developed countries	Mostly developing countries
Found in	Mostly marine (often oceanic) waters	Near-shore marine and inland waters
Vessels and equipment	Mechanised, advanced technology, possess distant water-fleet not limited to local waters	Manual, simple technology, fishing limited to local waters
Vessels and equipment	Mechanised, advanced technology	Manual, simple technology
Use of fuel	High (14 to19 million tonnes, 2 to 5 tonnes fish/t fuel oil)	Low (1 to 2.5 million tonnes, 2 to 5 tonnes fish/t fuel oil)
Use of catch	High value international markets for food and reduction to fishmeal	For food, mostly local, but increasingly global high-value
Direct employment	~500 000 fishers	~50 000 000 fishers
Catches per man hour	High	Low
Fishers	Full-time, professional, income often high relative to society	Full and part time, often poor
Complexity of fishery	Low, fewer fishing units, similar gear, few species	High, more fishing units and diverse gear, many species
Management capacity	High, large management bureaucracies, extensive scientific attention and capacity	Low, fishing communities remote from government, limited or no scientific information available

Sources: after Berkes *et al.,* 2001; Pauly, 2006; and Baelde, 2007.

relevant to small-scale marine fisheries as well as inland fisheries (which are generally small-scale in nature).

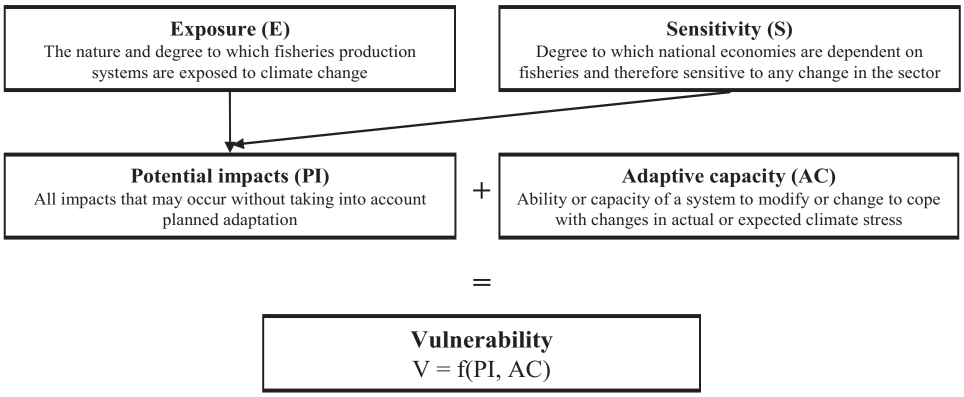
2.2 Vulnerability and resilience

Vulnerability has become a key concept in the climate change literature. It is defined as the susceptibility of groups or individuals to harm as a result of climatic changes. Vulnerability is often compounded by other stresses and recognizes that the way in which people and systems are affected by climate change is determined by external environmental threats, internal factors determining the impact of those threats and how systems and individuals dynamically respond to changes. The Intergovernmental Panel on Climate Change definition of vulnerability is "…a function of the character, magnitude, and rate of climatic variation to which a system is exposed, its sensitivity, and its adaptive capacity." (McCarthy *et al.,* 2001: p. 995). These elements are described in Figure 1, which clarifies the important distinction between impacts and vulnerabilities.

The vulnerability of an individual, community or larger social group depends on its capacity to respond to external stresses that may come from environmental variability or from change imposed by economic or social forces outside the local domain. Vulnerability is complex and depends on a combination of natural and socio-political attributes and geography. Non-climate factors such as poverty, inequality, food insecurity, conflict, disease and globalization can increase vulnerability by affecting the exposure, sensitivity and adaptive capacity of systems, communities and individuals (Adger *et al.,* 2007).

Resilience is a concept that is related to vulnerability and adaptive capacity. It has increasingly been applied to the management of linked social-ecological systems (SES) such as fisheries. Resilience is usually applied with an explicit recognition that SES are "complex systems" resulting in uncertain and surprising behaviours including path dependence, alternative stable states, thresholds and periods of apparent stability punctuated by rapid shifts to qualitatively different behaviours. A resilience perspective does not focus on the ability of a system to resist change. Instead it emphasises the importance of disturbance, reorganization and renewal. The dynamic nature of the concept makes it useful when considering uncertain effects of climate change on complex systems like fisheries. Social-ecological resilience includes the importance of social learning, knowledge systems, leadership, social networks and institutions for

FIGURE 1
Conceptual model of vulnerability



Source: adapted from Allison *et al.,* 2005.
Note: The word "system" can be interpreted as country, region, community, sector, social group or individual.

navigating disturbance, adapting to change and managing the resilience of a system to remain in a desirable state (Folke, 2006). Accordingly, resilience is seen as the capacity of a system to absorb disturbance while maintaining its basic functions, to self-organise and to build capacity for learning. Resilience of aquatic production in the developing world has been defined as the ability to "absorb shocks and reorganise… following stresses and disturbance while still delivering benefits for poverty reduction." (Allison, Andrew and Oliver, 2007.)

2.3 Fisheries, poverty, livelihoods and the socio-economic context of fisheries

The poverty of many fishing communities has conventionally been understood as deriving endogenously because of the inevitable overexploitation and poor returns from open-access resources (people are poor because they are fishers); or exogenously because the influx of the poorest of the poor into fisheries as a last resort (they are fishers because they are poor) (Bene, 2003). However, both Bene (2003) and Smith, Nguyen Khoa and Lorenzen (2005) suggest that this view is over simplistic and small-scale fisheries need to be understood within their wider socio-economic and cultural context. Both authors draw on Allison and Ellis (2001) who introduced the analytical framework of the sustainable livelihoods approach to explicitly detail aspects of small-scale fisheries that should be considered.

A livelihood can be defined as the capabilities, assets and activities required for means of living (Chambers and Conway, 1992). The concept of sustainable livelihood seeks to bring together the critical factors, assets and activities that affect the vulnerability or strength of household strategies (Allison and Ellis, 2001; Ellis, 2000). People can access, build and draw upon five types of capital assets: human, natural, financial, social and physical (Box 1).

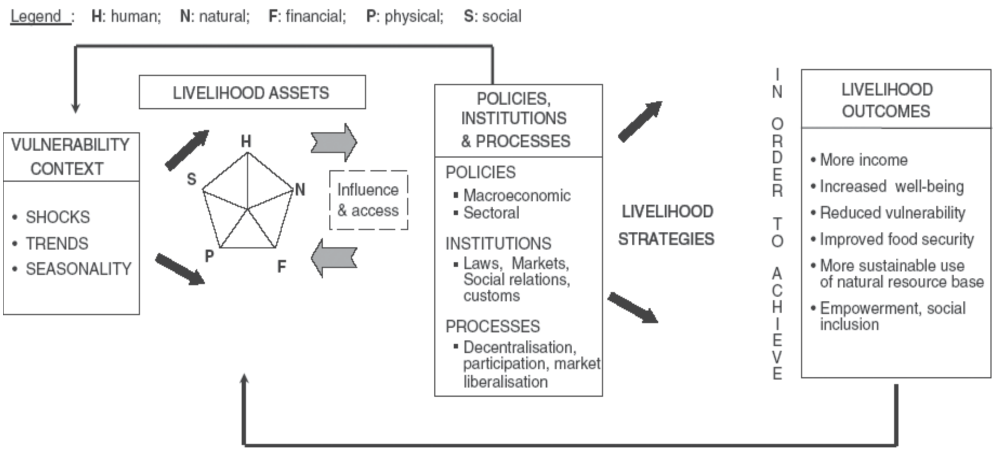
Access to assets is mediated by policies, institutions or processes (PIPs) such as market or organizations (see Figure 2). Livelihoods are also affected by a vulnerability context which includes, for instance, seasonality and changes in fuel prices (Allison and Horemans, 2006).

This framework and the perspective of fisheries being only one of a variety of sectors which individuals, households or communities draw on for their livelihoods (as is the case in many small-scale and inland fisheries, Smith, 2005) helps to understand some of the linkages of fisheries with wider systems and emphasises the importance of context. This leads to a more holistic analysis of fisheries and climate change because it sees fisheries, not as a simple relationship between a community and an aquatic

BOX 1
Livelihood assets identified by the sustainable livelihoods framework

Natural capital – the natural resource stocks (soil, water, air, genetic resources, etc.) and environmental services (hydrological cycle, pollution sinks, etc.) from which resource flows and services useful for livelihoods are derived.
Physical capital – physical assets comprise capital that is created by economic production processes. It refers to the basic infrastructure and producer goods needed to support livelihoods.
Economic or financial capital – the capital base (i.e. cash, credit/debt, savings and other economic assets) which are essential for the pursuit of any livelihood strategy.
Human capital – the skills, knowledge, ability to labour, good health and physical capability important for the successful pursuit of different livelihood strategies.
Social capital – the social resources (networks, social claims, social relations, affiliations, associations) upon which people draw when pursuing different livelihood strategies requiring coordinated actions.

FIGURE 2
The sustainable livelihoods framework



Source: after Allison and Horemans, 2006.
Note: Assets are indicated by letters: H: human, N: natural, F: financial, P: physical and S: social.

production system, but rather as part of a broader socio-economic system which is also affected by climate change. Climate change can be seen to impact each of the five types of assets (reviewed by Allison *et al*., 2005) as well as changing the vulnerability context and impacting on policies, institutions and processes.

2.4 Climate change and climate variability

Fisheries have always been affected by variable climate, including rare extreme events such as upwelling failures, hurricanes and flooding. Rather than a steady increase in temperature, climate change is likely to be experienced as an increased frequency of extreme events. Therefore, it is valid to analyse how fisheries react and adapt to existing climate fluctuations. This assumption, that future climate change will be manifested in the form of increasing severity of familiar phenomenon, may be appropriate to guide policy and actions for near-term climate impacts, but it should be borne in mind that thresholds, or "tipping points" may exist, which shift SES into qualitatively different conditions and present novel problems for fisheries sustainability and management.

2.5 Units and scales of analysis

Impacts of, vulnerability to, and adaptation to climate change can be examined for many different aspects of "fisheries" (e.g. sustainable fish production, well being, economies, food security and livelihoods) at a range of scales (e.g. nations, communities, sectors, fishing operations, households and individuals). Each of these aspects will be affected differently by climate change. For example, stopping fishing as an adaptation to reduced production would be viewed differently from a perspective of sustainable fish production compared to a perspective of the well-being of the communities involved. The scale of analysis can also affect findings. For example, national-level statistics might identify vulnerabilities of individual economies to certain impacts, but fail to discern vulnerable individuals or social groups within nations that are not highlighted as vulnerable by national statistics. This paper uses fisher folk and their communities as the main unit of analysis and examines vulnerability at a range of scales.

3. FISHERIES AND CLIMATE CHANGE MITIGATION

3.1 Fisheries' contribution to greenhouse gas emissions

Fisheries activities contribute to emissions of greenhouse gases (GHG), which are responsible for human-induced climate change, both during capture operations and subsequently during the transport, processing and storage of fish. Most work on fisheries' contribution to climate change has concluded that the minimal contribution of the sector to climate change does not warrant much focus on mitigation (Troadec, 2000), and there is limited information specific to fisheries on contributions to emissions. However, Tyedmers *et al.* (2005) calculate that fishing fleets consume the same quantity of oil as the whole of the Netherlands. This section discusses some of the emission pathways, potential mitigation measures, and examples.

3.1.1 Emissions from fisheries operations

Although most fisheries use vessels that are in some ways motorized and powered by fossil fuels, different types of fisheries use different fuels. Small fishing vessels use petrol or occasionally diesel in outboard and inboard engines, while medium-sized fishing vessels use diesel because it is less flammable than petrol. Only the very largest fishing vessels (more than 1 000 tonnes) use the most polluting heavy oil which fuels large freight vessels. This is because the heavy oil requires specialized equipment to treat it before it is passed to the engines (A. Smith, personal communication).

Current estimates suggest that aviation and the world shipping fleet, including commercial fisheries operations, contribute around the same amount of CO_2 emissions. In 2001 the 90 000 or so ships over 100 tonnes in the world fleet, consumed around 280 million tonnes of fuel, with emissions of around 813 Tg CO_2 and 21.4 Tg NO_x (a powerful GHG) in 2000 (Eyring *et al.,* 2005). There were around 23 000 fishing vessels and fish factory ships over 100 tonnes registered in 2001, making up 23 percent of the world's total fleet. Eyring et *al*., (2005) derive emission coefficients for these classes of vehicle, from which we estimate that total emissions from large fishing vessels is around 69.2 Tg CO_2 per annum, representing 8.5 percent of all shipping emissions. This estimate is midway between the higher estimate of Tyedmers, Watson and Pauly (2005), who used FAO catch statistics and typical fuel/catch efficiency for various fisheries to estimate fuel consumption of the global fishing fleet in 2000, and that of FAO (2007a) which analysed fuel oil use by fishing vessels in 2005 (Table 2).

The three estimates in Table 2 show substantial differences which, with the prospect of shipping being brought into emissions accounting systems, is an indication of the need for further research. Some of the differences may be explained by the different data

TABLE 2
Estimates of fuel consumption and CO_2 emissions from fishing vessels

Source	Vessel type	Year	Fuel consumption (million tonnes)	CO_2 emissions (Tg)	Fuel/CO_2 emissions ratio
Eyring (2005) (vessels >100 t only)	>100t (23 000 vessels)	2001	23.6[1]	69[1]	2.9
Tyedmers *et al.* (2005)	All vessels	2001	42	134	3.2
FAO (2007a)	1.3 million decked vessels	2005	14	43	3.05[2]

[1] Calculated by the proportion of large vessels which are fish factories or catching vessels.
[2] Average of the ratios used by Tyedmers and Eyering.
Source: FAO, 2007a.

TABLE 3
Fuel costs as a proportion of total revenue

	Gear category	Fuel cost as a proportion of total revenue in 2005 (percent)
Developing countries	Active demersal	52.3
	Active pelagic	33.4
	Passive gear	38.7
Developed countries	Active demersal	28.7
	Active pelagic	11.0
	Passive gear	9.2

Source: FAO, 2007a.
Note: fuel costs vary across countries.

BOX 2
Iceland: improving energy efficiency in the fisheries sector as a mitigation strategy

In countries and regions where fisheries are heavily industrialized and which are economically dependent on the fishing sector, emissions from fishing activity can be high. In Iceland, fishing and fish processing accounted for 40 percent of total exports in 2001 while the use of fossil fuels for fishing vessels explained about 26 percent of total GHG emissions. One of the Icelandic Government's objectives was to improve energy efficiency in the sector through education about energy saving options, equipping new vessels with the best available technology and the reduced use of HFC cooling systems.

Source: Iceland Ministry of Environment (2003) http://unfccc.int/resource/docs/natc/icenc3.pdf

sources and methodologies used. Eyring's estimate encompasses only the 23 000 largest vessels over 100 tonnes, whereas the world fleet contained 1.3 million decked vessels in 2004 (FAO, 2007a, p. 25). The methodology used by Tyedmers *et al.*, included all vessels and is thus, as would be expected, higher. FAO's estimate is considerably lower, perhaps reflecting reductions in the fishing fleet from 2001 to 2005. However, trends in vessel numbers would not explain the substantially lower estimate because reductions in some areas were compensated for by increases in others. For example, the number and total kW engine power of EU vessels declined by about nine percent (10 000 vessels and about 1 million kW), while, in spite of plans to address overcapacity, the size and power of China's fleet increased by seven and nine percent respectively (34 000 vessels and 1.3 million kW). Korean vessels declined slightly in number but their considerable engine power increased by about 2 million kW (14 percent, FAO 2007a, p. 27).

In some cases, mobile fishing gears, especially demersal trawls are less fuel efficient than static gears (Table 3). However, the energy efficiency of individual fishing operations needs to be specifically examined because some industrialized passive gear fisheries can be highly fuel intensive. Fuel costs in 2005 were estimated to be nearly

30 percent of revenue for mobile demersal gears in developed countries. Fleets in the developing world tend to be less fuel efficient in terms of costs and catch revenue, spending up to 50 percent of total catch revenue on fuel (Table 3). These figures do not allow absolute fuel consumption to be compared because they are affected by variable price of fuel and catch in different fisheries and countries.

Fuel efficiency can be reduced by poor fisheries management. The "race to fish" which can be exacerbated by certain management measures (e.g. total allowable catches without individual quotas) creates incentives to increase engine power. Meanwhile, overfished stocks at lower densities and lower individual sizes require vessels to exert more effort, catch a higher number of individual fish, travel to more distant or deeper fishing grounds and/or fish over a wider area to land the same volume of fish, all of which would increase fuel use per tonne of landings.

3.1.2 Mitigation of operational emissions

Increasing fuel costs are likely to continue to pressure the fishing industry to improve fuel efficiency in order to remain profitable. For example, switching to more efficient vessels or gears, such as from single to twin trawls (Tietze *et al.,* 2005). However, such practices are only estimated to offer a reduction in fuel use of up to 20 percent (FAO, 2007a). Options also exist for small-scale fishers to reduce their fuel use by improving the efficiency of their vessels, using sails or changing fishing behaviour (Wilson, 1999).

3.1.3 Emissions from trade

FAO estimates that 53 million tonnes of fish were internationally traded in 2004 (FAO, 2007a) including products of both fisheries and aquaculture. The transport of this fish will result in emissions of GHGs. High value fish products such as tuna imports to Japan, are frequently transported by air freight and thus would have especially large transport related emissions. Air freight imports of fish to the United States, Europe and Asia are estimated at 200 000, 100 000 and 135 000 tonnes, respectively (Conway, 2007). Fisheries may make a regionally significant contribution to air freight. For example fish, molluscs and crustaceans were the most frequently airfreighted commodity from New Zealand in 1997 (Statistics New Zealand, 2007), while 10 percent of all air freight from British Columbia in 1996 was fisheries products (British Columbia Stats, 1998).

Despite rapid increases in global air freight of fish products until the early 2000s, the quantities seem to have since stagnated. This may be because of competition with other airfreighted commodities, the reluctance of airlines to carry fish and a trend towards transport of fish frozen at source in refrigerated containers (Conway, 2007). Emissions per kilogram of product transported by air are many times higher than for those transported by sea. Saunders and Hayes (2007) estimate coefficients for the transport of agricultural products and the same coefficients should be relevant for fish export (though fish export may be higher if more refrigeration is used). Intercontinental air freight of fish may thus emit 8.5 kg of CO_2 per kilogram of fish shipped, which is about 3.5 times the emissions from sea freight and more than 90 times the emissions from local transportation of fish if they are consumed within 400 km of the source (Table 4).

Assuming that emissions per kilogram for fish were similar to intercontinental agricultural produce, the 435 000 tonnes of air freighted fish imports to the United States of America, Europe and Asia (Conway, 2007) would give rise to 3.7 Tg CO_2 emissions, which is approximately three to nine percent of the estimates for operational CO_2 emissions from fishing vessels. Emissions from the remaining, non-air freighted 52.5 million tonnes of internationally traded fish depend on the distance and transport mode used. From the figures in Table 5 for short-distance truck and non-bulk sea freight, this could range between 3 and 340 Tg CO_2 equivalent to between 2 and 780 percent of estimated operational fisheries emissions.

TABLE 4
CO_2 emissions associated with different transport modes for agricultural products

Transport mode and distance		gCO_2/kg
Short distance (<400km)		
	Truck	55
Intercontinental transport		
	Air freight	8 510
	Sea freight	
	Bulk	2 399
	Non bulk	6 424

Source: after Saunders and Hayes, 2007.

Clearly, more detailed information on transport modes is needed to provide a reliable estimate of emissions from fish transport, but it is possible that emissions from this sector are as significant as operational emissions. Continuing internationalization of the fish trade will increase fisheries' contributions to CO_2 emissions if transport efficiency and the ratio of air and surface freight remains the same, while increased use of bulk sea-freight or local consumption may reduce the overall emissions from fish transport.

3.1.4 Other potential contributions from fisheries to mitigation

Some initial research has been conducted into the utilization of waste products from fish processing for producing biodiesel. This may offer alternatives to fossil fuels or terrestrial biodiesels in specific instances where large quantities of fish fats are available. For example, a tilapia processing company in Honduras generates electricity and runs vehicles based on waste fish fat (Tony Piccolo, personal communication). This is based on the utilization of waste products from industrial processing of cultured fish. Given the nutritional value of fish, such uses are unlikely to be desirable in typical capture fisheries unless there are similarly large quantities of otherwise waste fish products.

3.2 Impacts of global mitigation actions on fisheries

Aviation and shipping currently lie outside any emissions trading scheme. Distant water fishing vessels that are supplied with fuel outside territorial waters are therefore not included and can also avoid domestic taxes on fuel. In contrast, vessels fishing within their own country's exclusive economic zone (EEZ) are liable to pay fuel duty and be incorporated into current mechanisms. As the post-Kyoto mechanism for 2012 is negotiated, aviation and shipping may become incorporated (EEA, 2008) with implications for the emissions and fuel use of all fishing vessels.

As the vast majority of fisheries operations are entirely reliant on fossil fuels, they are vulnerable to any decrease in the availability of, or increase in the price of fuel. The doubling of the diesel price during 2004 and 2005, for example, led to a doubling of the proportion of fishers' revenue that they spent on fuel and rendered many individual fishing operations unprofitable (FAO, 2007a).

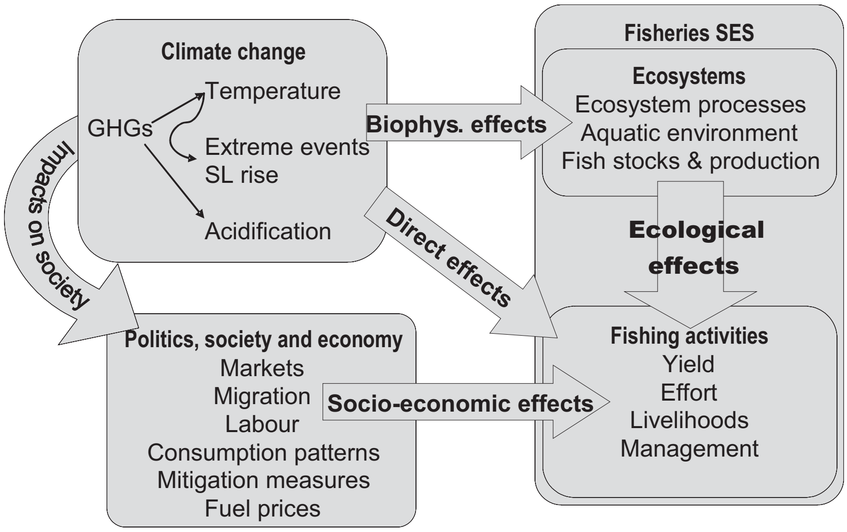
With 40 percent of fish catch being internationally traded (Delgado *et al.,* 2003) increases in transport and shipping costs (i.e. through carbon taxes or other mitigation measures) will affect markets and potentially reduce the profitability of the sector. This may also affect the food security of poorer fish-importing countries as the costs of importing fish increase.

4. CLIMATE CHANGE IMPACTS ON FISHERIES

4.1 Potential impacts and impact pathways

Climate change can be expected to impact fisheries through a diverse range of pathways and drivers. Figure 3 illustrates that the effects of climate change can be direct or indirect, resulting from processes in aquatic ecological systems or by political, economic and social systems. This report focuses on the consequences of climate change at the point at which they impact on fishing activities, fishers and their communities.

FIGURE 3
Ecological, direct and socio-economic impacts of climate change on fisheries and some examples of each



Ecological impacts (covered in paper 1)	Direct impacts	Socio-economic impacts
Change in yield Change in species distribution Increased variability of catches Changes in seasonality of production	Damaged infrastructure Damaged gears Increased danger at sea Loss/gain of navigation routes Flooding of fishing communities	Influx of migrant fishers Increasing fuel costs Reduced health due to disease Relative profitability of other sectors Resources available for management Reduced security Funds for adaptation

A wide range of potential indirect ecological, direct and indirect socio-economic impacts on fisheries have been identified (Table 5, Allison *et al.*, 2005). In chapter one of this report, Barange and Perry summarize impacts in terms of biophysical effects on aquatic ecosystems. These have been the focus of most studies of climate change and fisheries, perhaps because of the prominence of natural science within climate and fisheries science and the complexity of indirect socio-economic impacts. Box 3 however, presents a case in which the biophysical and ecological impacts of climate change appear to have been be overwhelmed by socio-economic impacts even in remote, subsistence fishing communities.

4.2 Impacts by sector

4.2.2 Small-scale and artisanal marine fisheries

The small-scale sector is susceptible to a variety of indirect ecological impacts depending on the ecological system on which the fishery is based. Coral reefs, for example, support small-scale fisheries throughout the tropical western Atlantic, Indian and Pacific oceans and are at risk from elevated water temperatures and acidification in addition to a range of more direct local impacts (Hoegh-Guldberg *et al.*, 2007). The risk of severe bleaching and mortality of corals with rising sea surface temperatures may threaten the productivity of these fisheries. The distribution of coral reefs,

TABLE 5
Potential impacts of climate change on fisheries

Type of changes	Physical changes	Processes	Potential impacts on fisheries
Physical environment (indirect ecological)	Increased CO_2 and ocean acidification	Effects on calciferous animals e.g. molluscs, crustaceans, corals, echinoderms and some phytoplankton	*Potentially* ***reduced production*** *for calciferous marine resources and ecologically related species and* ***declines in yields***
	Warming upper layers of the ocean	Warm-water species replacing cold-water species	***Shifts in distribution*** *of plankton, invertebrates, fishes and birds towards the North or South poles, reduced species diversity in tropical waters*
		Plankton species moving to higher latitudes	
		Timing of phytoplankton blooms changing Changing zooplankton composition	*Potential mismatch between prey (plankton) and predator (fish populations) and* ***reduced production and biodiversity*** *and* ***increased variability in yield***
	Sea level rise	Loss of coastal fish breeding and nursery habitats e.g. mangroves, coral reefs	***Reduced production and yield*** *of coastal and related fisheries*
Fish stocks (indirect ecological)	Higher water temperatures	Changes in sex ratios Altered time of spawning Altered time of migrations Altered time of peak abundance	*Altered timing and* ***reduced productivity*** *across marine and fresh water systems*
	Changes in ocean currents	Increased invasive species, diseases and algal blooms	***Reduced productivity*** *of target species in marine and fresh water systems*
		Changes in fish recruitment success	*Abundance of juvenile fish affected leading to* ***reduced productivity*** *in marine and fresh water*
Ecosystems (indirect ecological)	Reduced water flows and increased droughts	Changes in lake water levels Changes in dry water flows in rivers	***Reduced productivity*** *of lake fisheries* ***Reduced productivity*** *of river fisheries*
	Increased frequency of ENSO events	Changes in timing and latitude of upwelling	***Changes in distribution*** *of pelagic fisheries*
		Coral bleaching and die-off	***Reduced productivity*** *coral-reef fisheries*
Disturbance of coastal infrastructure and fishing operations (direct)	Sea level rise	Coastal profile changes, loss of harbours, homes.	***Increased vulnerability*** *of coastal communities and infrastructure to storm surges and sea level*
		Increased exposure of coastal areas to storm damage	*Costs of adaptation lead to* ***reduced profitability****, risk of storm damage* ***increases costs*** *of insurance and/or rebuilding*
	Increased frequency of storms	More days at sea lost to bad weather, risks of accidents increased	***Increased risks*** *associated with fishing, making it less viable livelihood options for the poor*
		Aquaculture installations (coastal ponds, sea cages) more likely to be damaged or destroyed	***Reduced profitability*** *of larger-scale enterprises, insurance premiums rise*
Inland fishing operations and livelihoods (indirect socio-economic)	Changing levels of precipitation	Where rainfall decreases, reduced opportunities for farming, fishing and aquaculture as part of rural livelihood systems	***Reduced diversity of rural livelihoods;*** *greater risks in agriculture; greater reliance on non-farm income.* ***Displacement of populations*** *into coastal areas leading to influx of new fishers*
	More droughts or floods	Damage to productive assets (fish ponds, weirs, rice fields, etc.) and homes	***Increasing vulnerability*** *of riparian and floodplain households and communities*
	Less predictable rain/dry seasons	Decreased ability to plan livelihood activities – e.g. farming and fishing seasonality	

Source: adapted from Allison *et al.*, 2005.

BOX 3

Importance of socio-economic drivers in Fijian fishing communities

The Lau islands lie in a remote southeast province of Fiji and have limited land and transport networks. The islands are some of the most traditional in Fiji and the majority of households participate in subsistence fisheries.

Following a temperature-induced mass coral mortality event in 2000, and damage to corals from crown of thorns starfish outbreaks in 1999, it might be expected that fisheries and local communities who used those reefs would be directly impacted. However, a socio-economic survey conducted in the area in 2006 found that, while some fishers were aware of the bleaching and starfish phenomena, few identified them as a threat to fish populations. Most fishers had not perceived a decline in fisheries and none had adjusted their fishing practises as a result. Despite the remoteness of these communities and the presence of subsistence fishing, the major change in livelihoods on the islands appeared to have been driven by an export market opportunity (carving ceremonial wooden bowls) rather than the ecological impacts from the climate-mediated bleaching and starfish outbreak.

This case is based on a relatively small survey of a particular island group and so should not be generalized, but it illustrates how assumptions about the prominence of biophysical and ecological drivers in subsistence fisheries can be misleading.

Source: Turner *et al.*, 2007.

coinciding with large numbers of developing country populations in Southeast Asia, East Africa and throughout the Pacific, suggest that many millions of small-scale fishers are dependent on coral reefs for their livelihoods (Whittingham, Campbell and Townsley, 2003a). Nearshore habitats and wetlands, like mangroves and seagrass beds which are often the target areas of small-scale fishers, or which may provide breeding or nursery areas for important species, may be impacted by sea level rise, especially where coastal development restricts landward expansion of the ecosystem (Nichols *et al.*, 2007a).

As species distributions change in response to climate change, small-scale fishers may be less able to adapt by following them because of limited mobility. Traditional area-based access rights institutions will become strained by the loss or relocation of local resources. However, while some fisher folk will see the disappearance of their target species, others could see an increase in landings of species of high commercial value. For example, in the Humboldt Current system during El Niño years, landings of shrimp and octopus increase in northern Peru while in the south, tropical warm-water conditions increase the landings of scallops. These species have higher market values than more traditional species and international markets have developed for them (Badjeck, 2008).

Additionally, input of fresh water in estuaries may favour the appearance of brackish water species. For example, during the El Niño of 1997 to 1998, increased rainfall in northern Peru changed salinity patterns in estuaries, favouring the mullet fishery (Badjeck, 2008) and in Columbia during the La Niña event of 1999 to 2000, a tilapia fishery boom was observed in Columbia. This was caused by salinity changes (Blanco, Narváez Barandica and Villoria, 2007).

Small-scale fishers are particularly exposed to direct climate change impacts because they tend to live in the most seaward communities and are thus at risk from damage to property and infrastructure from multiple direct impacts such as sea level rise, increasing storm intensity and frequency. Worsening storms also increase the risks associated with working at sea, and changes in weather patterns may disrupt fishing practises that are based on traditional knowledge of local weather and current systems.

Disruption of other sectors (e.g. agriculture, tourism, manufacturing) by extreme events could lead to indirect socio-economic effects. The displacement of labour into fishing can lead to conflicts over labour opportunities and increased fishing pressure. This was observed as a result of hurricanes in the Caribbean (Mahon, 2002). Droughts and resultant agricultural failure forecast in some areas of sub-Saharan Africa (Conway *et al*., 2005) may lead to so-called "environmental refugees" moving to coastal areas and creating an influx of surplus fishing labour.

The livelihoods of small-scale fishers are already vulnerable to a range of non-climate risks, including fluctuating resources, loss of access, HIV/AIDS, market fluctuations, conflict, political marginalization and poor governance (Allison, Beveridge and van Brakel, 2008). This insecurity inhibits investment in long-term strategies for sustainable fisheries and will be exacerbated by additional insecurities caused by climate change impacts. Small-scale fishers also generally lack insurance.

4.2.3 Large-scale marine fisheries

Many of the world's largest fisheries (most notably the Peruvian anchoveta – responsible for more than 10 percent of the world's landings) are based on upwelling ecosystems and thus are highly vulnerable to changes in climate and currents. Annual catches of Peruvian anchoveta, for example, have fluctuated between 1.7 and 11.3 million tonnes within the past decade in response to El Niño climate disruptions.

Large-scale changes affect the distributions of species and, hence, production systems. For example, the predicted northern movement of Pacific tuna stocks (Miller, 2007) may disrupt fish-based industries because existing infrastructure (e.g. landing facilities and processing plants) will no longer be conveniently located close to new fishing grounds. In addition, changes in the distribution of stocks and catches may occur across national boundaries.

A lack of well-defined and stable resource boundaries present particular challenges for fisheries governance in the context of climate change. Changes in fish stock distribution and fluctuations in the abundance of conventionally fished and "new" species may disrupt existing allocation arrangements. For instance, changes in Pacific salmon distribution as a result of sea surface temperatures and circulation patterns have led to conflicts over management agreements between the United States and Canada (Pacific Salmon Treaty, Miller, 2000). Similarly, it is forecast that temperature changes in the Pacific Islands could lead to a spatial redistribution of tuna resources to higher latitudes within the Pacific Ocean, leading to conflicts over the stock of tuna between industrial foreign fleets and national ones restricted to their EEZ (World Bank, 2000). Such problems can also occur on subnational scales between local jurisdictions, traditionally managed areas or territorial rights systems.

Rigid spatial management tools, such as permanently closed areas to protect spawning or migration areas, management schemes based on EEZ boundaries or transboundary fisheries management agreements may become inappropriate for new spatial fish stock configurations. Temporal management instruments (e.g. closed seasons) may also become ineffective if the seasonality of target species changes in response to altered climate regimes.

Industrial fisheries are also prone to the direct climate change impacts of sea level rise and increasing frequency and intensity of extreme weather. As with small-scale fisheries, fishing operations may be directly disrupted by poor weather, while extreme events can damage vessels and shore-based infrastructure. City ports and facilities required by larger vessels may be affected. An increasing number of large coastal cities are at risk from sea level rise and extreme weather, especially in rapidly developing Asian economies (Nicholls *et al.,* 2007a).

Indirect socio-economic impacts on industrial fisheries may include flooding or health impacts on vulnerable societies which may affect employment, markets or processing facilities. The aquaculture industry is a major market for fishmeal from capture fisheries and climate change impacts may affect markets for reduction fisheries, although current projections are for fishmeal and fish oil demands to continue to increase in the near future (Delgado *et al.*, 2003).

Positive indirect impacts for some fisheries may result from declines in other fisheries which compete for global markets. For example, while eastern pacific upwelling fisheries were adversely affected in El Niño years, Danish fishers received near record prices for Baltic sprat, a competing species for fishmeal production (MacKenzie and Visser, 2001).

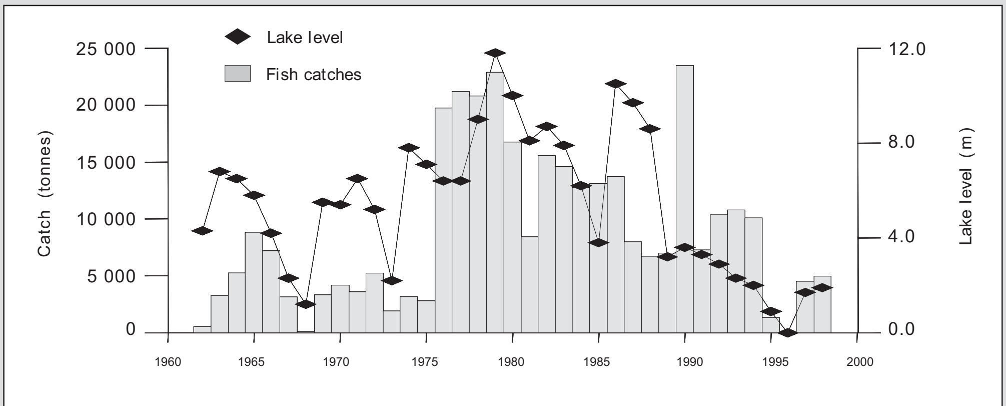
4.2.4 Inland fisheries

Inland fisheries ecology is profoundly affected by changes in precipitation and run-off which may occur due to climate change. Lake fisheries in southern Africa for example, will likely be heavily impacted by reduced lake levels and catches (Box 4).

In basins where run-off and discharge rates are expected to increase, the seasonal inundation of river floodplains such as those in the Ganges Basin in South Asia, fish yields may increase as larger areas of ephemeral spawning and feeding areas are exploited by lateral migrant species. In Bangladesh, a 20 to 40 percent increase in flooded areas could raise total annual yields by 60 000 to 130 000 tonnes (Allison *et al.*, 2005). However, whilst the discharge rates and flooded areas of many rivers in South and South-East Asia may increase, their dry season flows are often predicted to decline and exploitable biomass is more sensitive to dry, than flood season conditions (Halls, Kirkwood and Payne, 2001). Any increases in yield arising from more extensive flooding may therefore be offset by dry season declines. In addition, changes to the hydrological regime and the risk of droughts and flooding may create further incentives to invest in large-scale infrastructure projects like flood defences, hydropower dams and irrigation schemes, which are already known to have complex (and often negative) interactions with fisheries (e.g. Shankar, Halls and Barr, 2004).

BOX 4

Precipitation and inland African fisheries



The shallow, highly productive Lake Chilwa in Malawi supports a US$10 million a year fish trade. However, rainfall variations have led to periodic drying out of the entire lake and time-series demonstrate that the productivity of the fishery is strongly tied to the amount of water in the lake. During drought periods, some fishers diversified their livelihoods to farming, pastoralism and other occupations, while some wealthier, more specialized fishers, migrated to fisheries in other lakes in the region.

Source: after Allison *et al.*, 2007.

4.3 Market and trade impacts

Fisheries can be affected by direct climate impacts on processing and trade. For example, following hurricane Katrina, fishers in the Mississippi area of the United States were unable to sell, catch or buy fuel or ice (Buck, 2005) while heavy rain in Peru in 1998 disrupted road networks and prevented rural fishing communities from accessing their usual markets (Broad, Pfaff and Glantz, 1999).

Increasing frequency of algal blooms, shellfish poisoning and ciguatera poisoning because of warming seas, ecological shifts and the occurrence of water-borne human pathogens, like *Vibrio* in areas affected by flooding may lead to fears over fish contamination. These factors may adversely affect fish markets (Patz, 2000; Hales, Weinstein and Woodward, 1999) although this impact is still uncertain.

4.4 Potential positive impacts

In addition to negative impacts, climate change is likely to create opportunities and positive impacts in some fisheries, although these are not well understood or described in the literature. In chapter one of this report, Barange and Perry highlight several mechanisms in which fisheries production may increase or entirely new fisheries evolve. In inland waters, fisheries created by increases in flooded areas may partially offset the loss of land for agriculture or other economic activities. In Peru, increased sea surface temperatures negatively affect pelagic fisheries for small-scale artisanal fishers, but also bring a variety of (sub) tropical immigrants and expands the distribution zone of some species, illustrating very well how climate change could bring new opportunities to fisher folk and their communities. Indeed, during the El Niño of 1982 to 1983 and 1997 to 1998, penaeid shrimps and rock lobsters from the Panamic Province appeared in Peru (Arntz, 1986; Arntz *et al.*, 2006). These species, along with dolphin fish (*mahi-mahi*), tuna and diamond shark created a new economic opportunity for the artisanal fishing sector (CAF, 2000).

An extreme case is the potential creation of an entirely novel open water fishery as a result of the melting of the Arctic Ocean. The management of as yet nonexistent fisheries with no prior governance arrangements provides a challenge in terms of uncertainty and lack of experience, but also an opportunity to develop governance and management with precautionary limits before overcapacity develops. The adaptive capacity of economies, fishing sectors, communities, individuals and governance systems will determine the extent to which they are able to maximize the opportunities created by new fisheries.

4.5 Observed and future impacts

4.5.1 Observed impacts of climate change and variability

Many fisheries are known to be profoundly controlled by climate variability through ecological impacts (e.g. Box 5). Meanwhile, long-term climate-related changes have been observed in marine ecosystems (IPCC, 2007) including in targeted fish populations. However, in spite of the ecological changes that have been recorded, impacts on fisheries have largely yet to be discerned from pre-existing variability and non-climate impacts (of overexploitation, market fluctuations etc.). Even fisheries associated with coral reefs that have been profoundly impacted by climate change have yet to demonstrate a significant impact (see Box 6). Although a lowering of ocean pH of 0.1 unit has been observed since 1750, no significant impacts of acidification on fisheries have yet been observed (Nicholls *et al*., 2007b) although long-term forecasts are alarming (Orr *et al.,* 2005).

Coastal zones throughout the world are experiencing erosion (Nicholls *et al*., 2007b), threatening coastal communities with flooding and loss of coastal ecosystems. A variety of processes are responsible for this, including changes in land use. However, erosion may also be exacerbated by climate-mediated sea level rise, although the

BOX 5

The impacts of climate variability on Peruvian Anchoveta fisheries

More than 95 percent of Peruvian fisheries catches, which are dominated by pelagic resources such as anchovies (*Engraulis ringens*), are landed by the industrial sector (Majluf, Barandearán and Sueiro, 2005). Additionally, the sector is the second highest generator of foreign currency after mining, accounting for US$1 124 million in exports in 2001 (FAO, 2003b). However, the harvest of anchovies is extremely variable because of population fluctuations induced by warm modes of the El Niño-Southern Oscillation (ENSO), commonly known as El Niño. El Niño events reduce upwelling along the Peruvian coast, thereby impacting on the natural process that provides nutrients for the anchovies and causing a significant decrease in anchovy biomass. During the 1998 El Niño the anchovy biomass was estimated at 1.2 million tonnes, the lowest in the 1990s (Ñiquen and Bouchon, 2004). During the 1997 to 1998 El Niño, total volumes of fisheries landings decreased by 55 percent compared to 1996 (CAF, 2000). It is estimated that the direct cost to the fisheries sector was 73.7 million Peruvian soles (PEN) or US$26.3 million (1998 exchange rate), with a negative effect on the country's balance of payments of around PEN8.4 million (CAF, 2000). Because Peru is the main producer of fishmeal and fish oil in the world, fluctuations of anchovy stocks not only have an impact at national level but also on the global aquaculture feed market.

While the industrial fishery sector was adversely affected by the reduced stock of anchovies and sardines in the eastern Pacific upwelling areas, fisher folk in Denmark received near record prices for Baltic sprat, a competing species for fishmeal production (MacKenzie and Visser, 2001). And climate variability in Peru is not always synonymous with negative effects for the fishmeal industry; La Niña events (cooling of sea surface temperatures) have led to increased catches of anchovies and revenues for the industrial sector (Ordinola, 2002).

BOX 6

Coral bleaching impacts on fisheries in the western Indian Ocean

Coral bleaching is a biological phenomenon in which stony corals and related organisms, lose the symbiotic algae normally found in their tissues as a result of stress (including unusually high water temperatures). As a result, the corals appear white; they may recover but can die if bleaching is severe or prolonged. Coral reefs in the western Indian Ocean region experienced very severe bleaching and mortality because of the El Niño of 1998 to 1999 and were bleached again in 2005. Inner reefs of the Seychelles showed severe ecological consequences. Live coral cover dropped from 27 percent to three percent, and coral-feeding fish species disappeared (Graham *et al.*, 2006). However, fisheries landing statistics and surveys of the biomass of targeted species have yet to demonstrate the impact of the bleaching (Grandcourt and Cesar 2003; Graham *et al*., 2007). This may be because fish habitats were still provided by the structure of the dead corals. These have subsequently begun to erode, leading to a loss of structure. Ecological studies undertaken in 2005 found a reduced abundance of small fish. This may indicate a time lag in the impacts of bleaching on commercially important fish, with the erosion of dead corals eventually affecting recruitment of commercially important fish species (Graham *et al*., 2007).

complexity of coastal dynamics makes it difficult to isolate the impact of climate change (Nicholls *et al*., 2007b).

4.5.2 Likely additional impacts within the next 50 years

Existing climate trends will increase over the next century (IPCC, 2007) and are expected to impact more severely on aquatic ecosystems and, directly and indirectly, on fishing sectors, markets and communities. Loss of corals through bleaching is very likely to occur over the next 50 years, with consequent impacts on the productivity of reef fisheries and potentially on coastal protection as reefs degrade. Sea level will continue to rise and by 2100 will have increased by a further 20 to 60 cm, leading to elevated extreme high sea levels, greater flooding risk and increased loss of coastal habitats.

In addition to incremental changes of existing trends, complex social and ecological systems such as coastal zones and fisheries, may exhibit sudden qualitative shifts in behaviour when forcing variables past certain thresholds (Scheffer *et al.,* 2001; Lenton *et al*., 2008). In addition to this non-linearity in systems, assumptions of gradual change may be based on an incomplete understanding of the mechanisms which will lead to more rapid shifts. For example, IPCC originally estimated that the Greenland ice sheet would take more than 1 000 years to melt, but recent observations suggest that the process is already happening faster owing to mechanisms for ice collapse that were not incorporated into the projections (Lenton *et al*., 2008). Similarly, predictions of changes to fisheries' social and ecological systems may be based on inadequate knowledge of mechanisms and potential "tipping elements", which might be responsible for sudden or irreversible changes. Climate change may, therefore, result in sudden, surprising and irreversible changes in coastal systems (Nicholls, 2007). The infamous collapse of the Northwest Atlantic northern cod fishery provides a (non-climate-related) example where chronic overfishing led to a sudden, unexpected and irreversible loss in production from this fishery. Thus, existing observations of linear trends cannot be used to reliably predict impacts within the next 50 years.

4.5.3 Impacts of climate change in the context of other trends

Future impacts of climate change on fisheries need to be seen in light of the considerable changes which might be expected within society regardless of climate change, for example in markets, technology and governance (Garcia and Grainger, 2005). This evolving context for fisheries may mean that the impacts of climate change cannot be predicted by analysing how fisheries systems in their contemporary state will be affected by future climate change. It is likely that in the future, climate change will impact on future fisheries in different configurations from the current situation. For example, if fisheries are better managed in the future through incentive-based and participatory management of the ecosystem and with more efficient enforcement (Hilborn *et al*., 2003), then fish stocks will be better able to withstand biophysical impacts on recruitment and fisheries ecosystems will be more resilient to changes. In a world in which demand for fish increases, prices continue to rise and fisheries become increasingly globalized (Delgado *et al.,* 2003), commercial fisheries may be able to maintain profitability in the light of declining yields. However, subsistence fisheries and local markets in poorer countries may become more sensitive to economic demand from richer countries and as more fish production is directed to exports, the contribution of fisheries to food security may decline in poorer countries.

4.5.4 Synergistic impacts

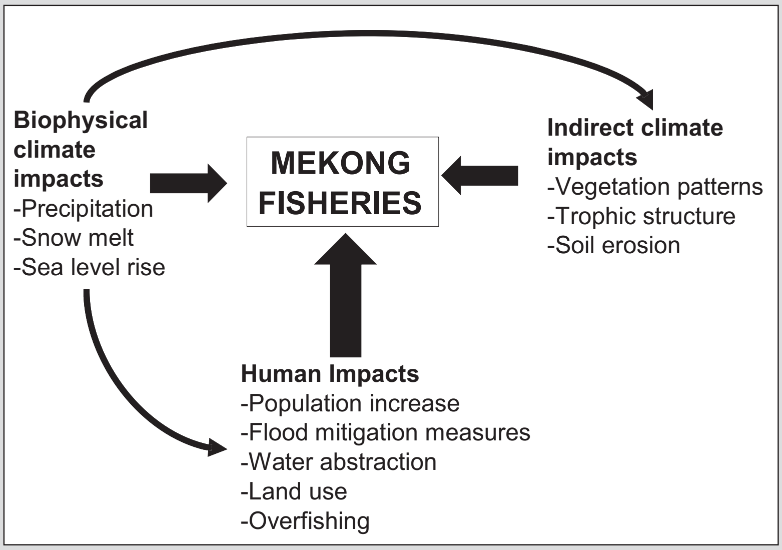
Literature on climate change impacts (including this report) necessarily tend to list separate impacts but it is important to be aware of potential synergistic and cumulative effects of multiple impacts (see Box 7, for example).

4.5.5 Uncertainty of impacts

While successive IPCC reports have documented an increasing scientific certainty that climate change is occurring and an increasing range of observed impacts, there is still

BOX 7
Multiple impacts on Mekong Delta fisheries

The lower Mekong Delta supports more than 1 000 fish species, a capture fishery of 1.5 million tonnes and fishery based livelihoods for 40 million people. These fisheries are threatened by a number of climate mediated processes, including changing precipitation, snow melt and rising sea level, which have impacts on various aspects of the delta's ecology and on human settlements.

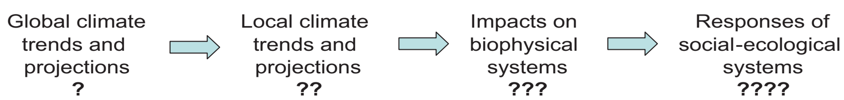


In addition to these interacting climate impacts, the overwhelming impacts on fisheries in the delta are from human activities including overfishing, land use changes and hydrological disruptions. Increased flooding in future has the potential to increase fishery yields, but planned flood mitigation measures to protect agriculture may result in reduced flooding and reduced fisheries productivity.

Source: Easterling *et al.*, 2007.

considerable uncertainty in the extent, magnitude, rate and direction of changes and impacts. Meanwhile, unlike for terrestrial systems supporting agriculture, there is a lack of quantitative predictions of climate effects on aquatic systems (Easterling *et al.*, 2007). The relative importance of different impacts and potential interactions between them are very poorly understood and the uncertainty in predictions about climate variables is amplified by poorly understood responses of biophysical systems. A further complexity and unpredictability is in how people and economies, and *their* complex relationships with local ecosystems might respond to change (Allison, Beveridge and van Brakel, 2008, Figure 4). This underscores the need for social scientists as well as economists and natural scientists to be engaged in policy recommendations and management. It also emphasises the need for fisheries governance regimes to be flexible

FIGURE 4
Increasing uncertainty along the pathway of impacts of climate change



enough to adapt to and learn from unforeseen changes (i.e. to have high adaptive capacity). Frameworks such as adaptive co-management (Armitage *et al.*, 2008) are being developed and may provide some of this flexibility but as yet they have not been fully tested on a larger scale.

4.6 Vulnerability of regions, groups and hot spots

Climate change impacts on fisheries will have uneven effects on different geographic areas, countries, social groupings and individuals. Vulnerability depends not only on the distribution of climate impacts (exposure) but on their sensitivity and adaptive capacity. Thus vulnerability is socially differentiated: virtually all weather-related hazards associated with climate variability, as well as human causes of vulnerability, impact differently on different groups in society. Many comparative studies have noted that the poor and marginalized have historically been most at risk from natural hazards and that this vulnerability will be amplified by climatic changes (IPCC, 2007). Poorer households are, for example, forced to live in higher risk areas, exposing them to the impacts of coastal flooding and have less capacity to cope with reduced yields in subsistence fisheries. Women are differentially at risk from many elements of weather-related hazards, including, for example, the burden of work in recovery of home and livelihood after a catastrophic event (Adger *et al.,* 2007).

Assessing the vulnerability of different geographic areas, countries, social groupings and individuals, aims to identify those who will be most adversely affected, which information can be used to guide policy and interventions to assist adaptation.

4.6.1 Geographic regions with high potential exposure

The greatest warming of air temperatures thus far has been experienced in high latitudes and this is likely to continue with future climate change. However, changes in water temperatures are less well predicted and are mediated by ocean currents. Only some climate impacts on fisheries are mediated by temperature (Figure 3), so projected air temperature changes commonly presented in climate forecasts are a poor measure of potential exposure. Low latitude regions, for example, where fisheries rely on upwellings, coral reef systems or susceptible fresh water flows may be more exposed to climate impacts than high latitude regions where most warming is predicted.

IPCC (2007) predictions suggest that tropical storm intensity will increase, specifically impacting fishing communities and infrastructure in tropical storm areas (Figure 5). It is also possible, but less certain, that the existing tropical storm belt will expand to affect more areas. In this case, communities for whom tropical storms are a novel disturbance may initially be more sensitive if they lack appropriate infrastructure design, early warning systems and knowledge based on previous experience.

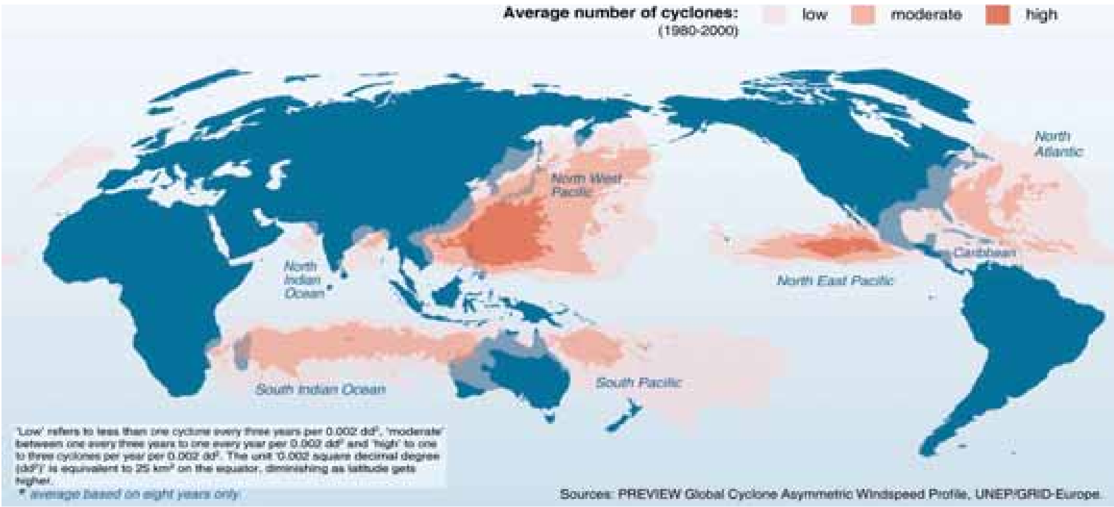
Fisheries communities located in deltas or on coral atolls and ice dominated coasts will be particularly vulnerable to sea level rise and associated risks of flooding, saline intrusion and coastal erosion (Nicholls *et al.,* 2007a).

4.6.2 Vulnerable economies

Developing countries in tropical regions are usually assumed to have lower adaptive capacities than countries with high levels of economic and human development. This is because of lower availability of resources and institutions necessary to facilitate adaptation.

A national level analysis of the vulnerability of 132 economies to climate impacts on fisheries used predicted climate change, the sensitivity of each economy to disruption to fisheries and adaptive capacity, as indicated by statistics on development and GDP (Allison *et al*., 2005). According to the resultant index, countries in western and central Africa (because of low levels of development and high consumption of fish), northwest South America (due to very large landings) and four Asian countries were most

FIGURE 5
Tropical cyclone frequency



Source: www.unep.org/newscentre/graphics/deadwater.

vulnerable (Figure 6).[2] Russia and Ukraine were the only two high latitude countries identified with high vulnerability due to the high degree of expected warming and low adaptive capacity scores.

The analysis highlighted the importance of low adaptive capacity for elevating the vulnerability of African countries even though greater warming is predicted at higher latitudes. While the analysis was a pioneering study of vulnerability of fisheries to climate change, there are several limitations. Firstly, projected increase in air temperature was assumed to be an indicator of exposure to climate change, whereas extreme events or non temperature mediated impacts may be most important. Secondly, data availability prevented the inclusion of most small island developing states, expected to be vulnerable because of a high reliance on fisheries, low adaptive capacity and high exposure to extreme events. Finally, analysis at the national scale required crude generalizations about countries which may miss sub national hotspots of vulnerable sectors or communities.

To improve large-scale mapping of vulnerability, more detailed predictions of changes in the likelihood of extreme events, hydrology and oceanography are needed to better characterise exposure. Integrative earth science and ecology projects such as the United Kingdom Natural Environmental Research Council (NERC)'s Quest-Fish project will make some advances to better characterizing aspects of exposure to move beyond use of projected air temperature changes (web.pml.ac.uk/quest-fish). Meanwhile, higher resolution, sub national data on resource use, fish consumption and trade, fisheries production and poverty will allow more detailed mapping of sensitivity and adaptive capacity.

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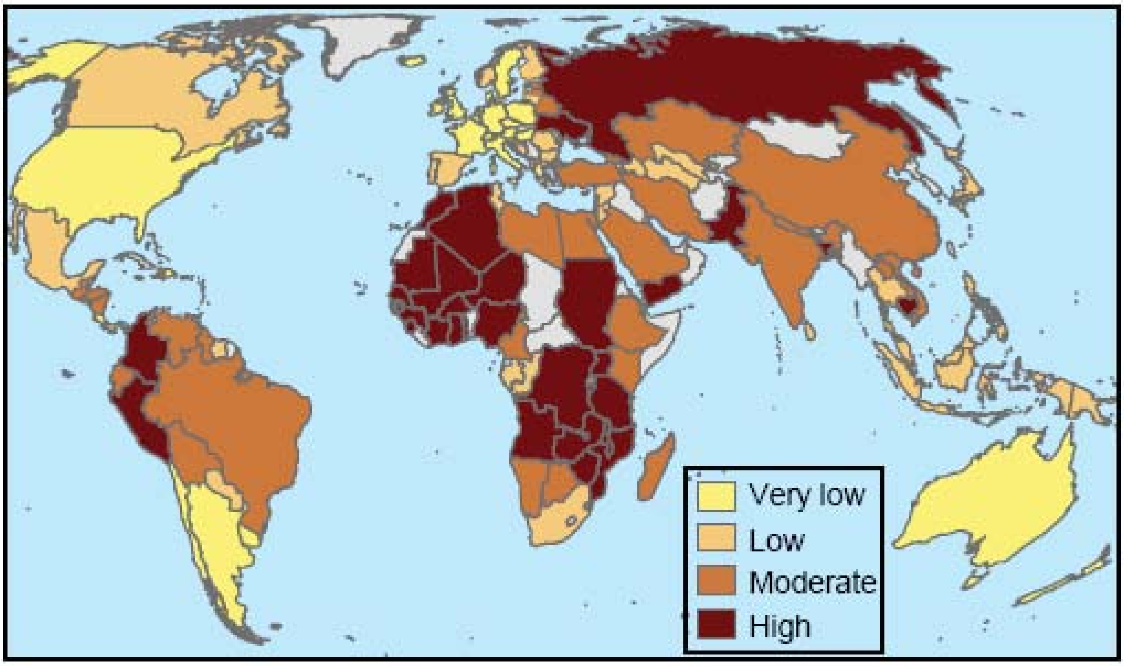
[2] From Allison *et al.* (2005): "Vulnerability was assessed as a function of risk exposure, sensitivity and adaptive capacity. Risk exposure was assessed in terms of projected mean temperature change; sensitivity was based on the relative importance of fisheries in terms of production, employment, export revenues and proportional contribution to GNP and agricultural GNP, as well as contribution to dietary protein. Adaptive capacity was assumed to be related to human development indices (HDIs) and economic performance data – countries with higher HDIs and higher per capita gross domestic product (GDP) are assumed to have higher adaptive capacity. Because poverty data are not widely available for fisher folk, it was necessary to use national level averages and assume the distribution of poverty was similar to the average national distribution".

FIGURE 6
Comparative vulnerability of national economies to climate impacts on fisheries



Source: Allison *et al.*, 2005.

4.6.3 Vulnerability of communities

Vulnerability can also be analysed based on statistics at the sub national level. For example, McClanahan *et al*. (2008) derived an index of adaptive capacity with respect to a loss of fishing livelihoods of 29 coastal communities in five nations in the western Indian Ocean (Kenya, Madagascar, Mauritius, Seychelles and Tanzania). The index combined eight variables proposed to be important for adaptive capacity weighted according to relative importance as judged by experts from across the region. The resultant ranking of communities (Figure 7) could broadly have been predicted from national level development statistics but exceptions include communities in Madagascar (with the lowest development status of the five nations), which score more highly than communities in richer countries because of high occupational mobility, "decline response" and "social capital" (e.g. Sahasoa). Thus a range of factors indicate adaptive capacity, and wealth may not be a complete indicator.

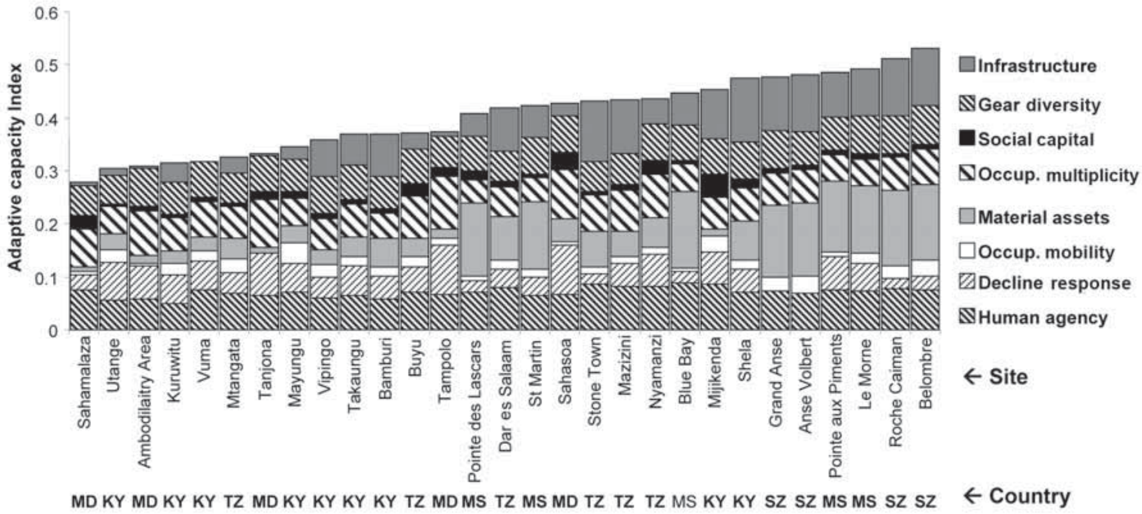
4.6.4 Vulnerable groups within society (demographic variations in vulnerability)

At even finer scales, vulnerability varies between individuals within a community, with some groups particularly vulnerable. Figure 8 is derived from the same data as Figure 7 but shows the range of household adaptive capacity within each community and country. There is as much variation in adaptive capacity between individual households as between communities or between countries, exemplifying the way in which adaptive capacity varies at national, community and individual household level.

Vulnerability is often assumed to be generally correlated with poverty. Hurricane Katrina, which hit New Orleans in August 2005, demonstrated how the poor are particularly vulnerable, even in the most prosperous countries. Poor families, including a high proportion of African Americans, were less likely to evacuate in advance of the hurricane leading to higher death tolls and subsequent impacts on housing, education and psychological state (Save the Children, 2007). Poorer members of communities are also least likely to have insurance or access to early warning information.

FIGURE 7

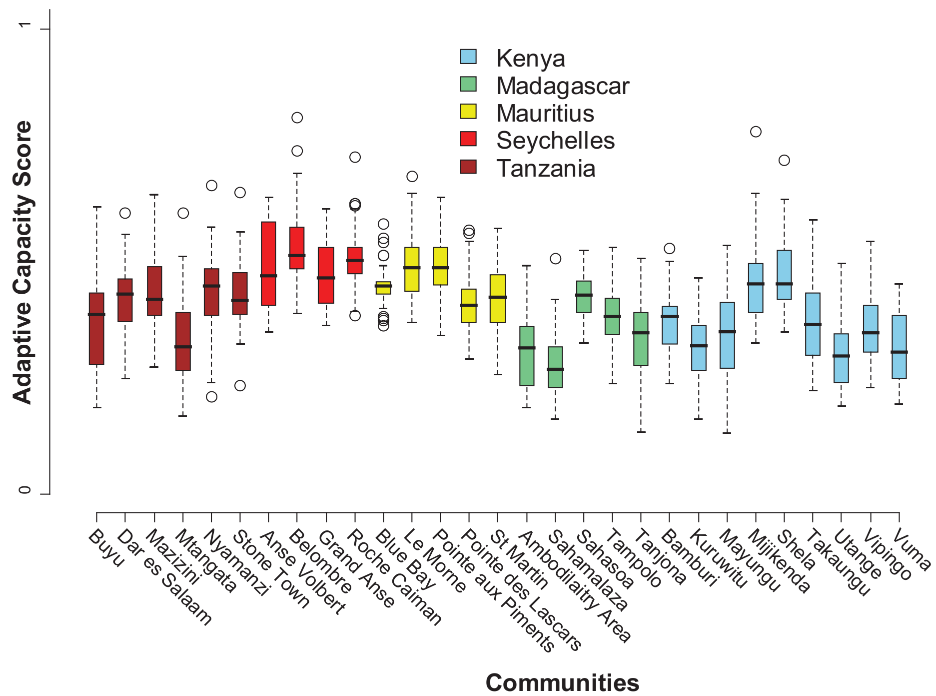
Assessment of the adaptive capacity of 29 East African communities



Source: McClanahan *et al.*, 2008.
Notes: MD - Madagascar, KY - Kenya, TZ - Tanzania, MS - Mauritius, SZ – Seychelles.
Adaptive capacity is measured as a compound of seven household and one community level (infrastructure) variables.
"Decline Response" is an index reflecting the proportion of fishers who would envisage exit from a declining fishery.

FIGURE 8

Range of adaptive capacity index for individual households within communities in five countries in the western Indian Ocean



Source: McClanahan *et al.* (unpublished data).

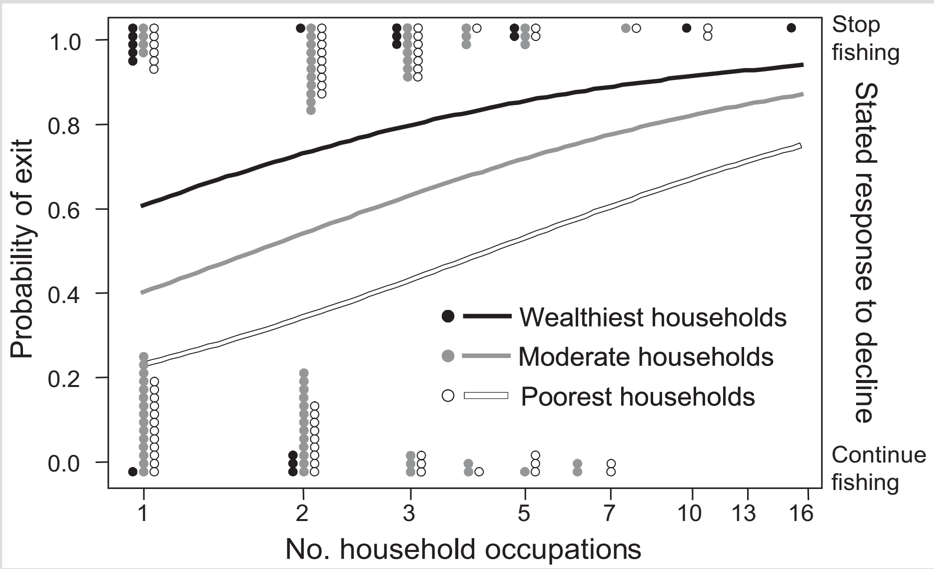
In addition to vulnerability to disasters, the poorest members of society are generally assumed to have less adaptive capacity to cope with gradual changes or declines in livelihoods. For example, in a fisheries context, Kenyan fishers from poorer households were more likely to be trapped in a declining fishery (Box 8).

Individual factors other than poverty can also affect vulnerability. For example, women are more vulnerable to natural hazards and climate change impacts owing to

BOX 8

Adaptive capacity of Kenyan fishers related to household socio-economics

A study of Kenyan fishers' readiness to exit from fishing in the face of declining catches found significant relationship between those who said they would stop fishing in response to a 50 percent decline in catches and socio-economic variables at the household level. Fishers from wealthier households (as judged by material style of life, house materials and ownership of appliances) were more likely to say they would exit the fishery. Livelihood opportunities at the household level were also significant; the probability of exit was significantly related to the total number of occupations in the household.



Statistical relationship between wealth, household occupations and probability of fishers saying they would exit in response to a 50 percent catch decline. The points show the actual data; lines show the relationships from a binomial logistic regression.

Source: Cinner *et al.* (2009).

increased likelihood of being around the home and increased burdens of care after hazards. It is also assumed for many societies that women possess lower levels of adaptive capacity to men. For example, they have fewer economic options, generally lower education attainment, a greater lack of rights and access to resources and may be more likely to endure the burden of care after hazards. Women headed households, which tend to be among the poorest households in many societies are considered especially vulnerable. The importance of contextual factors is well illustrated by studies of the impacts of the 2004 Indian Ocean Tsunami (Oxfam International, 2005). Throughout the affected coastal region, many more women than men were killed; in some communities two to three times more women than men. A range of factors made women more vulnerable and some were very locale and context specific. For example, they included ability to swim, physical strength and the need to protect and care for children and elderly. At some locations, because of women's roles in processing and marketing fish, women were waiting on the shore for fishing boats to return at the time of day the tsunami struck. Because of this they suffered higher levels of mortality than the men at sea. Of course these differential deaths have significant implications for relief and rehabilitation and long-term impacts on families and communities. However, there are relatively few rigorous empirical studies (see Vincent, 2006), so the literature abounds with generalizations and unproven assumptions. In many situations, for example, women may have access to abundant and diverse forms of social capital which may provide excellent support to overcome certain types of impacts or extreme events.

4.6.5 Gaps in knowledge about vulnerability

The ability to identify those most vulnerable to climate change is limited by the lack of high resolution data at appropriate scales and by uncertainty as to the processes that make people and places vulnerable. The IPCC Fourth Assessment highlighted that, in terms of impacts and adaptation, knowledge, monitoring and modelling of observed and future impacts is skewed towards developed nations (IPCC, 2007).

Changing resource scarcity or unpredictability as a result of climate change will clearly affect those whose entire livelihoods are directly dependent on fisheries. But it is unclear whether such dependence on fisheries will underpin efforts to attain sustainable management (as observed in some circumstances and explained by commons management theory); will result in greater overexploitation as future availability becomes uncertain; or will lead to an emphasis on diversification out of fisheries based livelihoods altogether, which may have significant social and even environmental impacts. All three generic responses are likely to occur. Hence defining the goals of desirable and sustainable adaptation for different stakeholders is an important research task for regions at risk.

There is a lack of understanding of how adaptation strategies in general, in coastal areas affected by multiple impacts of climate change, may impact other strategies and neighbouring coastal areas. For example, it has been shown that flood mitigation measures in Bangladesh to protect farmland may negatively affect fisheries (e.g. Shankar, Halls and Barr, 2004). Similarly, hard engineering coastal protection can impact on sediment loading and coastal dynamics in neighbouring coastal areas or countries. And increased "roving" of commercial fishing fleets as stocks migrate will have impacts on neighbouring or even distant countries.

Finally, there may be major thresholds in ecological and physical systems in oceans and coastal areas that directly affect vulnerability of these regions. These include stock collapse thresholds, ocean acidification and its impact of calcifying organisms and rises in temperature above a threshold for mass coral bleaching. The risk of such major shifts in ecology increases the exposure and vulnerability of dependent communities, but may not be known until after a threshold is passed.

5. ADAPTATION OF FISHERIES TO CLIMATE CHANGE

Adaptation to climate change is defined in the climate change literature as an adjustment in ecological, social or economic systems, in response to observed or expected changes in climatic stimuli and their effects and impacts in order to alleviate adverse impacts of change, or take advantage of new opportunities. In other words, adaptation is an active set of strategies and actions taken by people in reaction to, or in anticipation of, change in order to enhance or maintain their well-being. Adaptation can therefore involve both building adaptive capacity to increase the ability of individuals, groups or organizations to predict and adapt to changes, as well as implementing adaptation decisions, i.e. transforming that capacity into action. Both dimensions of adaptation can be implemented in preparation for, or in response to impacts generated by a changing climate. Hence adaptation is a continuous stream of activities, actions, decisions and attitudes that informs decisions about all aspects of life and that reflects existing social norms and processes. There are many classifications of adaptation options summarised in Smit *et al*. (2000) based on their purpose, mode of implementation, or on the institutional form they take.

Coulthard (2009) highlights the difference between adaptations in the face of resource fluctuations that involve diversifying livelihoods in order to maintain a fishery-based livelihood, and those which involve "hanging up our nets", exiting fisheries for a different livelihood source. Another response often observed during the development of a fishery to cope with reduced yield is to intensify fishing by investing *more* resources into the fishery. This can be in terms of increasing fishing effort (by spending more time at sea), increasing fishing capacity (by increasing the number, size or efficiency of gears or technology) or fishing farther or deeper than previously. Such adaptation responses obviously have potentially negative long-term consequences if overexploitation is a concern in the fishery. The state of many of the world's fisheries offers little opportunity for sustainable intensification of fishing as an adaptation strategy.

Inevitably adaptation strategies are location and context specific. Indeed, Morton (2007) argues that both impacts of and adaptation to climate change, will be difficult to model and hence predict, for smallholder or subsistence agricultural systems. This is because of factors such as the integration of agricultural and non agricultural livelihood strategies and exposure to various stressors, ranging from natural stressors to those related to policy change. The same conditions are likely to prevail in the subsistence fisheries sector, though this has not been researched in the same manner as marginal and subsistence agricultural systems. Faced with this complexity there have been various suggestions and typologies of how adaptation actually occurs for such livelihoods.

Adaptation responses can be conceptually organized based on timing and responsibility (see Table 6). Specific adaptations of industrialised fisheries are likely to differ from those of small-scale fisheries. For example Thornton *et al.* (2007) suggest that intensification, diversification and increasing off farm activities are the most common adaptations in pastoralist settings, while Eriksen *et al.* (2005) observe, in addition, the use of greater biodiversity within cropping systems and use of wild foods. In fisheries, analogous responses can be seen as intensifying fisheries, diversifying species targeted or exiting fishing for other livelihoods. Agrawal and Perrin (2007) examine strategies for subsistence resource dependent livelihood systems and suggest all involve functions that pool and share risks through mobility, storage, diversification, communal pooling and exchange. Although most fisheries (even small-scale) are not purely subsistence (Berkes *et al.,* 2001), this typology of adaptation may be useful for conceptualising small scale fishery adaptations to climate change.

5.1 Examples of adaptation in fisheries

Fisher folk and their communities around the world are already constantly adapting to various forms of change (Coulthard, 2009). Thus, much can be learned by examining how fishers have adapted to climate variability such as El Niño and non climate pressures and shocks such as lost markets or new regulations. Table 6 suggests specific adaptations to impacts identified in Table 5. Examples of adaptation in fisheries are dominated by diversification or flexible livelihoods (see Allison, Beveridge and van Brakel, 2008) and migration (Box 9) in response to climate-mediated fluctuations in yield.

Responses to direct impacts of extreme events on fisheries infrastructure and communities are believed to be more effective if they are anticipatory as part of long-term integrated coastal and disaster risk management planning (Nicholls, 2007a). Adaptations to sea level rise and increased storm and surge damage include hard (e.g. sea walls) and soft (e.g. wetland rehabilitation or managed retreat) defences, as well as improved information systems to integrate knowledge from different coastal sectors and predict and plan for appropriate strategies.

Indirect socio-economic impacts are arguably less predictable, making it more difficult to discuss specific adaptation measures. Diversified products and markets would make fisheries less prone to economic shocks, while information technologies are becoming more available to small-scale fishers and may help them to navigate international markets and achieve fair prices for their fish (FAO, 2007b). Generally

TABLE 6
Specific adaptations to climate impacts on fisheries

Impact on fisheries	Potential adaptation measures	Responsibility	Timescale
Reduced fisheries productivity and yields (indirect ecological)	Access higher value markets	Public/private	Either
	Increase effort or fishing power*	Private	Either
Increased variability of yield (indirect ecological)	Diversify livelihood portfolio	Private	Either
	Insurance schemes	Public	Anticipatory
	Precautionary management for resilient ecosystems	Public	Anticipatory
	Implementation of integrated and adaptive management	Public	Anticipatory
Change in distribution of fisheries (indirect ecological)	Private research and development and investments in technologies to predict migration routes and availability of commercial fish stocks*	Private	Anticipatory
	Migration*	Private	Either
Reduced profitability (indirect ecological and socio-economic)	Reduce costs to increase efficiency	Private	Either
	Diversify livelihoods	Private	Either
	Exit the fishery for other livelihoods/investments	Private	Reactive
Increased vulnerability of coastal, riparian and floodplain communities and infrastructure to flooding, sea level and surges (direct)	Hard defences*	Public	Anticipatory
	Managed retreat/ accommodation	Public	Anticipatory
	Rehabilitation and disaster response	Public	Reactive
	Integrated coastal management	Public	Anticipatory
	Infrastructure provision (*e.g.* protecting harbours and landing sites)	Public	Anticipatory
	Early warning systems and education	Public	Anticipatory
	Post-disaster recovery	Public	Reactive
	Assisted migration	Public	Reactive
Increased risks associated with fishing (direct)	Private insurance of capital equipment	Private	Anticipatory
	Adjustments in insurance markets	Private	Reactive
	Insurance underwriting	Public	Reactive
	Weather warning system	Public	Anticipatory
	Investment in improved vessel stability/safety	Private	Anticipatory
	Compensation for impacts	Public	Reactive
Trade and market shocks (indirect socio-economic)	Diversification of markets and products	Private/public	Either
	Information services for anticipation of price and market shocks	Public	Anticipatory
Displacement of population leading to influx of new fishers (indirect socio-economic)	Support for existing local management institutions	Public	Either
Various	Publicly available research and development	Public	Anticipatory

Sources: Categories adapted from Tompkins and Adger (2004) and Smit *et al.* (2000).

Note: *Adaptations to declining/variable yields that directly risk exacerbating overexploitation of fisheries by increasing fishing pressure or impacting habitats.

decreasing the marginalization and vulnerability of small-scale fishers is thought to be an anticipatory adaptation to a range of threats, as well as facilitating sustainable management (FAO, 2007c).

Cultural and socio-economic aspects limit people's adaptive capacity in apparently unpredictable ways. In Pulicat Lake in India, for example, access to fish and prawn fisheries is mediated by caste identities. The non fishing caste members do not have traditional hereditary rights of access and subsequently tend to be economically poorer and more marginalized. However, in the face of declines in catches, these non fishing caste fishers were more adaptable to do jobs outside of the fisheries sector. Hence,

BOX 9

Adaptation of individuals and formal institutions to climate variability in Peruvian scallop fisheries

The Peruvian scallop fishery has been subject to major fluctuations caused by shifts between El Niño/La Niña climate regimes which affect the extent of upwelling and sea temperature off the coast of Peru. Fishers' informal reactive adaptations to these fluctuations are rapid and flexible and mostly involve migration between sites which experience opposite fluctuations in yields as a result of El Niño events. In contrast, formal fisheries management institutions have been slow to respond to fluctuations and show limited capacity to learn from earlier experiences. However, formal institutions are necessary to take account of large-scale and long-term factors to prevent maladaptations like unsustainable levels of effort.

Sources: Badjeck, 2008; Badjeck *et al.* (2009).

they had a greater adaptive capacity and were in many ways less vulnerable to annual fluctuations in stocks (Coulthard, 2006).

5.1.1 Adaptation of fisheries management

Much fisheries management is still loosely based on maximum sustainable yields or similar fixed ideas of the potential productivity of a stock. For example, North Sea groundfish fisheries have recently been managed in order to recover cod to a target biomass of 150 000 tonnes. Although climatic influences on cod productivity are recognised (Anonymous, 2007), there is currently no formal strategy by which environmental processes can be incorporated into management targets and measures. As climatic change increases environmental variation, more fisheries managers will have to explicitly consider such variations and move beyond static management parameters for particular stocks. Such changes create an additional imperative to implement the ecosystem approach to fisheries (EAF), a holistic, integrated, and participatory approach to obtain sustainable fisheries (FAO, 2006).

5.1.2 The role of institutions in adaptation

Institutions, in the broadest sense, mean formal and informal traditions, rules, governance systems, habits, norms and cultures. A technical approach to adaptation can underestimate the importance of institutions (especially informal) to facilitate or limit adaptation. For example, traditional practises or links with alternative livelihoods can be drawn on to adapt to declining fish yields, while cultural identities connected with fishing may limit adaptation, in terms of leaving fisheries, that fisher folk are willing to consider (Coulthard, 2009). An extensive literature documents examples of local resource management institutions that facilitate management of common pool resources and it is proposed that such institutions allow adaptive and sustainable management (e.g. Berkes, Colding and Folke, 2000; Ostrom, 1990). However, in the face of increasing climate change impacts they can also be a barrier to the flexibility needed for adaptive management (Coulthard, 2009). Formal institutions can also constrain adaptation, for example in Peru, the establishment of access rights institutions to improve management of scallop stocks may prevent future migration responses to El Niño shocks (Box 9), while increasing regulation of gears and sectors in Newfoundland fisheries meant that when cod stocks collapsed, cod fishers who previously exploited a range of species, were "locked-in" to the collapsed cod fishery and unable to benefit from expanding shellfish fisheries (Hilborn *et al.*, 2003).

5.2 Building adaptive capacity in fisheries

5.2.1 Uncertainty, surprise and the need for general adaptive capacity

There is great uncertainty in the nature and direction of changes and shocks to fisheries as a result of climate change. Investments in generic adaptive capacity and resilient fisheries systems seem to be a good strategy to support future adaptations which are not currently foreseen. Better managed fisheries with flexible, equitable institutions are expected to have greater adaptive capacity. For example, implementation of the EAF could make an important contribution to adaptation in preparation for the effects of climate change.

Many fishers are vulnerable to a range of disturbances which together decrease their adaptive capacity in the face of climate change impacts (FAO, 2007c,d). Thus, for example, working to address the marginalization of fishing communities and their vulnerability to HIV/AIDS and other diseases and resource insecurity can be seen as a form anticipatory adaptation to climate change shocks.

5.2.2 Have we been here before?

Good management for sustainable stocks, enhanced wellbeing and reduced vulnerability of fisher folk will increase generic adaptive capacity. Therefore, working towards equitable and sustainable fisheries, which has been a goal of fisheries management, may be seen as advancing the adaptive capacity of fishing communities. It has also long been recognized that fisheries management must take account of inherent uncertainty within fisheries which results from climate variability, variable recruitment and unknown linkages within the ecological and social aspects of fisheries (e.g. Charles, 1998).

Thus, adaptation for climate change, in terms of building the resilience of fish stocks and communities and taking account of uncertainty, could be seen as implementation of good fisheries governance as recommended over the past decade, irrespective of climate change, which raises the question of whether new interventions are required to assist adaptation.

Despite the familiarity of the challenges, increased resources and efforts are likely to be needed to adapt fisheries in the face of climate change. The majority of fisheries are still not managed in a sustainable, equitable fashion that takes due account of uncertainty; sudden shifts in systems may result from climate change presenting new challenges; and the magnitude of change may simply overwhelm current options for "good fisheries governance". There may be a need for focused adaptation for poorer, marginalized and most vulnerable fisher folk and communities, which would go beyond previous international development assistance. International financing mechanisms exist and are being developed to support adaptation under the United Nations Framework Convention on Climate Change (UNFCC). These have, for example, funded the creation of National Adaptation Programmes of Action (NAPAs) in poor countries. Significant funds are therefore becoming available for targeted adaptation, but these are thought to be inadequate to address the massive costs of adaptation, while issues of defining and funding adaptation to climate change as distinct from general building of adaptive capacity complicate the process of allocating funds for adaptation (Ayers and Huq, 2009).

6. CONCLUSION

Climate change is predicted to have a wide range of impacts on fisheries and those who depend on them. As is common across climate change science, there is a significant body of knowledge on the biophysical impacts of climate change on aquatic ecosystems, but much less knowledge on how these impacts will be mediated by the socio-economic context of fisheries and how adaptation will proceed. Our sense from this review of knowledge in areas analogous to climate change suggests that impacts resulting from changes in the human context of fisheries (supply, demand, technology and the ability to manage collective resources) will be at least as significant as ecological or direct impacts of climate change on the vulnerability of livelihoods in fishing communities in the near future.

Vulnerability of fisheries to climate change is not only determined by degree of change or impact, but also the sensitivity of individuals or fisheries systems and their adaptive capacity. Adaptive capacity relies on various assets and can be constrained by factors including culture or marginalization. We have reviewed the contribution that the sustainable livelihoods framework can make in representing and objectively measuring the importance of context for understanding the role of fisheries in livelihoods.

The priority responsibility for governments, civil society and international organizations with regard to climate change, is to aggressively pursue reductions in greenhouse gas emissions (GHG), because the long-term consequences of climate change are highly complex, unknowable and potentially irreversible and many already marginalised groups appear most vulnerable to its impacts. Fisheries make a moderate contribution to GHG emissions through fossil-fuel-based catching operations and transportation, which may be reduced with improved technology and management of stocks. Previous global emissions already mean that climate change will affect marine and freshwater systems and fishing communities. Governments therefore have a responsibility to facilitate adaptation, especially for groups vulnerable because of their exposure, sensitivity or lack of adaptive capacity. A research imperative is therefore to:

- identify the most vulnerable individuals and communities;
- investigate possible government facilitated adaptation;
- consider constraints on private adaptations; and
- seek desirable adaptations which contribute to long term reductions in vulnerabilities, rather than short-term coping strategies which may enhance vulnerability.

Reviewing the potential impacts of climate change on fisheries suggests a role for public policy in adaptation: to reduce vulnerability, to provide information for planning and stimulating adaptation and to ensure that adaptation actions do not negatively affect other ecosystem services and the viability of fisheries in the long run.

The first rationale for promoting adaptation is to protect those parts of the fishing sector and communities in coastal areas that have the least ability to cope. Coastal regions facing climate change for example are subject to multiple stresses associated with globalization of fisheries, and in the case of developing countries, lack of public infrastructure, high disease burden and many other factors that limit the ability to adapt.

The second public policy response is the provision of high quality information on the risks, vulnerability and threats posed by climate change. Such information includes scenarios of change at the global scale, but it also involves significant investment in incorporation of climate information into coastal land use planning and other forms of regulation. Hence the need for policy integration across government sectors, such as coastal planning, river basin management, agriculture, fisheries themselves and health and nutrition where climate change risks interact.

The third area of public policy response is in the provision and enhancement of the public good aspects of fisheries and related biodiversity and ecosystem services. The Millennium Ecosystem Assessment highlighted the importance of ecosystem services for human wellbeing. Climate change impacts represent enhanced reasons for sustainable fisheries management and incentives to promote biodiversity conservation within coastal regions, given the potential for habitat decline and species extinction throughout the world.

There is already an imperative to improve fisheries governance to take account of natural variability, uncertainty and sustainability and to address overcapacity and overfishing, which lead to economic losses, endanger future fisheries and degrade aquatic ecosystems (e.g. calls to implement the Ecosystem Approach to Fisheries).

In addition, pro-poor governance of small-scale fisheries is now promoted by international organizations to address marginalization of fishers and equity (FAO, 2005a). These familiar challenges for governance will continue and perhaps become more imperative in the face of climate change. Variability and uncertainty, which have historically been important factors that managers have struggled to take account of, will become more prevalent under climate change. Meanwhile poverty in small-scale fisheries and marginalization of fishers reduces their adaptive capacity.

The wider context of fisheries is also important because of the ways in which politics, socio-economics, demographics, ecology and markets can influence fisheries (and be important pathways for climate change impacts) but also because they are evolving rapidly with processes of globalization. Future climate change will not interact with fisheries in the way it would today because it will affect future fisheries within a future context. This creates additional uncertainty and emphasizes the need for adaptive governance as well as integration of fisheries with other linked sectors, particularly agriculture, which may itself affect fisheries due to climate impacts and adaptation.

Current problems with fisheries management call for strong and reliable institutions governing resource use but, paradoxically, top down or rigid approaches which may seem attractive may not offer the flexibility to ensure resilient fisheries systems and communities under climate change. Approaches such as adaptive co-management, proposed to address uncertainty and harness the knowledge and commitment of resource users at multiple scales (Armitage *et al.,* 2008) may offer the best hopes for resilient fisheries. Experiments with such approaches should be extensively trialled and analysed as a priority. Governance systems with a focus on continual learning from experience, which openly treat policy as experimentation, will be more likely to address new challenges as they arise. Policies which place too much emphasis on stability, certainty and top down control may lead to unexpected consequences and may "lock in" fisheries, preventing desirable and sustainable adaptation.

The process of fisheries and their associated communities adapting to climate change is facilitated and constrained by various social factors and involves value-based decisions and trade-offs. Abandoning fisheries as a livelihood may become a necessary reality in some fisheries. The political and value laden nature of adaptation emphasizes the need for equitable and just deliberative processes, for example, if there is a trade-off between actions and policies that assist the most vulnerable and those which provide optimally efficient adaptation or large-scale resilience.

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Climate change and aquaculture: potential impacts, adaptation and mitigation

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ABSTRACT

This document addresses the potential impacts of climatic change on the aquaculture sector and to a lesser extent the contribution of aquaculture to climate change. In order to achieve these objectives, the status of this subsector in relation to the total food fish supply, recent changes therein and other related aspects are analysed with a view to addressing potential adaptations and mitigation.

Currently, the proportionate contribution of aquaculture to food fish consumption approximates 45 percent; this is also reflected in the increasing contribution of aquaculture to total fisheries figures recorded in the gross domestic product (GDP) of some of the main producing countries. Considering human population growth and stagnation in the growth of capture fisheries, it is expected that the supply of food fish from aquaculture will be required to increase even further to meet future demand for fish.

Aquaculture is not practised evenly across the globe and to evaluate the potential impacts of climate change, the document analyses current aquaculture practices in relation to: three climatic regimes, *vis-à-vis* tropical, subtropical and temperate; in relation to environmental types *vis-à-vis* marine, fresh and brackish waters; and in relation to geographic divisions by continents. It is seen that aquaculture is predominant in tropical and subtropical climatic regions and geographically in the Asian region. Furthermore, the most cultured commodities are finfish, molluscs, crustaceans and sea weeds, but species that feed low down in the food chain predominate. The geographic and climatic concentration of aquaculture necessitates, for the time being, a focus on the development of adaptive strategies for addressing or mitigating climate change impacts in these regions, especially if the predicted gap between supply and demand for food fish

is to be realised through aquaculture. However, we cannot disregard the potential for aquaculture growth in other regions.

The main elements of climate change that could potentially impact on aquaculture production – such as sea level and temperature rise, change in monsoonal rain patterns and extreme climatic events and water stress – are highlighted and the reasons for such impacts evaluated. By virtue of the fact that the different elements of climate change are likely to be manifested or experienced to varying degrees in different climatic zones, the direct impacts on aquaculture in the different zones are considered. For example, it is predicted that global warming and a consequent increase in water temperature could impact significantly and negatively on aquaculture in temperate zones because such increases could exceed the optimal temperature range of organisms currently cultured. Such impacts may be balanced with positive impacts that might occur as a result of climate change, such as enhanced growth and production in tropical and subtropical zones. However, positive impacts are unlikely to occur without some potential negative impacts arising from other climatic change elements (e.g. increased eutrophication in inland waters). In both instances possible adaptive measures for reducing or maximizing the impacts are considered. An attempt is also made to deal with the climatic change impacts on different culture systems, for example, inland and marine systems and different forms of culture practices such as cage culture. Furthermore, it is likely that diseases affecting aquaculture will increase both in incidence and impact.

Nearly 65 percent of aquaculture production is inland and concentrated mostly in the tropical and subtropical regions of Asia. Climate change impacts as a result of global warming are likely to be small on aquaculture practises taking place in such systems and if at all positive, brought about by enhanced growth rates of cultured stocks. On the other hand, climate change will impact on water availability, weather patterns such as extreme rain events, and exacerbate eutrophication and stratification in static (lentic) waters. The influence of the former on aquaculture is difficult to project. Some adaptive measures related to the location of farms are discussed here. However, based on current practices, particularly with regard to inland finfish aquaculture that is predominantly based on species feeding low in the food chain, the greater availability of phytoplankton and zooplankton through eutrophication could possibly enhance production. On the other hand, in marine cage culture, adaptive measures will revolve around the introduction of improved technologies to withstand extreme weather events.

Sea level rise and consequent increased salt water intrusion in the deltaic areas of the tropics where there is considerable aquaculture production is likely to occur. Adaptations to related impacts will involve the movement inland of some operations that culture species with limited saline tolerance. Equally, aquaculture is seen as an adaptive measure to provide alternative livelihood means for terrestrial farming activities that may be no longer possible and or cost effective due to sea water intrusion and frequent coastal flooding. One of the most important, though indirect, impacts of climate change on aquaculture is considered to be brought about by limitations on fishmeal and fish oil availability (for fish feeds) as a result of a reduction in raw material supplies. Other types of raw materials might also be affected. The negative impacts are likely to be felt mostly in the temperate regions where the finfish aquaculture is based entirely on carnivorous species. Adaptive measures to counteract these impacts are suggested.

The ecological cost of different aquaculture species and systems, as opposed to other sources of animal protein production, is presented and the indirect contribution to carbon emissions is considered. As a mitigation measure to curtail the contribution of aquaculture to carbon emissions, it is suggested that the consumer is made aware of the carbon emissions associated with various products, in the same way that traceability is indicated. In this context, it is demonstrated that on the whole aquaculture is less energy costly and could contribute to carbon sequestration more than other terrestrial farming systems.

The document concludes by reviewing more general policy-oriented adaptation measures that can be implemented regionally, nationally or could be site specific.

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CONTENTS

1. INTRODUCTION

World population is predicted to reach nine billion by 2050, resulting in increased global food needs in the first half of this century (McMichael, 2001). The capacity to maintain food supplies for an increasing and expectant population will depend on maximizing the efficiency and sustainability of the production methods in the wake of global climatic changes that are expected to adversely impact the former. A recent analysis of global food production within the Special Report on Emission Scenarios (SRES) of the Inter Governmental Panel on Climate Change (IPCC), when linked to the food trade system model indicates that the world will be able to feed itself well into the next century, a heartening conclusion. However, the model that demonstrated this outcome was based on the production of developed countries, which are expected to benefit mostly from climate change. This compensated for the declines projected in the terrestrial food crops of developing countries, suggesting that regional differences in crop production are likely to grow stronger with time (Parry *et al*., 2004). Perhaps aquaculture, an industry of the developing world, may provide a different scenario in relation to its contribution to our future food needs.

Humans and fish have been inextricably linked for millennia, not only because fish is an important source of animal protein, providing many millions of livelihood means and food security, but also from an evolutionary view point. Indeed, one school of thought has suggested that the development of the human brain and hence what humans are today, is linked to food sources rich in n- 3 (DHA, EPA) and n- 6 (AA) PUFAs – literally fish constituting a major part of the diet of our ancestors. In this regard, a large quantum of evidence has been brought forward to show that *Homo sapiens* evolved not in a savannah habitat but in a habitat that was rich in fish and shellfish resources (Crawford *et al*., 1999). More and more medical studies are emerging on the positive aspects of fish in a healthy diet, physical growth and general well-being. Currently, it is well documented that deficiencies of some of these PUFAs are associated with major health risks (Stansby, 1990; Ulbricht and Southgate, 1991; de Deckere *et al*., 1998) and some diseases and clinical conditions can be alleviated by supplementing with PUFAs (Hunter and Roberts, 2000). As a result of this increasing awareness of the importance of fatty acids in the human diet, there has been a general growth in fish consumption in most societies, particularly in the developed world. On the other hand, fish provide an affordable and often fresh and unique source of animal protein to many rural communities in developing countries.

Of all current animal protein food sources for humans, only fish is predominantly harvested from wild origins as opposed to others which are of farmed origin. Overall, there have been significant changes in global fish production and consumption patterns (Delgado *et al*., 2003) with a major shift in dominance over a 25-year period towards developing countries and China. This changing scenario is accompanied by one in which supplies from capture fisheries are gradually being superseded by farmed and/or cultured supplies, accounting for close to 50 percent of present global fish food consumption (Figure 1, FAO, 2008b).

Over the last decade or so, especially among the public, climate change, its impacts and consequences have been used rather indiscriminately and loosely. Climate change, defined and interpreted variously, but supported by rigorous and robust scientific data and analyses, is accepted as a reality even though it is still refuted by a few (e.g. Lomborg, 2001). As a result, it is commonly agreed that our lives will be impacted in many ways by climate change and one of the primary ways will be food production and the associated environments (IPCC, 2007). In the present synthesis, the definition[1]

[1] "Climate change refers to a change in the state of climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity".

provided by the IPCC is adopted (IPCC, 2007). Equally, how the global community collectively mitigates the causative factors of climate change and adapts measures to confront it, will determine the degree of impact on the various sectors in the ensuing decades and perhaps centuries. However, this synthesis deals mainly with adaptation measures to confront climate change.

It is also important to point out that considerations on climate change and food fish production, apart from a few dedicated studies on the subject (see Section 4), has thus far received only scant attention, especially in comparison to all other primary production sectors. Fisheries *per se* have been referred to only once in the Synthesis Report of the IPCC (2007), which suggests that in relation to the meridional overturning circulation in the Atlantic Ocean there are likely to be changes in ecosystem productivity and fisheries.

The most notable and significant changes associated with climate change are the gradual rise of global mean temperatures (e.g. Zwiers and Weaver, 2000) and a gradual increase in atmospheric green house gases (Brook, Sowers and Orchardo, 1996), both of which have been aptly synthesized and documented (IPCC, 2007). Our planet has experienced more floods (in 1960 approximately 7×10^6 persons were affected but today the figure is 150×10^6, annually), more hurricanes and irregular monsoons than in previous decades. The debate and controversies, however, lie with the degree of change of the main elements such as global temperature, sea level rise and the extent of precipitation that result in the changes we experience. Global warming and sea level rise will occur but to what degree will these changes take place in the coming decades? There is agreement that our planet will heat up by 1.1 °C this century and if green house gases continue rising at the current rate, it will result in a 3 °C rise in temperature. Earth's average temperature is around 15 °C, and whether we allow it to rise by a single degree or 3 °C will decide the fate of thousands of species and perhaps billions of people (Flannery, 2005; Kerr, 2006).

Food fish production, as is the case in all other primary production sectors, is expected to be influenced and or impacted to varying degrees by climate change and the manifestations thereof are expected to occur in varying forms and to varying degrees in different parts of the world. However, unlike other animal food production sectors, food fish production is divisible into two subsectors: capture fisheries which overly depend on naturally recruited and occurring wild populations, the great bulk (approximately 85 to 90 percent) of which are in the oceans; and the cultured or farmed food fish subsector, that is growing in relative importance and is popularly referred to as "aquaculture".

This synthesis attempts to deal with the potential impacts of climatic change on aquaculture only. In order to achieve this objective, the status of this subsector in relation to the total food fish supply, the recent changes therein and other related aspects are analysed with a view to addressing issues and potential adaptations and mitigation. As very limited primary data were available to the authors, modelling of any suggested changes and or impacts were not attempted in this synthesis.

2. FOOD FISH PRODUCTION AND NEEDS

A synthesis on climate change and its impacts on fish production has to consider the potential needs of food fish for human consumption and the amounts available for reduction processes such as fishmeal and fish oil. These products are used in the manufacture of feeds for domesticated animals and form the basis of a significant proportion of feeds for cultured aquatic organisms, in particular shrimp and carnivorous finfish and to a lesser extent the intensive culture of omnivorous species such as tilapias and carps, especially in relation to the production volumes of these commodities.

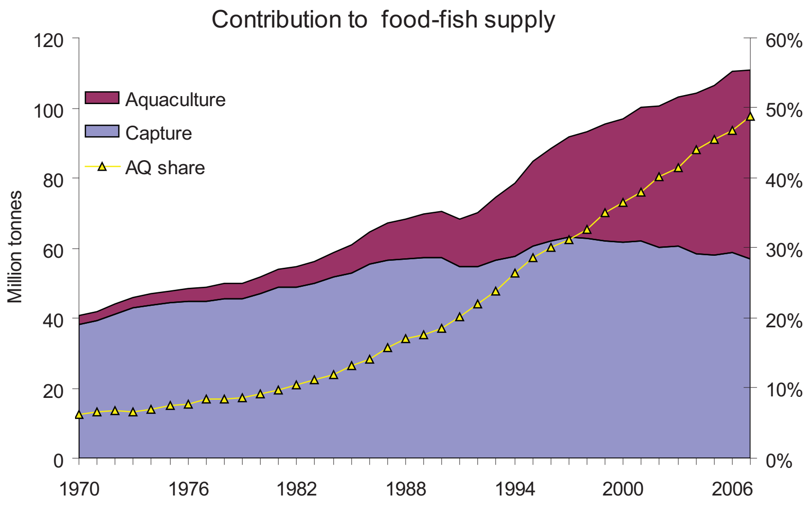
2.1 Food fish needs

Cultured food fish supplies currently account for nearly 50 percent of that consumed globally (FAO, 2009) and are targeted to increase to 60 percent by 2020 (FAO, 2008; Figure 1).

The contribution of cultured components to the global fish supply has increased significantly over the last ten year period to reach 47 percent in 2006 (Figure 2). Within that, fresh water production reached 30 percent.

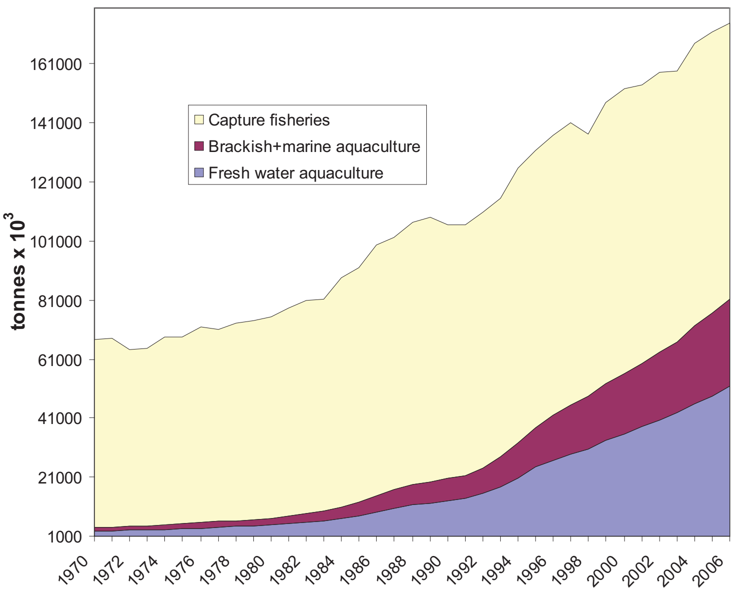
Considering that the capture fisheries component of fish supply has almost reached a saturation level of approximately 100 million tonnes per year, and that nearly 25 percent

FIGURE 1
Food fish contribution from aquaculture and capture fisheries and percentage contribution from aquaculture from FAO Fishstat, FAO (2008a) and Food Outlook



Source: FAO, 2008b.

FIGURE 2
The total global fish production and the contribution from capture fisheries and aquaculture (fresh water and brackish + marine), years 1975 to 2006



Source: FAO FishStat, 2008.

of this is channelled to reduction processing industries and is therefore unavailable for direct human consumption, (Jackson, 2006; Hassan *et al.*, 2007), it is unlikely that there will be any further increases to the human food basket from capture fisheries, perhaps with the exception of potential developments in the inland fisheries sector in the tropics which appears to be gaining some momentum. This means that growing food fish needs for human consumption, as a consequence of population increase and increasing per capita consumption among certain sectors (driven by the health benefits of consuming fish) will have to be provided primarily through aquaculture.

Numerous predictions have been made about food fish supplies for the future and these have been aptly summarized (Siriwardene, 2007, personal communication) in Tables 1 and 2. In all instances it is clear that there has been a significant increase in the demand for food fish in the ensuing years, this demand being variable between continents and related to population growth predictions.

TABLE 1
Projections on food fish demands in relation to population growth predictions

Continent	Population (x 10^3)		Fish supply (2001)		Demand by 2020 (tonnes)[d]
	2005[a]	2020[a]	Total (tonnes)[b]	Per capita (kg)[c]	
Africa	905 936	1 228 276	7 066 301	7.8	9 580 553
Asia	2 589 571	3 129 852	36 512 951	14.1	44 130 913
China	1 315 844	1 423 939	33 685 606	25.6	36 452 606
Europe	728 389	714 959	14 422 102	19.8	14 156 838
Latin America and Caribbean	561 346	666 955	4 939 845	18.8	5 869 204
North America	330 608	375 000	5 719 518	17.3	6 487 500
Oceania	33 056	38 909	760 288	23.0	894 907
World	6 464 750	7 577 889	105 375 425	16.3	123 519 591

a- UN; b- 2005 population x 2001 per capita supply; c- FAO; d- 2020 population x 2001 per capita supply.
Source: modified after Siriwardene, P.P.G.S, personal communication.

TABLE 2
Projected global food fish demands

Forecasts	Needs		Estimated needs from aquaculture (x10^6 tonnes)	
	Per capita consumption (kg/yr)	Total demand (x10^6 tonnes)	Considering fisheries as:	
			Growing (0.7%)	Stagnating
Baseline[a]	17.1	130	53.6 (1.8%)	68.6 (3.5%)
Lowest	14.2	108	41.2 (0.4%)	48.6 (1.4%)
Highest	19.0	145	69.5 (3.2%)	83.6 (4.6%)
2010[b]	17.8	121	51.1 (3.4%)	59.7 (5.3%)
2050	30.4	271	177.9 (3.2)	209.5 (3.6%)
1999[c]	15.6	127	45.5 (0.6%)	65.1 (2.0%)
2030	22.5	183	102.0 (3.5%)	121.6 (4.2%)

a- Delgado *et al*. (2003), to 2020; b- Wijkström, 2003.
Source: modified after Brugère and Ridler, 2004.

TABLE 3
Projected demand for aquaculture production, 2020

Continent	Food fish demand 2020 (t)	Aquaculture production 2003 (t)[a]	Aquaculture demand 2020 (t)[b]	Needed change (%)
Africa	9 580 553	520 806	3 035 058	482.8
Asia	44 130 913	8 686 136	16 304 098	87.8
China	36 452 838	28 892 005	31 659 237	9.6
Europe	14 156 188	2 203 747	1 937 833	-12.1
Latin America and Caribbean	5 869 204	1 001 588	1 930 947	92.8
North America	6 487 500	874 618	1 642 600	87.8
Oceania	894 907	125 241	259 860	107.5
World	123 519 591	42 304 141	60 448 307	42.9

a- FAO Stats; b- 2020 fish demand minus estimated current fisheries production.
Source: modified after Siriwardene, P.P.G.S, personal communication.

The demand for aquaculture to provide increasing food fish needs is estimated to be around 60 million tonnes, a nearly 43 percent increase on production in 2003. The projected breakdown, continent by continent, is presented in Table 3. If food fish demands are to be satisfied by 2020 an increase in aquaculture production needs to occur on all continents with the exception of Europe, to varying degrees. The above is one scenario that has to be considered in evaluating the impacts of climate change on aquaculture.

2.2 Food fish production: changing scenarios

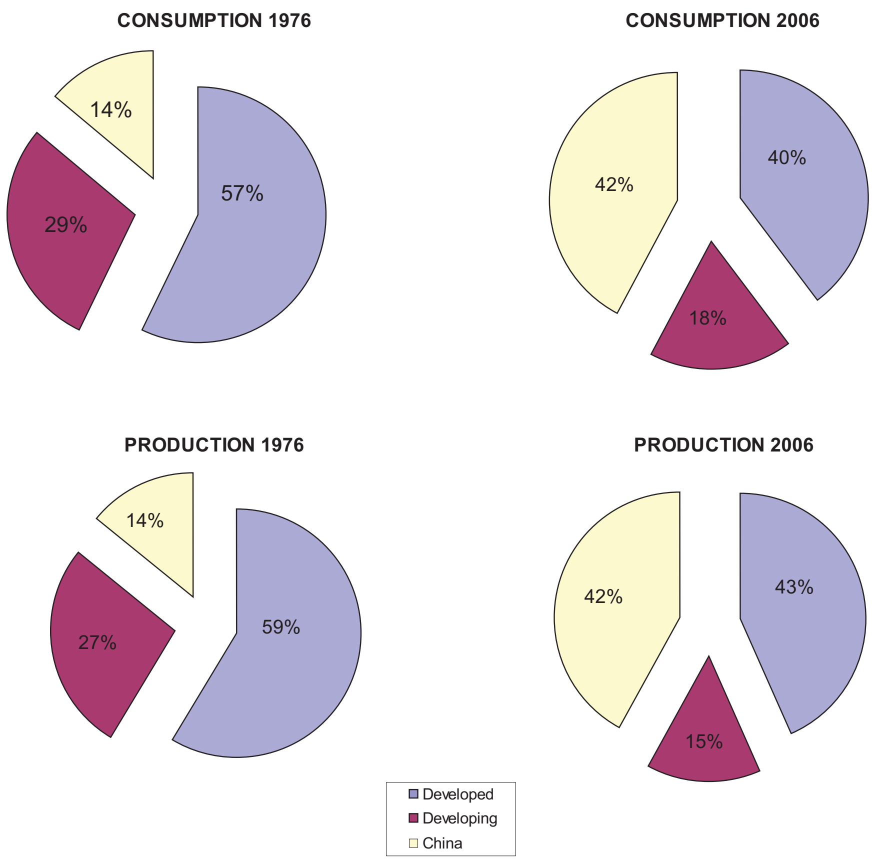
Figure 3 illustrates the major changes that have occurred in global food fish supplies and availability and consumption patters over the past three decades.

The gradual increase in the role of aquaculture in the global food fish supply (Figure 1) and particularly the inland sector (Figure 2), contrasts with capture fisheries stagnation, where nearly 85 to 90 percent of supply comes from marine stocks. However, these are gross details and do not essentially reflect those that are required to investigate and or evaluate the major impacts of climate change on human food supplies and/or aquaculture.

2.3 Food security and fish

The accepted definition of food security is: "food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet

FIGURE 3
Changes in the global food fish production and consumption patterns for developed countries, developing countries excluding China, and China



Source: for consumption values: Laurenti, 2007 and production values: FAO FishStat, 2008.

their dietary needs and food preferences for an active and healthy life" (FAO, 2003). Food security, according to Sen (1981) may be achieved directly and or indirectly through:

- production-based entitlements – producing food for self;
- trade-based entitlements – selling/bartering goods or other assets;
- labour-based entitlements – selling own labour;
- transfer-based entitlements – receiving gifts or transfers of food.

Food security is a universal human right. Issues related to food security have been the subject of much debate and resulting in acceptance of general principles by the world at large. These were aptly summarized by Kurien (2005).

The accepted recommended minimal daily calorie intake for a healthy life is 1 800 which has been increased to 2 100 per day by the United States Department of Agriculture (USDA), Economic Research Service[2]. Worldwide, it is estimated that there are one billion undernourished people in 70 lower income countries. It is also important to note that the great majority of such people live in rural areas. Over the last two decades the number of hungry people in Asia has recorded a decline. Fish food does not necessarily significantly contribute to daily calorie intake but at present it contributes an estimated 20 percent to animal protein intake and significantly more than that in the developing world. Fish food also provides essential micro nutrients in the form of vitamins, minerals (e.g. best sources of iodine and selenium) and some co-enzymes (Q 10), among others.

In general, consumption of fish does not directly account for food security *per se*, primarily because of its low calorie content. However, fish production, capture fisheries and aquaculture contribute significantly to food security through livelihoods and by ensuing income generation. It is estimated that 35 million people are directly employed in the fisheries sector, approximately 80 percent in fishing and 20 percent in aquaculture (FAO, 2003b). The greater proportions of livelihoods dependent on fisheries are concentrated in developing countries, particularly in Asia. It is also important to note that the sector supports several times the number of those directly employed through households and ancillary support sectors (Williams, 2004). Overall, fish and fish trade are considered to be important sources of direct and indirect food security, although until recently most concerns with regard to fish and food security have tended to focus on the direct dimension of fish on consumption (Kurien, 2005). This author further emphasized that in 10 out of 11 developing countries the top foreign exchange earner was fish, indicating its importance in ensuring food security at the aggregate level. It is also becoming increasingly apparent that aquaculture is bypassing the capture fisheries sector in production, currently contributing nearly 45 percent to total fisheries in Asia and nearing 70 percent in countries such as the People's Republic of China. This gain in the relative importance of the aquaculture sector will be indirectly reflected in the associated trade and therefore its relative importance in contributing to food security.

"Fish workers" is a common term used to categorize workers who perform post harvest services in any fishery economy and essentially include those involved in sorting, packing and transporting fish; those involved in various processing activities that enhance the shelf life of fish and in value adding; and those engaged in the supply of fish to exporters, processors, wholesale and retail markets or directly to consumers. It appears that those involved in the reduction and feed manufacture industries are excluded, traditionally. However, it is known that this sector also provides a considerable number of jobs that contribute to overall food security. In this context, some of the emerging aquaculture commodities that aim for export are reported to provide significant employment opportunities to relatively impoverished

[2] www.ers.usda.gov/Briefing/GlobalFoodSecurity/

BOX 1

In most Asian aquaculture, and in Latin America, the processing sector is dominated by female employees. This empowers women in rural households and in addition to contributing to food security may contribute to household harmony and wellbeing, a factor that has that has hardly been taken into account in traditional analyses of aquaculture. Photos depict women in the aquaculture processing sector in Viet Nam (shrimp) and Myanmar (rohu).

rural communities. Examples are catfish (*Pangasianodon hypophthalmus*) and rohu (*Labeo rohita*) aquaculture in Viet Nam and Myanmar, respectively. In Myanmar, in order to service the growing export market of rohu (Aye *et al*., 2007) which currently amounts to about US$70 million (equivalent to 60 000 tonnes of 1 to 2 kg rohu), 80 processing plants have been established. On average, eight labour units are required for processing one tonne of rohu, thereby equating to year round employment for nearly 1 300 to 1 400 people in this processing sector. Vinh Hoan Corporation, one of the largest processors of catfish in the Mekong Delta employs 2 500 people, 80 percent of whom are women,[3] working in three shifts, to enable the processing of 200 tonnes per day, yielding approximately 80 tonnes of processed product for export (Vinh Hoan Corporation, undated). On the above basis, the catfish sector in the Mekong Delta that produced 1.2 million tonnes in 2007, almost all of which were processed and exported, would have provided year round employment for 40 000 to 45 000 people, which is very significant direct employment from the subsector within a geographical area. Undoubtedly, such a high degree of employment would have a significant impact on food security in that region.

In the case of high valued cultured commodities such as salmon and shrimp (and increasingly tilapia), the bulk of production is processed for export. As such, even though the overall energy cost is significantly higher, high value products provide a considerable number of livelihood opportunities and thereby contribute to overall food security. For example, in Thailand, the leading global cultured shrimp producing nation (375 320 tonnes valued at US$1 196 billion in 2005), only 30 percent is consumed as fresh, the rest being processed fresh chilled and frozen (37 percent) and/or canned (29 percent) (Fishery Information Technology Centre, 2006). Here again, the aquaculture sector provides considerable livelihood opportunities and contributes to food security. Another example is that of salmon farming in Chile. Salmon was the third largest export commodity in Chile with a value of US$2.2 billion in 2007. That year the industry provided employment to approximately 53 000, thereby impacting very strongly on the growth of local economies in the rural salmon farming areas. Participation of women, particularly concentrated in the processing plants, is also high

[3] www.vinhoan.com.vn

TABLE 4
Total world population in millions (2000 to 2002), the numbers of undernourished people and the latter expressed as a percent of the total population

Region/subregion	Total population	Undernourished	
		Total	*Percent*
Developing world	4 796.7	814.6	17
Asia-Pacific	3 256.1	519	16
East Asia	1 364.5	151.7	11
Southeast Asia	522.8	65.5	13
South Asia	1 363.3	301.1	22
Latin America and the Caribbean	521.2	52.9	10
Near East & North Africa	399.4	39.2	10
Sub-Saharan Africa	620.0	203.5	33
Countries in transition	409.8	28.3	7

Source: extracted from WFP, undated.

in the salmon industry, accounting for approximately 50 percent of the total in the sector.

Poverty is linked to food security and malnourishment; the poor have a lesser probability of ensuring food security. Malnutrition often leads to disease. The status of malnourishment, by region, is summarized in Table 4.

The level of malnourishment is evident within the Asia-Pacific region, illustrating that poverty in south Asia is considerable. What appears to hold in most of the Asia-Pacific region is the relatively high dependence on fish as the main animal protein source. While malnourishment is highest in sub Saharan Africa, dependence on fish in that region is lower and aquaculture has barely started there. If the aquaculture sector ever develops in a sustainable way, it could provide significant benefits to the region through direct nutrition and social and economic development.

Aquaculture has been growing relatively rapidly over the last 15 years or so in Latin American and Caribbean countries, notably, Brazil, Chile, Ecuador, Honduras and Mexico (Morales and Morales, 2006). Two continents that have the highest growth potential in aquaculture are South America and Africa, whereas in Asia, the growth rate of aquaculture is decreasing (De Silva, 2001). It is probable that developments in aquaculture in the coming decades in South America and Africa will contribute even further to global food security and poverty alleviation. In countries such as Chile, Ecuador and Honduras the cultured commodities require processing and transport (as well as several other associated services) and therefore will indirectly contribute to food security.

3. AQUACULTURE PRODUCTION

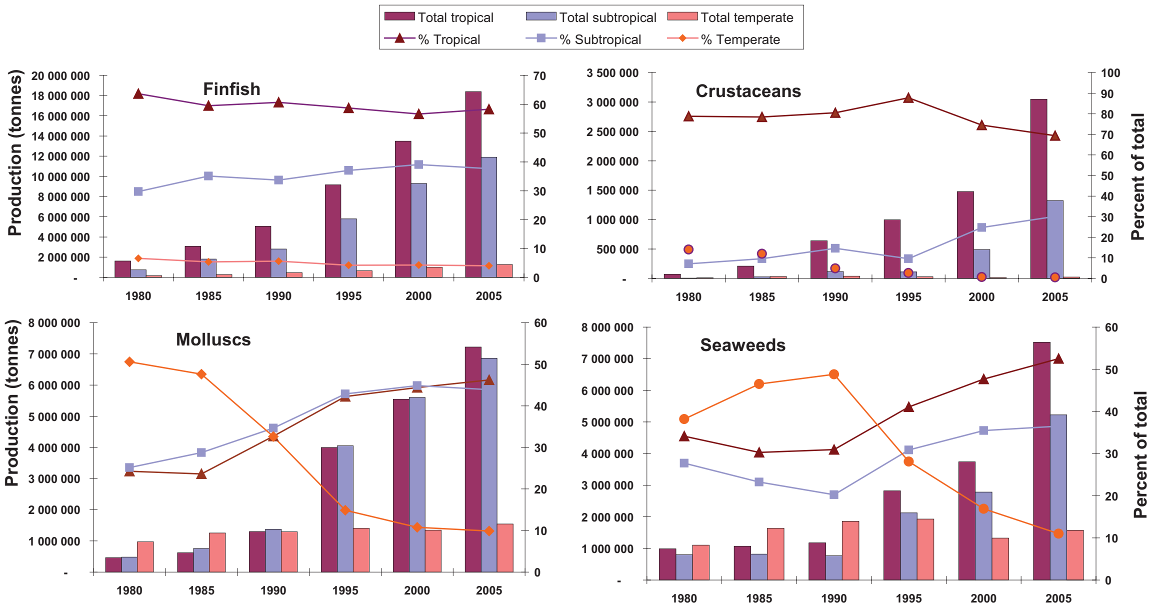
In order to assess potential changes in aquaculture under different climate change scenarios it is important to base the evaluations on the past trends of aquaculture production on the basis of approximate climate regimes *vis-à-vis* tropical, subtropical and temperate regions.

3.1 Climatic distribution of production

To date most analysis of aquaculture production (see for example FAO, 2007, among others) has been based on nations/territories/continents and regions. From a climate change impact point of view, such analyses will be of relatively limited use unless those of individual nations/territories are considered. Accordingly, in this synthesis the trends in aquaculture production, at five year intervals (1980 to 2005), for each of the cultured commodities (vis-à-vis finfish, molluscs, crustaceans, and seaweeds), based on FAO Statistics (FAO, 2008) for three climatic regimes viz. tropical (23°N to 23°S), subtropical (24–40°N and 24–40°S) and temperate (>40°N and >40°S) are considered (Figure 4). Admittedly, this approach is not perfect. For example, aquaculture

FIGURE 4

Aquaculture production of the four major commodities, at five yearly intervals from 1980 to 2005, distributed by climatic zones and the percent contribution from each zone to the total



Source: FAO Statistics, 2008.

production in China (roughly 20 to 42°N and 75 to 130°E) occurs across many degrees of latitude. In this analysis, the assumption was made that 60 percent of aquaculture production in China is considered to be subtropical and the remainder tropical.

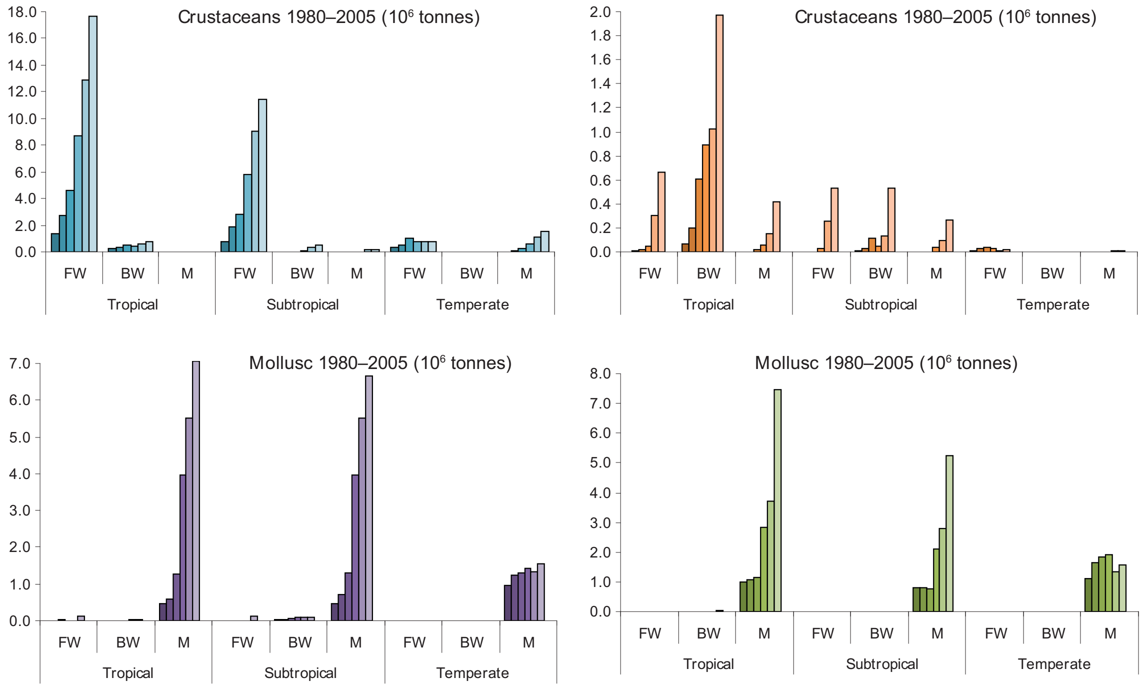
It is evident from the analysis, that all of the major cultured commodity groups are primarily confined to the tropical and subtropical regions of the globe (Figure 4). For three of the four major cultured commodity groups, production in the tropics accounted for more than 50 percent, the highest being for crustaceans which approximated 70 percent. It is also important to note the trend over the last 25 years for molluscs and seaweed culture in temperate regions. The culture of these two groups was dominant in this climatic region until about a decade ago and since then has sunk below the other two regions and currently contributes around 10 percent to the total. This is largely as a result of the high growth rate of aquaculture in tropical and subtropical regions, rather than a reduction in absolute production in the temperate region *per se*.

3.2 Environmental-climatic distribution of aquaculture

Aquaculture is an activity that occurs in three basic environments; fresh water, marine and brackish waters, each of the se environments being distributed throughout the three climatic regimes under consideration. In Figure 5, production of each of the major aquaculture commodities (at five yearly intervals from 1980 to 2005 in 10^6 tonnes) in relation to the climate regime and fresh water, marine and brackish water environments are presented.

It is evident that, apart from molluscs, the culture of all other major commodities occurs predominantly in the tropics, followed by that in the subtropics, and significantly less in the temperate regions. In essence, over the last 25 years, cultured production of all four major commodities in temperate regions, except perhaps finfish, has declined its percent contribution because of the substantial increases in production in the other regions (Figure 5). Also, in all the regions, the total production of finfish far exceeds that of other commodities and this trend is consistent through the years. Finfish culture occurs predominantly in fresh water while crustaceans and mollusc culture occurs

FIGURE 5
Production of each of the major aquaculture commodities (x10⁶ t) in relation to climate zone and habitats (at five yearly intervals from 1980 to 2005)



in brackish and in marine waters, respectively (Figure 5). Here again the production trends are rather consistent over the 25 year period. It is therefore important to notice that climate change impacts, if any, are likely to produce more significant net effects on the fresh water aquaculture subsector in tropical and subtropical regions than elsewhere because production is concentrated there.

3.3 Climatic-national-regional distribution of aquaculture

In order to obtain a view of the importance of the distribution of aquaculture production in relation to climatic regimes (tropical, subtropical, and temperate) by continents, the production of the four major commodities in 2005 in accordance with these two factors was analysed (Figure 6). This clearly shows that production of all four major cultured commodities in the three climatic regimes under consideration occurs predominantly in Asia. The differences in production between Asia and the other continents are extremely large, in excess of 90 percent in all instances. Therefore, adaptive strategies needed to prevent and counteract the potential impacts of climatic change on aquaculture should be initially be targeted at Asian aquaculture.

3.4 Value of aquaculture products

The value of aquaculture commodities produced in the different climatic zones followed a similar trend to that of the overall production of each. The trend in values depicted in Figure 7, shows that in 2005, the value of products from the tropical region was highest, followed by the subtropics and lastly the temperate zone. In the case of the value of cultured molluscs and seaweeds, the differences between the climatic zones were much smaller than for finfish and crustaceans where the value of the respective produce exceeded 50 percent of the total (Figure 7). On the other hand, although in the temperate region finfish accounts for only about four percent of global production, it is worth nearly 11 percent of global total value of finfish production, indicating the predominance of higher valued finfish produced in this climatic region. Therefore,

FIGURE 6
Production (2005) of the four major commodities by climatic zone and region

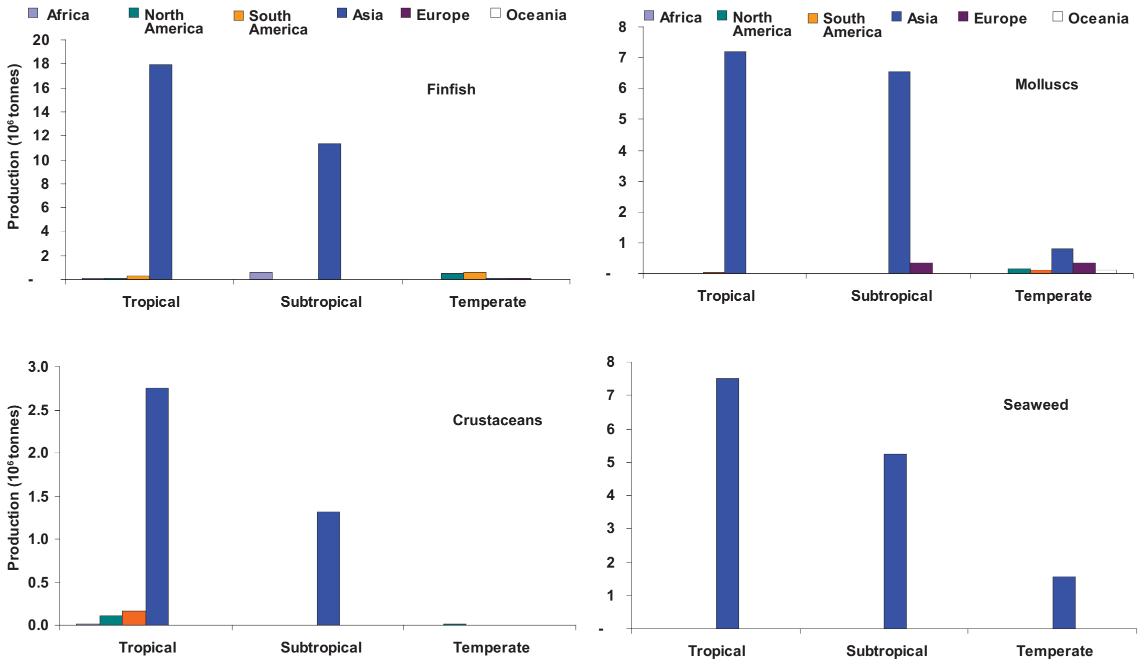
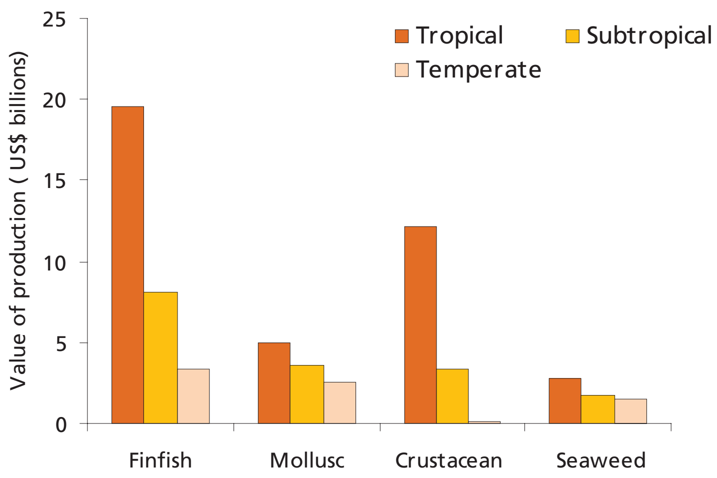


FIGURE 7
Value (in US$ thousands) of aquaculture produce in 2005 for each of the climatic regions



in the temperate zone, changes in production may have a greater potential impact on livelihoods per tonne of fish.

3.5 Growth trends in aquaculture

Aquaculture is often referred as the fastest growing primary production sector in the last three decades, having witnessed an annual rate of growth of nearly 10 percent. However, trends data indicate that the rate of growth is decreasing (Figure 8) and it is generally accepted that aquaculture growth cannot proceed at the same rate in most regions (De Silva, 2001; FAO, 2007). However, it is important to bear these growth trends in mind when considering the impacts that climate change might have on aquaculture and its potential for growth.

FIGURE 8
Line of best fit indicating the average percent change in average percent aquaculture production in five year blocks commencing from 1980 (from De Silva and Hasan, 2007)

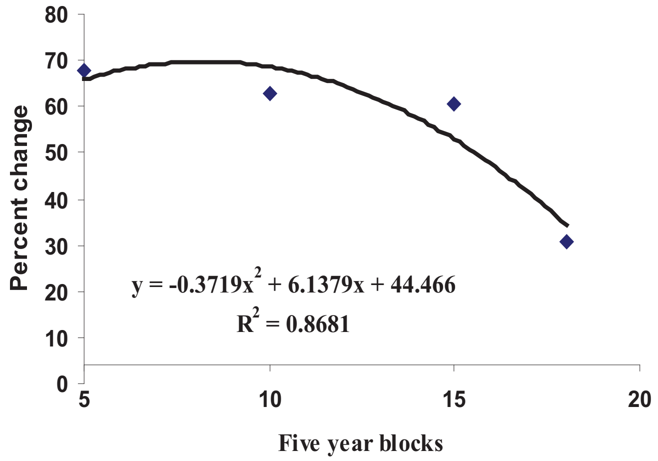


TABLE 5
Estimated relative contribution from capture fisheries and aquaculture to the GDP in some selected Asian countries and Chile, South America (2004–2006)

Country	Capture	Aquaculture
Bangladesh#	1.884	2.688
People's Republic of China#	1.132	2.618
Indonesia#	2.350	1.662
Lao People's Democratic Republic	1.432	5.775
Malaysia#	1.128	0.366
Philippines#	2.184	2.633
Thailand#	2.044	2.071
Viet Nam*	3.702	4.00
Chile**	2.17	2.63

Sources: # Sugiyama, Staples and Funge-Smith, 2004; * Viet NamNet Bridge; ** WWW.SUBPESCA.CL

3.6 Aquaculture and GDP

Kurien (2005) highlighted the increasing relevance of the global fisheries trade, and showed that the contribution of fisheries to the GDP of many developing countries has bypassed that of traditional commodities such as coffee and tea. In 10 out of 11 developing countries fish was the top foreign exchanger earner and very important for ensuring food security at the aggregate level. In Asia, irrespective of climate regimes (Figure 6), the contribution of aquaculture to total fish production has been increasing over the last two decades (Figure 1), a trend that has been observed in many of the current major aquaculture producing countries on that continent (De Silva, 2007).

This trend is being reflected in the GDPs of some of the major aquaculture producing countries in the region and elsewhere, where aquaculture is becoming an increasingly important food fish production sector (Table 5) with positive impacts on food security.

4. BRIEF SYNTHESIS OF PREVIOUS STUDIES ON CLIMATE CHANGE EFFECTS ON AQUACULTURE AND FISHERIES

Apart from a few dedicated studies, fisheries and aquaculture have thus far received only scant attention in the major considerations of climate change induced impacts on food fish production. This is especially so in comparison to all other primary production sectors as well as in relation to other pertinent and important issues such as climatic change influences on biodiversity (IPCC, 2002). However, it is important to note that the first notable attention to climate change issues in relation to fisheries was made almost a decade ago (Wood and McDonald, 1997). In this treatise, climate change influences on fisheries were dealt more from a physiological view point, with treatments on effects of temperature on growth (Jobling, 1997), larval development (Rombough, 1997) and reproductive performance (Van der Kraak and Pankhurst, 1997).

Two policy briefs pertaining to the threat to fisheries and aquaculture dealt with the significance of fisheries and aquaculture to communities depending on these sectors for livelihoods and the need for strategies to adapt to climate change induced effects on these sectors were considered briefly (WFC, 2006). This was followed by a brief in which it was stated that the two sectors could provide opportunities to adapt to climate change through, for example, integrating aquaculture and agriculture and suggested that fisheries management should move away from seeking to maximize yield but to increasing adaptive research (WFC, 2007). Furthermore, the brief called for further research to find innovative ways to improve existing adaptability of fishers and aquaculturists.

Sharp (2003) considered future climate change effects on regional fisheries by examining historical climate changes and evaluating the consequences of climate related dynamics on evolution of species, society and fisheries variability. The author ranked the impacts of climatic changes on regional fisheries and recognized the following fisheries as most responsive to climatic variables (in descending order of sensitivity):

- fresh water fisheries in small rivers and lakes, in regions with larger temperature and precipitation change; fisheries within exclusive economic zones (EEZ), where access–regulation mechanisms artificially reduce the mobility of fishing groups and fleets and their abilities to adjust to fluctuations in stock distribution and abundance;
- fisheries in large lakes and rivers;
- fisheries in estuaries, particularly where there are species *sans* migration or spawn dispersal paths or in estuaries impacted by sea level rise or decreased river flow, and
- high seas fisheries. Furthermore, it was pointed out that large scale production sea fisheries are not under immediate imparted impacts by climate change and those that are most impacted are the ones affected by human interventions such as dams, diminished access to up- or down-river migrations and other issues related to human population growth and habitat manipulation (Sharp, 2003).

Perhaps the most comprehensive study dedicated to aquaculture and climate change was that of Handisyde *et al.* (2006). In that synthesis, the authors dealt with the influence of predicted climate changes such as temperature, precipitation, sea level rise, extreme events, climate variability and ocean currents on global aquaculture. Impacts on aquaculture production, aquaculture dependent livelihoods and indirect influences on it through fishmeal and fish oil availability were also dealt with. An extensive modelling exercise was included and a series of sub models developed that covered exposure to extreme climatic events, adaptive capacity and vulnerability. The study was complemented with a case study on Bangladesh, a country with one of the most extensive deltaic areas in the world and one of the most sensitive ones to sea level rise and to severe weather damage.

A very comprehensive treatise on the influence of climatic change on Canadian aquaculture is also available (2WE Associate Consulting, 2000).

In their review of the physical and ecological impacts of climate change on fisheries and aquaculture, Barrange and Perry indicate that considerable uncertainties and research gaps remain (see Chapter 1, this Section). Of particular concern are the effects of synergistic interactions between current stressors, including fishing and ecosystem resilience and the abilities of marine and aquatic organisms to adapt and evolve according to climatic changes.

Roessig *et al*. (2004) called for increased research on the physiology and ecology of marine and estuarine fishes, particularly in the tropics. Regarding fresh water fisheries, Ficke, Myrick and Hansen (2007) suggested that the general effects of climate change on fresh water systems will occur through increased water temperature, decreased oxygen levels and the increased toxicity of pollutants. In addition, it was concluded that altered hydrological regimes and increased groundwater temperatures would impact on fish communities in lotic systems. In lentic systems eutrophication could be exacerbated and stratification become more pronounced with a consequent impact on food webs and habitat availability and quality. A more specific case study on the recruitment success of cyprinid fish in low lying rivers, in relation to the potential changes induced on the Gulf Stream by climatic change, was dealt with by Nunn *et al.* (2007).

There have been a number of studies on climate change and its impacts on fisheries that could indirectly affect aquaculture, such as a decline in ocean productivity (Schmittner, 2005). At this stage no attempt is made to be exhaustive in reviewing these studies as the most relevant ones are dealt with in Section 5.4. However, here attention is drawn to a few selected examples. Atkinson *et al*. (2004) described a decrease in Antarctic krill density (*Euphausia superba*) and a corresponding increase in salps (mainly *Salpa thompsonii*), one of the main grazers of krill. It is supposed that this trend is likely to be exacerbated by climatic changes, sea temperature increases and a decrease in polar ice. The use of krill as a major protein source for replacement of fishmeal in aquaculture feeds has been advocated (Olsen *et al*., 2006; Suontama *et al*., 2007) but the current trend appears to indicate that this would not be a possibility (De Silva and Turchini, 2008). This situation is complicated by the fact that krill is the major food item of baleen whales and many wild fish species.

5. IMPACTS OF CLIMATE CHANGE ON AQUACULTURE

Impacts of climate change on aquaculture could occur directly and or indirectly and not all facets of climate change will impact on aquaculture. Aquaculture practices, as in any farming practice, are defined in space, time and size and have a fair degree of manoeuvrability. Furthermore, aquaculture production concentrates in certain climatic regions and continents (see Sections 3.1, 3.2, 3.3) with a well defined concentration of the sectoral practices. It may be that these developments, at least in the early stages of the sector's recent history, were driven by cultural attributes, such as of "living with water" and the associated historical trends to farm fish by certain ethnic groups. Yet it must be recognized that aquaculture growth in different regions may in fact change as a result of climatic change particularly in areas and regions where aquaculture in itself can provide adaptation possibilities for other sectors (e.g. coastal agriculture).

5.1 Major climatic changes that would potentially impact on aquaculture

Not all climatic changes are likely to equally impact fisheries and aquaculture, either directly and or indirectly. Also, it is difficult to discern the causative effect of different elements of impacts of climate change on aquaculture and fisheries. Furthermore, the potential impacts on farming activities cannot be attributed to one single factor of climatic change. In most instances it is a chain of confounded effects that become causative and not a single recognizable factor. Those elements of climatic change that are likely to impact on aquaculture, based on the IPCC forecast (2007) can be summarized as follows:

- Global warming: There is agreement that our planet will heat by 1.1 °C this century and the increase could be up to 3 °C.

- Sea level rise: rise in sea level will be associated with global warming. The IPCC has estimated that oceans will rise ten cm to 100 cm over this century; thermal expansion contributing 10 to 43 cm to the rise and melting glaciers contributing 23 cm. Sea level increases will profoundly influence deltaic regions, increase saline water intrusion and bring about major biotic changes.
- Ocean productivity and changes in circulation patterns: major changes in ocean productivity and circulation patterns are predicted; the most impacted being the North Atlantic (Schmittner, 2005) and Indian oceans (Gianni, Saravanan and Chang, 2003; Goswami *et al.*, 2006). These changes will impact on individual fisheries and other planktonic plant and animal group biomasses and result in changes in food webs.
- Changes in monsoons and occurrence of extreme climatic events: frequency of occurrence of extreme climatic events such as floods, changes in monsoonal rain patterns (Goswami *et al.*, 2006) and storminess in general.
- Water stress: IPCC (2007) estimates that by 2020 between 75 and 250 million people in Africa are expected to be under water stress and fresh water availability in Central, South, East and Southeast Asia, particularly in larger river basins is projected to decrease. South America and Europe are better placed.
- Changes in hydrological regimes in inland waters: atmospheric warming is likely to bring about changes that could impact on aquaculture activities in both lentic and lotic waters. For example, eutrophication could be exacerbated and stratification more pronounced and consequently could impact on food webs and habitat availability and quality (Ficke, Myrick and Hansen, 2007), both aspects in turn could have a bearing on aquaculture activities, in particular inland cage and pen aquaculture.

5.2 Facets of aquaculture vulnerability to climate changes

Unlike other farmed animals, all cultured aquatic animal species for human consumption are poikilothermic. Consequently, any increase and/or decrease of the temperature of the habitats would have a significant influence on general metabolism and hence the rate of growth and therefore total production; reproduction; seasonality and even possibly reproductive efficacy (e.g. relative fecundity, number of spawnings (see Wood and McDonald, 1997); increased susceptibility to diseases and even to toxicants (Ficke, Myrick and Hansen, 2007). The lower and upper lethal temperature and the optimal temperature range for fish species differ widely (Table 6). Therefore, climate change induced temperature variations are bound to have an impact on spatial distribution of species specific aquaculture activities.

Furthermore, aquaculture occurs in three widely different environments viz fresh water, marine and brackish water, each suited to particular groups of aquatic species with particular physiological traits. Climate change is likely to bring about significant changes particularly with respect to salinity and temperatures in brackish water habitats and will therefore influence aquaculture production in such environments. In this context, current aquaculture activities could respond to the degree of sea level rise and the influx of brackish water inland by relocating farms or alternately farming more saline tolerant strains. There are interactive effects between temperature and salinity; one influencing the other. Such influences vary widely between cultured aquatic organisms and have to be taken into consideration in developing adaptive measures.

5.3 Direct impacts

The impacts on aquaculture from climate change, as in the fisheries sector, will likely to be both positive and negative arising from direct and indirect impacts on natural resources required for aquaculture; the major issues being water, land, seed, feed and energy.

TABLE 6
Temperature tolerances of selected, cultured species of different climatic distribution

Climatic/temperature guild/Species	Incipient lethal temp. (°C)		Optimal range (°C)
	Lower	Higher	
Tropical			
Redbelly tilapia (*Tilapia zillii*)	7	42	28.8–31.4
Guinean tilapia (*Tilapia guineensis*)	14	34	18–32
Warm water (subtropical)			
European eel (*Anguilla anguilla*)	0	39	22–23
Channel catfish (*Ictalurus punctatus*)	0	40	20–25
Temperate/polar			
Arctic charr (*Salvelinus alpinus*)	0	19.7	6–15
Rainbow trout (*Oncorhynchus mykiss*)	0	27	9–14
Atlantic salmon (*Salmo salar*)	-0.5	25	13–17

Source: modified after Ficke, Myrick and Hansen, 2007.

5.3.1 Known direct impacts to date

To date, there has been only one reported direct impact from human induced climatic change on aquaculture. This relates to a smog cloud generated over Southeast Asia during the 2002 El Niño. Although the phenomenon was not attributed to human activities *per se*, it cut sunlight and heat to the lower atmosphere and the ocean by 10 percent and, some authors suggest, contributed to dinoflagellate blooms that impacted aquaculture in coastal areas, from Indonesia to the Republic of Korea, causing millions of US dollars worth of damage to aquaculture (Swing, 2003).

Major recent climatic disasters with relevant impacts on coastal communities, such as the 2008 cyclone in Myanmar or the repetitive hurricanes in the Caribbean have been connected to climate change but there is no scientific consensus on this.

5.3.2 Potential impacts

In the following sections we attempt to evaluate climate change impacts on different aquaculture practices in different environments and in certain instances in relation to commodities. Whenever possible we also address the most immediate adaptation measures.

5.3.2.1 Global warming and temperature increase associated impacts

Global warming is a major impact of climate change. Increased temperature brings about associated changes in the hydrology and hydrography of water bodies, exacerbates the occurrence of algal blooms and red tides etc., all factors that could have important impacts on aquaculture.

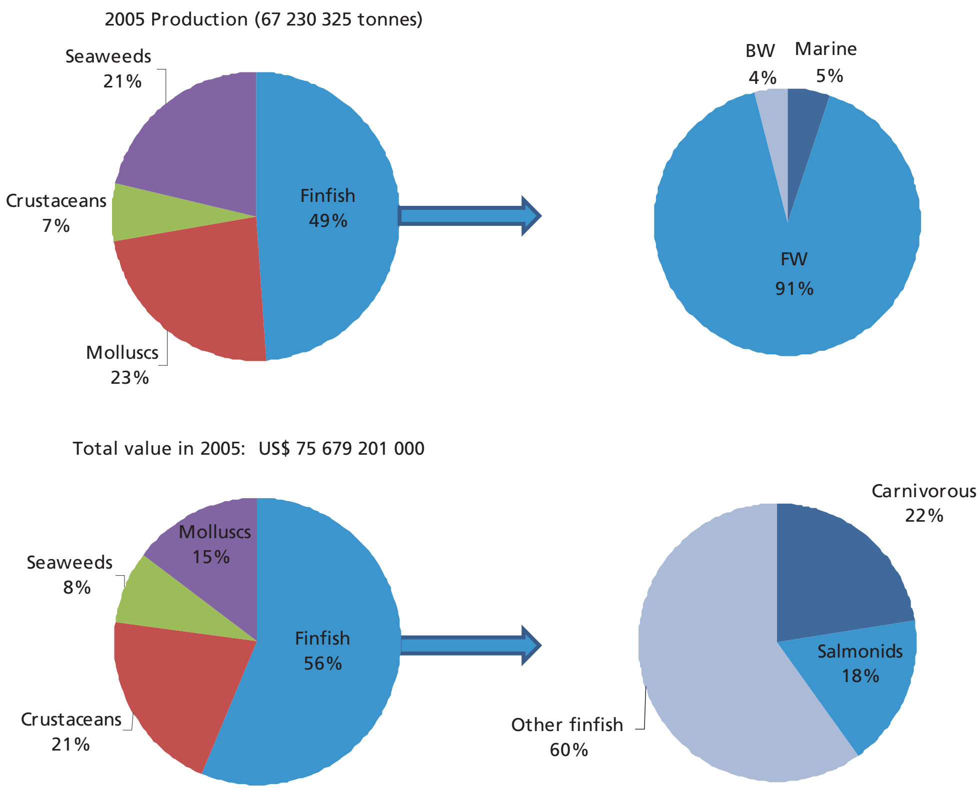
In order to assess this impact on aquaculture and consider appropriate adaptive measures, it is thought best to deal with different major culture systems *vis-à-vis* fresh water and marine environments as separate entities.

Inland aquaculture

Pond aquaculture

The great bulk of aquaculture in the tropical and subtropical regions is finfish culture (Figure 9). The dominant form of inland finfish aquaculture is in ponds, the size of which range from a few hundred square meters to a few hectares. Often the ponds are shallow; the deepest aquaculture ponds in operation being catfish ponds in Viet Nam with an average water depth of 4 to 4.5 m. The main factors that contribute to determining pond water temperature are solar radiation, air temperature, wind

FIGURE 9
Percent contribution to global aquaculture production and value in 2005 commodity wise, together with the finfish production in relation to environment (FW - fresh water, BW - brackish water; M - marine) and habitat type



Source: Based on FAO statistics (FAO, 2008).

velocity, humidity, water turbidity and pond morphometry. The predicted increase in air temperature will cause an increase in vaporization and cloud cover (IPCC, 2007) and thereby reduce solar radiation reaching the ponds. Overall therefore, an increase in global air temperature may not directly be reflected in corresponding increases in inland aquaculture ponds. This suggests there may be no need to plan species changes or the *modus operandi* of the current aquaculture practices, particularly in the tropics and sub tropics.

However, the scenario may be slightly different in pond aquaculture in temperate regions; such activity on a global scale is small and confined primarily to the salmonid species and to a lesser extent, carps. The most popularly cultured salmonids in fresh water are rainbow (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*); these have a very narrow optimal range of temperature and a relatively low upper lethal limit (Table 6). These species are also cultured in tropical highland areas, albeit to a smaller extent, but provide livelihood means for poor farming communities. The air temperature increase could be reflected in temperature increases in aquaculture ponds impacting productivity and in extreme cases, causing mortality (see following section on cage culture for more details). In most cases the culture practices for trout and salmonids occur in high water exchange ponds or in raceways with a free flow of water, literally 24 hours a day through the culture cycle (see Section 5.3.2.4 for details). Such water exchange may soften the potential impact on increased temperatures. However, the availability of water becomes an issue for these systems when climate-change-driven droughts take place, as is already happening where glaciers are retreating in some areas on the Andes in South America.

Integrated aquaculture

Integrated aquaculture is a very old practice that may take many forms: rice *cum* fish culture and/or aquaculture integration with animal husbandry. All these forms are very traditional practices, conducted on small-scale, often single unit family operations.

Integrated aquaculture is still relatively popular in rural China and is also practiced in other tropical Asian countries and a few temperate regions in eastern Europe. The exact production level of fish and other commodities from such practices is not accurately known, but suffice to say they are important to rural communities where aquaculture is practiced often as the sole livelihood (Miao, in press).

In general, the fish species cultured are those feeding low in the trophic chain and more often than not external feeds are not provided; stock fending for itself on the natural production of phyto- and zoo-plankton and the benthos. Consequently, these practices essentially act as carbon sinks. Feare (2006) suggested that integrated poultry/duck aquaculture could spread the avian influenza virus, especially in view of the fact that integrated aquaculture falls within sectors 3 and 4[4] of the FAO (2004) farm management guidelines for biosecurity. There are increasing concerns that these practices may imperil certification of the aquaculture produce and marketability and there is a need to adopt further precautionary approaches.

Highly pathogenic avian influenza, commonly known as bird flu, is mostly caused by the H5N1 strain of type A virus from the Orthomyxoviridae virus family. It is highly pathogenic i.e., easily spread among both domestic fowl and wild birds. The question is: would climate change impact on integrated fish farming in relation to the spread of the avian influenza virus, with increased risks to human health?

It turns out that the opposite may be true. The potential climatic change impact lies in the fact that an increase in water temperature could occur, albeit to less significant levels than in temperate climates. However, it has been shown that the persistence of H5 and H7 avian influenza viruses are inversely proportional to temperature and salinity of water and that significant interactive affects between the latter parameters exist (Brown *et al*., 2006). Overall therefore, climatic change influences on integrated aquaculture could be minimal, if the fears of these practices impacting on the spread of avian flu viruses disappear or minimize. Perhaps as an adaptive measure these practices, which help carbon sequestration (see Section 6.1.2), should be further popularized and encouraged and developed to meet the food safety standards.

Cage culture

Globally cage aquaculture is becoming an increasingly important facet of aquaculture development and will continue to do so for the foreseeable future (Halwart, Soto and Arthur, 2007). This trend is possibly being driven by:

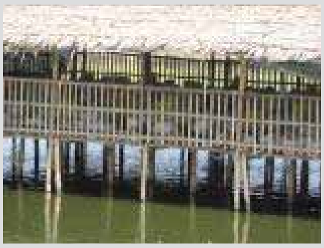
- a realization, in the wake of limitations on land and water availability, of the need to utilize existing inland waters for food fish production (De Silva and Phillips, 2007) and
- in the marine environment to fulfil the increasing demands for higher quality/high valued food fish;
- inland cage culture is also considered an important means of providing alternative livelihoods for people displaced from reservoir impoundment (Abery *et al*., 2005), a situation occurring at the highest rate in Asia (Nguyen and De Silva, 2006).

Inland cage culture practices are very variable in intensity and mode of operation and in the species cultured. However, a large proportion of inland cage culture occurs

[4] Sector 3 – commercial production systems with low to minimum biosecurity and birds/products usually entering live bird markets; birds are in open sheds and may spend time outside the shed; and sector 4 – village or backyard production systems with minimal biosecurity and birds/products consumed locally).

BOX 2

Integrated fish farming is a popular activity which originated in China and has been adopted by many Asian countries as an effective rural food production system. These farming practices are an efficient and effective means of recycling biological wastes, but are encountering important questions about food quality. Photos: integrated fish and poultry and pig farming.



in tropical regions, primarily in reservoirs and lakes, with more traditional and less commercial practices occurring in rivers. Almost as a rule, inland cage culture is confined to low- to mid-value food fish production (De Silva and Phillips, 2007). Unregulated proliferation of cage culture practices in many water bodies in the tropical region has resulted in the regular occurrence of fish kills, disease transmission and consequently lower profits mostly as a result of a high density of cages in a single water body without any consideration of the carrying capacity of the ecosystem (Abery *et al.*, 2005).

Ficke, Myrick and Hansen, (2007) suggested that climatic changes could exacerbate eutrophication and produce more pronounced stratification in lentic systems. Increased eutrophication could result in oxygen depletion in the dawn hours; sudden changes in wind patterns and rainfall could result in upwelling bringing deep/bottom oxygen depleted waters to the surface, with adverse effects on cultured stocks and naturally recruited fish stocks in the water body. Currently in some water bodies, deoxygenation problems caused by upwelling have resulted in restricting cage culture to one crop per year as opposed to two crops per year previously. In the presence of climatic changes it may be that in the tropics cage culture activities would have to be better planned to avoid such effects, otherwise those culture systems will no longer be possible. In this regard, adaptive measures would need to consider an ecosystem perspective with a high degree of conformity between the extent of cage culture practices and the carrying capacity of each water body. The siting of cages should also avoid very shallow areas and limited water circulation zones.

Traditional, river based cage culture occurs in most tropical regions in Asia. Although from a production point of view, the contribution from such practices is thought to be relatively minor; they provide a means of subsistence farming for many of those living in the vicinity of rivers. Often these farms tend to culture relatively low-valued fish for local markets and most of them rely on natural seed supplies (De Silva and Phillips, 2007). Although most aquaculture practices are now independent of wild caught seed resources (a major exception being eels and a few marine carnivorous species), there are still a few artisanal practices in rural areas, particularly by communities living in the vicinity of rivers, where some degree of subsistence cage culture is based on wild caught seed stocks (De Silva and Phillips, 2007). Climatic change could affect breeding patterns of natural populations and could impact on such seed supplies; also reduced water availability in the rivers could indirectly impact on this subsistence aquaculture. Improved farming practices, including more efficient feeding, could be an adaptation required to face the mentioned potential changes.

Mariculture

Mariculture practices involving sand and bottom culture and raft and cage culture, occur inshore and offshore areas in all three climatic regimes viz tropical, subtropical and temperate. The main aquaculture activity in temperate regions is the mariculture of salmonids in cages (Halwart, Soto and Arthur, 2007). Mariculture in tropical and subtropical regions consists of relatively high priced finfish varieties such as groupers (e.g. *Epinephalus* spp., snappers, *Sparus* spp., cobia, *Rachycentron canadum*, etc.). In addition, there are mariculture operations for molluscs such as *Ruditapes* sp., *Mytilus* sp., and seaweeds such as *Gracilaria* sp. (see Figures 4, 5, 6). Seaweeds, oysters and clams constitute the largest proportion of mariculture production worldwide. The culture of these latter groups implies minimal energy consumption and they are essentially carbon sequestering. The main energy costs associated with the culture of these organisms are in the transportation of the product to the consumer. These cultures are carbon friendly to a very high degree and in general, providing they are appropriately located, cause only minor environmental perturbation if any at all. Essentially, recorded perturbations have been associated with changes to the hydrographical conditions in the culture area and with sedimentation of faeces and pseudo-faeces on the bottom.

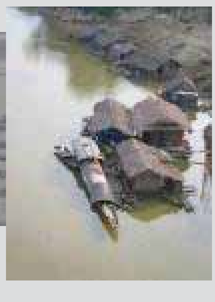
Climate changes and in particular global warming, could both directly and indirectly impact on mariculture in temperate regions. Species cultured in those regions, predominantly salmonids (e.g. *Salmo salar*) and emerging culture of cod, *Gadus morhua*, have a relatively narrow range of temperature optima (See Table 6). The salmon farming sector has already witnessed an increase in water temperature over the recent past and it is acknowledged that temperatures over 17 ºC would be detrimental, when feed intake drops and feed utilization efficacy is reduced. In order to develop possible adaptive measures, research has been initiated on the influence of temperature on feed utilization efficacy and protein and lipid usage for growth as opposed to maintaining bodily functions at elevated temperatures, e.g. 19 ºC.

Some authors have shown that low fat feeds result in better performance at higher temperatures (Bendiksen, Jobling and Arnesen, 2002); therefore there is some room for improvement and adaptation through feeding. Equally, there is the potential for increasing the culture of marine fish species such as cobia (*Rachycentron canadum*),one

BOX 3

Cage culture in inland waters take many forms, often traditional, more subsistence, cage culture practices occur in tropical rivers and more commercial developments in lakes and reservoirs. The latter is often carried out intensively, often exceeding the carrying capacity of the water body and over the years in some instances, fish kills have begun to occur on a regular basis. Climate changes could perhaps exacerbate this situation unless mitigating measures are set in place. The photos show an array of cage culture activities in tropical Asia.





of the fastest growing species with high food conversion efficiency and requiring relatively less protein in its diet than many other cultured marine finfish species. Unlike many other cultured marine species, it is highly fecund and the hatchery production of seed is routinely achieved with a high survival rate of larvae (Benetti *et al.*, 2008).

Sea temperature rise in tropical and subtropical regions would result in increased rate of growth and hence in overall production. The predicted temperature rise itself will be within the optimal ranges for most species cultured in such waters (marine, brackish and/or fresh water) and therefore global warming could impact positively on the bulk of aquaculture production, provided the feed inputs required for compensating the enhanced metabolism are met and that other associated factors, such as disease, do not become more detrimental.

In 2006 the production of marine and brackish water fish reached 4 385 179 tonnes, of which 39 percent were salmonids. Most of that production was based on feed, the major ingredients of which were fishmeal and fish oil. Feed management in salmonid culture is probably the most efficient of all aquaculture practices, however, the high degree of dependence on fishmeal and fish oil becomes a very pertinent issue under most climate change scenarios. The potential impacts of climate change on future availability of these commodities for aquafeeds are dealt with in detail later (see Section 5.4). Feed developments for salmon over the last two decades and more have resulted in a significant reduction of feed conversion factors and in the use of less fishmeal in diets, primarily through the adoption of high energy diets utilising the protein-sparing capabilities of salmonids. In general other marine fish farming operations lag behind in these replacement trends as they do in reducing food conversion rates (FCRs) partly because their industries are relatively younger. The challenge that confronts the sector is to ensure that high energy density feeds are equally effective in an increased temperature *milieu*.

Climate change is predicted to increase global acidification (Hughes *et al.*, 2003; IPCC, 2007). Apart from its impact on coral formation, there is the possibility that increased acidification could impede calcareous shell formation, particularly in molluscs, an effect perhaps exacerbated by increased water temperature and thereby to have an impact on mollusc culture. This has received little attention and warrants urgent research. Currently, mollusc culture accounts for nearly 25 percent of all aquaculture (approximately 15 million tonnes in 2005) and therefore any negative impacts on shell formation could significantly impact on total aquaculture production. There is practically no information on the potential impact of increased water temperature on the physiology of the most relevant aquaculture bivalves. Nevertheless, if coastal plankton productivity is enhanced by higher temperatures and provided that nutrients are available, there may be a positive effect on the farming of filter feeders. However, increased temperatures associated with eutrophication and harmful algal blooms (Peperzak, 2003) could enhance the occurrence of toxic tides and consequently impact production, and also increase the possibilities of human health risks through the consumption of molluscs cultured in such areas. Clearly more research is needed to provide better forecasts of expected net effects.

5.3.2.2 Saline water intrusion

In addition to estuarine shrimp farming activities in Asia, South America and the Caribbean, in tropical regions of Asia significant aquaculture activities occur in deltaic areas of major rivers in areas at the middle to upper levels of the tidal ranges. Most notable among these are the relatively-recently-emerged catfish culture (*Pangasianodon hypophthalmus*) and rohu (*Labeo rohita*) in the Mekong, Viet Nam (Nguyen and Hoang, 2007) and the Irrawaddy in Myanmar (Aye *et al.*, 2007), respectively.

The former two aquaculture operations have exploded in the last decade, accounting for production of 1.2 and 100 million tonnes respectively, generating considerable

BOX 4

Catfish and rohu culture of the Mekong Delta and Irrawaddy region in Viet Nam and Myanmar respectively are aquaculture practices that have witnessed the highest growth ever. The regions in which these activities occur can be impacted by saline water intrusion from predicted sea level rise. The species intensively cultured at very high stocking densities and with high levels of feeding, are fresh water species with relatively low salinity tolerance. As such culture areas must be shifted further upstream to mitigate climatic change effects. On the other hand, climate impacts could make extra pond space available for shrimp farming, providing adequate links in the supply chains. The pictures depict catfish farming activities in the Mekong Delta.

foreign exchange earnings and providing additional livelihoods to rural communities. The brackish water of most deltaic areas in tropical regions in Asia are also major shrimp culture areas.

More importantly, both fish and shrimp culture practices are still in a growth phase and almost all the produce is processed and exported. The consequence of this is that a large number of additional employment opportunities are created with a profound impact on the socio-economic status of the community at large.

Sea level rise over the next decades will increase salinity intrusion further upstream of rivers and consequently impact on fresh water culture practices. Adaptive measures would involve moving aquaculture practices further upstream, developing or shifting to more salinity tolerant strains of these species and/or to farming a saline tolerant species. Such shifts are going to be costly and will also impact on the socio-economic status of the communities involved. Most significantly, adaptive measures could result in a large number of abandoned ponds, reflecting what happened with shrimp farms a decade ago. On the positive side for aquaculture, salinity intrusions that render areas unsuitable for agriculture, particularly for traditional rice farming, could provide additional areas for shrimp farming. Shrimp is a much more highly valued commodity than many agriculture products and has greater market potential but it also has higher management risks. If these shifts are to be made, major changes in the supply chains have to be adopted and nations should build these needs into their planning and forecasting. Sea level rise and saline water intrusion will also impose ecological and habitat changes, including mangroves that act as nursery grounds for many euryhaline species. Although in general terms, most aquaculture practices presently rely only to a small extent on naturally available seed supplies (a notable exception being fresh water eel (*Anguilla* spp.), the need for continued monitoring of such changes is paramount to developing adaptive measures.

Specific predictions from sea level rise are available for the Mekong Delta, Viet Nam. The Mekong Delta is literally Viet Nam's food basket, accounting for 46 percent of the nation's agricultural production and 80 percent of rice exports (How, 2008). A one metre sea level rise is predicted to inundate 15 to 20 000 km^2, with a loss of 76 percent of arable land. The Mekong Delta is already the home of a thriving aquaculture development and the loss of arable land may present a clear instance where alternative livelihoods through aquaculture should be explored.

5.3.2.3 Changes in monsoonal patterns and occurrence of extreme climatic events
The frequency of extreme weather events such as typhoons, hurricanes and unusual floods has increased dramatically over the last five decades. The number of such events increased from 13 between 1950 and 1960 to 72 from 1990 to 2000 (IPCC, 2007). These extreme events result in huge economic losses. For the above two decades the average economic losses have been estimated at between US$4 and US$38 billion (fixed dollars) and in some individual years as high as US$58 billion (IPCC, 2007). Extreme climatic events are predicted to occur mostly in the tropical and subtropical regions. In past events the damages to aquaculture were not estimated.

El Niño and La Niña events also produce extreme weather in temperate regions. For example, during El Niño 1994 to 95 very large storms in southern Chile damaged the salmon industry significantly and resulted in a large number of escapes from sea cages (Soto, Jara and Moreno, 2001). El Niño is also known to induce ecological effects on terrestrial ecosystems with consequent effects on land and sea vegetation and fauna (Jaksic, 2001). An El Niño event also increases the severity of winter storms in North America which may hamper development of offshore aquaculture. With the prediction that climatic change is likely to increase, the frequency of these phenomena could have a significant impact on coastal and offshore aquaculture in temperate regions, in addition to those impacts that are related to fishmeal and fish oil supplies (see Section 5.4.1).

Extreme weather has the potential to impact aquaculture activities in tropical and subtropical regions in Asia and elsewhere. Potential impacts could range from physical destruction of aquaculture facilities, loss of stock and spread of disease. Recent extreme climatic events, unusually cold temperatures and snow storms that occurred in southern China, provide an example of the extent of impacts on aquaculture of such climate induced changes (it is not suggested that the recent events are a cause of global climatic change, however). Similarly, central Viet Nam experienced the worst flood in 50 years in 2007 and the damage to aquaculture is yet to be estimated (Nguyen, 2008).

Preliminary estimates suggest that in central China there was a loss of nearly 0.5 million tonnes of cultured finfish stocks, mostly warm water species and mostly alien species, e.g. tilapia, of which a considerable proportion was broodstock (W. Miao, personal communication). The possible environmental perturbations that escapees, in particular cultured exotic/alien species would cause are yet to be determined.

Asian inland aquaculture is dependent on alien species to a significant extent (De Silva *et al*., 2006). Although escape from aquaculture installations is almost unavoidable under normal circumstances and remains a persistent problem (Anonymous, 2007), the possibilities of large numbers of cultured stock entering natural waterways, because of the destructive effects of extreme climatic events, are far greater. Such large scale unintentional releases have a greater probability of causing environmental disturbances and the potential for impacting biodiversity becomes considerably higher. In addition, there are direct financial losses and damage to infrastructure of the aquaculture facilities.

It is, however, almost impossible to take adaptive measures to avoid such potential events, except perhaps a reduction on the dependence on alien species that would thereby limit damage to immediate financial losses only (lost stock). Yet this is not a perfect solution because escapes of native species can be a problem when they affect the genetic diversity of native stocks, as has been well documented for Atlantic salmon (Thorstad *et al*., 2008); extreme weather events are cited as the most frequent causative factor for such escapes. However, the effect of escapes of other native farmed species has been largely neglected worldwide.

Climate change in some regions of the world is likely to bring about severe weather (storms), water quality changes (e.g. from plankton blooms) and possibly increased pollutants and other damaging run off from land based sources caused by flooding, impacting on coastal areas. Such weather conditions will increase the vulnerability of sea based aquaculture, particularly cage aquaculture, the predominant form of marine aquaculture of finfish and seaweed farming in coastal bays in Asia, which is gradually becoming the major contributor to cultured seaweed production globally (see Figure 7). There is an increased vulnerability of near-shore land based coastal aquaculture, of all forms, to severe weather, erosion and storm surges, leading to structural damage, escapes and loss of livelihoods of aquaculture farmers. Some of the most sensitive areas will be the large coastal deltas of Asia which contain many thousands of aquaculture farms and farmers, primarily culturing shrimp and finfish. Downstream delta ecosystems are also likely to be some of the most sensitive because of upstream changes in water availability and discharge, leading to shifts in water quality and ecosystems in the delta areas. Few adaptive measures are available for such impacts although they are perhaps similar to those suggested for inland aquaculture.

Hurricane seasons in Central America have had impacts on coastal rural aquaculture; such was the case in Nicaragua where shrimp farming flourished from early 1990 until 1998 when Hurricane Mitch devastated many farms and small farmers did not have the capacity to replace production. Other storms which caused heavy damage have been hurricanes Dennis and Emily in Jamaica, hurricane Stan in El Salvador and Guatemala and more recently hurricane Felix which wiped out many rural areas in Nicaragua, some of them with incipient aquaculture activities. In general, most relevant adaptive measures involve evaluation of weather related risks in the location of farms and this is highlighted under "aquaculture zoning" in section 7.2.4.

5.3.2.4 Water stress

Projected water stresses brought about by climate change could have major impacts on aquaculture in tropical regions, particularly in Asia. The predicted stress is thought to result in decreasing water availability in major rivers in Central, South, East and Southeast Asia and in Africa (IPCC, 2007), areas where there are major aquaculture activities. For example, the deltaic areas of some of the major rivers such as the Mekong, the Meghna-Brahamaputra and Irrawardy, are regions of intense aquaculture activity, contributing to export incomes and providing many thousands of livelihoods. Apart from this, prudent use of this primary resource is becoming an increasing concern for sustaining aquaculture.

The amount of water used in food production varies enormously between different sectors. Zimmer and Renault (2003) suggested the need to differentiate between food production sectors, such as, for example, in the main:

- primary products (e.g. cereals, fruits, etc.);
- processed products (e.g. food items produced from primary products);
- transformed products (e.g. animal products because these are produced using primary vegetable products); and
- low- or non-water consumptive products (e.g. seafood).

A comparison of specific water needs for unit production for selected commodities of the animal husbandry sector are given in Table 7. However, apart from pond aquaculture, other practices such as cage culture are

TABLE 7
Specific water demand (m^3/t) for different animal food products* and comparation with needs for aquaculture

Product	Water demand
Beef, mutton, goat meat	13 500
Pig meat	4 600
Poultry	4 100
Milk	790
Butter + fat	18 000
Common carp (intensive/ponds)[a]	21 000
Tilapia (extensive/ponds)[a]	11 500
Pellet fed ponds[b]	30 100

a- Muir,1995: b- Verdegem, *Bosma and Verreth,* 2006.
Source: *data from Zimmer and Renault, 2003.

almost totally non water consuming, directly, except for the need for feeds. In general, reduction of aquaculture water use could be achieved through (a) selection of feed ingredients that need little water to be produced, (b) enhancement of within-aquaculture-system feed production through periphyton based technologies and (c) integration of water with agriculture (Verdegem, Bosma and Verreth, 2006). Some of the above measures are already being used in Asian aquaculture based on finfish species feeding low in the food chain, such as for example, increasing naturally available food sources through appropriate periphyton production in carp polyculture systems (Wahab *et al*., 1999; Van Dam *et al*., 2002).

The predicted reduced water availability in major river systems in the deltaic regions of Asia, where major aquaculture activities exist, has to be considered in conjunction with saline water intrusion arising from sea level rise (Hughes *et al*., 2003) and the expected changes in precipitation or monsoon patterns (Goswami *et al*., 2006).

Along major river systems in tropical Asia there is extensive water extraction and discharge into rivers, particularly from very intensive aquaculture practices such as shrimp and catfish farming. As such, a major modelling attempt incorporating these variables for deltaic regions such as the Mekong, Meghna-Brahamputra in Bangladesh and Irrawardy in Myanmar, among others, will enable to determine more accurately:

- the degree of sea water intrusion in the river and into the adjoining wetlands;
- assessment of agricultural activity that is likely to be lost as a result of sea water intrusion;
- gross changes in habitats (also see Section 5.3.2.1.b). The potential impacts on spawning migrations and therefore the changes in seed availability for subsistence cage farming;
- overall socio-economic impacts of the resulting events.

Such information will allow adaptive actions; for example it would answer the question: would the loss in agricultural activity in these deltaic areas be compensated for by providing alternative livelihoods through aquaculture (mariculture)? This possibility can be considered as a potential non-detrimental impact of climate change on poor rural communities where a more lucrative livelihood could be found. If such an adaptive measure is to be undertaken there is a need for speedy capacity building in aquaculture among the agricultural communities and provision of suitable government support to facilitate the shift from agriculture to aquaculture, including perhaps financial support for infrastructure e.g. ponds, hatcheries and development.

Increasingly, inland culture of salmonids in temperate regions and in highlands, low temperature areas of subtropics and tropics, is tending to adopt a raceway culture, in which the demand for water is extremely high. The likelihood is that water stress will impact on these forms of aquaculture and consequently there needs to be a change in the practices if salmonid aquaculture in raceways is to survive. In upstream areas, because of increased melting of the snow cover, new areas for aquaculture of cold and temperate species may become a possibility.

Non consumptive uses of water in aquaculture, such as cage culture (apart from inputs into feed production) and the use of small lentic waters for culture-based fisheries (CBF) (De Silva, 2003; De Silva, Amarasinghe and Nguyen, 2006) based on naturally produced feed within the water system, are being encouraged. CBF is a community based activity that utilises a common property water resource, is less capital intensive and is known to be most effective in non perennial water bodies that retain water for six to eight months. Climate change in some regions, particularly in Asia and Africa, is predicted to increase drought periods (Goswami *et al*., 2006; IPCC, 2007), resulting in less water retention time in non perennial water bodies. This will make such water bodies relatively unsuitable for aquaculture purposes because a minimum period of six months of water retention is needed for most fish to attain marketable size.

To relieve major constraints or the impacts of potential water stresses dedicated efforts are needed to conserve this primary resource in land based aquaculture, still the most predominant form of inland aquaculture. In this regard recirculation technology is considered a plausible solution. However, the capital outlay and maintenance costs for recirculation technology that is currently available are rather high, so are the required skill levels for routine management (De Ionno *et al.,* 2006). In order to be profitable, the accepted norm is that species cultured in recirculation systems, should command a relatively high market price. This entails the culture of species feeding high in the food chain, which means problems of feed need to be addressed. One of the main goals of adaptive measures to minimize climate change impacts is that they revolve around "energy savings". Energy costs of maintaining recirculation systems are rather high (De Ionno *et al*., 2006) and even if the operations are financially rewarding, they would contribute to green house gas emissions, the primary causative factor for climate change, far more than other traditional aquaculture activities.

Over the last two decades, more often than not, development of offshore mariculture has been advocated as a plausible means of increasing food fish production and doing so with minimal immediate environmental perturbations. Such developments have been impeded by technical and logistical challenges and the capital outlays required (Grøttum and Beveridge, 2008). Needless to say, such developments will also have to encounter the inevitable problem facing most aquaculture that of supplying adequate levels of fishmeal and fish oil in the feeds.

5.4 Indirect impacts of climate change on aquaculture

Indirect impacts on a phenomenon and or a production sector can be subtle, complex and difficult to unravel and the challenges in developing adaptation measures to combat or overcome them may be formidable.

Because fisheries are a major source of inputs for aquaculture, providing feed in particular and seed to some degree, changes in fisheries caused by global climate change will flow through into aquaculture systems. The suitability of different areas for aquaculture species will be particularly important and the availability and prices of resources such as fish protein for fish feed will also be pertinent factors. Handisyde *et al*. (2006) considered two indirect impacts that climate change may have on aquaculture *vis-à-vis* possible influences on price fluctuations of capture fishery produce and impacts on the availability of fishmeal and fish oil. The report dealt with production changes in fishmeal and fish oil and the need to change the extent to which fishmeal and fish oil are utilized in aquaculture but did not elaborate further.

It is also important to point out that a relatively unpredictable scenario is likely to come about with respect to the production of aquafeed. This might be caused by the increasing diversion of some raw plant materials to produce biofuels. This competition could create impacts such as a limited availability and high cost of ingredients for aquafeed. As the production of biofuels and the diversion of raw materials for this purpose are in a somewhat transient stage, with opposing viewpoints being expressed by different stakeholders, it is premature for us to dwell on this in any detail, let alone to predict its impacts on future availability of aquafeed.

5.4.1 Fishmeal and fish oil supplies

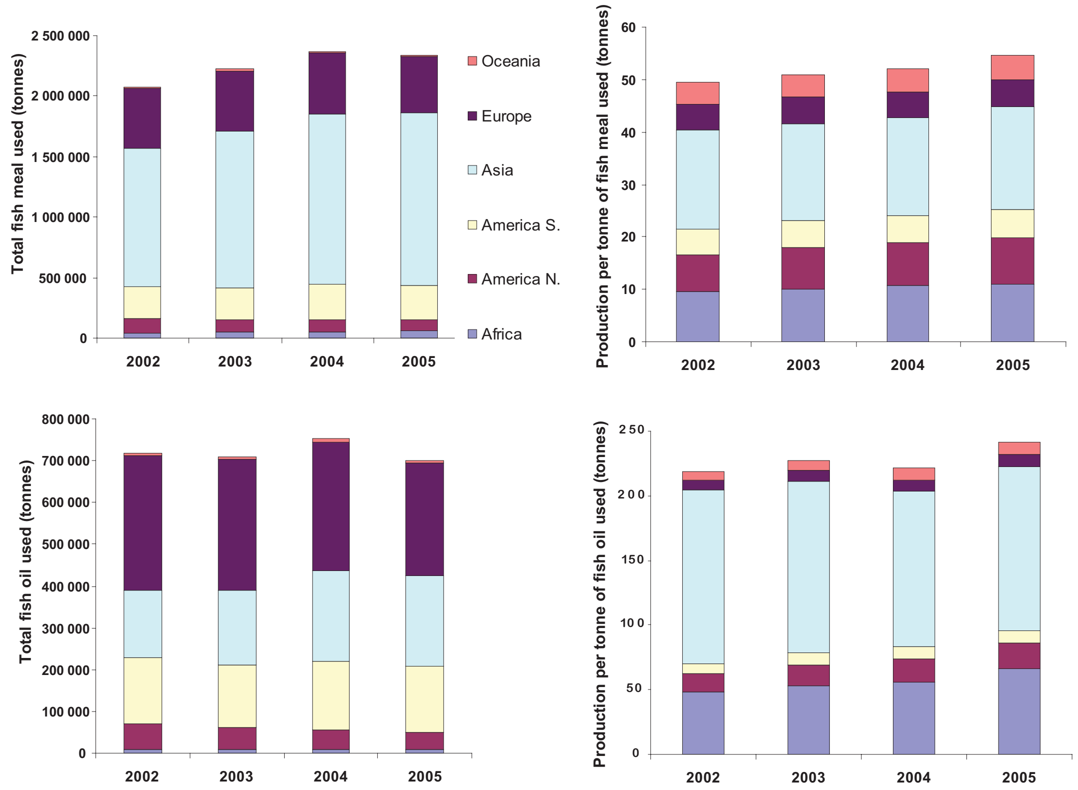
The most obvious and most commonly discussed indirect impact of climate change on aquaculture is related to fishmeal and fish oil supplies and their concurrent usage in aquaculture. Tacon, Hasan and Subasinghe, (2006) estimated that in 2003, the aquaculture sector consumed 2.94 million tonnes of fishmeal globally (53.2 percent of global fishmeal production), considered to be equivalent to the consumption of 14.95 to 18.69 million tonnes of forage fish/trash fish/low valued fish, primarily small pelagics. Globally there has been a significant research effort to combat this burgeoning problem. Studies have been conducted on almost every cultured species to test fishmeal replacement with other readily available and cheaper sources of protein, primarily agricultural by-products. The literature in this regard is voluminous and exhaustive. Unfortunately, however, the transfer of the findings into practice remains relatively narrow and negligible, the only notable exception being the relatively high amounts of soybean and corn meal being used in aquatic feeds. The problems encountered in this transfer, as well as other related issues have been dealt with in detail previously (e.g. Tacon, Hasan and Subasinghe, 2006; Hasan *et al.*, 2007; De Silva, Sim and Turchini, 2008).

Industrial fishmeal and fish oil production is typically based on a few, fast growing, short lived, productive stocks of small pelagic fish in the subtropical and temperate regions. The major stocks that contribute to the reduction industry are the Peruvian anchovy, capelin, sandeel, and sardines. It has been predicted that the biological productivity of the North Atlantic will decrease by 50 percent and ocean productivity worldwide by 20 percent (Schmittner, 2005). Apart from the general loss in productivity and consequently its impact on capture fisheries and hence the raw material available for reduction processes, there are other predicted impacts of climate change on fisheries. It is a possibility that predicted changes in ocean circulation patterns will, result in the occurrence of El Niño type influences being more frequent. The latter, in turn, will influence the stocks of small pelagics (e.g. Peruvian anchovy, *Engraulis ringens),* as has occurred in the past. The influence of El Niño on the Peruvian sardine and anchovy landings and consequently on global fishmeal and fish oil supplies and prices are well documented (Pike and Barlow, 2002). Similarly, the changes in the North Atlantic oscillation winter index (Schmittner, 2003), resulting in higher winter temperatures, could influence sandeel (*Ammodytes* spp.) recruitment. Such changes in productivity of fisheries that cater to the reduction industry will limit the raw material available for reduction and particularly the main fisheries on which fishmeal and fish oil production is based.

Bearing in mind that aquaculture is not evenly spread across the globe, essentially predominating in tropical and subtropical regions, it is appropriate to consider which practices would be impacted most, and how. It is evident from Figure 10 that, although fishmeal usage in aquafeeds is considerably higher in Asia, fish oil usage is higher in Europe. More importantly, the production per unit of fishmeal and fish oil usage is considerably higher on those continents where aquaculture is mostly based on omnivorous fish species which are provided with external feeds containing much less fishmeal and very little fish oil. The latter fact is highlighted when cultured species groups are considered in relation to the return per unit use of fish oil and fishmeal in the feeds (Figure 11). This analysis is based on the amount of fishmeal and fish oil used in the feeds for each group of finfish and crustaceans, the average food conversion rate (FCR) for each and the extent of use of such feeds for each group. The analysis presented indicates that, in the wake of possible climate changes and consequent negative impacts on wild fish populations that cater to the reduction industries, the way forward is to make a concerted effort to increase and further develop omnivorous and filter feeding finfish aquaculture in the tropics and subtropics.

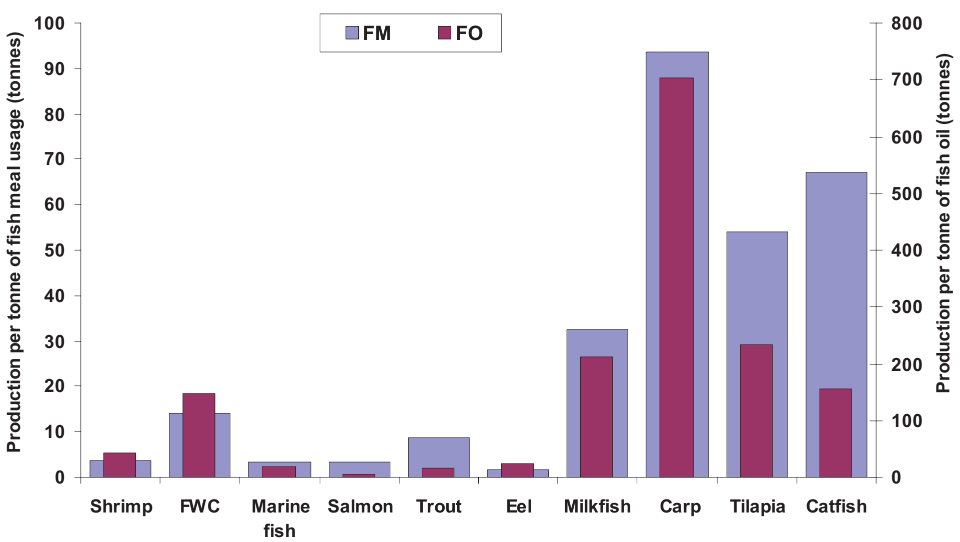
This suggestion has been made many times, by several authors (Naylor *et al.*, 1998; 2000, among others). Such an adaptation would require profound changes in consumer and market demands. Bringing the attention of the public to this issue transforms it into an ethical debate. Bearing in mind that many groups are, purely on ethical grounds, already advocating the channelling of the primary resources used in the reduction industries towards the poor as a direct food source (Aldhous, 2004; Allsopp, Johnston and Santillo, 2008), changes in public opinion could occur with time. Indeed, as further evidence becomes available on the channelling of fish resources for purposes other than the production of human food (De Silva and Turchini, 2008) there is a high probability that public demand would move slowly towards omnivorous and filter feeding finfish aquaculture.

FIGURE 10
Estimates fishmeal and fish oil used in aquaculture in the different continents and the aquaculture production per unit use of fishmeal and fish oil



Source: calculated from data from the IFMFO.

FIGURE 11
Aquaculture production per tonne of fishmeal and fish oil used in the different cultured groups that are provided with aquafeeds containing these commodities



5.4.2 Other feed ingredients used in aquaculture

Although the emphasis has been on how to reduce fishmeal and fish oil usage in feeds for cultured aquatic organisms, over the last few years new problems are surfacing. For example soybean meal and corn meal are often used in feeds for cultured aquatic organisms and rice bran in tropical semi-intensive aquaculture. With the global quest to find suitable alternatives for fossil fuels, the current primary alternative is thought to be the production of biofuels. The use of some of the above ingredients for production of biofuels has resulted in many economic and social challenges resulting in a ripple effect (Naylor *et al*., 2000) and the ultimate impact of this on the aquaculture sector is difficult, if not impossible, to predict at this stage.

Apart from the above, the rising food price and the diminishing returns for the farmers (Anonymous, 2008a), also termed a "silent tsunami" (Anonymous, 2008b) are matters of concern for the aquaculture sector in that the availability of feed ingredients and the corresponding increased prices could impact on feed costs. In aquaculture, irrespective of the commodity and place of culture, farm gate prices have not increased significantly over the years; in fact for commodities such as shrimp (Kongkeo, in press) and salmon (Grøttum and Beveridge, 2008) it has declined in real terms. Profit margins in aquaculture are extremely narrow and such increases could impact them to the extent that at least some aquaculture activities become economically unviable. An important positive consideration is that in aquaculture feeds the agricultural ingredients used are almost always by-products. For example, soy bean meal used in aquafeeds is a by-product from the extraction of soy oil. Similarly, in semi-intensive aquaculture of carp species, for example in India mustard and peanut oilcakes, by-products after the extraction of oils, are used extensively in feeds (De Silva and Hasan, 2007).

Climate change impacts on terrestrial agriculture are beginning to be quantified and it is generally known that tropical terrestrial agriculture will be negatively impacted, more so than temperate regions (McMichael, 2001). A great majority of the agricultural by-products used in aquafeeds are of tropical origin. Unfortunately studies on price fluctuations of by-products are not readily accessible. There is an urgent need to evaluate the changes in availability, accessibility and price structure for agricultural by-products used in aquafeeds and to develop adaptive strategies to ensure that aquafeed supplies at reasonable prices could be retained well into the foreseeable future, so that aquaculture could remain economically viable.

5.4.3 Trash fish/low valued fish/forage fish supplies

There are other possible indirect impacts of climate change on specific aquaculture practices that are relatively large and, in a socio-economic context of great importance to certain developing countries. Again, these indirect impacts are related to aquafeed supplies and the ingredients thereof; in particular trash fish, low valued fish and forage fish (see Box 5).

It has been estimated that in the Asia-Pacific region the aquaculture sector currently uses 1 603 000 to 2 770 000 tonnes of trash fish or low valued fish as a direct feed source. The low and high predictions for year 2010 are 2 166 280 to 3 862 490 tonnes of trash fish or low valued fish as direct feed inputs (De Silva, Sim and Turchini, 2008). Sugiyama, Staples and Funge-Smith, (2004) estimated that in China 72.3 percent of five million tonnes (3 615 000 tonnes) of trash fish or low valued fish and 144 638 tonnes in the Philippines are used as feed for cultured stocks. Edwards, Lee and Allan, (2004) estimated that in Viet Nam 323 440 tonnes are used in aquaculture, the bulk of it to make farm-made feeds for pangasiid catfish cultured in the Mekong Delta. The summary of the different estimates of use of trash fish or low valued fish in Asia-Pacific aquaculture is given in Table 8 and it is evident that the quantities used are relatively large. It is important to note that the great bulk of this trash fish or low valued fish is produced by coastal artisanal fisheries in the region that provide thousands of livelihoods to fisher communities.

TABLE 8

The total usage of trash fish/low valued fish as a direct feed source in Asian-Pacific aquaculture

Activity	Countries/ region	Grade*	Quantity (x 1000 tonnes)		
			Current (range)	2010a	2010b
Marine fish	SE Asia	A, B	1 603–2 770	913	1 663
S. Blue fin tuna	South Australia	B	50–60	45	50
Fresh water fish	Asia	A,B	332.44	na (332.44)	na (332.44)
Crab fattening	SE Asia	B	480–700	600	700
Mollusc farming	Asia	C	0.035–0.049	0.050	0.055
Total			2 166 280–3 862 490	1 890 490	2 745 495

Grade A– low grade, unsuitable for human consumption; Grade B– may be suitable for human consumption; Grade C– good quality, suitable for human consumption. 2010 a = low and b = high predictions are based on increased production rates and associated changes in feed management given in previous Tables. For crabs and mollusc the predictions are based on an increase of a percent production from the current. na = not available.

Source: De Silva *et al*., 2008.

BOX 5

Trash fish/low valued fish/forage fish obtained primarily from small-scale artisanal, mostly coastal fisheries are an important entity in aquaculture activities in tropical Asia. This raw material may be used directly to feed the cultured stocks, as in the case of marine finfish or dried and powdered, as a cottage industry, or at the aquaculture facility and used in farm-made feeds in combination with other ingredients. Climatic changes could influence these small-scale fisheries through reduced ocean productivity (Schmittner, 2005), including the Indian ocean (Gianni, Saravanan and Chang, 2003) and consequently the supply of an important feed ingredient in rural small-scale aquaculture. The pictures depict the ingredient (dried fish), grinding and resulting pellet feed, prepared according specification at a farm site, being delivered to catfish in ponds in Viet Nam.

Apart from the general predicted reduction in ocean productivity it has been suggested that the Indian Ocean is the most rapidly warming ocean and consequently climate change would bring about major changes in it and on land, primarily on productivity and changes in current patterns (Gianni, Saravanan and Chang, 2003). The situation could be further exacerbated by extreme climatic events such as changes in monsoonal rain patterns (Goswami *et al.*, 2006) that influence inshore fish productivity and overall impact on the supplies of trash fish or low valued fish. Although issues related to reducing the dependence on trash fish or low valued fish of the growing mariculture sector in tropical Asia are being addressed, the impacts of the coming decade or so on this aquaculture sector cannot be ignored and needs to be addressed urgently. This is more so as subsistence and other small-scale fishers who lack mobility and alternatives and are often the most dependent on specific fisheries, will suffer disproportionately from alterations and occurrence of such changes which have been rated at medium confidence by the IPCC (2007).

5.4.4 Impacts on diseases

There has been much debate about climate change and the associated risks for human health (e.g. Epstein *et al*., 1998; McMichael, 2003; Epstein, 2005). There is general consensus that the incidence of terrestrial vector borne and diarrhoeal diseases will increase. The potential trends of climatic change on aquatic organisms and in turn on fisheries and aquaculture are less well documented and have primarily concentrated on coral bleaching and associated changes. An increase in the incidence of disease outbreaks in corals and marine mammals, together with the incidence of new diseases has been reported (Harvell *et al.*, 1999). Coral bleaching was linked to the high El Niño temperatures in 1997 to 1998 and it was suggested that both climate and human activities may have accelerated global transport of species, bringing together pathogens and previously unexposed populations (Harvell *et al.*, 1999; Hughes *et al*., 2003).

Daszak, Cunningham and Hyatt, (2000) suggested that increased agricultural intensification and associated translocations could exacerbate emerging infectious diseases in free living wild animals and impact on biodiversity because of climatic changes, in particular global warming in some arid parts of the globe. However, a decreasing trend is predicted in other areas, such as in Europe (IPCC, 2007).

It has been pointed out that there is a dearth of knowledge about parasites of aquatic animals other than those deleterious parasites that cause disease in humans. In the wake of the associated effects of climate change on circulation patterns and so forth and using predictions from a General Circulation Model, attempts were made to understand changes in parasite populations in temperate and boreal regions of eastern North America (Marcogliese, 2001). The overall conclusion from the simulations was that climatic change may influence selection of different life-history traits, affecting parasite transmission and potentially, virulence. It is difficult to predict the consequences of such changes on aquaculture *per se*, but the exercise points to the need for the aquaculture sector to be aware of potential and new threats from parasitism.

Because of anthropogenic influences, over the last two to three decades, there had been an increase in the rate of eutrophication in some oceans and the associated occurrence of harmful algal blooms-HABs (Smayda, 1990). It has been suggested that the rate of eutrophication and HABs would increase, resulting from oceanic changes brought about by climate change in some oceans and particularly in the North Atlantic and the North Sea (Peperzak, 2003; Edwards *et al*., 2006), not homogenously but, for example, along the Norwegian coast and elsewhere. HABs will impact marine life and human health through the consumption of affected filter feeding molluscs, commonly referred to as shellfish poisoning. Apart from this impact, the HABs could also bring about harmful effects on cage culture operations of salmon, for example. Accordingly, adaptive measures need to be set in place for regular monitoring and vigilance of aquaculture facilities in areas of potential vulnerability to eutrophication and HABs.

The possibility of climate change enabling both highly competitive species, such as the Pacific oyster (*Crassostrea gigas*) and associated pathogenic species to spread into new areas has been highlighted (Diederich *et al.*, 2005). Related, comparable evidence of the spread of two protozoan parasites (*Perkinsus marinus* and *Haplosporidium nelsoni*) northwards from the Gulf of Mexico to Delaware Bay (Hofmann *et al*., 2001) has resulted in mass mortalities in the Eastern oyster (*Crassostrea virginica*). It has been suggested that this spread was brought about by higher winter temperatures, when the pathogens otherwise were kept in check by temperatures < 3 °C. All of the above host species are cultured. With the predicted poleward increase in temperatures brought about by climate change, we could witness the emergence of pathogens that were kept in check by lower winter temperatures and hence see an impact on cultured organisms such as molluscs, in particular. Another such example is emerging: an outbreak of *Vibrio parahaemolyticus* has occurred in oysters in Alaska and in all seafood products in southern Chile (Karunasagar, I., 2008; personal communication). In the latter country, the first important outbreak started in early 2004 and has remained since then during summer months (Paris-Mancilla, 2005), apparently related to warmer seawater temperatures during summer. However, other factors, such as increasing nutrients in coastal zones, cannot be ignored (Hernandez *et al*., 2005). Main adaptation measures are essentially of two kinds: on the one hand to avoid the edible organisms (especially bivalves) reaching high temperatures while in transit or in storage (since multiplication of the pathogen takes place at an optimum temperature of 37 ºC; H. Lupín, personal communication) and to well cook shellfish and seafood.; Therefore, practices of eating raw seafood ("ceviche"[5]) are being banned in Chile, especially in summer.

It is not difficult to predict a general impact of water warming on the spread of diseases such as bacterial diseases in aquaculture because in most cases, incidence and persistence of these are related to fish stress. Increased water temperatures usually stress the fish and facilitate diseases (Snieszko, 1974). There are plenty of examples in the literature. Very recently it has been shown that ocean acidification could impact on the immune response of mussels, specifically shown for the blue mussel, *Mytilus edulis*, a popular aquaculture species (Bibby *et al*., 2008). It has been suggested that the impacts are brought through changes in the physiological condition and functionality of haemocytes which in turn are caused by calcium carbonate shell dissolution.

In fresh water aquaculture, an increased uptake of toxicants and heavy metals through accelerated metabolic rates from increased temperature by cultured, filter feeding molluscs is suggested to be plausible (Ficke, Myrick and Hansen, 2007), consequently leading to food safety and certification issues. In the above context there are few adaptation measures that could be utilised; perhaps the most appropriate would be for regular monitoring of the water quality and the cultured product for human health risks would be the primary option.

It is clear that the spread of diseases is the most, or one of the most, feared threats to aquaculture. Examples of disease related catastrophes in the aquaculture industry include the spread of the white spot disease in shrimp farming in Ecuador and other Latin America countries (Morales and Morales, 2006) and more recently the case of ISA (Infectious Salmon Anemia) which is seriously impacting Chile's Atlantic salmon industry to the point where the industry might shrink in the coming two to five years at least. Given that the spread of pests and diseases is thought to be a major threat under climate change scenarios, the issue must be made a priority for aquaculture considering relevant biosecurity measures as a main adaptation.

5.4.5 Impacts on biodiversity

One of the special issues that received attention from the early stages of the deliberations of the Inter Governmental Panel on Climate Change was the impact on biodiversity (IPCC, 2002). Generally, these impacts on biodiversity are predicted to occur in terrestrial habitats and less so in aquatic habitats, apart from those brought about through coral bleaching and subsequent loss of coral habitats, one of the most biodiverse habitats on earth. However, to date only the extinction of one species is clearly related to climatic change, that of the golden toad (*Bufo periglenes*) from Costa Rica (Crump, 1998). Predictions on overall loss of biodiversity arising from climate change are nevertheless staggering; the study of Thomas *et al*. (2004) for example, when extrapolated, indicates that at least one out of five living species on this planet is destined for extinction by the current levels of emissions of green house gases.

In all climatic regimes, continents and regions one of the main features of the aquaculture sector is its heavy dependence on alien species, (Gajardo and Laikre, 2003; De Silva *et al*., 2005; Turchini and De Silva, 2008) the associated translocations of new species beyond their normal geographical range and constant transfer of seed stocks

[5] Ceviche, cebiche or seviche, common name for raw fish dishes in Latin America and the Caribbean.

between nations and watersheds. To date, some introductions of internal parasites associated with such translocations for aquaculture purposes have been reported. But for the devastating impact of one such translocation associated with the introduction of a fungal plague and the consequent dissemination of the native European fresh water crayfish (Edgerton *et al.*, 2004), explicit evidence arising from alien species in aquaculture *per se* on biodiversity is not readily available; but this is no reason for complacency (De Silva *et al.,* 2004).

The impacts on biodiversity from alien species have mostly resulted from competition for food and space with indigenous species (e.g. Moyle and Leidy, 1992; Soto *et al*., 2006), alteration of habitats (e.g. Collares-Pereira and Cowx, 2004), the transmission of pathogenic organisms (Dobson and May, 1986), as well as through genetic interactions such as hybridisation and introgression (Dowling and Childs, 1992; Leary, Allendor and Forbes, 1993; Rhymer and Simberloff, 1996; Araguas *et al*., 2004) and other indirect genetic effects (Waples, 1991). Gienapp *et al*. (2008) addressed the issue on possible relatedness between climate change and evolution and concluded that:

- many alterations perceived as adaptation to changing climate could be environmentally induced plastic responses rather than micro evolutionary adaptations, and
- clear cut evidence is lacking to indicate a significant role for evolutionary adaptation to ongoing climate warming.

The question therefore, is whether the continued, if not increasing, dependence on alien species in future aquaculture developments and the associated seed stock translocations, in the wake of the global climatic change induced phenomena, would impact adversely on disease transmission as well as on biodiversity. The balance of evidence suggests that global climate change will not enhance impacts on biodiversity through aquaculture *per se.* However, in view of the changes in temperature regimes and so forth, particularly in the temperate region, the possibilities of diseases occurring among filter feeding molluscs and fish, for example, could be higher. Furthermore, any new introductions for aquaculture purposes will have to take into consideration such factors in the initial risk assessments undertaken for purposes of decision making.

In global aquaculture developments there are three major species groups that have been translocated across all geographical regions and have come to play a major role in production; these include salmonids in cool temperate waters and tilapias in warm tropical waters. The two species now account for over a million tonnes of production beyond their native range of distribution, closely followed by the white legged shrimp, *Penaeus vannamei,* and so are among the most important alien species in aquaculture. Climate change could impact the culture of all three species groups; warming in the temperate regions will narrow the distribution range of salmonids aquaculture, whilst the opposite could be true for tilapia and shrimp. In the latter case, extending the distribution well into the subtropics, where currently the culture period is limited to a single growth cycle in the year and the bulk of broodstock is maintained in green-house conditions.

Climatic change impacts on coral bleaching and associated loss of biodiversity have been relatively well documented and understood. The decline of coral reefs, from bleaching, weakening of coral skeletons and reduced accretion of reefs are estimated to be as high as 60 percent by year 2030 (Hughes *et al*., 2003). According to these authors the drivers of coral reef destruction are different from the past and are predominantly climate change associated. The direct relevance of loss of coral reefs and biodiversity to aquaculture is not immediately apparent. However, one of the drivers of coral reef deterioration, destructive fishing methods (McManus, Reyes and Nanola, 1997; Mous *et al*., 2000) employed to supply the luxurious "live fish" restaurant trade (Pawiro, 2005; Scales, Balmford and Manica, 2007) is on the decline. This decline is primarily related to the fish supplies being met by aquaculture production, mainly the grouper species. There is the possibility that the coral reef supply of fishes could be almost totally replaced through aquaculture which would remove a driver of coral reef destruction and contribute to conserving these critical habitats and hence biodiversity.

Extreme events such as tropical cyclones and storm surges may increase incidence of aquaculture stocks escaping into the wild environment. An impact of alien species on local biodiversity was discussed, but impacts of aquaculture of indigenous species were not. Often the genetic make-up of aquaculture stocks has been altered through selective breeding, breeding practices, genetic drift and adaptation to captive environment and in some instances severe inbreeding (e.g. Eknath and Doyle, 1990). Such alteration in genetic make-up of aquaculture stocks would potentially impact the gene pools of wild counterparts of the cultured species through genetic interactions between escapees and wild individuals. However, as pointed out by Rungruangsak-Torrissen (2002), healthy not genetically manipulated escapees should not threaten wild salmon stocks. This view is diametrically opposed to that of other authors (e.g. Jonsson and Jonsson, 2006), and is indicative of the problem's complexity. Lack of agreement, scientifically or otherwise, is no reason for complacency. A similar problem is being addressed with newly emerging aquaculture species such as cod (Jørstad *et al.*, 2008). Thorstad *et al.* (2008) discuss both the impacts of escaped Atlantic salmon as a native (e.g. in Norway) and as exotic species (e.g. in Chile) and are clear that, regardless of the species being cultured or its genetic background, preventive and mitigation measures to control escapes should always be in place.

Apart from causing genetic changes, escapees from aquaculture are thought to be responsible for increased parasitic infestation of wild stocks, for example, salmon in coastal waters of Canada (Krkošek *et al*., 2007; Rosenberg, 2008), among others. Perhaps mass escapes from aquaculture facilities caused by extreme weather events - very different to the small number of escapees at any one time in normal culture practices -, could influence the genetic makeup of native stocks, to their detriment in the long term. Perhaps the design of aquaculture facilities, particularly those located in areas vulnerable to unusual climatic events, needs to consider measures that would minimise mass scale escape.

5.5 Social impacts of climate change on aquaculture

The social impacts of climate change on capture fisheries have received much attention, compared to those on aquaculture (e.g. Allison *et al*., 2005). This analysis concentrates on the vulnerable, poor fishing communities. In essence, the potential social impacts on fisheries are manifold, and primarily arise from:

- decreased revenues to fishers resulting from declines in catch and stock abundance (Luam Kong, 2002; Mahon, 2002);
- changes in migratory routes and biogeography of stocks affecting fishing effort, an example being increased travel time to fishing grounds (Dalton, 2001; Mahon, 2002);
- changes in harvest technologies and processing costs brought about by the need to capture new species (Broad, Pfaff and Glantz, 1999);
- damage to physical capital from severe weather events (Jallow, Barrow and Leatherman, 1996);
- impacts on transportation and marketing chains/systems (Catto, 2004); and
- reduced human capital from severe weather events, increased incidence of red tides and associated shellfish poisoning (Patz, 2000).

Some of the above, for example, damage to physical capital, impacts on transportation and marketing systems/channels, are most likely to have some effect on aquaculture. Considering the majority of aquaculture practices in the tropics and subtropics are small-scale enterprises, often farmer owned and managed, but clustered together (see

Box 6) in areas conducive to aquaculture, damages resulting from extreme weather events will impact on the livelihoods of such clusters and have the potential to affect many poor households.

Such farming communities will be among the most vulnerable in the aquaculture sector and the possibilities of reducing their vulnerability are relatively limited. As an adaptive measure, in order to enable such clusters to spring back to their livelihoods, it may be necessary to develop a form of cluster insurance scheme, and in this regard, there could be a need for governmental policy changes and assistance.

In the tropics, currently the fastest growing aquaculture subsector is marine finfish farming, driven by high commodity prices and better profit margins, supported by improved hatchery technologies. Such activities in the tropics are almost always confined to enclosed coastal bays and consist of small holdings clustered together, becoming potentially vulnerable to extreme climatic events such as sea storms and wave surges. These farming communities are very vulnerable to adverse weather events. Bearing in mind that this sector, at least in Asia, is serviced to a significant extent by small-scale artisanal fishers providing the required trash fish or low valued fish to feed the cultured stock, any increased vulnerability of the former will impact on these finfish farming communities, often family managed enterprises. Indeed, climate change impacts will make both groups highly vulnerable, with the potential effects greater on artisanal fishers because they would have no choice but to find alternative livelihoods, whereas finfish farmers could shift to feeding stock with commercial feeds, if economically feasible.

It was pointed out earlier that sea level rise, water stress and extreme climatic events would have a major influence on deltaic regions and the possibility exists that land based agriculture may have to be abandoned and replaced by aquaculture as means of alternative livelihoods. Such changes involve major social upheavals in lifestyles and have to be carefully tailored with the provision of initial capacity building needed to efficiently effect a change in livelihood patterns. Examples of effective change of livelihood patterns from agriculture to aquaculture are known, especially with respect to communities displaced by reservoir impounding. In this regard, in the few reported instances there had been a socio-economic improvement of the incumbents after the adoption of aquaculture (Pradhan, 1987; Abery *et al*., 2005; Wagle *et al.*, 2007).

There could be indirect negative social impacts in the aquaculture processing sector where relatively low valued cultured products are being processed in the vicinity and

BOX 6

In most of the tropical and subtropical regions of Asia, which is the mainstay for the great bulk of aquaculture activities, coastal and inland, more often than not individual small holdings are clustered together in areas conducive to aquaculture. Unusual weather events resulting from climatic changes could impact on such clusters and many livelihoods adversely. Pictures show dense marine cage farming in Xin Cuin Bay, Ling Shui County, China, small-scale seaweed farming in Sulawesi, Indonesia and inland cage farming in Cirata reservoir, Indonesia.

with easy access to culture facilities. However, with sea level rise and corresponding saline water intrusion (see Section 5.3.3.) there could be a shift of these culture practices further upstream, perhaps causing the processing plants to follow suit. This would result in loss of employment opportunities in some communities but gains in others, creating at least temporary social problems and capital disengagement. Another indirect factor is that some of the adaptive mechanisms being evolved globally to combat carbon emissions and therefore climatic change could increase the vulnerability of the aquaculture sector. One of the major social cum industrial changes occurring globally is the increasing emphasis on the production of biofuels and the lobby (Naylor *et al*., 1998; 2000; Aldhous, 2004) that is advocating the use of raw material used for fishmeal and fish oil production for direct human consumption. These trends will affect aquaculture by making the availability of key feed ingredients increasingly scarce and expensive, making the culture of carnivorous fish and shrimp almost prohibitive.

Some lobby groups take the view that aquaculture is not ecologically sustainable in a world that is becoming increasingly conscious of carbon emission processes, including those caused by food production. Two decades ago, consumers did not pay much attention to quality, ecolabelling and traceability but now they are becoming important in marketing, particularly in the developed world. It has been pointed out that some cultured commodities are energy costly but command a high consumer price at the upper scale of markets. It is possible that in the near future, consumers could create a demand for carbon emission labelling, with the result that eco-labelling of products such as shrimp and salmon could increase causing a drop in demand for energy costly products over the years. The above scenario is not unrealistic and would result in very significant socio-economic impacts in the producing countries and the upmarket end of aquaculture production and processing. On the positive side, however, is the possibility that there could be a return, particularly in the case of shrimp, to indigenous species such as *P. monodon* cultured using better management practices (BMPs) that are less energy demanding (see Table 11).

An increase of diseases affecting aquaculture because of climate change will have important social impacts on small producers and on workers associated with the sector. This is presently being seen in Chile's salmon farming industry, which was badly affected by the ISA virus[6] although the disease have not been connected to climate change so far. The disease has caused a drastic increase in unemployment at all levels, from farm workers to the services sectors with strong impacts on the local economy.

6. POTENTIAL IMPACTS OF AQUACULTURE ON CLIMATE CHANGE

Aquaculture, on a global scale and in comparison to animal husbandry, became a significant contributor to the human food basket relatively recently. The aquaculture sector has experienced very strong growth over the last two decades, making it the fastest growing primary production industry (FAO, 2007). It began to blossom during a period when the world was becoming increasingly conscious and concerned about sustainability, use of primary resources and the associated environmental degradation issues. Sustainability, biodiversity and conservation became an integral part of all development efforts following the publication of the Brundtland Report, "Our common future" in 1987 (UNEP, 1987), and follow-up global initiatives such as the establishment of the Convention on Biological Diversity (1994).

In this scenario of increasing global awareness and public "policing" the sector has been targeted on many fronts. Foremost among these has been the use of fishmeal and fish oil, obtained through reduction processes of raw material supposedly suitable for direct human consumption (Naylor *et al*., 1998; 2000; Aldhous, 2004). Another target has been that of mangrove clearing during the shrimp farming boom (Primavera, 1998;

[6] www.salmonchile.cl/frontend/seccion.asp?contid=1109&secid=4&subsecid=61&pag=1

2005). Admittedly, in the past, mangrove clearing was a major issue with respect to shrimp farming but the practise no longer takes place. In fact, it has been estimated that less than five percent of mangrove areas have been lost due to shrimp farming, most losses occurring due to population pressures and clearing for agriculture, urban development, logging and fuel (GPA, 2008).

A counter argument is that positive contributions from aquaculture may not have been totally quantified because benefits other than those to the human food basket have not been taken into consideration. Aquaculture's positive influence, on issues such as climate change has gone unheeded while society at large needs to consider that all food production has environmental costs which have to be compared in a fair way (Bartley *et al*., 2007). Consequently, an attempt is made below to outline the positive contributions of aquaculture towards the global problem of climate change.

6.1 Comparison of carbon emissions/contributions to green house gases from animal husbandry and aquaculture

Carbon emissions, viz. green house gases, in one form or the other, driven by anthropogenic activities, are a root cause of climate change (Brook, Sowers and Orchardo, 1996; Flattery, 2005; Friedlingstein and Solomon, 2005; IPCC, 2007) and all mitigating measures revolve around reducing the carbon emissions. Itis therefore relevant to consider the degree of carbon emissions of the various animal food production sectors with a view to gauging the degree to which aquaculture contributes to this primary cause. It is conceded that accurate and/or even approximate estimations of total emissions from each of the sectors is difficult, if not impossible, to compute. However, any approximation will bring to light the indirect role that aquaculture plays in this regard.

The United States Environmental Protection Agency (EPA) recognised 14 major sources responsible for methane emissions in the USA and ranked enteric fermentation and manure management from animal husbandry as the third and fifth highest emitters, respectively. The emissions from these two animal food production sources were 117.9 and 114.8, and 31.2 and 39.8 $TgCO_2$ Equivalents for years 1990 and 2002, respectively.[7] Domesticated livestock, the ruminant animals (cattle, buffalo, sheep, goats, etc.) produce significant amounts of methane in the rumen in the normal course of food digestion, through microbial fermentation (= enteric fermentation) that is discharged in the atmosphere. Equally, the solid waste produced – manure - needs to be managed and this process results in the emission of significant amounts of methane. The atmospheric methane level has increased from 715 ppb in the pre-industrial revolution period to 1775 ppb at present. Comparable trends have been recorded from ice cores from Greenland (Brook, Sowers asnd Orchardo, 1996). It has been suggested that the world's livestock accounts for 18 percent of greenhouse gases emitted, more than all transport modes put together, and most of this is contributed by 1.5 billion cattle (Lean, 2006). Overall, the livestock sector is estimated to account for 37 percent of all human-induced methane emissions. The global warming potential (GWP) of methane is estimated to be 23 times that of carbon dioxide. Farmed aquatic organisms do not emit methane and therefore are not direct contributors to the causative problems. Surprisingly and unfortunately this has not been taken into account, particularly by those who tend to advocate the view that aquaculture is polluting and non-sustainable (e.g. Allsopp, Johnston and Santillo, 2008).

The world is requiring more animal food products, fuelled by rising incomes and urbanization, particularly in the developing world. It is estimated that in the developing world the per capita meat consumption rose from 15 kg in 1982 to 28 kg in 2002 and is expected to reach 37 kg by 2030 (FAO, 2003). The increasing demand for animal food

[7] www.epa.gov/methane/sources.html#anthropogenic

products in developing countries has resulted in an accelerated rate of production and in 1995 surpassed that of the developed world (Gerber *et al*., 2007). Any analysis has to revolve around human food needs and the proportionate contribution of each food producing sector to green house gas emissions.

6.1.1 Carbon sequestration

One of the major causative factors of climatic change, if not the major causative factor, is the accumulation of green house gases in the atmosphere, irrespective of the source(s) of emission (Brook, Sowers and Orchardo, 1996; Flattery, 2005; Friedlingstein and Solomon, 2005; Kerr, 2006; IPCC, 2007). Carbon sequestration is the process through which agriculture and forestry practices remove atmospheric carbon dioxide, Forestation, reforestation and forest preservation are considered to be favourable practices that sequester and/or preserve carbon and all help alleviate climate change by enhancing carbon storage (Lal, 2004; Miller, 2008).[8]

6.1.1.1 Methods used in determining energy costs

A number of different methods, direct and indirect, can be used for estimating carbon sequestration. An indirect measure is to estimate the energy costs of production of a commodity, also referred to as "environmental costs" for an entity/commodity. Among such methods are "Ecological Footprints (EF)" and "Ecoindicator 99", for example. It is acknowledged that the methodologies used are far from perfect and there is a need for standardization to obtain meaningful and comparable results (Bartley *et al.*, 2007). More recently, Huijbregts *et al*. (2007) attempted to compare the use of EF and Ecoindicator 99 methods to evaluate 2 360 products and services, including agriculture. These authors concluded that the usefulness of EF as a stand-alone indicator for environmental impact is limited for the life cycles of certain products and that the use of land and fossil fuels are important drivers of overall environmental impact.

6.1.1.2 Comparisons on energy costs from aquaculture and other food types

Notwithstanding the relative uncertainties in assessing the ecological costs of production processes, there have been many studies on the energy costs of production of farmed animals (Bartley *et al.*, 2007). For example, a comparison of energy costs of some aquaculture produce and selected farmed animals and a ranking of food according to edible protein energy and industrial energy inputs are given in Tables 9 and 10, respectively. What is most obvious is the degree of discrepancy in the data by different authors for the same commodity and reiterates the need for standardization of the techniques and the units to facilitate direct comparisons. (Bartley *et al.*, 2007; Huijbregts *et al*., 2007; Tyedmers and Pelletier, 2007).

In spite of such discrepancies some general trends are evident. With regard to aquaculture the total energy cost for culturing shrimp and carnivorous finfish such as salmon are rather high and results in relatively low protein output compared to the energy inputs. In fact, the percent protein output to energy inputs to produce a unit weight of shrimp and salmon are even lower than that for chicken, lamb and beef (Table 10). On the other hand, salmon and marine fish provide other nutritional elements that are relevant for human health and these should also be taken into account in such comparisons.

Similarly, the relative returns from omnivorous finfish culture and other commodities such as mussels and seaweeds are far better than those from carnivorous finfish and/or other husbanded livestock. It is evident that the culture of carps, an omnivorous species group, feeding low in the food chain, is profitable energy wise; a fact that was also evident from the previous analysis in relation to fishmeal and fish oil usage

[8] www.epa.gov/sequestration/forestry.html

TABLE 9
Energy used in different farming systems

System	Industrial energy consumption			
	Direct energy	Indirect energy	Total	Units
Semi-intensive shrimp f.[@]	55	114	169	GJ t^{-1}
Thai shrimp[#]	na	na	45.6	MJ kg^{-1}
Marine shrimp[$]	54.2	102.5	156.8	MJ kg^{-1}
Salmon cage f. [@]	9	99	105	GJ t^{-1}
Salmon cages intensive[@]	na	na	56	GJ t^{-1}
Salmon[$]	11.9	87	99	MJ kg^{-1}
Norwegian farmed salmon[#]	na	na	66	MJ kg^{-1}
Trout ponds[@]	na	na	28	GJ t^{-1}
Grouper/seabass cage f. [@]	na	na	95	GJ t^{-1}
Carps, intensive recycle[@]	na	na	56	GJ t^{-1}
Carp, recirculating[$]	22	50	50	MJ kg^{-1}
Carp ponds feeding & fertilizer[@]	na	na	11	GJ t^{-1}
Carp, semi-intensive[$]	26	01	27	
Catfish ponds[@]	na	na	25	GJ t^{-1}
Catfish[$]	5.4	108	114	MJ kg^{-1}
Tilapia[$]	0	24	24	MJ kg^{-1}
Norwegian chicken[#]	na	na	55	MJ kg^{-1}
Swedish beef[#]	na	na	33	MJ kg^{-1}

Data from: @- Bunting and Pretty, 2007; #- Munkung and Gheewala, 2007; $- Troell *et al.*, 2004. na = not available.

TABLE 10
Ranking of selected foods by ratio of edible protein energy (PE) output to industrial energy (IE) inputs, expressed as a percentage

Food type including technology, environment and locality	% PE/IE
Carp extensive, fresh water, various	100-111
Seaweed, mariculture, Caribbean	50-25
Chicken, intensive, United States of America	25
Tilapia, extensive, fresh water ponds, Indonesia	13
Mussels, marine long lines, Scandinavia	10-5
Tilapia, fresh water, Zimbabwe	6.0
Beef, pasture, United States of America	5.0
Beef, feed lots, United States of America	2.5
Atlantic salmon, intensive, marine net pen, Canada	2.5
Shrimp, semi intensive, Colombia	2.0
Lamb, United States of America	1.8
Sea bass, intensive marine cage culture, Thailand	1.5
Shrimp, intensive culture, Thailand	1.4

Source: Tyedmers and Pelletier, 2007. Please refer to these authors for original references.

in aquaculture (Section 5.4.1). Carp culture provides a return of over 100 percent on protein output to energy input (Table 10), unmatched by any other farming system. It is timely for the aquaculture sector, in the context of pressing issues such as climatic change, to develop quantitative models on these aspects to help in planning major aquaculture developments globally. These analyses are particularly relevant for developing countries where the bulk of aquaculture occurs and provide not only livelihoods but also make significant contributions to foreign exchange earning.

6.2 Estimating aquaculture's potential contribution to climatic change

It has to be accepted that all forms of farming will incur some energy costs and in this regard aquaculture is no exception. This must be balanced against other factors including that, unlike for terrestrial agriculture and animal husbandry, there are potentially over 300 species to choose from in aquaculture (FAO, 2007). In a good number of instances, the practices to be adopted are driven by market forces.

Good examples in this regard are shrimp, salmonid and marine finfish aquaculture, the latter gradually witnessing a major growth phase in the wake of market demand

TABLE 11
Comparative life cycle impact assessment results of block tiger prawn and IQF Pacific white-leg shrimp (Pws)

Impact category	Unit	Block (1.8 kg) of black tiger prawn[#]	4 (x 453 g) pouches of IQF Pws [@]
Abiotic depletion potential (ADP)	kg Sb eq*	0.32	0.19
Global warming (GWP100)	kg CO_2 eq	19.80	27.31
Human toxicity	kg 1.4-DB eq	1.79	3.04
Fw aquatic ecotoxicity	kg 1.4-DB eq	0.25	0.41
Mar. aquatic ecotoxicity	kg 1.4-DB eq	1660.00	2071.00
Terrestrial ecotoxicity	kg 1.4-DB eq	0.02	0.02
Acidification	kg SO_2 eq	0.07	0.14
Eutrophication	kg PO_4 eq	0.22	0.19

* equivalents of Antimony extraction (depletion); ** kg 1,4-dichlorobenzene equivalents (1,4-DB)/kg emission, as normalized units for toxicity.
Sources: #- Mungkung, 2005; @- Mungkung ***et al.***, 2007

for species such as groupers, snappers and wrasses, all of which are on the decline in the capture fisheries. The increased market demand for such high valued species is also driven by factors similar to those that have resulted in increased meat consumption in developing countries.

Of all aquaculture commodities, the environmental cost of shrimp aquaculture is the highest. Shrimp aquaculture is economically very important to a number of tropical regions in Asia and South America. Because it needs constant aeration and water exchange, in general shrimp culture consumes a lot of energy compared to most other cultured commodities. Furthermore, shrimp culture is essentially destined for export markets and consequently needs a high level of processing, which is relatively costly in terms of energy. Recent publications on the "life cycle assessments" of "Individually Quick Frozen", Pacific white leg shrimp, *Penaeus vannamei* production, (Munkung, 2005; Munkung *et al.*, 2007; Mungkung and Gheewala, 2007 (Table 11) revealed that the culture of the native tiger shrimp, *P. monodon*, in Asia is far more ecologically cost effective than that of the alien *P. vannamei*. In all ecological aspects and from the point of view of contribution to global warming, culture of *P. monodon* is better. Such factors need to be taken into account in debates around the introduction of alien species, such as the recent one in relation to Asian shrimp farming in Asia (De Silva *et al.*, 2006). Perhaps it is time that as an adaptive measure to climate change, aquaculture should be considered not only in the light of straight forward economic gains (which often tend to be short term), but also in its contribution to factors impacting on climate change as a whole. A case in point is the issue of the introduction of *P. vannamei*, a high yielding species with quick economic return, (Wyban, 2007), as opposed to the native *P. monodon*.

The great bulk of aquaculture production is slanted towards relatively more environmentally cost effective commodities than shrimp (Table 12). The table shows that overall, global growth in finfish aquaculture production has tended towards organisms feeding low on the food chain, and maximally ecologically less energy consuming. Consequently, global growth in finfish aquaculture carbon emissions is minimal and less than the great majority of other food commodities.

TABLE 12
The production of cultured finfish ($x10^3$ tonnes) feeding low on the trophic chain in 1995 and 2005 and the overall growth in the ten year period

Species	1995	2005	Growth %
Silver carp	2 584	4 153	60.7
Grass carp	2 118	3 905	84.4
Common carp	1 827	3 044	66.6
Bighead carp	1 257	2 209	75.7
Crucian carp	538	2 086	287.7
Nile tilapia	520	1 703	227.5
Rohu	542	1 196	120.7
Catla	448	1 236	175.9
Mrigal carp	330	421	21.6
Black carp	104	325	212.5
Total	10 359	20 187	94.9
Fw fish (nei)	2 581	5 591	116.6
Total (fw)	12 940	25 778	99.2
All finfish	15 616	31 586	102.2

In addition, aquaculture of molluscs and the expanding seaweed culture (also see Figures 10 and 12), particularly in tropical regions contributes significantly to carbon sequestration. Moreover, the rapid turnover in seaweed culture, approximately three months per crop (in the tropics) with yields of over 2 500 tonnes per ha, far exceeds the potential carbon sequestration that could be obtained through other agricultural activity for a comparable area. Cultivation of shrimp and carnivorous finfish are the most energy consuming activities in aquaculture and have been the basis for criticism from environmental lobby groups of the entire sector. Much of the criticism is unfair because it is based on two commodities, which account for far less than ten percent of global aquaculture production.

7. OTHER ADAPTIVE MEASURES

In the foregoing sections, plausible adaptive measures for combating or mitigating the impacts of climatic change on aquaculture are examined, primarily from a technical viewpoint, including the associated social aspects. It has been demonstrated recently that successes in aquaculture almost always had to be complemented with relevant institutional, policy and planning changes or adaptations (De Silva and Davy, in press), and one would expect climatic change impact adaptations to follow suite if they are to be effective and sustainable.

7.1 Institutional, policy and planning measures

In terms of institutional and policy measures the following are priority areas for development of the sector:

- to implement an ecosystem approach to aquaculture (EAA) as a global strategy;
- to prioritize and enhance mariculture and specially non-fed aquaculture (filter feeders, algae);
- to enhance the use of suitable inland water bodies through culture-based fisheries and appropriate stock enhancement practices.

The ecosystem approach to aquaculture (EAA) aims to integrate aquaculture within the wider ecosystem in such a way that it promotes sustainability of interlinked social-ecological systems (SOFIA, 2006; Soto *et al*., 2008).

As with any system approach to management, EAA encompasses a complete range of stakeholders, spheres of influences, and other interlinked processes. In the case of aquaculture, applying an ecosystem-based approach must involve physical, ecological, social and economic systems in the planning of community development, and must take into account stakeholder aptitudes and experiences in the wider social, economic and environmental contexts of aquaculture.

The EAA emphasizes the need to integrate aquaculture with other sectors (e.g. fisheries, agriculture, urban development) that share and affect common resources (land, water, feeds, etc.) also focusing on different spatial scales; i) the farm, ii) the aquaculture zone, water body or watershed where the activity takes place, and iii) the global scale (Soto *et al*., 2008).

Perhaps the implementation of EAA at the waterbody scale is one of the most relevant adaptations to climate change. Geographical remit of aquaculture development authorities (i.e. administrative boundaries) often do not include watershed boundaries and this is a particular challenge because climate change prevention and adaptation measures need watershed management, e.g. protecting coastal zones from landslides, siltation, discharges, or even simply providing enough water for aquaculture. On the other hand, aquaculture can provide adaptation for coastal agricultural communities that may face salinization effects because of rising sea levels. In coastal regions, mariculture can provide an opportunity for producing animal protein when fresh water becomes scarce. Such a watershed perspective needs policy changes and integration between different sectors (e.g. agriculture-aquaculture) aside from capacity building and infrastructure requirements. Because climate change does not recognize political boundaries, adaptation policies and planning within international watersheds can be a major challenge. However, the common threat of climate change impacts can provide the opportunity for such trans-boundary management.

For the aquaculture sector, the watershed scale approach is also needed for an organized–cluster-type adaptation to negotiate collective insurance, to implement appropriate bio-security measures, etc. Instances of such adoptions, initiated not necessarily as an adaptive measure for climate change impacts, are best exemplified in the shrimp farming sector on the east coast of India (Umesh *et al*., in press). This case has proven the ability to extend this approach to other comparable small-scale farming sectors.

An ecosystem approach to aquaculture is being increasingly considered as a suitable strategy to ensure sustainability, including adequate planning required to take into account climate change impacts. Other relevant elements to consider in the policies and planning are described below.

7.1.1 Aquaculture Insurance

An adaptive measure that will help limit bankruptcies in aquaculture businesses as a result of losses caused by climatic events is to encourage aquaculture participants to take insurance against damage to stock and property from extreme climatic events. Appropriate insurance cover will at least ensure that finance is available for businesses to recommence operations. Aquaculture insurance is well established for major commodities such as salmon and shrimp produced at industrial scales but this is not the case for small farmers. This is particularly relevant for Asia (Secretan *et al*., 2007) where the bulk of small-scale farming takes place; governments could consider making insurance mandatory for aquaculture businesses above a certain size and accordingly reduce long term losses in production, livelihoods and potential environmental damages, such as those associated with escapes.

7.1.2 Research and technology transfer

Relevant research is required for aquaculture to adapt to climate change and countries and regions need to streamline work on issues such as new diseases and preventive treatments, aquatic animal physiology, the search for new and better adapted species, better feeds and feeding practices that are more ecosystem friendly. Technology transfer mechanisms must reach farmers, especially small farmers. It is in this context that application of better management practices (BMPs) into small-scale farming practices need to be integrated into EAA strategies. Some practical measures available for many countries are explored below.

7.1.2.1 Using lessons from the expansion of farming species outside their natural range of distribution

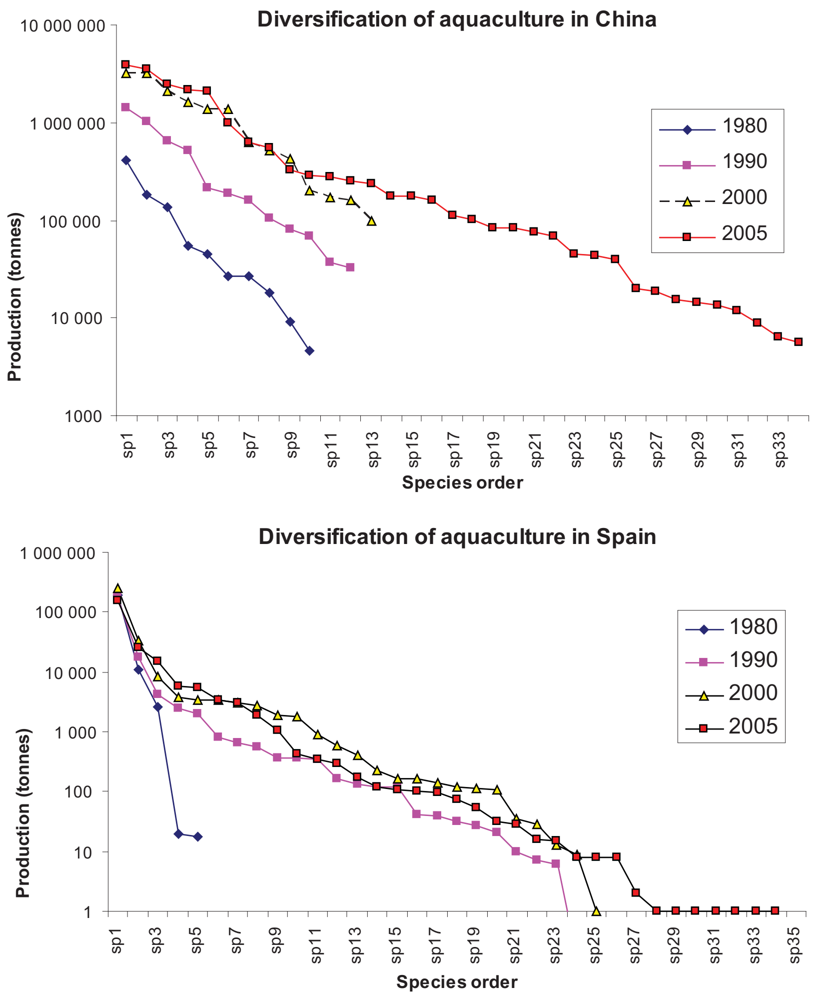
Global warming is an imminent potential threat and there is a clear need to assess the required adaptations for cultured species, especially in temperate regions. A simple approach can be “learning from the experience of expansion of farming species outside their original range”. A great deal of the “adaptation knowledge” may be already available within the aquaculture sector among pioneer farmers and perhaps it is time to collect such information globally. For example, there is a body of knowledge about salmon aquaculture beyond its natural range of distribution, facing different climates and weather conditions and vulnerability to old and new diseases. Similar examples can be found with tilapia and the white legged shrimp. Perhaps it is also possible to use the genetically improved strains that have been more successful under certain alien conditions. But care should be taken with the movement of live organisms.

7.1.2.2 Aquaculture diversification

In many countries and regions, there is a clear tendency to diversify farmed species and technologies (FAO, 2006). Duarte *et al*. (2007) show the very fast diversification process and what they call "domestication of new species for aquaculture" and particularly mariculture. According to the authors, this process is developing much faster than happened in animal or plant husbandry and they highlight the potential adaptive significance. Figure 12 shows the relatively fast aquaculture diversification in China and Spain. In China, there is a high leap in aquaculture diversification, rising from 13 species being cultured in 2000 to 34 species in 2005. In evolutionary terms, it is commonly understood that diversity provides the ground for natural selection and for adaptation, it can also be proposed that culturing more species provides a form of insurance and offers better adaptation possibilities under different climate change scenarios, especially unexpected events such as diseases or market issues.

FIGURE 12

Species diversification in China and in Spain based on FAO statistics. Figures show species organized according to production from left to right (log scale in the Y axes) in such a way that Sp1 is the species with the largest production. A steeper slope indicates one or few species monopolizing production. This is the case in Spain and China in 1980. However the increase in number of species cultured is noteworthy by 1990, and further on in Spain and by 2005 in China with 34 cultured species and a softer slope of the curve in the later case, that is a more even production



Source: FAO FishStat, 2008.

Diversification requires educating consumers and providing them with adequate information about new species and products, hand in hand with the successful transfer of the technologies to new practitioners. National and global policies can facilitate aquaculture diversification while strengthening the consolidated species.

Diversification can be part of an insurance programme for the sector at the country and regional levels.

7.1.3 Aquaculture zoning and monitoring

Adequate site selection and aquaculture zoning can be important adaptation measures to climate change. When selecting aquaculture sites it is very important to determine likely threats through risk assessment analysis. When selecting the best locations for aquaculture farms, particularly in coastal and more exposed areas, weather related risks must be considered. For example, coastal shrimp farms may need levies or other protective structures. Fish cages have to be securely fastened to the bottom or a holding structure; submersible cages have been proposed and are being used in a few offshore sites where they can withstand adverse weather events. Water warming and related low oxygen, potential eutrophication enhancement, etc. can be avoided or minimized in deeper sites with better circulation. However there are always tradeoffs with exposure to more extremes conditions. The likelihood of disease spread can be minimized by increasing the minimum distance between farms and by implementing tight biosecurity programmes for aquaculture clusters or zones. Implementing proper risk communication is also very important but communications have to be reliable and fast and the information accurate. In this regard, weather information systems around the world are improving in a bid to prevent major damages to infrastructure and biomass.

For aquaculture, some of the most important prevention systems must rely on critical and effective monitoring of water bodies and aquatic organisms. A very important adaptation measure at local level and at the water body/watershed scale is the implementation of effective integrated monitoring systems. Such monitoring systems should provide adequate information on physical and chemical conditions of aquatic environments, early detection of diseases and presence of pest species, including harmful algal blooms. Often, rural farmers may not have the conditions and facilities to implement such monitoring by themselves. However, some very simple measurements can be implemented such as water temperature and Secchi disk readings. The latter can often be used for early detection of algal blooms. Ideally, local authorities can assist in implementing integrated monitoring systems with accompanying risk communication strategies and early warning systems to prepare and warn stakeholders. Some interesting examples are the monitoring programmes for red tides in connection with mussel farming in the coastal inlets (rías) in Galicia, Spain and the monitoring programmes for salmon farming. In Galicia the Technological Institute for the control of the marine environment (INTECMAR) has a permanent monitoring programme on the internet which is easy to access; it provides alerts and early warnings regarding red tides and other water conditions relevant to mussel farming.[9] The salmon farming industry in Chile through the Salmon Farmers Association maintains an integrated monitoring system which provides different water parameters through a permanent recording mechanism (automatic buoys plus manual samplings) and the information is provided daily to farmers through the web and also through local radio programmes that can reach the more remote areas.[10]

8. CONCLUSIONS

Over the last two to three decades, aquaculture has successfully established itself as a major food sector providing a significant proportion of the animal protein needs

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[9] www.intecmar.org/informacion/biotoxinas/EstadoZonas/Mapas.aspx?sm=a1

[10] www.pronosticos.salmonchile.cl/antecedentes.asp

across all communities irrespective of living standards. It has done so through many adversities during which it has shown resilience and adaptability. As in all food producing sectors, aquaculture now confronts another major challenge, that of the impacts of climatic change. It is likely that aquaculture, in view of its resilience and adaptability and its cultivation of a wide array of species/species groups will be able to respond positively to climate change impacts. In order to do so there needs to be related policy, institutional and socio-economic changes, backed up and supplemented by relevant technical developments. Preferably, there should be a holistic approach and one that works from the bottom up rather than top down. The latter is crucial because the great bulk of aquaculture is small–scale, farmer owned, operated and managed, particularly in Asia – the epicenter of global aquaculture. Only by incorporating indigenous knowledge and obtaining cooperation at grass root level will it be possible for adaptive changes to be implemented effectively and in a timely manner.

Over many thousands of millennia, many climatic changes are thought to have occurred on our planet, bringing about major floral and faunal changes. The reasons for such changes are not always obvious and/or universally accepted But we know that the climate change now facing the earth is primarily brought about by anthropogenic activities and started at the beginning of the last industrial revolution. The causative agents of the changes and therefore the required mitigating measures are well understood and have been subjected to rigorous scientific scrutiny (IPCC, 2007). Human food needs and food production are impacted by climate and such changes in the coming decades are a major concern, particularly for developing nations. Considering the predicted human population growth over the next few decades coupled with the fact that food production is not evenly distributed throughout the globe and nor is the ability to attain food security (Kerr, 2006), it is predicted that climate change impacts will be most negative for the poor developing countries and hit them hardest. Another casualty will be the flora and fauna least capable of adapting to the changes; it is believed that even a modest climate change in the next few decades will begin to decrease crop production in low latitudes (Kerr, 2006) – these include the very regions where aquaculture is most predominant. It is heartening to note, however, that a significant proportion of innovations regarding aquaculture have originated from grass roots initiatives, which have been quick to take the lead and adapt crucial technical advances. In this sense, the rural, small-scale aquaculture farmers can be expected to be alert to climate change impacts and make the necessary adaptations.

In the overall scenario of animal protein food sectors, the contribution of fish falls far behind terrestrial animal protein sources. For example, the per capita consumption of meat in the developing world is much greater, rising from 15 kg in 1982 to 28 kg in 2002, and is expected to reach 37 kg by 2030 (Gerber *et al.*, 2007), as opposed to 16.6 kg of fish in 2005 (FAO, 2007). Meat production and fish production sectors have witnessed a shift of dominance from developing to developed countries (Gerber *et al.*, 2007 and Delgado *et al*., 2003). We know that daily meat consumption has increased linearly in relation to per capita income (Houtman, 2007) but such analysis is not available for fish.

The main difference between the two sectors is that food fish supplies are still predominantly capture fisheries, as opposed to farmed, but future increases in demand will be met mostly by aquaculture (see Sections 2.1, 2.2.). The importance of capture fisheries will at best be static and there is a high probability that climate change will cause it to decline. Consequently aquaculture will fill the supply gap and meet growing human fish food needs.

Although it is only a relatively small food production sector, aquaculture is a significant contributor to the animal protein component of the food basket. Aquaculture has increased from 0.7 kg per capita in 1970 to 6.4 kg per capita in 2002, with approximately 10 million people active in the production sector. This increase is significantly higher than that witnessed for terrestrial livestock farming which grew only at a rate of 2.8 percent per year for the same period (Bunting and Pretty, 2007) and reflects the late emergence of aquaculture as a significant contributor to the human food basket. It is also important to stress that aquaculture has been overly scrutinized from an environmental impact viewpoint; presumably because this sector gained prominence only in the last three decades or so, coinciding with a surge of global awareness about sustainable development and environmental integrity (UNEP, 1987; CBD, 1994).

Unlike many other animal meat production sectors, aquaculture, which farms poikilothermic animals, is patchily distributed with concentrations in tropical and subtropical regions of Asia, inland and coastal and to a lesser extent on the temperate coasts of Europe and South America. Given this distribution, it would be expected that major climatic change impacts on aquaculture would be through global warming and consequent temperature increases in water. These are predicted to be most significant

TABLE 13
A summary of the important impacts of the different elements of climate change on aquaculture and potential adaptive measures

Aq. /other activity	Impact(s)		Adaptive measures
	+/-	Type/form	
All: cage, pond; fin fish	-	Raise above optimal range of tolerance	Better feeds; selective breeding for higher temperature tolerance
FW; all	+	Increase in growth; higher production	Increase feed input
FW: cage	-	Eutrophication & upwelling; mortality of stock	Better planning; sitting, conform to cc, regulate monitoring
M/FW; mollusc	-	Increase virulence of dormant pathogens	None; monitoring to prevent health risks
Carnivorous fin fish/ shrimp*	-	Limitations on fishmeal & fish oil supplies/price	Fishmeal & fish oil replacement; new forms of feed management; shift to non-carnivorous commodities
Artificial propagation of species for the "luxurious" LFRT*	(+)	Coral reef destruction	None; but aquaculture will impact positively by reducing an external driver contributing to destruction and help conserve biodiversity
Sea level rise and other circulation changes			
All; primarily in deltaic regions	+/-	Salt water intrusion	Shift upstream stenohaline species- costly; new euryhaline species in old facilities
	+/-	Loss of agricultural land	Provide alternative livelihoods- aquaculture: capacity building and infrastructure
Marine carnivorous fin fish*	- /+	Reduced catches from artisanal coastal fisheries; loss of income to fishers	Reduced feed supply; but encourages use of pellet feeds- higher cost/environmentally less degrading
Shell fish	-	Increase of harmful algal blooms- HABs	Mortality and increased human health risks by eating cultured molluscs
Habitat changes/loss	-	Indirect influence on estuarine aquaculture; some seed availability	None
Acidification			
Mollusc /seaweed culture	-	Impact on calcareous shell formation/deposition	None
Water stress (+ drought conditions etc.)			
Pond culture	-	Limitations for abstraction	Improve efficacy of water usage; encourage non-consumptive water use aquaculture, e.g. CBF
Culture-based fisheries	-	Water retention period reduced	Use of fast growing fish species; increase efficacy of water sharing with primary users e.g. irrigation of rice paddy
Riverine cage culture	-	Availability of wild seed stocks reduced/period changed	Shift to artificially propagated seed; extra cost
Extreme climatic events			
All forms; predominantly coastal areas	-	Destruction of facilities; loss of stock; loss of business; mass scale escapement with the potential to impacts on biodiversity	Encourage uptake of individual/cluster insurance; improve design to minimize mass escapement; encourage use of indigenous species to minimize impacts on biodiversity

Temp.- temperate; Tr.- tropical; STr.- Sub- tropical; LFRT- live fish restaurant trade; CBF- Culture based fisheries. * instances where more than one climatic change element will be responsible for the change.

in cooler waters and would affect aquaculture practices the temperate regions, where salmonid and mollusc farming take place.

There is also the possibility of warming resulting in a more frequent occurrence of harmful algal blooms and emergence of hitherto dormant pathogens, which would particularly threaten mollusc cultivation. There are very few adaptive measures to counteract these negative effects, apart from being more vigilant through regular monitoring measures.

For salmonid farming, an adaptive measure could be to explore possibilities of developing strains tolerant to higher temperatures of 19 to 20 °C.

The predicted increases in water temperatures are often well within the optimal temperature range of most cultured species, particularly in the tropics and subtropics. This means that warming would actually enhance growth of cultured stocks in these regions and increase production (see Table 13).

Sea level rise and associated salt water intrusion, compounded by monsoonal weather pattern changes are a concern in the tropical and subtropical regions where the bulk of aquaculture activities take place. The impact is likely to be more profound in major deltaic areas in the tropics. However, adaptive measures are feasible such as changing a species or moving major current aquaculture operations away from the shore. Seawater intrusion would make some land based agricultural practices impossible or less cost effective. Aquaculture may provide alternative livelihoods and perhaps increase its contribution to the human food basket. This process might be fuelled in part by the fact that financial returns from aquaculture production tend to be significantly higher than those from traditional agriculture on a unit area basis and is relatively less energy demanding than terrestrial animal husbandry.

In the tropics and subtropics, inland aquaculture is predominant and is likely to remain so in the near future. However, considering the potential increased pressure on fresh water availability and quality and the potential impacts of climate change on water resources, it is difficult to predict the expansion of fresh water aquaculture in the mid term. Inland water aquaculture in existing water bodies such as lakes, reservoirs and rivers is increasing, primarily through cage culture. Expected climatic changes could have a profound influence on static water bodies through enhanced eutrophication and stratification and bring about mortality of cultured stocks through upwelling, oxygen depletion and the like. However, there are many adaptive measures available to avoid such calamities, foremost being the development of aquaculture activities in accordance/compliance with the potential carrying capacities of the water bodies and continual monitoring of environment variables in relation to nutrient loading, externally and internally.

The impacts of climate change on wild fish populations are likely to have a significant impact on aquaculture, in particular with regard to the availability of raw materials for the production of fishmeal and fish oil. Feeds for farmed animals bear a very high ecological cost (Bartley *et al.*, 2007) and aquaculture of carnivorous species, which currently constitute only a small proportion of all cultured commodities, is no exception. Such fish are highly valued so the most appropriate way to address this issue would be for the development of suitable diets that use decreasing amounts of fishmeal and fish oil. This process got underway 15 years ago, with the development of high energy diets for salmonids but since then there has been a hiatus.

It is also important to curtail the use of diets containing fish oil through the grow-out phase and adopt "finishing diets" (Jobling, 2003, 2004; Turchini, Francis and De Silva, 2007) prior to harvesting in order to satisfy consumer demands and maintain the fish quality (Menoyo *et al.*, 2004; Mourente, Good and Bell, 2005).

On the other hand, the uncertainty associated with fishmeal and fish oil supplies and their projected reduction as a result of climate change do not apply only to aquaculture. The same ingredients are used in other animal husbandry sectors and in the pet food industry and recently this latter use for non-human food production has been highlighted (Naylor *et al.*, 2000; Aldhous, 2004). There is a need for dialogue around the use of a potentially limiting biological resource (De Silva and Turchini, 2008).

The present analysis also points out the wide range in the returns from use of a unit of fishmeal and or fish oil on the overall production of aquaculture commodities. Aquaculture, unlike terrestrial animal husbandry, relies on a wide range of species, currently around 300 (FAO, 2007). In an attempt to make a meaningful comparison of the environmental costs of aquaculture and other food production sectors, the need to present a balanced picture of the environmental costs of all food producing sectors and to formulate environmental policies considering the impacts of all sectors were considered as a priority (Bartley *et al.*, 2007). However, it is evident that aquaculture is in a stand alone situation, in that the differences between the ecological costs of culturing a carnivorous species such as salmon and an omnivorous/herbivorous fish such as common carp are so widely apart and far different to poultry husbandry and any of the above species, and therefore calls for treating different cultured commodities as separate entities.

Coral bleaching exacerbated by climatic changes and its effects on biodiversity is a major and a growing concern. It is important to consider the process in conjunction with coral destruction caused by destructive fishing methods undertaken to meet the demands of the live fish restaurant trade, a growing luxury trade in limited locations in Asian tropics and subtropics. In view of growing public concern the dependence on wild caught fish for this trade has markedly declined and this niche market is increasingly making use of cultured fish (see Section 5.4.4.). This indicates that aquaculture seems capable of helping lessen the exacerbation of coral reef destruction and enhancing the preservation of biodiversity.

More often than not aquaculture is criticised as ecologically costly and environmentally degrading. Such conclusions are almost always based on aquaculture of high value commodities such as shrimp and carnivorous finfish species such as salmonids and have created erroneous perceptions among public, planners, developers and investors. The fact is that the great bulk of aquaculture is still dependent on fish and molluscs feeding low in the food chain and seaweed commodities that essentially act as carbon sinks and aid in carbon sequestration.

In the wake of climate change, aquaculture has an increasingly important role to play by increasing carbon sequestration, furthering the increased production of fish and molluscs feeding low in the food chain and of seaweeds. Aquaculture offers a high degree of elasticity and resilience to adapt to changes that would even further reduce the sector's contribution to climatic change. For example, the adoption of simple techniques of providing a suitable and/or enhanced food source(s) for cultured stock through measures to increase periphyton growth could be a major energy saving measure (e.g. Van Dam *et al.*, 2002).

Overall, climatic changes impacts on aquaculture are predicted to be very variable, depending on the current climatic zones of activity. The more negative impacts are likely to be on aquaculture operations in temperate regions, viz:

- impinging on the growth rates of cultured, cold water species, resulting from exceeding the optimal temperature ranges for body function, and
- increasing the potential hazards of diseases through the increase of virulence resulting from increased temperatures beyond the dormancy range of these pathogens.

In tropical and subtropical regions, where aquaculture activities predominate, increase in water temperature would bring about the opposite, resulting in increased production. In addition, sea level rise will also impact aquaculture positively, with the possibility of it providing an alternative livelihood means for many practitioners of terrestrial agriculture in deltaic areas. Most importantly, aquaculture offers a less energy consuming food production alternative in comparison to all others and needs to be recognised as such.

Life cycle assessment studies indicate that certain cultured aquatic commodities; in particular shrimp and carnivorous finfish or any aquatic organism relying mainly on fishmeal and fish oil for feeds are energy costly. However, these are increasingly sought after commodities, as a consequence of improvements in living standards and disposable income in developed and developing countries. Production of such commodities are driven by market forces and because there is demand, production will continue to contribute to carbon emissions overall, as compared to the bulk of other aquaculture commodities that are essentially carbon sequestering. A possible solution lies in persuading consumers to move away from the consumption of commodities that are net contributors to carbon emissions. Such a shift will invariably have major social and economic impacts on the producing countries and there is a need to strike a balance in this regard. Perhaps the adaptive measure of including potential carbon emissions from high value food products, as much as eco-labelling, could be most appropriate.

Finally, it has to be conceded there is a need to collate robust quantitative information to address issues regarding the role of aquaculture with relation to climatic change. The efforts of the world are directed towards reducing all forms of carbon emissions, be they from food production processes or transport. With regard to food production, one may wonder if the analysis of impacts in terms of industrial energy is sufficient. For example, carp aquaculture uses minimal industrial energy but has a potential significance in the carbon cycle, fixing CO_2 through phytoplankton, some of which end as fish by way of the food web. Equally, are fertilization and phytoplankton based aquaculture systems more climate/carbon friendly than more intensive forms which utilise considerable amounts of external energy inputs? All of the above questions have to be balanced against the food and development needs; to arrive at considered decisions a large amount of data would be needed as well as global political will.

This treatise cannot end by addressing climatic change influences on aquaculture *per se*. After all, aquaculture does not occur in a vacuum. In order to mitigate further exacerbation of global climate change the world has accepted there should be unified actions to reduce green house gas (GHG) emissions. In this regard, one option is to reduce dependence on fossil fuels as an energy source and to do so by increasing dependence on biofuels. The first generation production of biofuels is from conversion of plant starch, sugars, oils and animal fats into an energy source that could be combusted to replace fossil fuels. Of the biofuels, currently, the most popular is bio-ethanol, produced by fermentation of a number of food crops such as maize, cassava and sugar cane (Worldwatch Institute, 2006). At present, and accounting for energy inputs, Brazilian sugarcane bio-ethanol is observed to have the highest net GHG mitigating potential (Macedo, Verde and Azevedo, 2004). Whilst the world looks to biofuels as an alternative it has had a ripple effect on food crops, prices, availability, access, food security and poverty and an overall impact on sustainable development (Naylor *et al.*, 2007). Aquaculture and most forms of animal husbandry depend, to varying extents, on some of the same food crops used for biofuels production, for feeds. The equation on climatic changes on aquaculture therefore, is not straight forward; many other factors have to be built into this complex equation to bring about adaptive measures and they have to evolve collectively, with an ecosystem perspective rather than sector by sector.

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This document provides an overview of the current scientific knowledge available on climate change implications for fisheries and aquaculture. It contains three technical papers that were presented and discussed during the Expert Workshop on "Climate Change Implications for Fisheries and Aquaculture" (Rome, 7–9 April 2008). A summary of the workshop outcomes as well as key messages on impacts of climate change on aquatic ecosystems and on fisheries- and aquaculture-based livelihoods are provided in the introduction. The first paper addresses climate variability and change and their physical and ecological consequences on marine and freshwater environments. The second paper tackles the consequences of climate changes impacts on fishers and their communities and reviews possible adaptation and mitigation measures that could be implemented. Finally, the third paper addresses specifically the impacts of climate change on aquaculture and reviews possible adaptation and mitigation measures that could be implemented.

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