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CLIMATE CHANGE IMPLICATIONS FOR FISHERIES AND AQUACULTURE

Summary of the findings of the Intergovernmental Panel on Climate Change Fifth Assessment Report




Cover photos: Anika Seggel

CLIMATE CHANGE IMPLICATIONS FOR FISHERIES AND AQUACULTURE

Summary of the findings of the Intergovernmental Panel on Climate Change Fifth Assessment Report

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ABSTRACT

This report aims to facilitate the use of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) by those concerned with the fisheries and aquaculture sector and their dependent communities. The extensive information within the AR5 is condensed from the fisheries and aquaculture perspective, and guiding links to the relevant IPCC documents facilitating further investigation are provided. The report moves from the chemical and physical changes already observed and forecasted within the aquatic systems (inland and marine), to the implications of these changes for fisheries and aquaculture production systems. The AR5 is then reviewed for knowledge on the effects, vulnerabilities and adaptation options within the sector and its dependent communities at the continent and regional scales. The report concludes with a review of knowledge gaps from the fisheries and aquaculture perspective that would support further IPCC efforts.

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ABBREVIATIONS AND ACRONYMS

AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
$CaCO_3$	Calcium carbonate
CFP	Ciguatera fish poisoning
CBS	Coastal Boundary Systems
CO_2	Carbon dioxide
EBA	Ecosystem-based adaptation
ENSO	El Niño-Southern Oscillation
EBUEs	Eastern Boundary Upwelling Ecosystems
EUS	Equatorial Upwelling Systems
GDP	Gross domestic product
GMSL	Global mean sea level
GPS	Global positioning system
HLSBSs	High-Latitude Spring Bloom Systems
HZ	Hypoxic zone
MPA	Marine protected areas
OA	Ocean acidification
O_2	Oxygen
SLR	Sea level rise
SESs	Semi-enclosed seas
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SFP	Summary for Policymakers
STG	Subtropical Gyres
SSF	Small-scale fisheries
SST	Sea surface temperature
STG	Subtropical gyre
PDO	Pacific decadal oscillation
PES	Payment for environmental services

1. INTRODUCTION

Fisheries, aquaculture and the associated post-harvest activities support millions of livelihoods and contribute significantly to food security and economic well-being in coastal zones,[1] freshwater systems and beyond (WGII (A), p. 384). Fisheries alone provide "3 billion people with almost 20 percent of their average [per] capita intake of animal protein" with 400 million depending critically on fish for their food security (WGII (A), p. 452). Globally, 850 million people live within 100 km of tropical coastal ecosystems, such as coral reefs and mangroves, deriving multiple benefits, including food security, coastal protection, cultural services, and income from industries such as fishing, aquaculture and tourism (WGII (B), p. 1688).

Climate change – alongside climate variability events such as El Niño-Southern Oscillation (ENSO) and extreme weather events – is affecting the abundance and distribution of fisheries resources and suitability of geographical locations for aquaculture systems. Underlying climate-related physical and chemical changes are linked to yet growing carbon dioxide (CO_2) emissions, which are being absorbed in large part by the aquatic systems and trigger substantial shifts of aquatic ecosystems and related services, with socio-economic consequences around the globe. Scientific knowledge on the impact of individual climatic drivers varies and is limited on their combined effects; such uncertainty complicates adaptation planning within the sector.

This report aims to facilitate the use of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) by those concerned with the fisheries and aquaculture sector and its dependent communities. The extensive information within the AR5 is condensed from the fisheries and aquaculture perspective and guiding links to the relevant IPCC documents facilitating further investigation is provided. The report moves from the chemical and physical changes already observed and forecasted within the aquatic systems (inland and marine), to the implications of these changes for fisheries and aquaculture production systems. The AR5 is then reviewed for knowledge on the effects, vulnerabilities and adaptation options within the sector and its dependent communities at the continent and regional scales. The report concludes with a review of the knowledge gaps in the IPCC AR5 with regard to capture fisheries, aquaculture and the dependent human systems under climate change.

The Intergovernmental Panel on Climate Change (IPCC) took the decision to prepare the Fifth Assessment Report (AR5) in 2008. The AR5 consists of three Working Group (WG) documents and Special Reports. Information for the *Summary of IPCC AR5 Findings on Climate Change Implications for Fisheries and Aquaculture* has been derived from Working Group documents I and II (A and B) (referenced in this document as WGI and WGII (A) and WG II (B)); the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (referenced in this document as SREX); and the WGII Summary for Policymakers (referenced in this document as SFP). To note, the Working Group III document is not included, although the authors of this summary report acknowledge the important links between adaptation and mitigation within fisheries, aquaculture and the aquatic systems.

To note, the citations within the IPCC Working Groups documents and reports are not included in the summary report.

[1] Natural systems of coastal zones: Next to coral reefs and mangroves, wetlands and seagrass beds, coastal aquifers, estuaries, lagoons and deltas are important elements of coastal ecosystems and – dependent on the region – threatened by climate change and variability (WGII (A), p. 380).

2. CHEMICAL AND PHYSICAL DRIVERS OF CHANGE

This section summarizes the key chemical (salinity, O_2 content, carbon uptake and acidification) and physical (temperature, sea level, ocean circulation, storm systems) changes affecting the global marine (including coastal) and freshwater systems presented by the IPCC AR5 report.

2.1 Oceanic systems

Physical changes I: temperature change and thermal stratification
The upper ocean mean temperature has evidently and with certainty increased from 1971 to 2010 (by 0.11 °C/decade in 0–75 metre depths and by 0.015 °C/decade in 0–700 metre depths) (WGI, p. 261). Fewer data are available for ocean depths below 700 metres. Available data, however, indicate that the mean global temperature of oceans has increased between 700 and 2 000 metres since 2005 (WGI, p. 263). Ocean warming is subject to regional, seasonal, annual and decadal fluctuations. Variability in inter- and intraregional oceanic temperature changes is evident over the 1950–2000 period, with an increase in temperature of 0.11°C/decade in the Indian Ocean, of 0.08 °C/decade in the South Atlantic, and of 0.08 °C/decade in the South Pacific; the North Pacific, however, did not show a clear warming trend during this period (WGII (B), p. 1664). In spite of intraregional differences, all three oceans experience a mean warming trend of surface layers, with the Indian Ocean (+ 0.11°C/decade) warming the fastest, followed by the Atlantic (+ 0.07 °C/decade) and the Pacific (+ 0.05 °C/decade) (ibid.). A direct consequence of the relative intensification of the ocean surface warming is the increased thermal stratification of the upper ocean by 4 percent (between 0–200 metres) from 1971 to 2010 (WGI, p. 263), with regionally different implications for upwelling systems (WGII (B), p. 1672).

Physical changes II: sea level change, including extremes
Sea level changes can be influenced by a variety of factors, such as the warming or cooling of the ocean and the subsequent thermal expansion or contraction of water volume (WGI, p. 285). The global mean sea level (GMSL) has risen by 1.7 mm/year from 1901 to 2010 (WGI, p. 287). Deviations from long-term global trends can exist for periods of several years, especially during El Niño (e.g. 1997–1998) and El Niña (e.g. 2011) events. The satellite altimetry method, available since 1993, has provided evidence that the sea level in the warm pool of the western Pacific is increasing at rates three times higher than the GMSL, while rates for most parts of the eastern Pacific are neutral or negative (WGI, p. 288). Evidence exists that the strong increase in GMSL in the eastern Pacific is caused by an intensification of trade winds since the late 1980s, possibly related to the Pacific Decadal Oscillation (PDO) (ibid.). Examining long tide gauge records in the North Atlantic, several studies have identified decadal-scale fluctuations along the east coast of the United States of America and the European coasts (ibid.). Strong decadal-scale fluctuations have been observed for the coastlines of the Indian Ocean as well. Consequently, local and regional rates of sea level changes can (i) fluctuate and (ii) can be considerably higher or lower than the GMSL for years or even decades. These changes are with high certainty related to interannual and decadal changes in large-scale winds and ocean circulations (WGI, p. 291). The rate of sea level rise (SLR) is very likely to further increase between 2010 and 2100 owing to increased thermal expansion and the continuous process of melting glaciers and ice sheets (WGII (B), p. 1669). Uncertainty concerning predictions on the global mean and regional SLR persists (WGI, p. 288).

Physical changes III: ocean circulation, surface wind, storm systems and waves
Many of the chemical, physical and biological characteristics of oceans are driven by the circulation of the atmosphere and ocean. Phenomena, such as primary production, coastal upwelling, ocean ventilation and biogeochemical cycling, are particularly driven by this circulation, which is important for transporting nutrients from deep waters to the upper water layers (WGII (B), p. 1671). Storms (and surface winds) are also important agents of water column mixing and circulating nutrients. They can reduce local water temperatures and thus counteract associated stressors, but they can also impact coastal habitats such as coral reefs and mangrove forests as well as coastal infrastructure including aquaculture systems (ibid.). Although there is low confidence (due to limited long-term data) in the long-term trends of storm intensity and frequency, available data indicate that: (i) the frequency of intense cyclones in the Atlantic has increased since 1987; (ii) there are inter-decadal changes in storm activity in the North Pacific and North Atlantic; and (iii) land-falling tropical cyclones are twice as common in La Niña versus El Niño years (ibid.). The AR5 statements regarding these ocean circulation, wind, storm and wave patterns are made with medium or low certainty, pointing at the need for further in-depth research to improve the understanding of these critical factors – also with regard to future developments (ibid.).

Chemical changes I: salinity and freshwater content
Ocean salinity trends vary regionally and contain implications for oceanic circulation and stratification and therefore the ocean's capacity to store heat and carbon and circulate nutrients (WGI p. 265, WGII (B) p. 1673). In general, a freshening of mid- and high-latitude waters together with increased salinity at low latitudes has been observed with particular large-scale documented changes in ocean salinity from 1955 to 1998 (WGII (B), p. 1664). The observed trends in ocean salinity are likely to continue as the average global temperature increases (WGII (B), p. 1673).

Chemical changes II: oxygen concentration
The concentration of dissolved oxygen (O_2) is a key determinant of the distribution and abundance of marine organisms. A long-term trend in global mean deoxygenation of surface water has been observed, which is consistent with the rise of the mean global surface temperature and relates back to the fact that warm water holds less O_2 (WGI, p. 295). There is high agreement that O_2 concentrations have particularly decreased in the upper layer of the equatorial Pacific and Atlantic Oceans (WGII (B), p. 1675). On the contrary, O_2 concentrations have increased in the North and South Pacific, North Atlantic, and Indian Oceans. The trend of increasing O_2 concentrations in certain regions is attributed to strengthening wind systems and subsequent ventilation of ocean systems (ibid.). In fact, studies on oxygen changes indicate that about 15 percent of the decrease of available oceanic oxygen between 1979 and 1990 could be explained by warming, and 85 percent of the remainder by increased microbial respiration and increased stratification (WGI, p. 295). High agreement exists that O_2 concentrations will continue to decrease in many parts of the global oceans (WGII (B), p. 1676). Regional variations with regard to this trend are very likely (WGII (B), p. 1677).

Chemical changes III: carbon uptake and acidification
The oceans act as a reservoir for inorganic carbon and currently store roughly 50 times more carbon dioxide than the atmosphere. Trends in regional surface seawater pCO_2 (partial pressure of CO_2) were computed[2] for the North Atlantic and the North Pacific from the 1980s (different start dates for

[2] The air-sea flux of CO_2 is computed from the observed difference in the partial pressure of CO_2 (pCO_2) across the air-water interface, the solubility of CO_2 in seawater, and the gas transfer velocity between air- and sea-surface water (WGI, p. 292).

different stations) to 2006/08 (WGI, p. 299). At all locations and over all time periods tested, pCO_2 in both the atmosphere and ocean has increased (WGI, p. 292). Based on a variety of independent studies, the IPCC AR5 is virtually certain that the global oceanic CO_2 inventory increased from 1994 to 2010 (WGI, p. 299). The increased uptake of CO_2 changes the chemical balance in the ocean, as dissolved CO_2 forms a weak acid (H_2CO_3) resulting in a gradual decrease of the pH value and a subsequent acidification of seawater. Currently, the mean pH of surface waters ranges between 7.8 and 8.4 in the open ocean (WGI, p. 293). Estimates of future atmospheric and oceanic CO_2 concentrations indicate that, by the end of this century, the "average surface ocean pH could be lower than it has been for more than 50 million years" (WGI, p. 295).

Key IPCC AR5 Information: Physical and Chemical Changes in Oceanic Systems

- The global mean upper ocean temperature (0–700 metres) has evidently and with certainty increased during the past three decades. Strong regional variability exists.
- The global mean sea level has risen by 1.7 mm/year (1901–2010). The sea level of the western Pacific is rising three times faster than the global mean sea level. Changes in sea level can be subject to strong annual and/or decadal fluctuations. Sea level is predicted to further rise due to thermal expansion and melting glaciers.
- Information provided on long-term ocean circulation trends, surface winds, storms systems and wave patterns indicate regional changes have occurred for most of the phenomena but data appear limited.
- Salinity levels are decreasing in high- and mid-latitude systems and increasing in low-latitude systems.
- A long-term trend in global mean deoxygenation of surface waters has been observed, which is consistent with the rise of the mean global surface temperature and relates to the fact that warm water holds less O_2.
- Oceans store more than 50 times more CO_2 than the atmosphere. Virtual certainty exists that the global oceanic CO_2 inventory increased from 1994 to 2010 and contributes to the increasing acidification of the oceanic environment. Estimates indicate that the global oceanic CO_2 inventory is very likely to further increase.
- The global mean rate of sea level rise is likely to further increase.
- High agreement exists that O_2 concentrations will continue to decrease in most parts of the global oceans.
- The observed trends in ocean salinity are likely to continue as the average global temperature increases.
- Future developments of ocean circulations, wind, storm and wave systems are made with medium or low certainty.

2.2 Coastal systems

Part of oceanic systems, coastal systems deserve special attention as they are particularly exposed to changes in SLR, sea surface temperatures, ocean acidity and extreme (weather) events[3] (WGII (A), p. 364). Additionally, coastal systems are influenced by a variety of human drivers, which often exacerbate the climatic drivers (WGII (A), p. 367). Key human drivers include, *inter alia*, nutrient runoff, related spread of hypoxic zones, unsustainable infrastructure and sediment delivery (ibid.).

Sea level rise (SLR)

The main underlying climate drivers for the rising sea level (mean and relative) include, *inter alia*: (i) thermal expansion due to warming oceans; (ii) melt water from glaciers, icecaps and ice sheets of Greenland and Antarctica; and (iii) storms (WGII (A), p. 369; p. 371). When looking at the exposure of coastal systems to rising sea levels, it is important to note that: (i) SLR is not uniform in time and space, as regional, seasonal and decadal variations exist; (ii) there is not yet a consensus on a twenty-first century upper boundary of the global mean sea level; and (iii) it is virtually certain that

[3] These are not exclusive to coastal systems, but for food production and livelihoods on a global scale.

the global sea level will continue to rise beyond the twenty-first century (WGII (A), p. 369). The AR5 expresses high confidence that coastal systems and low-lying areas will increasingly be exposed to impacts such as submergence, coastal flooding, coastal erosion and saltwater intrusion (WGII (A), p. 364).

Sea surface temperature (SST)

SST has significantly warmed during the past 30 years along more than 70 percent of the world's coastlines (WGII (A), p. 371). Coastal areas have, on average, warmed by 0.18 ± 0.16 °C per decade, whereas the global open ocean has, on average, warmed by 0.11 °C per decade (WGII (A), p. 372). High confidence exists that coastal SST trends will continue (ibid.).

Changes in pH value

Under the IS92a CO_2 emission scenario,[4] the global mean coastal pH value is predicted to decrease from 8.16 (1850) to 7.83 (2100) due to anthropogenic climate change (WG II (A), p. 372). Hence, the overall decrease of coastal pH values – including immense spatial variations – is predicted to be higher than the decrease of the pH value in the open ocean (see section 2.1.) (WG II (A), p. 372). High confidence is expressed that coastal acidification will continue but with large variations regionally and locally (ibid.).

Extreme events

The concept of extreme events is split by the AR5 into three categories: (i) weather and climate variables (temperature, precipitation, winds); (ii) phenomena related to weather and climate extremes (monsoons, El Niño and other modes of variability, [extra-] tropical cyclones); and (iii) impacts on the physical environment (droughts, floods, extreme sea level rise) (SREX, p. 119). Global mean projected changes of extremes (up to 2100 with respect to the late twentieth century) include the following predictions:

- **Likely – certain** that unusually hot days (per year) are increasing on a global scale, heavy precipitation is becoming more frequent (particularly in high latitudes and tropical regions) (SREX, p. 13), and that (global mean) tropical cyclones will either decrease or not change regarding frequency, but will increase in mean maximum wind speed and will cause increasing precipitation (SREX, p. 119).
- **Medium confidence** exists on the reduction of mid-latitude storms (storm track is shifting poleward), that droughts are becoming more severe (length and intensity) in some regions, such as southern Europe (including the Mediterranean), central Europe, central North America, Central America and the United Mexican States, in the northeast of the Federative Republic of Brazil, and southern Africa. Overall, low agreement exists for other regions due to insufficient agreements of projections (SREX, p. 119).
- **Low confidence** exists on global projections on flood magnitude, regional projections of extratropical cyclones and projections on extreme winds (SREX, p. 119). However, increasing evidence for a strengthening wind field in the Southern Ocean since the early 1980s exists (WGII (A), p. 371). Furthermore, wave activity is projected to increase in the Southern Ocean with implications for large parts of the global oceans, as swell waves can propagate into the northern part of the three ocean basins (WGII (B), p. 1632).

[4] Find more information on the six alternative IPCC emission scenarios at http://sedac.ipcc-data.org/ddc/is92/.

Key IPCC AR5 Information: Physical and Chemical Changes in Coastal Systems

- High confidence that coastal systems and low-lying areas will increasingly be exposed to impacts such as submergence, coastal flooding, coastal erosion and saltwater intrusion owing to sea level rise. However, strong regional variation exists.
- Sea surface temperature in coastal areas is warming up faster than in the open oceans. This trend is likely to continue.
- Decrease of pH value – and thus acidification – is higher in coastal areas than in the open oceans. This trend is likely to continue.
- Various types of extreme (weather) events are predicted to occur more frequently with potentially strong implications for coastal areas in many regions around the globe.
- Globally, the number of unusually hot days per year is likely to increase, while heavy precipitation is becoming more frequent in many regions.

2.3 Freshwater systems

Freshwater ecosystems (inland systems) are composed of "biota (animals, plants and other organisms) and their abiotic environment in slow-flowing surface waters such as lakes, man-made reservoirs or wetlands; in fast-flowing surface waters such as rivers and creeks; and in the groundwater" (WGII (A), p. 253). On a global scale, freshwater ecosystems have been more adversely impacted by human activities than marine ecosystems (ibid.). According to the Living Planet Index, populations of freshwater species have declined on average by 50 percent (compared with 30 percent for marine species) between 1970 and 2000 (ibid.). Clear attribution of climate change related changes in freshwater ecosystems is often difficult owing to the variety of human drivers potentially affecting these systems through, for example, pollution, freshwater extraction (WGII (A), p. 239) and construction projects such as dams and dykes (WGII, (A), p. 253). The key climatic drivers influencing freshwater systems are evaporation and precipitation levels, temperature (influencing oxygen content and stratification intensity) (WGII (A), p. 240), and storms (WGII (A), p. 257).

Evaporation and precipitation

As the global mean temperature is virtually certain to rise in the foreseeable future, global mean precipitation is predicted to increase accordingly. However, regional variability regarding the changes in precipitation levels are tremendous (WGII (A), p. 240). In general, precipitation "tends to decrease in subtropical latitudes, particularly in the Mediterranean, Mexico and Central America, and parts of Australia, and to increase elsewhere, notably at high northern latitudes and in India and parts of central Asia" (ibid.). By the end of the twentieth-first century, meteorological droughts (less rainfall) and agricultural droughts (drier soil) are projected to "become longer, or more frequent, or both, in some regions and some seasons, because of reduced rainfall or increased evaporation or both. But it is still uncertain what these rainfall and soil moisture deficits might mean for prolonged reductions of streamflow and lake and groundwater levels" (WGII (A), p. 247). The Middle East and North Africa region is already facing dwindling water resources because of decreasing precipitation and rising water demand related to the growing population and could potentially face up to 30–70 percent less water per person by 2025 (relative to 2011) (WGII (A), p. 803). Droughts are also projected to intensify in southern Europe and the Mediterranean region, central Europe, central and southern North America, Central America, northeast Brazil, and southern Africa. (WGII (A), p. 247). Limited data suggest an increase in the frequency and intensity of flood hazards from inland systems (especially smaller river basins), in particular in "central and eastern Siberia, parts of Southeast Asia including

India, tropical Africa, and northern South America, but decreases are projected in parts of northern and Eastern Europe, Anatolia, central and East Asia, central North America, and southern South America" (WGII, p. 247).

Temperature

According to the AR5, there is widespread evidence of rising stream and river temperatures over the past few decades (WGII (A), p. 313). Rising temperatures are likely to cause fluctuations in the thermal dynamics of freshwater systems, including increasing stratification, decreasing nutrient circulation, and implications for primary production and hence higher trophic levels. In addition, the predicted more intense eutrophication and algal blooms are likely to have implications for local aquatic ecosystems (WGII (A), p. 237). Higher algal production in freshwater systems may also be stimulated by rising CO_2 concentrations. The trophic consequences of rising CO_2 concentrations in freshwater systems are difficult to predict (WGII (A), p. 287).

Storms

More frequent storms can decrease the risk of algal blooms and eutrophication in freshwater systems such as estuaries and lakes. The risk is reduced by storms flushing away nutrients (nutrient runoff is often one key human stressor enhancing climate change related impacts) (WGII (A), p. 257). However, where storms carry nutrients to the sea, exacerbating eutrophication in marine ecosystems can be a possible consequence (ibid.).

Key IPCC AR5 Information: Physical and Chemical Changes in Inland Systems

- Global mean precipitation is predicted to increase with strong regional variations.
- The Middle East and North Africa region, southern Europe, the Mediterranean, central Europe, central and southern North America, Central America, northeast Brazil, and southern Africa are projected to experience decreasing precipitation levels and droughts.
- Precipitation is expected to increase elsewhere, notably at high northern latitudes and in India and parts of central Asia.
- Where precipitation increases, floods are a likely consequence in the future.
- Rising global temperatures are very likely to reduce oxygen levels and stratification dynamics of freshwater systems.
- Trophic consequences of rising CO_2 concentrations in freshwater systems are difficult to predict.

3. FISH STOCKS, SHELLFISH AND AQUACULTURE UNDER CLIMATE CHANGE

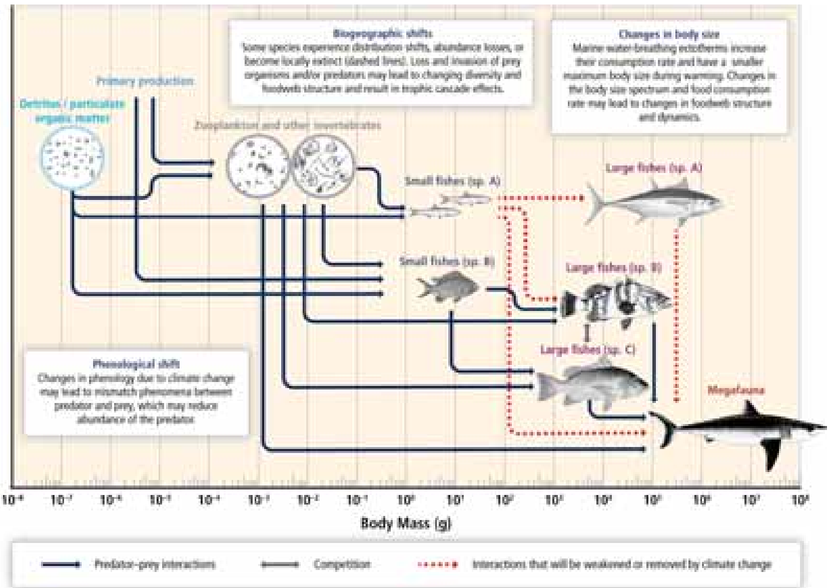
This section summarizes the information provided by the AR5 on the implications of changing chemical and physical drivers for fish stocks, shellfish and aquaculture systems. Section 3.1 presents an overview on observed and predicted responses of the biological systems including possible implications for capture fisheries. Section 3.2 provides information on observed and predicted implications for corals, fish and shellfish in six[5] major ocean systems and inland systems. Section 3.3 summarizes AR5 information on aquaculture systems.

[5] Deep seas (> 1 000 m) not included as available data are very limited.

3.1 Overview: changing climate, shifting ecosystems and migration of marine species

The combination of sea surface warming, the spread of hypoxic zones and decreasing pH values is contributing to a variety of changes in biological systems, such as the reduction in body size of individual animals, the shifting of the biogeographies of whole stocks, which are influencing species abundance and composition, trophic linkages and interaction dynamics (WGII (A), p. 449). Expected responses of the marine food web to these drivers are illustrated in Figure 1.

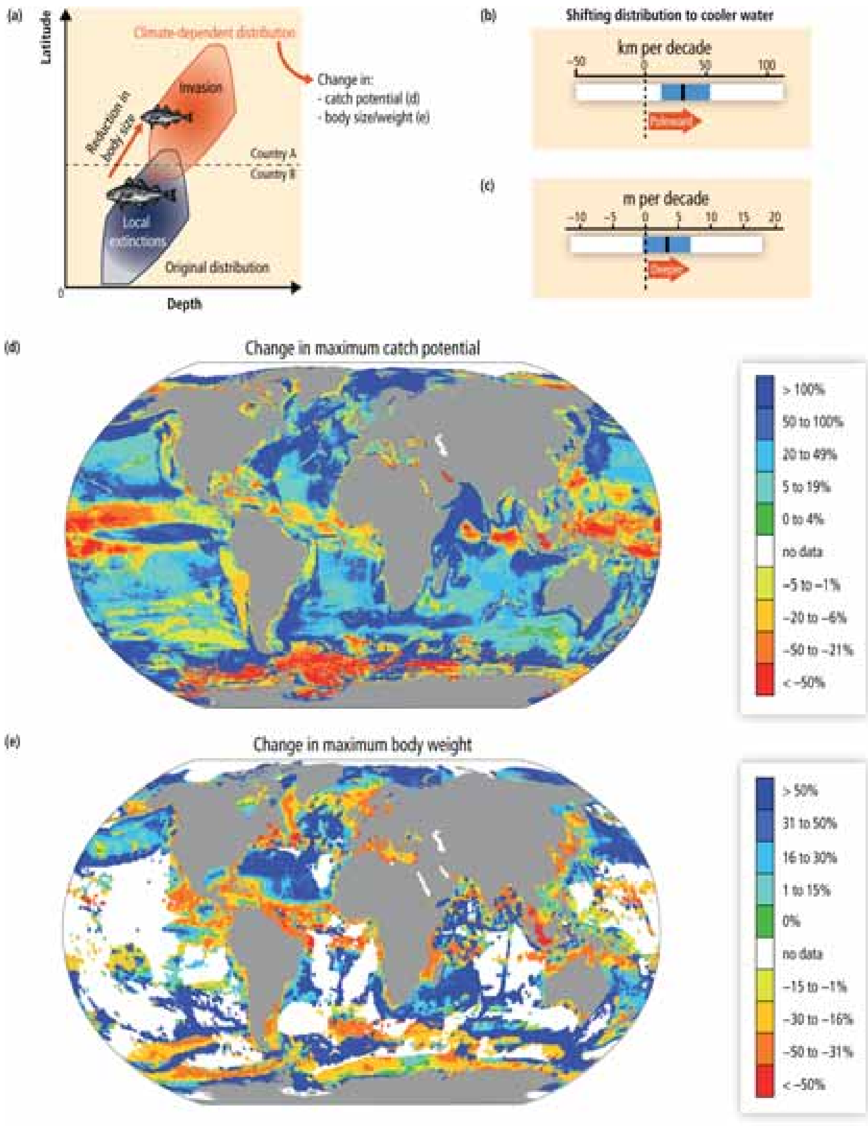
Figure 1: Schematic diagram of expected responses to climate change in a marine food web



Source: IPCC AR5 WGII (A), p. 449

The AR5 refers to shifts in biogeographical ranges as a “simple mode of adaptation”. On the contrary, where species acclimatize to rising temperatures, reduced oxygen availability and lowered pH levels in their traditional habitat, AR5 refers to “evolutionary adaptation” (WGII (A), p. 426). Active marine animals (e.g. fishes and crustaceans) tend to have high O_2 demands and are thus often excluded from permanently hypoxic zones (WGII (A), p. 443). However, temporary adaptation of, for example, bigeye tuna to reduced O_2 conditions has been observed (WGII (A), p. 423) and hypoxia-adapted lifeforms (e.g. Humboldt squid) are likely to benefit from expanding oxygen minimum zones (WGII (A), p. 443). Nevertheless, rapid evolutionary adaptation might be outside the adaptive capacity of many marine organisms (WGII (A), p. 423). Where phenological shifts occur, mismatches between predator and prey can ensue, with potentially disruptive implications for the marine food web (Figure 1). The report notes that the removal of large-bodied fish species through fishing often undermines clear attribution of food web responses to climate change (WGII (A), p. 449). The relatively low evolutionary adaptive capacity of aquatic species to climate change is predicted to shift the biogeographies of many species, with tremendous implications for capture fisheries during the next decades and beyond. Figure 2 illustrates the potential extent of biogeographic and body size changes of 610 species of marine fish from 1991–2010 to 2041–2060 under SRES A2. Where biogeographical change is not sufficient for entering habitats that satisfy oxygen, food and temperature requirements of species, animals are predicted to experience a reduction in body size (WGII (A), p. 458). Figure 2 does not take acidification and fishing into consideration.

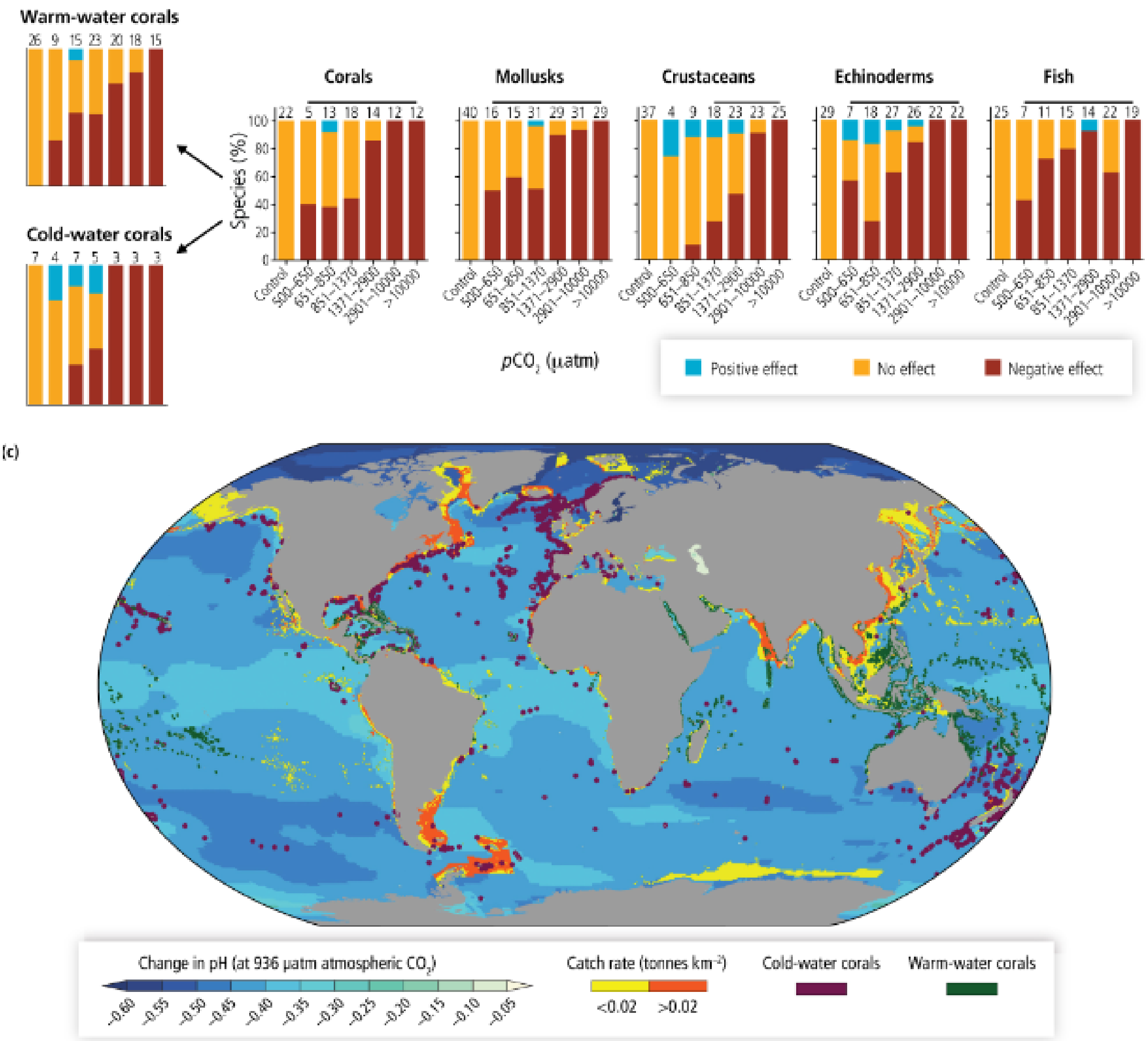
Figure 2: Climate change effects on the biogeography, body size and fisheries' catch potential of marine fishes and invertebrates[6]



Source: IPCC AR5 WGII (A), p. 458).

[6] More detailed information on (a), (b), (c), (d) and (e) of this graphic can be found in WGII (A), p. 458.

Figure 3: The oceans – visualizing the impact of increasing CO_2 uptake on calcifying organisms and fish[7]



Source: IPCC AR5 WGII (A), p. 438.

Complementing Figure 2, Figure 3 visualizes the predicted impacts of increasing CO_2 uptake on calcifying organisms and fish. Observed and predicted changes in regional pH values are of particular concern for calcifying organisms, as these organisms use seawater calcium to produce calcium carbonate ($CaCO_3$) to construct their skeletons or shells. In the process of building up shells and skeletons, species have to transport calcium into specific sites of their bodies and raise the alkalinity (increase pH value) at these sites to values higher than in other parts of their body and surrounding seawater (WGII (A), p. 463). The conversion of carbon to $CaCO_3$ consumes high amounts of energy, and the energy required to maintain alkalinity levels to build shells and skeletons goes up as CO_2 level in the ambient waters increase (ibid.). Problematically, "the more energy is needed for calcification, the less is available for other biological processes such as growth or reproduction, reducing the organisms' weight and overall competitiveness and viability" (ibid.). Furthermore, exposure of external shells to more acidic water can affect their stability by weakening or actually dissolving

[7] More detailed information on Figure 3 can be found in WGII (A), p. 438.

carbonate structures. However, certain mussels have been observed to conduct a special coating procedure to protect their shells from direct contact with seawater (ibid.).

The AR5 estimates that climate change processes could lead to an average 30–70 percent increase in marine capture fisheries yields from high latitude regions (> 50 N), and decreases of up to 40 percent in the tropics by 2055 relative to 2005 with implications for food security (WGII (A), p. 414).

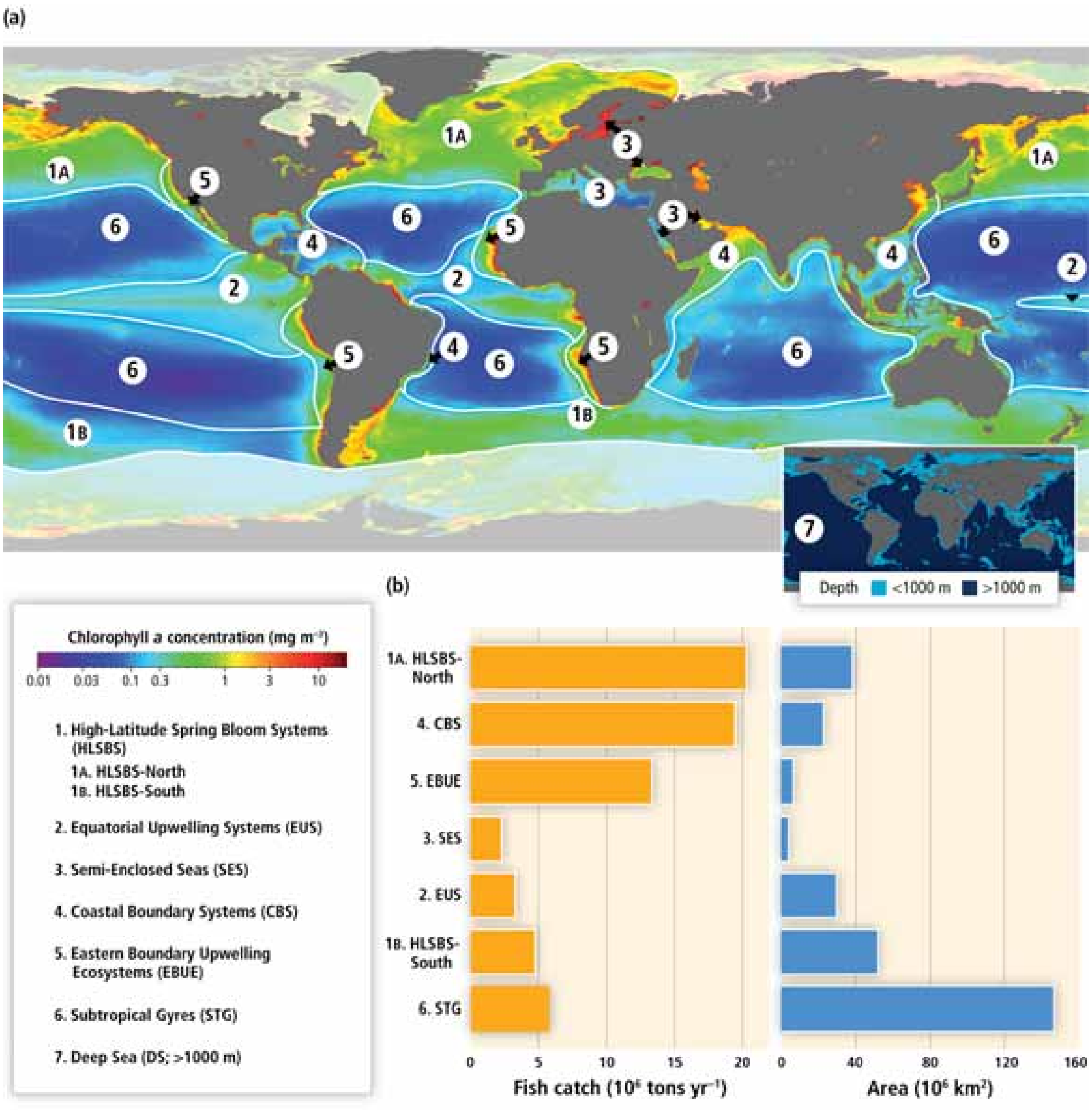
Key IPCC AR5 Information: Changing Climate, Shifting Ecosystems and Migration of Marine Species

- Marine biological systems are changing due to factors such as sea surface warming, the spread of hypoxic zones and decreasing pH values (strong regional variations).
- Biogeographic (simple mode of adaptation) and phenological shifts are possible consequences.
- CO_2 uptake of oceans is of particular concern for calcifying organisms.
- High latitude regions could experience an average of 30–70 percent increase in marine capture fisheries, while tropical regions could see a decrease of up to 40 percent (2055 relative to 2005).

3.2. Observed and predicted implications for corals, fish and shellfish in six major ocean systems and inland systems

The oceans are major contributors to global food security, with total global marine capture fisheries having stabilized in the mid-1990s at about 90 million tonnes per year and marine aquaculture (primarily molluscs and crustaceans and mostly concentrated in coastal areas) contributing more than 63 million tonnes annually to seafood production (WGII (A), p. 452). More than 80 percent of the global marine fisheries catch is associated with three ocean subregions: Northern Hemisphere High-Latitude Spring Bloom Systems (HLSBSs); Coastal Boundary Systems (CBSs); and Eastern Boundary Upwelling Ecosystems (EBUEs) (WGII (B), p. 1662) (Figure 4). High certainty is expressed that species and ecosystems are responding to climate change in all oceanic subregions (see Figure 5) (WGII (B), p, 1658). These responses include “marine organisms (…) moving to higher latitudes, consistent with warming trends (high confidence), with fish and zooplankton migrating at the fastest rates, particularly in HLSBS regions” (ibid.).

Figure 4: The world's oceans and relationship between fish catch and area for each ocean subregion



Source: IPCC AR5 WGII (B), p. 1663.

High-Latitude Spring Bloom Systems (HLSBSs)

North Atlantic, North Pacific and Southern Hemisphere: Related to continuous warming, the North Atlantic has experienced a northward expansion of plankton, invertebrate and fish communities (WGII (B), p. 1658). Overall, the North Atlantic is predicted to experience an increase in total fish biomass owing to the poleward expansion of stocks from low- and mid-latitude regions (WGII (B), pp. 1677). The AR5 concludes that "the diversity of zooplankton and fish has increased as more diverse warm-water assemblages extend northward in response to changing environmental conditions (high confidence)" (WGII (B), p. 1678). Being subject to strong climatic variability, the North Pacific does not show any significant overall warming trends. In spite of decadal fluctuations, pelagic fish species such as yellowtail and Spanish mackerel were observed to shift poleward and these two species are predicted to "shift 39–71 km poleward from the 2000s to the 2030s" (WGII (B), p. 1680). Over a vast region of the Eastern Pacific – ranging from the Republic of Chile to the Aleutian Islands – sporadic upwelling of low O_2 waters is well documented resulting in hypoxic zones, which is the major driver behind reduced growth maximum body weight of individual animals. The predicted upwelling of low O_2 water and the subsequent spread of hypoxic zones will very likely trigger mortality events of coastal fish communities, oyster hatcheries and populations, and invertebrates (WG II (B), p. 1680). However, HLSBSs will most likely experience increasing fish and invertebrate biomass because of the northward expansion of fauna (WGII (B), p. 1678).

Coastal Boundary Systems (CBS)

The Bohai Sea, Yellow Sea, East China Sea, South China Sea, Southeast Asian Seas, Arabian Gulf and Somali Current, East Africa Coast and the Republic of Madagascar, and Gulf of Mexico and Caribbean Current: CBSs include the marginal seas of the northwest Pacific, Indian, and Atlantic Oceans and comprise 10.6 percent of primary production and 28 percent of global fisheries production (WGII (B), p. 1686). AR5 notes that ecosystems within CBSs are often strongly affected by activities such as overexploitation of fisheries, pollution and unsustainable coastal development. These human drivers interact with incrementally increasing ocean temperatures and acidification and have caused substantial changes to a number of ecosystems in the CBS (WGII (B), p. 1686). Medium confidence is expressed by AR5 that “northward shifts in catch distribution for some pelagic fish species in Korean waters were driven, in part, by warming SST (…), the frequency of harmful algal blooms and blooms of the giant jellyfish *Nemopilema nomurai* in the offshore area of the CBS have increased and have been associated with ocean warming and other factors such as eutrophication” (WGII (B), p. 1686), and that it is “very likely that coral-dominated reef ecosystems within the CBS will continue to decline and will consequently provide significantly less ecosystem goods and services for coastal communities if sea temperatures increase by more than 1°C above current temperatures” (WGII (B), p. 1690). In addition to direct climatic drivers, concerns are rising that climate change could cause the spread of pathogens with potential impacts on wild fish (WGII (A), p. 500).

Eastern Boundary Upwelling Ecosystems (EBUEs)

Canary Current, Benguela Current, California Current and Humboldt Current: The EBUEs comprise less than 2 percent of the ocean area, but contribute about 7 percent of global marine primary production (WGII (B), p. 1690). AR5 notes that EBUEs are vulnerable to changes in sea surface temperature, O_2 concentration, wind strength and direction, stratification and carbonate chemistry, but that the extent of vulnerability will depend on local contexts (i.e. their location and on factors such as nutrient runoff and uncontrolled fishing pressure) (WGII (B), p. 1693). Catches are dominated by planktivorous sardine, anchovy, horse and jack mackerel and piscivorous fish such as hake (WGII (B), p. 1690). Detection and attribution of changes within EBUEs to anthropogenic climate change is difficult owing to natural decadal variability. It has been observed that the California Current and Canary Current (medium agreement exists that primary production in the latter decreased during the last two decades) have warmed by 0.73 ºC and 0.53 ºC, respectively, while no significant trends in surface temperatures have been observed for the Benguela and Humboldt Currents[8] (WGII (B), p. 1690). Changing temperatures in the Canary Current is observed to result in changes to important fisheries species and Mauritanian waters, for example, “have become more suitable as feeding and spawning areas for some fisheries species (e.g. *Sardinella aurita*) as temperatures increased” (WGII (B), p. 1691). It is currently being debated whether climate change will intensify ocean upwelling and whether upwelled water (already low in O_2 and undersaturated with aragonite in EBUEs) will be increasingly acidified (WGII (B), p. 1701). Seasonal upwelling of acidified water onto the continental shelf in the California Current region has already affected oyster hatcheries along the coast of Washington and Oregon, but uncertainty persists whether this event is attributable to climate change

[8] The Humboldt Current system – flowing along the west coast of South America – is the most productive upwelling system of the world in terms of fish productivity (WGII (B), p. 1525).

(ibid.). AR5 expresses medium certainty that acidification of seasonally upwelling water will continue to impact shellfish farms in the California Current (WGII (B), p. 1700).

Equatorial Upwelling Systems (EUSs)

The largest EUSs are found in the eastern Pacific and Atlantic Oceans. EUSs experience strong natural annual and decadal variability, most prominently due to El Niño and La Niña events (WGII (B), p. 1682). The average sea temperature associated with the Pacific EUSs has increased significantly (especially but not only during El Niño events) by 0.43 °C and 0.54 °C from 1950 to 2009 in the Pacific and Atlantic EUSs, respectively, and is associated with negative effects on corals (bleaching), kelps and organisms dependent on these ecosystems (ibid., WGII (B), p. 1700). The changes in carbonate chemistry will negatively affect some marine calcifiers even though certain calcifying species in EUSs are used to low aragonite and calcite saturation states and thus might be able to adapt (WGII (B), p. 1683). Projections suggest that fish in the EUSs, especially small pelagic species, will experience increased vulnerability linked to lower O_2 availability owing to the predicted spatial expansion of the subtropical gyre in the Pacific (ibid., WGII (B), p. 463).

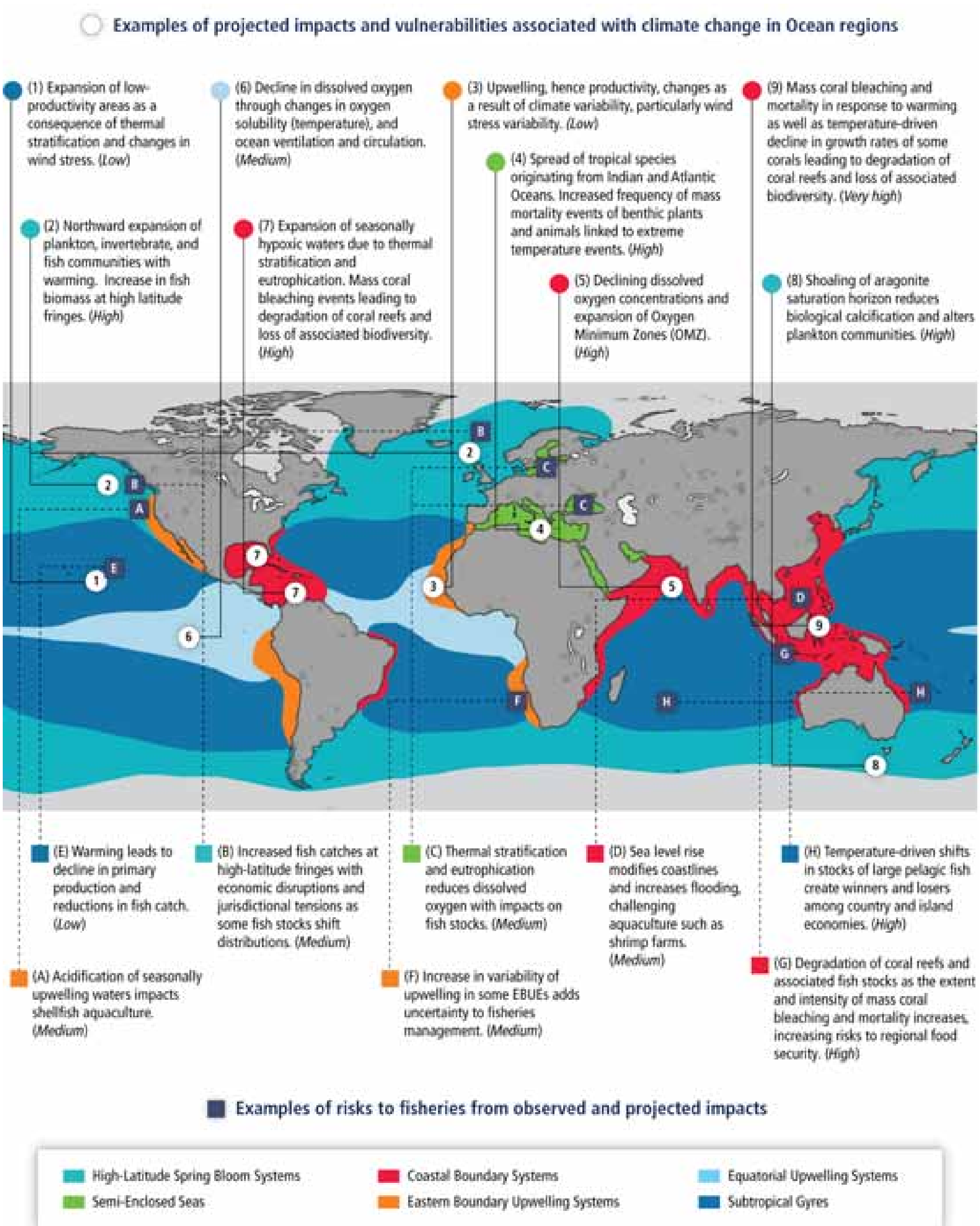
Semi-enclosed seas (SESs)

Arabian Gulf, Red Sea, Black Sea, Mediterranean Sea and Baltic Sea: Risks to ecosystems in SESs are linked to continuous stratification, rising temperatures, changes in pH values, reduced O_2 concentration, and subsequent effects on corals, primary production and larger commercially valuable fish stocks. Even though corals in the Arabian Gulf are used to high temperatures, this subregion has recorded (next to increasing algal blooms) high levels of coral bleaching and subsequent reductions in coral-associated invertebrates (WGII (B), p. 1683). At the same time, the abundance of herbivores and planktivorous fish has increased (ibid.). In the Red Sea, long-term monitoring of the coral community structure has revealed an overall decrease in community size. However, in the Northern Red Sea, coral communities were found that appear to benefit from the warming, suggesting they have lived in suboptimal conditions previously (ibid.). The Black Sea is particularly affected by non-climatic stressors in addition to climate impacts, and has experienced expanding hypoxic zones, declining levels of primary production and collapsing fish stocks (WGII (B), p. 1684). The temperature increase in the Baltic Sea is among the highest in all SESs and has – in combination with decreased salinity levels and overfishing – important negative implications for commercially important species such as cod (ibid.). Increasing temperatures, algal bloom changes in the diversity of zooplankton and the "tropicalization" of the fauna have been observed in the Mediterranean (ibid.).

Subtropical gyres (STGs)

Pacific Ocean Subtropical Gyre, Indian Ocean Subtropical Gyre and Atlantic Ocean Subtropical Gyre: The STGs dominate the Pacific, Atlantic and Indian Oceans and their oligotrophic areas represent one of the largest (and most unproductive) water habitats on earth, contributing solely 8.3 percent of the global fish catch (WGII (B), p. 1694). Temperatures within the STGs of the North Atlantic, South Atlantic, North Pacific, South Pacific, and Indian Oceans have increased from 1998 to 2010 (WGII (B), p. 1694). The increasing temperature has caused thermal expansion with severe implications for a number of small island nations located in the STGs. High confidence exists that decreased wind speed, increasing sea surface temperature and stratification are predicted to reduce the vertical transport of nutrients and will, hence, likely reduce the rate of primary productivity and, thus, fisheries (ibid.). Evidence exists that the North and South Pacific STGs have expanded in size since 1993 (ibid.). The AR5 states that "changes in sea temperature also lead to changes in the distribution of key pelagic fisheries such as skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), bigeye tuna (*T. obesus*) and South Pacific albacore tuna (*T. alalunga*)" (ibid.). Habitats in the Pacific are further predicted "to contract for the blue whale, salmon shark, loggerhead turtle, and blue and mako sharks, yellowfin and skipjack tuna, while potential habitats for the sooty shearwater, black-footed albatross, leatherback turtle, white shark, elephant seal, and albacore, bluefin and yellowfin tuna are predicted to expand" (WGII (B), p. 1695). The AR5 expresses high confidence that certain large pelagic fish species will continue to move several hundred miles east of where they are today in the Pacific in response to rising sea surface temperature (WGII (B), p. 1697). Coral dominated ecosystems in the STGs are very likely to disappear by the mid-part of the twenty-first century (WGII (B), p. 1696).

Figure 5: Examples of projected impacts and vulnerabilities associated with climate change in Ocean regions



Source: IPCC AR5 WGII (B), p. 1700.

Inland systems

Compared with oceanic systems, the AR5 provides considerably less information on climate change impacts on fishery resources and aquaculture in inland systems. Yet, freshwater ecosystems are considered to be among the most threatened on the planet, as they are heavily impacted by climatic and non-climatic drivers (WGII (A), p. 313). The warming of water temperatures has caused species range shifts in river fish communities, combined with a decrease in recruitment and survival as well as range contraction of cold-water species such as salmonids (WGII (A), p. 295). Even though changing river temperature regimes are opening up new habitats at higher latitudes or altitudes for migratory aquatic species, AR5 expresses high confidence "that range contraction threatens the long-term persistence of some fully aquatic species" (ibid.). Freshwater systems that are most vulnerable to direct climate impacts, especially rising temperatures, are those at high altitude and high latitude, including alpine and Arctic streams and lakes (WGII (A), p. 312). It is noteworthy that these high-latitude systems currently experience a relatively low level of threat from human activities (ibid.). Climatic drivers (e.g. temperature) affecting inland ecosystems and species distribution interact and are often exacerbated by non-climatic drivers such as invasive species, anthropogenic pollution and habitat modification such as fragmentation of rivers by dams (WGII (A), p. 300; p. 505). A major non-climatic driver – especially in the Northern Hemisphere – is the leakage of nitrogen and phosphorus (WGII (B), p. 286).

Regionally, freshwater reservoirs will also be increasingly under pressure because of the growing demand for irrigation in agriculture. In general, inland fisheries will be at risk in areas that experience water stress and competition for water resources (WGII (A), p. 501). It is estimated that the combined effects of freshwater withdrawal and climate change will cause up to 75 percent[9] (2070 relative to 2005) of freshwater fish biodiversity to be "headed towards extinction", with the highest rates occurring in tropical and subtropical areas (WGII (A), p. 508). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g. Australia, California and South Africa) are projected to "experience a shortened wet season and prolonged, warmer summer season, increasing the vulnerability of fish communities to drought…and floods" (WGII (A), p. 313). Currently, freshwater fish are already experiencing the highest documented extinction rate of all vertebrates with, however, most extinction cases having been attributed to non-climatic drivers (WGII (A), p. 300). It is estimated that increased temperature has caused a decrease of approximately 30 percent in fish yields in Lake Tanganyika in East Africa (WGII (A), p. 493). However, other studies referred to in AR5 attribute the observed decreases in yields to unsustainable fishing practices (ibid.). A similar disagreement exists on Lake Kariba, with scientists explaining the decrease in biomass either by referring to climatic drivers or unsustainable management of fisheries (ibid.). Uncertainty remains concerning attributing these decreases in resource abundance in the Great African lakes to climatic or human drivers (WGII (B), p. 1216).

[9] Freshwater fish for 133 rivers have been examined.

Key IPCC AR5 Information: Observed and Predicted Implications for Corals, Fish and Shellfish in Oceanic and Inland Systems

- Total marine capture fisheries produce approximately 90 million tonnes per year.
- Changes in biological systems in all major ocean systems have been observed or are predicted.
- Biogeographic shift of species poleward and/or to deeper waters potentially contributes to overall reduction of catch potential in low- and mid-latitudes.
- Globally, corals suffer from heat stress and acidification. However, certain species benefit from changes in pH levels suggesting they lived in suboptimal conditions before.
- The subtropical gyres are expanding in size and hence reducing habitat of species dependent on high oxygen availability.
- Fewer data and information are available on concrete biological changes in inland systems, as it is difficult to understand whether ecosystem and fish stock degradation is due to climate change and/or human drivers.
- Clear attribution of climate change impacts on biological systems is yet often difficult owing to a lack of long-term data, limited understanding of combined effects of diverse chemical and physical factors, and the impact of human drivers on the aquatic systems.

3.3. Aquaculture – oceanic and inland systems

Responding to the increasing demand for fish, aquaculture production has expanded rapidly during the past decades. According to the AR5, an additional 71 to "117 million tonnes of fish will need to be produced by aquaculture to maintain current average per capita consumption of fish" (WGII (A), p. 500). Even though the growth of aquaculture has decelerated recently, it is still considered a development opportunity for regions in Africa and Latin America (WGII (A), p. 452). AR5 predicts that climate change will impact aquaculture production on various levels (WGII (B), p. 1702). Aquaculture systems will be affected by climate change through "gradual warming, ocean acidification, and changes in the frequency, intensity and location of extreme" (WGII (A), p. 494).

- Feed for aquaculture – The expansion of aquaculture adds pressure on capture fisheries, as "two-thirds of farmed food fish production (marine and freshwater) is achieved with the use of feed derived from wild-harvested, small pelagic fish and shellfish" (WGII (B), p. 1702). Fluctuations in the availability and price of fishmeal and fish oil for feeds challenge the growth of sustainable aquaculture production (ibid.). Availability and price of feeds are particularly concerning given increasing uncertainties regarding changes in fisheries yields in EBUEs (ibid.).
- Vulnerability of farmed species to chemical change – Exposed through cages and racks placed directly in the sea or utilizing seawater in inland tanks, invertebrate fisheries and aquaculture appear most vulnerable to ocean acidification (WGII (A), p. 452). Changes in carbon chemistry seem to be especially detrimental for aquaculture systems that specialize in calcifying organisms (WGII (A), p. 436). One prominent example for acidification impacts on aquaculture occurred in 2011 when acidic waters brought up from the deeper ocean to the surface by wind and currents off the northwest coast of the United States of America and affected oysters grown in that area (ibid., WGII (B), p. 1700). Yet, comparative studies on "animal sensitivities to acidification over a complete life cycle or during critical transition phases (e.g. fertilization, egg development and hatching, metamorphosis, molting) are scarce and do not support generalizing conclusions" (WGII (A), p. 441). Many investigated species display greater sensitivity to ocean acidification when forced to "exist at the edges of their thermal ranges" (WGII (A), p. 436).

- Changes in physical conditions – Flooding and inundation by seawater may be a problem to shore facilities on low lying coasts. For example, shrimp farming operations in the tropics will be "challenged by rising sea levels, which will be exacerbated by mangrove encroachment and a reduced ability for thorough drying of ponds between crops" (WGII (B), p. 1702). With regard to the river Ganges in the Republic of India, the increase in air temperature, regional monsoon variation, regional increase in intensity of severe storms, etc., have caused changes in species composition and a reduction of available fish spawn for aquaculture while at the same time benefiting the major carp aquaculture through extending their breeding periods, and thus underlining the potential for occurring opportunities related to climate change (WGII (A), p. 493). In the tropical Pacific, the production of freshwater species such as tilapia, carp and milkfish will probably benefit from the expected climate changes (WGII (A), p. 508). Aquaculture operations will be at risk in areas that face water stress and competition for water resources (WGII (A), p. 501). Recently, the permitted harvesting period for the mussel aquaculture industry was reduced in the Iberian Atlantic because of harmful algal blooms resulting from changes in phytoplankton communities linked to a weakening of the Iberian upwelling (WGII (B), p. 1290).

- Diseases – As sea surface temperature continues to increase, a number of endemic diseases of both wild and farmed salmonid populations are likely to become more prevalent, and threats associated with exotic pathogens will potentially rise (WGII (B), p. 1290). The scenario of spreading pathogens is not limited to salmonid populations. In fact, the concern exists that climate change could cause the spread of pathogens with implications for aquaculture systems and wild fish in general (WGII (A), p. 500).

- Economic implications – AR5 estimates that global shelled molluscs' production will experience a substantial decline globally between 2020 and 2060 under the SRESA2 business-as-usual scenario (WGII (A), p. 452). AR5 expresses certainty that acidification has and will have implications for the profitability of aquaculture farms, depending on target species and farm location (WGII (A), 366; WGII (B), p. 1701). Vulnerability to these scenarios differs between countries according to the contribution of such resources to their economy (WGII (A), p. 452). Countries predicted by the AR5 to be most affected are the People's Republic of Bangladesh, the Kingdom of Cambodia, the Republic of Colombia, the Republic of Guinea, the Republic of Malawi, the Islamic Republic of Mauritania, the Kingdom of Morocco, the Republic of Mozambique, the Islamic Republic of Pakistan, the Republic of Peru, the Republic of Senegal, the Republic of Sierra Leone, the United Republic of Tanzania, the Republic of Uganda, Ukraine, Venezuela (Bolivarian Republic of) and the Republic of Yemen. These countries were identified based on "potential vulnerabilities of national economies to the effects of climate change on fisheries, in terms of exposure to warming, relative importance of fisheries to national economies and diets, and limited societal capacity to adapt" (WGII (B), p. 1702).

Key IPCC AR5 Information: Observed and Predicted Implications for Aquaculture

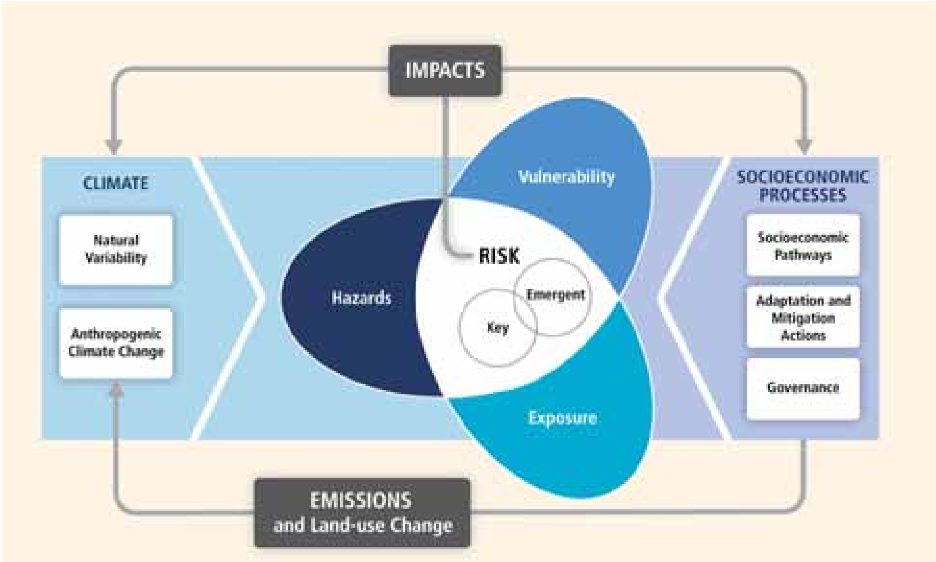
- Global aquaculture is a major increasingly important contributor to total global fish production and food security.
- Dependence on capture fisheries for feed is a problem for aquaculture production owing to increasing uncertainty in the Eastern Boundary Upwelling Ecosystems and adds to pressure on capture fisheries and thus on already stressed ecosystems.
- Acidification impacts global shellfish and mussel production (shell construction, reproduction and life cycle). There is a definite need for more scientific data on implications of acidification for aquaculture production.
- Flooding and inundation are likely to affect aquaculture facilities in coastal areas.
- Aquaculture production of tilapia, carp and milkfish in certain regions will probably benefit from expected climate change.
- The AR5 predicts a substantial global decline of global shelled molluscs' production from 2020–2060 onwards.

4. IPCC AR5: UNDERSTANDING THE RECONCEPTUALIZATION OF RISK

To improve the understanding of how to support the adaptation process of natural and human systems to climate-related changes, the IPCC has modified its theoretical framework in its Fifth Assessment Report (Figure 6). The AR5 emphasises the social construction of risk[10] by underlining that "climate change is not a risk *per se*" (WGII (A), p. 1050). In fact, risks are determined by complex and dynamic interactions of climate-related hazards[11] with the exposure[12] and vulnerabilities[13] of societies and ecosystems (ibid.). According to the AR5, development pathways[14] can contribute to the construction of key and emergent risks through influencing both "the likelihood and nature of climate-related hazards, and the societal and ecological conditions determining exposure and vulnerability" (WGII (A), p. 1052). It is to be noted that the AR4 has incorporated the concept of exposure as a direct component of vulnerability, whereas AR5 has defined exposure as a direct component of risk (WGII (A), p. 840). The modified conceptualization of vulnerability relates to an increasing emphasis on "contextual vulnerability". Contextual vulnerability focuses on the strongly intertwined relationship of contextual conditions (socio-economic, biophysical, institutional and technological) with climatic drivers (FAO, 2015)[15] and underlines the understanding of risk as a social construct. According to the AR5, the new conceptual framework "translates information more easily into a risk management approach that facilitates policy-making" with regard to sustainable adaptation strategies (WGII (A), p. 1050).

[10] The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure and hazard. In this report, the term risk is used primarily to refer to the risks of climate-change impacts (Glossary, p. 1772).
[11] Climate-related hazards (single events or trends), such as sea level rise, acidification, increases in water temperatures.
[12] Exposure of a certain system to a hazard: for example, the number of coastal communities in a region, the number of commercially important fish species in a lake, the existence of coral reefs.
[13] Refers to sensitivity of exposed system to hazard and capacity to adapt to hazard.
[14] Development pathways describe possible trends in demographic, economic, technological, environmental, social and cultural conditions.
[15] FAO. 2015. Assessing climate change vulnerability in fisheries and aquaculture: Available methodologies and their relevance for the sector, by Cecile Brugère and Cassandra De Young. FAO Fisheries and Aquaculture Technical Paper No. 597. Rome, Italy. Available at http://www.fao.org/3/a-i5109e.pdf.

Figure 6: The concept of risk



Source: IPCC AR5 WGII (A), p. 1046.

Risks are considered key "due to high hazard or high vulnerability of societies and systems exposed" – in that context, "key" vulnerabilities have to be understood (defined by exposure of society, importance of system affected, limitations of societies and systems to cope with changes and to build adaptive capacities to limit adverse consequences, persistence of vulnerable conditions and irreversibility of consequences, presence that make societies highly susceptible to cumulative stressors in complex and multiple-interacting systems) (WGII (A), p. 1051). In addition, to fully understand the exposure of a system to risk, magnitude, frequency and intensity of hazardous events and trends linked to climate change and variability have to be understood (WGII (A), p. 1052). Conceptually overlapping with key risks, emergent risks "arise from the interaction of phenomena in a complex system[16]" (ibid.). Once fully understood, emergent risks can become key risks. Finally, AR5 emphasises the need to assess and understand the spatial and temporal coincidence of impacts in different sectors in the same region in order to comprehend the risks arising through synergistic processes (compound risks). Understanding such synergistic processes is crucial for multifaceted adaptation strategies and reducing the risk of maladaptation (WGII (A), p. 1057).

[16] For example: "feedback processes between climate change, human interventions involving mitigation and adaptation, and processes in natural systems" (WGII (A), p. 1052). Example: ocean acidification (WGII (A), p. 1064).

5. AR5 ADAPTATION STRATEGIES FOR ECOSYSTEMS, FISHERIES AND AQUACULTURE, AND HUMAN SYSTEMS

According to AR5, adaptation[17] "involves reducing risk and vulnerability; seeking opportunities; and building the capacity of nations, regions, cities, the private sector, communities, individuals, and natural systems to cope with climate impacts, as well as mobilizing that capacity by implementing decisions and actions" (WGII (A) p. 839). According to AR5, adaptation options fall into three main categories: structural/physical, social and institutional (Box 1). These adaptation options can be applied to increase the resilience of societies and natural systems to risk factors associated with climate change. In general, "governance of fisheries and management will need to follow an ecosystem approach to maximize resilience, and to be adaptive and flexible to allow for rapid responses to climate-induced changes" (WGII (A), p. 516). The AR5 notes that habitat restoration is a highly desirable ecosystem approach to increase resilience of aquatic systems – especially coastal and inland – to climate change (ibid.).

Box 1: Examples of General Adaptation Option Categories

- ***Structural/Physical:***
  - engineered and built environment (e.g. seawalls and coastal protection, floating houses, flood levees and culverts);
  - technology (e.g. genetic variety, early warning systems, efficient irrigation, rainwater harvesting);
  - ecosystems-based management (e.g. ecological restoration, controlling overfishing, fisheries co-management, green infrastructure); and
  - services (e.g. social safety nets and social protection, international trade, municipal and public health services).

- ***Social:***
  - educational (e.g. integration of awareness-raising into education, knowledge-sharing, migration);
  - informational (e.g. hazard and vulnerability mapping, early warning system, community-based adaptation planning, participatory scenario development); and
  - behavioural (e.g. accommodation, retreat, migration, livelihood diversification, changing aquaculture practices).

- ***Institutional:***
  - economic (e.g. financial incentives, including taxes and subsidies, payments for ecosystem services, insurance, microfinance);
  - laws and regulations (e.g. building standards, defining property rights and land tenure, marine protected areas, fishing quotas); and
  - government policies and programmes (e.g. mainstreaming climate change into national and regional adaptation/development plans, integrated coastal zone management, fisheries management, community-based adaptation, disaster planning and preparedness).

This box contains a brief overview of IPCC AR5 adaptation option categories across sectors. It is to be noted that: (i) the list in this box is non-exhaustive; and (ii) that the AR5 does not connect all the examples above with practical cases from the fisheries and/or aquaculture sector.

Source: IPCC AR5 WGII (A), p. 845.

[17] The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects (WGII, Glossary).

5.1. Adaptation strategies – overview

The IPCC AR5 provides a table on adaptation options for fisheries and aquaculture under climate change (WGII (A), p. 462). However, not all adaptation options provided within WGII are included in this table. Therefore, Table 1 provides a comprehensive overview of adaptation options suggested across the WG II document. Information referenced pages 1–1132 were derived from WGII (A) and information referenced pages 1133–1713 were derived from WGII (B).

Table 1: Adaptation Options suggested by AR5 relevant for Fisheries and Aquaculture

Risk	Climatic driver*	Regions most likely exposed to drivers	Natural and human adaptation option from the IPCC AR5
		Ecosystems	
Marine biodiversity loss with high rate of climate change	Ocean acidification (OA), warming trend, extreme temperature events	Global trend but most certainly in low latitude systems	**Human adaptation:** options are limited to the reduction of other stressors (reduction of pressures from fisheries, tourism and pollution) (p. 462). **Natural adaptation:** Hypoxia-adapted lifeforms will benefit from expanding oxygen minimum zones (p. 443). Removal of invasive species to support recovery of the traditional flora and fauna needed for resilient ecosystems (p. 1633).
Spatial redistribution of fish and invertebrate species in coastal areas and open ocean	Hypoxic zones (HZs), warming trend, extreme temperature events	Global trend	**Natural adaptation:** evolutionary adaptation to changing environment is limited, as indicated by already observed spatial redistribution of stocks (p. 462). Aquatic species react through spatial redistribution and decreased body size (p. 458). **Human adaptation:** options are limited to following (expected) stock shifts and reducing human stressors on stocks. Besides large-scale translocation of commercial fishing activities (p. 1629), flexible management of stocks that can react to variability and change is needed. Exploiting newly arrived fish species can substitute for decreases in traditional stocks (due to climatic drivers or other stressors). In the Mediterranean, one new species has arrived every four weeks in recent years (from the tropics) (p. 1295). In some regions, identification of alternative livelihoods will be needed (p. 462). The expansion of sustainable aquaculture production might be suitable for substituting regional reductions of caught fish. It is estimated that Africa has to increase aquaculture production by almost 500 percent by 2020 to respond to rising nutritional needs of growing population (p. 1220).
High mortalities and loss of habitat for larger fauna	HZ	Subtropical gyres (STGs), semi-enclosed seas (SESs)	**Human adaptation:** include translocation of fishing fleets (pp. 462, 1393). Resources will be increasingly exposed to fishing activities and require careful management. Reduction of nutrients and pollution running off agriculture areas can help to stop the formation of hypoxic zones (p. 462).
Reduced growth and survival of shellfish (oceans and coastal areas)	OA, warming trend	Global trend with cold water being more reactive to CO_2. EBUEs appear to increasingly transport "acidic" water (p.1701). pH low in coastal areas (p. 372)	**Natural adaptation:** appears to be limited. However, mussels in the Baltic Sea appear to adapt to acidification (presumably because food is abundant and mussels increase energy expenditure to cope with chemical changes) (p. 377). On the contrary, shell dissolution has been observed in the Southern Ocean (p. 1587). The red king crab is reacting to elevated CO_2 emissions by increasing hatch durations, decreased egg yolk, increased larval size, and decreased larval survival (p. 1587). **Human adaptation:** includes the exploitation of more resilient species and the reduction of human-related stressors (e.g. overfishing, pollution) (p. 462).
Reduced biodiversity, fisheries abundance, and coastal	OA, warming trend, extreme temperature events	CBS, SES, STG	**Natural adaptation:** some coral species might be able to adapt through migration. However, movement of entire reef systems is unlikely as they would have to move at the speed of 10–20 km per year to keep up with climate change (p. 462). **Human adaptation:** Reduction of other stressors. Creation of marine

Risk	Climatic driver*	Regions most likely exposed to drivers	Natural and human adaptation option from the IPCC AR5
protection by coral reefs.			protected areas** to reduce human stressors on marine resources (p. 1527). However, process, e.g. coral bleaching, can only be slowed down and not stopped assuming continuous CO_2 emissions.
Coastal inundation and habitat loss.	OA, changes in precipitation, sea level rise, extreme events (cyclones)	CBS, STG subregions	**Human adaptation:** reduce stressors to maintain ecosystem integrity (e.g. reduce/stop unsustainable aquaculture, pollution, fishing, tourism). Increase mangrove, seagrass, coral reef protection and restauration (p. 462).
Fisheries and Aquaculture			
Reduction in global shellfish production	OA, warming trend, extreme temperature events		Relocation of aquaculture shellfish production. Growing resilient species. The potential for increasingly spreading pathogens (e.g. due to rising temperatures) and the importance of efficient disease management is mentioned in the context of shellfish production (p. 1393). Shift to alternative livelihoods, changes in food consumption patterns, adjustment of markets including prices (p. 463).
Decrease of total fisheries catch potential and reduction of body weight of individual animals	Warming trend	Especially in low latitude regions	Growth of aquaculture sector, marine spatial planning, enhanced industrialized fishing efforts (p. 463).
Redistribution of catch potential of large pelagic highly migratory species (e.g. tuna)	Warming trend	Tropical Pacific	Adjustment of international fishing agreements and instruments (p. 463).
Increasing variability of small pelagic species	OA, HZ, warming trend	Already observed for EBUEs and other oceanic regions	In United Kingdom waters, declining recruitment of lesser sandeel (key species for food web) has been observed since 2002. Further reduction expected due to warming trend (p. 1290). Reduction of fishing activities will increase resilience of the fisheries (p. 463). Reassessment of fisheries management thresholds to reflect changes in abundance of traditional stocks and sustainably utilize immigrant species where possible (p. 1290). Development of new management tools might have limited success to sustain yields (p. 463). Many aquaculture facilities are dependent on small pelagic species for feed. It is recommended to: (i) increase the feed efficiency; (ii) the farming of herbivorous finfish; and (iii) a reduction of fishmeal and fish oil usage (p. 1393).
Decrease in catch and species diversity in coral reefs	OA, warming trend, extreme temperature events	Tropical coral reefs	Restoration of fisheries and reduction of human stressors (p. 463). Assisted colonialization to maintain production might be feasible for high-value species such as lobster (p. 1393). Adoption of alternative livelihoods and usage of alternative food sources (p. 463).
Increasing vulnerability of aquaculture systems	OA, warming trend, extreme temperature events, extreme events (cyclones)		Technological advances and changes in management such as increasing feed efficiency, using alternatives to fishmeal and fish oil, and farming of herbivorous finfish, coupled with economic and regulatory incentives, will reduce the vulnerability of aquaculture to the impacts of climate change on small, pelagic fish abundance (p. 516, p. 1393). Other adaptation strategies include disease management, alternative side selection, selective breeding (p. 1393), and switching to shellfish more tolerant of acidification and fish species more tolerant of higher temperatures (p. 516, p. 454). Efficiency of water use should be improved in aquaculture operations (p. 516). Integrated water use planning should take into account the

<table>
<tr><th>Risk</th><th>Climatic driver*</th><th>Regions most likely exposed to drivers</th><th>Natural and human adaptation option from the IPCC AR5</th></tr>
<tr><td></td><td></td><td></td><td>water requirements and the benefits of fisheries and aquaculture in addition to other sectors (p. 516).
The production of freshwater species such as tilapia, carp and milkfish will probably benefit from the expected climate changes in the tropical Pacific while coastal enterprises/marine fisheries are likely to encounter problems (p. 508).
Insurance schemes should be made available to small-scale producers and it is likely that a need to shift property lines arises in certain geographical locations due to the displacement of the mean high water mark landwards (p. 516).</td></tr>
<tr><td>Occurrence of mycotoxin in post-harvest sector</td><td></td><td></td><td>Concrete implications of climate change on post-harvest sector in fisheries and aquaculture are yet unclear with regard to mycotoxins, but could be addressed through controls of storage facilities (p. 1291).</td></tr>
<tr><td>Negative effects on traditional food processing practices</td><td></td><td>Example is provided for indigenous communities in the Arctic (p. 1583)</td><td>More detailed information is needed on adaptation strategies for the post-harvest sector of fisheries and aquaculture.</td></tr>
<tr><td colspan="4">Notes:
* High confidence exists in the detection of climate change impacts on the spatial redistributions of marine fishes and on the timing of events like spawning and migration. However, impacts of ocean warming and acidification on fish stocks vary from region to region. To date, the impact of climate change on changes in fish stocks and fishery yields is, in most cases, minor (high confidence) in relation to other factors such as harvesting, habitat modification, technological development and pollution (p. 997).
** AR5 recognizes that current spatial management units (e.g. MPAs) need to adapt to the implications of climate change to serve as appropriate adaptation option in the future due to shifting ecosystems and stocks. Continuous revision and shifting of MPA borders is hence required (p. 463).</td></tr>
<tr><td colspan="4">Human Systems</td></tr>
<tr><td>Reduced coastal socio-economic security</td><td>Extreme events such as damaging cyclones, sea level rise</td><td>90 percent of the global population exposed to extreme events such as tropical cyclones is in Asia (p. 1346)</td><td>Adaptation options include protection using coastal defences such as seawalls and soft measures (mangrove replanting and enhancing coral growth). Making changes to human activities and infrastructure to allow continued occupation of coastal areas. Managed retreat as the last option (p. 387, p. 392). Early flood warning systems and using submerged agriculture land for aquaculture practices (p. 391). Removal of human barriers to landward migration of flora and fauna is important (p. 1411).
Private and public insurance schemes to help fishing communities rebuild after extreme events. Skills upgrading where fisheries activities can no longer be sustained and people need to enter alternative occupations (p. 1231). Microfinance programmes (p. 1350).</td></tr>
<tr><td>Reduced livelihoods and increased poverty of those dependent on fisheries</td><td>OA, changes in precipitation, sea level rise, extreme events (damaging cyclones), reduced ecological resilience</td><td></td><td>Large-scale translocation of industrial fishing fleets (p. 1692). Small-scale fisheries (SSF) are limited in their available adaptation options. However: possible options for SSF include: (i) introduction of harvest controls (e.g. size limits, closed seasons and areas, gear restrictions and protection of spawning aggregations) to avoid irreversible damage to stocks in the face of uncertainty; (ii) flexible modification of these controls through monitoring; and (iii) investing in the social capital and institutions needed for communities and governments to manage SSF (p. 1701). Fishing and aquaculture communities should be provided with the opportunity and capacity to respond to new opportunities brought about by climate change; adaptive strategies should be multisector to reduce the consequence of negative impacts in any particular sector (p. 514).
The importance of traditional knowledge (and its combination with modern scientific knowledge and technology) for climate change adaptation is highlighted. Indigenous communities in the Arctic Ocean apply traditional strategies such as changing of resource base,</td></tr>
</table>

Risk	Climatic driver*	Regions most likely exposed to drivers	Natural and human adaptation option from the IPCC AR5
			changing timing and location of fishing, improving communication and education. Indigenous communities in the Arctic have historically been exposed to strong climate variability events and might thus have a competitive advantage when compared with communities that are now exposed to climate change effects but have not been exposed to variability in the past (p. 1594). To improve the resilience of communities, the importance of ecosystem-based adaptation in combination with payment for environmental services schemes (PES) is highlighted. PES are most developed in South America and Central America (p. 1523). Globally, there is limited application of PES schemes in fisheries due to the challenges related to understanding the origin, monitoring the resource, and the definition of resource boundaries in offshore waters (p. 1541). Marine protected areas (MPAs) as key climate adaptation strategy that – if designed in a way that allows for co-management of local fishers – can benefit natural and socio-economic systems are referred to. Example: Marine Extractive Reserve in Brazil (p. 1527). Private and public insurance schemes to help fishing communities rebuild after extreme events. Skills upgrading where fisheries activities can no longer be sustained and people need to enter alternative occupations (p. 1231).
Increased frequency of harmful algal bloom	OA, warming trend, extreme temperature events	CFP cases in the lesser Antilles and in the Pacific. Spread is also predicted for Mediterranean (pp. 1625).	Some algal blooms might cause production of phycotoxins that cause the uptake of marine biotoxins in seafood and thus endanger aquaculture production and/or food safety (p. 1291). Harmful algal blooms can contribute to: (i) outbreaks of paralytic shellfish poisoning, ciguatera fish poisoning, and neurotoxic shellfish poisoning (observed in oysters); (ii) the development of cyanobacteria that produce toxins causing liver, neurological, digestive and skin diseases; and (iii) the development of neurotoxin that bio accumulate in shellfish and finfish (p. 726). Improved monitoring and early warning systems, reducing pollution to stop enhancing of algal blooms. Avoidance of contaminated areas and fisheries products (p. 464).
Spread of diseases	Warming trend		Rotavirus infections and diarrhoea cases might increase (p. 726). Response: Improved monitoring and early warning systems (p. 464).
Notes: AR5 emphasizes the need for more data on regional vulnerability, hazards (especially extreme events), and exposure to design and implement appropriate and multifaceted adaptation strategies and increase resilience of human and natural systems (p. 1236). More certainty is required to clearly attribute observed changes to climate and variability impacts. Especially small island states are exposed to climate change impacts and require special attention on an individual level as their vulnerabilities and exposure differ widely (p. 1635). Danger of territorial disputes to overcome food security challenges may increase. Regional decrease in marine resources in combination with extreme events coupled with increasing combination will potentially drive migration of people and increase humanitarian crises (p. 464). AR5 underlines the importance of participatory processes and involvement of communities regarding MPAs (p. 1638).			

6. IPCC AR5 FISHERIES AND AQUACULTURE INFORMATION BY CONTINENT

The impacts of physical and chemical changes on fish stocks and aquaculture production opportunities have varying implications for different continents and their subregions. This section presents the changes to the natural environment and vulnerability of fisheries and aquaculture systems – and dependent communities – by continent. Note that the information directly linked by the AR5 to fisheries and aquaculture is provided, as well as general information judged to be relevant for each continent with regard to fisheries and aquaculture and dependent communities. AR5 suggested adaptation strategies for each continent are also outlined. Climate-related key risks for human systems directly and indirectly dependent on fisheries and aquaculture systems depend on the intensity and frequency of hazards, exposure to these hazards, and level of vulnerability. Efforts to assess the vulnerability of those dependent on fisheries and aquaculture have increased in recent years, and it has become evident that natural and human processes in fisheries and aquaculture are particularly vulnerable to climate-related impacts.

Globally, the AR5 identifies small-scale fisheries (SSFs) as a particularly vulnerable group to climate change (WGII (B), p. 1701). The SSFs are located in coastal areas and inland systems, account for around half of the fish harvested from the ocean, and provide jobs for approximately 47 million people with about 12.5 million directly engaged in fishing and another 34.5 engaged in post-harvest activities (ibid.). SSFs in tropical developing countries are perceived vulnerable in the AR5 because of: (i) the high exposure of low latitude regions to climate change related impacts (e.g. acidification, temperature changes, natural hazards) on the marine environment and thus aquatic resources; and (ii) the low capacity of many SSFs to adapt to climate change and variability. The low capacity to adapt is influenced by: (i) SSFs in many tropical subregions being politically weak and operating from decentralized locations; (ii) poor governance and management structures; and (iii) no or low availability of sufficient data to monitor catches effectively (ibid.). Furthermore, the movement of fish stocks has been suggested to increase “transboundary rivalry” between communities and/or states, resulting in economic and geopolitical tensions (WGII (A), p.776). The AR5 suggests the following approaches to support climate change adaptation of SSFs: (i) introduction of harvest controls to avoid irreversible damage to stocks in the face of uncertainty; (ii) flexible modification of these controls through monitoring; and (iii) investing in the social capital and institutions needed for communities and governments to manage SSFs (WGII (B), p. 1701).

Africa

Capture fisheries (marine and inland) and aquaculture are an important source of livelihoods in many African countries and contribute more than one-third to the continent's total animal protein intake (WGII (B), p. 1220). In certain coastal countries, fish contributes even up to two-thirds of total animal protein intake (ibid.). A global analysis of the vulnerability of economies to climate change through their fisheries sector, published in 2009, revealed that of 132 countries an estimated two-thirds of the most vulnerable economies are in Africa (ibid.). However, contextualizing food security in Africa under climate change in a text box, the AR5 exclusively refers to livestock and crops and does not make reference to (farmed) fish (ibid.). It has been estimated that the increasing demand for fish requires African aquaculture production to increase by almost 500 percent in order to meet nutritional needs by 2020 (ibid.).

Many coastal countries of West Africa are likely to experience negative impacts from climate change with regard to capture fisheries. One model projected that by 2050 the annual landed value of marine fish for that region is estimated to decline by 21 percent, resulting in a nearly 50 percent decline in fisheries-related employment and a total annual loss of US$311 million to the region's economy relative to 2012 (WGII (B), p. 1221). Evidence exists that an increase in temperature in the Canary Current has resulted in changes of fish species (e.g. Mauritanian waters have become increasingly suitable for *Sardinella aurita*) (WGII (B), p. 1216). Regarding the Benguela current, there is medium agreement despite limited evidence that the Benguela system will experience changes in upwelling intensity as a result of climate change. Changes in temperature in the Benguela current have not yet been observed (ibid.). In general, the exposure to the physical effects of climate change, the sensitivity of economies to impacts on fisheries, and the low adaptive capacity are especially pronounced in the Republic of Angola, the Democratic Republic of the Congo, Mauritania and Senegal (due to the importance of fisheries to the poor and the close link between climate variability and fisheries production) (WGII (B), p. 1220).

Coastal countries of East Africa (Mozambique, the United Republic of Tanzania, the Republic of Kenya and the Federal Republic of Somalia) are bordering Coastal Boundary Upwelling Systems, where warming, decreased oxygen, acidification, and the spread of pathogens affecting fish stocks are perceived to be threats in the future (WGII (A), p. 458). A reduction of maximum body weight is predicted for the Mozambique Channel and surrounding areas (ibid.). Predictions are positive for offshore fisheries potential in the Southern Ocean around South Africa and the Republic of Namibia (less positive for certain coastal areas). Coral vulnerability to heat anomalies is high in the western Indian Ocean, whereas corals in the south-western Indian Ocean (the Comoros, Madagascar, the Republic of Mauritius, Mayotte, Réunion, and Rodrigues) appear to be more resilient than those in eastern locations. Social adaptive capacity to cope with such change varies, and societal responses (such as closures to fishing) can have a positive impact on reef recovery, as observed in the United Republic of Tanzania (WGII (B), p. 1216).

Several northern African countries, such as the People's Democratic Republic of Algeria, Libya, the Arab Republic of Egypt, the Republic of the Sudan and the State of Eritrea, border the Mediterranean and Red Seas. These two semi-enclosed seas are especially vulnerable to physical and chemical climate drivers and are heating up much faster than the global mean ocean temperature due to their shallow physical structure and their land-locked location (WGII (B), pp. 1683). Reduction of total catch potential is assumed to be as high as 50 percent in some parts of the Mediterranean and Red Seas (WGII (A), p. 458).

Evidence exists that climate drivers are changing African inland systems, as even small variations[18] in climate drivers have been observed to cause wide fluctuations in the thermal dynamics of freshwater systems, including increasing stratification and reduced nutrient circulation, and thus negative implications for primary production and hence higher trophic levels. Climate change is evidently "beginning to affect freshwater systems in Africa, as elevated SSTs have been reported for the Lakes Kariba, Kivu, Tanganyika, Victoria and Malawi (WGII (B), p. 1216).

However, the interacting factors driving fisheries decline in African lakes are uncertain, given the extent to which other factors, such as overfishing, pollution and invasive species, also impact lake ecosystems and fisheries production (WGII (B), p. 1216). It is estimated that the increased temperature has caused a decrease of approximately 30 percent in fish yields in Lake Tanganyika, East Africa (WGII (A), p. 493). On the contrary, another study has attributed the same observed reduction to changed unsustainable fishing practices (ibid.). A similar disagreement exists on Lake Kariba, in southern Africa, with scientists explaining the reduction in biomass either by impacts related to climate change or by unsustainable management and overexploitation of fisheries (ibid.).

Many African coastal systems are likely to experience SLR and storm swells, as observed in Durban, South Africa, in March 2007, when a storm swell of up to 14 metres due to winds generated by a cyclone combined with a high tide at 2.2 metres led to damages estimated at US$100 million (WGII (B), p. 1216). Sea level rise along coastal zones, including coastal settlements, could disrupt economic activities such as tourism and fisheries. More than a quarter of Africa's population lives within 100 km of the coast and more than half of Africa's total population living in low-elevation coastal zones is urban, accounting for 11.5 percent of the total urban population of the continent (WGII (B), p. 1225). In eastern Africa, an assessment of the impact of coastal flooding due to SLR in Kenya found that, by 2030, 10 000 to 86 000 people would be affected, with associated economic costs ranging between US$7 million and US$58 million (ibid.). Large uncertainties surround projected changes in tropical cyclone landfall from the southwest Indian Ocean that have resulted in intense floods in the past (WGII (B), p. 1119).

Medium confidence exists that east and southern Africa will experience an intensification of droughts in the twenty-first century in some seasons. Low confidence persists in projected increases of heavy precipitation over most of Africa except over East Africa, where high confidence in a projected increase in heavy precipitation exists (WGII (B), p. 1206). In northern Africa, the north-western Sahara experienced 40 to 50 heat wave days per year during the 1989–2009 time period, which are predicated to increase over the twenty-first century (WGII, p. 1210). The rainfall pattern in the Sahara appears to be subjected to climate variability and is currently increasing again overall (WGII (B), p. 1209). A reconstruction of drought history in Algeria and the Republic of Tunisia, based on tree ring records, indicates that a 1999–2002 drought was the most severe since the fifteenth century (WGII (B), p. 1214). In addition, the south-western regions are projected to be at a high risk to severe droughts during the twenty-first century and beyond. Increasing droughts are very likely to have an overall negative effect on yields of major cereal crops across Africa, with strong regional variability in the degree of yield reduction (WGII (B), p. 1218) and might cause substantial losses of livestock. Regions of particular concern are northern and southern Africa regarding potential livestock losses (WGII (B), p. 1220).

[18] Change of wind strength or change of temperature, for example.

The AR5 identifies Africa's urgent adaptation needs given the continent's foremost sensitivity and vulnerability to climate change, together with its low levels of adaptive capacity and emphasizes the "continent's wealth in natural resources, well-developed social networks, and longstanding traditional mechanisms of managing variability through, for example, crop and livelihood diversification, migration and small-scale enterprises, all of which are underpinned by local or indigenous knowledge systems for sustainable resource management" as a strong foundation for climate change adaptation (WGII (B), p. 1226). Nevertheless, overall adaptive capacity is considered low in Africa with some indication of higher adaptive capacity in North Africa (ibid.). Climate uncertainty, high levels of variability, lack of access to appropriate real-time and future climate information, and poor predictive capacity at a local scale are commonly cited adaptation barriers from the individual to national level (WGII (B), p. 1236). In addition, The AR5 refers to unclear land tenure as an underlying issue over resources in Africa that might cause short-term thinking and often results in maladaptation – no reference is made to fisheries tenure (ibid.).

Adaptation strategies suggested by the AR5 to help people adapt and increase resilience include private and public insurance schemes to assist fishing communities rebuild after extreme events, as well as education and skills upgrading to enable broader choices and livelihood diversification when fishery activities can no longer be sustained (WGII (B), pp. 1230). Furthermore, marine protected areas (MPAs) – in combination with improved natural resource management – are recommended to address the decay of coral reefs and related services (WGII (B), p. 1237). The AR5 emphasizes the need for behavioural change incentives in addition to education on climate change risks and how to minimize them. Data collection, early warning systems and improved vulnerability mapping are also mentioned as crucial.

Asia

Globally, Asia dominates both capture fisheries and aquaculture output, with the West Pacific and Indian Oceans having produced more than half of the global marine catch in 2008, and the lower Mekong River Basin supporting the largest freshwater capture fishery in the world (WGII (B), p. 1345). It is predicted that climate change will adversely affect food security in Asia by the middle of the twenty-first century, with South Asia being most affected (WGII (B), p. 1343).

In 2010, it was predicted that the redistribution of Asian marine capture fisheries includes large increases in high-latitude regions, including Asian Russia, and large declines in the tropics, particularly the Republic of Indonesia (WGII (B), p. 1345). The AR5 states that – after Indonesia – Cambodia and the Socialist Republic of Viet Nam are the most vulnerable countries to climate impacts on marine fisheries (ibid.). One major factor behind this statement is the vulnerability of coral reefs to both warming and ocean acidification (WGII (B), p. 1355). Continuation of current trends in sea surface temperatures and ocean acidification is predicted to result in large declines in coral-dominated reefs by mid-century with immense consequences for millions of livelihoods dependent on them (WGII (B), p. 1351). Warming would permit the expansion of coral habitats to the north, but acidification is expected to limit this. Acidification is also expected to have negative impacts on other calcifying marine organisms (algae, molluscs, larval echinoderms), while impacts on non-calcified species are unclear (WGII (B), p. 1342).

Increased water temperatures, for example, may also explain documented declines in large seaweed beds in temperate Japan, and the northward expansion over recent decades of tropical and subtropical macroalgae and toxic phytoplankton, fish and tropical corals, including key reef-forming species (WGII (B), p. 1342). Increased algal blooms have been observed (mostly related to temperature) in

South Asia (WGII (B), p. 1348). Even though the total catch potential for marine fisheries is predicted to decrease in many areas where the Asian continent borders with subtropical gyres and/or Coastal Boundary Systems, the coastline (and beyond) of West India (Arabian Sea) is predicted to see a decrease in catch potential (Figure 2). Additionally, it is estimated that the total body weight of individual animals (depending on species) could be reduced by up to 50 percent in subregions of the Java Sea and the Gulf of Thailand (Figure 2).

Compared with other continents, the AR5 states that Asia has the greatest exposure in terms of population and assets to climate-related risk factors (WGII (A), p. 373), with more than 90 percent of the global population exposed to extreme events (e.g. tropical cyclones) being located in Asia (WGII (B), p. 1346). Trends in cyclone frequency and intensity are unclear. However, a combination of cyclone intensification and sea level rise could further increase coastal flooding and add to the losses of coral reefs and mangrove forests that would exacerbate wave damage (WGII (B), p. 1342). Flooding and associated human and material losses are heavily concentrated in India, Bangladesh and the People's Republic of China. For vast parts of Asia, future rates of sea level rise are expected to exceed those of recent decades, increasing risk of coastal flooding, erosion and saltwater intrusion into surface and groundwater reservoirs (ibid.) In the absence of other impacts, "coral reefs may grow fast enough to keep up with rising sea levels, but beaches may erode and mangroves, salt marshes, and seagrass beds will decline, unless they receive sufficient fresh sediment to keep pace or they can move inland" (ibid.).

Observations of climate change over the past 30 to 50 years in the Lower Mekong Delta include an "increase in temperatures, an increase in rainfall in the wet season and decreases in the dry season, intensified flood and drought events, and sea level rise" (WGII (B), p. 1355). Agricultural production has been affected by intensified floods and droughts, which caused almost 90 percent of rice production losses in Cambodia (1996–2001) (ibid.). Regionally, the Socialist Republic of Viet Nam and Cambodia are among the countries most vulnerable to climate change impacts on Lower Mekong Delta fisheries (ibid.). Hydropower dams along the Mekong River will also have "severe impacts on fish productivity and biodiversity, by blocking critical fish migration routes, altering the habitat of non-migratory fish species, and reducing nutrient flows downstream" (ibid.). Climate impacts, though less severe than the impact of dams, will exacerbate these changes (ibid.).

The AR5-suggested strategies to increase resilience of coral coastal systems include the implementation of MPAs where sea surface temperature is projected to change least (WGII (B), p. 1343). Furthermore, maintaining or improving the connectivity of marine habitats and dispersal abilities of marine organisms is recommended by the AR5 to support autonomous adaptation (ibid.). Landward buffer zones that allow for inward migration of mangroves and human settlements are to be preferred when compared with hard coastal defences (e.g. sea walls), as the latter prevents adjustments by natural ecosystems such as mangroves, salt marshes and seagrass beds to rising sea levels (ibid.). Landward buffer zones can provide a suitable strategy for protecting human settlements while allowing for future inland migration of ecosystems. More generally, maintaining or restoring natural shorelines where possible is expected to provide coastal protection and other benefits (ibid.).

Livelihood diversification, including assets and skills, has been suggested by AR5 as an important adaptation option for buffering climate change impacts on livelihoods. The diversification should occur across assets, including productive assets, consumption strategies and employment opportunities. Among financial means, low-risk liquidity options such as microfinance programmes and risk transfer products can help lift the rural poor from poverty and accumulate assets (WGII (B),

p. 1350). The AR5 also recommends that climate change be included as a topic in higher education to train more people for analysing extremes, variability, and climate change and resulting risks (WGII (B), p. 1352).

Australasia (Australia and New Zealand)

The population in New Zealand and Australia is expected to grow significantly during the next decades with Australia being predicted to see an increase from 22.3 million people (2011) to potentially 43 million (2056) and New Zealand from 4.4 million people (2011) to potentially 7.1 million (2061) (WGII (B), p. 1379). The economies of both countries depend on natural resources (even though the relative dependence differs and is stronger in New Zealand) (ibid.). The marine ecosystems of both countries are considered hotspots of global marine biodiversity with many rare, endemic and commercially important species (WGII (B), p. 1393).

High confidence exists that climate change is already warming the oceans around Australia and the Tasman Sea in northern New Zealand (WGII (B), p. 1392). However, the sea surface temperature appears to increase faster in Australian waters (0.12 °C/decade for north-western and north-eastern Australia, 0.2 °C/decade for south-eastern Australia since 1950) than in New Zealand waters (0.07 °C/decade over 1909–2009) (WGII (B), p. 1380). To note, average climate zones have been observed to have shifted by more than 200 km along the northeast coast and by 100 km along the northwest coasts of Australia since 1950 (ibid.). The warming rate is thereby faster in southeast Australia, with the East Australia current having advanced poleward by 350 km during the last six decades (ibid.).

In Australia, medium certainty is expressed that capture fisheries and aquaculture production face high risks from "changes in ocean temperature and chemistry, potential changes in species composition, condition, and productivity levels" (WGII (B), p. 1406). Recently observed changes in marine systems include changes in phytoplankton productivity and species abundance of macroalgae, southern rock lobster, (coastal) fish, corals and sea urchins (WGII (B), p. 1392). Climate change vulnerability of indigenous Australians is disproportionally high as indicated by socio-economic disadvantages and poor health (WGII (B), p. 1405).

The 2011 marine heat wave in Western Australia resulted in the bleaching at Ningaloo Reef, causing coral mortality and changes in community structure (WGII (B), p. 1392). Since 1985, about 10 percent of the observed 50 percent decline in coral cover on the Great Barrier Reef has been attributed to temperature-related bleaching (ibid.). Reduced calcification has been observed in the Great Barrier Reef and other reef systems (WGII (B), p. 1393). Evidence of the ability of corals to adapt to rising temperatures and acidification remains limited to date (ibid.). It is projected that pelagic fishes such as sharks, tuna and billfish will move south along the Australian coastlines (ibid.). The movements of the individual species depend on sensitivity to water temperature. Resulting shifts in species overlap are likely to have implications for bycatch management strategies (ibid.).

In New Zealand, at the community and individual level, "Māori regularly utilize the natural environment for hunting and fishing, recreation, the maintenance of traditional skills and identity, and collection of cultural resources" (WGII (B), p. 1405). These activities are already often compromised due to the degradation and modification of the natural environment (ibid.). Medium confidence is expressed that climate change related shifts in natural ecosystems will add further challenges to some Māori's capacities to maintain their livelihoods (ibid.). In spite of existing evidence on likely climate change impacts, biodiversity research and management in New Zealand has, so far, taken little account of climate change (WGII (B), p. 1391).

To date, ENSO-related variability has been identified as the key driver of change in the distribution and abundance of marine species in New Zealand (WGII (B), p. 1392). Capture fisheries play an important role for the national economy (New Zealand has exported more than NZ$1.5 billion worth of products in 2012), and the local fish abundance is sensitive to the variability in ocean circulation and temperature. At this stage, no climate change impacts have been reported, although this may be related to insufficient monitoring (WGII (B), p. 1392).

In spite of, to date, limited evidence of climate impacts on coastal habitats, high confidence is expressed that negative impacts related to continued climate change will arise (WGII (B), p. 1393). It is expected that a strengthening East Auckland Current will promote the establishment of tropical or subtropical species that currently occur as vagrants in La Niña years (ibid.). In addition, robust evidence exists that 45 fish species (inshore) have exhibited major distributional shifts in Tasmanian waters since the 1980s, and that these shifts are related to the increasing SST (WGII (B), p. 1394). Such shifts suggest substantial changes in production and profit of both wild fisheries and aquaculture species such as salmon, mussels and oysters (WGII (B), p. 1393).

Changes in key climate variables and extreme events have been observed during the past decades for Australia and New Zealand (WGII (B), p. 1380). The mean air temperature has increased equally for both countries, and extreme air temperature events appear to be more frequent and intense (Australia heat wave 2012/13) for both countries since the 1950s (ibid.). Tropical cyclones are predicted to increase in intensity and stay similar or decrease in number and occur further south (Australia), and increase in their average intensity during winter in the south of New Zealand (WGII (B), p. 1381). In 2011, the Tropical Cyclone Yasi, in combination with related flood events, created economic losses of AU$590 million for the Queensland tourism industry (due to, *inter alia,* damage to the Great Barrier Reef) (WGII (B), p. 1401). The AR5 expresses high confidence that sea level rise is a significant risk for the whole region. Local studies in Australia and New Zealand demonstrate high risks for commercial and residential assets (Australia: a total SLR of more than 1.1 metre would result in total financial damage of AU$226 billion) due to SLR (WGII (B), p. 1384). Secondary effects of the expected SLR and weather extremes include erosion, landslip and flooding with severe implications for coastal ecosystems and dependent species (WGII (B), p. 1392).

The AR5 suggests planned adaptation options to SLR, including: (i) removal of human barriers to landward migration of fauna and flora; (ii) management of environmental flows to maintain estuaries; (iii) habitat provision; and (iv) assisted colonization of seagrass to complement limited natural adaptation (capacity for natural adaptation is unknown for most species) (WGII (B), p. 1411). Moreover, resilience of coral reefs could be increased by reducing fishing pressure on herbivorous fish, protecting top predators, managing runoff and minimizing human-related stressors in general (WGII, p. 1393). The AR5 recommends the implementation of MPAs as a suitable framework to reduce human pressure on the ecosystem. However, the AR5 underlines that MPAs can slow down but not stop the degradation of ecosystems once critical temperature and/or acidification levels have been exceeded (WGII (B), p. 1393). Furthermore, assisted colonization to maintain production might be feasible for high-value species such as lobster (ibid.). Finally, the fishing industry could adapt to shifting distribution ranges of key species (ibid.).

The AR5 also refers to raising minimum floor levels of buildings and infrastructure, creating coastal setbacks to limit further development in areas of high risks, and managing retreat policies as appropriate tools for reacting to the anticipated SLR (WGII (B), p. 1385). Furthermore, strategies for reacting to increasing freshwater scarcity include water recycling, desalination and rainwater harvesting (WGII (B), p. 1407). In order to increase the resilience of communities and society to extreme events, the AR5 suggests spreading the risk through insurance schemes (WGII (B), p. 1403).

Central America and South America

The development of Central America as well as South America "has traditionally displayed four characteristics: low growth rates, high volatility, structural heterogeneity, and very unequal income distribution" (WGII (B), p. 1515). The combination of these factors has generated high poverty. However, the GDP of South America is twice as high as the GDP of Central America, and poverty in Central America is 50 percent higher than in South America (ibid.). In Central America, projected climate change and variability events could severely affect food and nutrition security of the poorest (WGII (B), p. 1530). The AR5 refers to the Ocean Health Index (OHI) and emphasizes that the index is particularly low for Central American countries. The OHI measures the condition of marine ecosystems and their capacities to support key ecological, social and economic benefits (WGII (B), p. 1524).

As emphasized by the AR5, "climate change is altering coastal and marine ecosystems" and the vulnerability of natural coastal systems, in particular coral reefs and mangroves, to climate drivers is often further enhanced by overfishing, habitat pollution and destruction (WGII (B), p. 1524). Extremely high SSTs have been documented in the western Caribbean near the coast of Central America and have caused some of the most recent bleaching events of the Mesoamerican Coral Reef (1993, 1998, 2005 and 2010) (WGII (B), p. 1525). It is estimated that the Mesoamerican Reef will collapse by mid-century if high SSTs continue, with huge economic implications for the whole region (ibid.). The reef contributes an estimated US$395 to US$559 million annually, primarily through tourism and fisheries, to the economy of Belize alone (ibid.). However, coral reefs in the wider region are not only suffering from acidification and rising temperatures, but also suffering from diseases that further trigger mortality events with potentially huge adverse impacts over the next 50 years (as observed in the southwest Atlantic in front of the Brazilian coast) (ibid.). In Brazil, a 0.16 trophic level decline per decade (as measured by the Marine Trophic Index, which refers to the mean trophic level of the catch) has been observed through large parts of the north-eastern coast between 1978 and 2000 (ibid.). This rate is, de facto, one of the highest rates documented in the world (ibid.).

In Central America and South America, the major underlying reasons for the loss of mangroves are deforestation and land conversion, agriculture and shrimp ponds (WGII (B), p. 1526). The situation of collapsing mangrove ecosystems is especially dramatic in Brazil and Colombia, with original mangrove forests in Colombia (Tumaco Bay) having a survival rate between 12.8 percent and 47.6 percent (ibid.). These low survival rates can result in "ecosystem collapse, fisheries reduction, and impacts on livelihoods" and will be worsened by the predicted increase in sea levels, causing thousands of hectares of mangrove forest to be flooded along the coastline of French Guiana alone (ibid.).

The AR5 identifies Colombia and Peru to be among the most vulnerable countries in the region to climate change impacts on fisheries (WGII (B), p. 1526). This ranking is based on the combined effects of observed and projected warming trends, to species and productivity shifts in oceanic upwelling systems, to the relative importance of fisheries to national economies and diets, and to the limited societal capacity to adapt to potential impacts and opportunities (ibid.). However, the overall confidence in changes in fish stock abundance and the attribution of any observed changes to climate change is low.

With regard to freshwater systems, Brazil has the richest icthyofauna of the planet: 540 Brazilian microbasins host 819 fish species (WGII (B), p. 1523). However, "29 percent of these microbasins have already lost more than 70 percent of their natural vegetation cover and only 26 percent show a significant overlap with protected areas or indigenous reserves" (ibid). Moreover 40 percent of the microbasins overlap with hydrodams, have few protected areas, and suffer from high rates of habitat loss (ibid.). Climate change is predicted to negatively affect freshwater fisheries in South America due to alterations in the physiology and life histories of various fish species (ibid.). In addition to climate change impacts at the individual species level, biotic interactions will be affected (ecological networks, predator-prey interactions) (ibid.).

Depending on the region, freshwater resources in Central America and South America are likely to be affected by climate change; for example, a drying trend was observed for rivers in Central America (WGII (B), p. 1518). In the tropical Andes, the semi-arid basins in Chile and the Argentine Republic, and the northern Central America basins, retreating glaciers are likely to exacerbate water resources-related vulnerabilities (WGII (B), p. 1521). The Central America region is likely to experience continuous runoff reduction in the future. For example, climate projections for the Lempa River basin, one of the largest basins in Central America, imply a reduction of 20 percent in inflows to major reservoirs in the future (ibid.). Changes in precipitation levels vary between subregions, and are often strongly influenced by interannual scales linked to ENSO or decadal variability (WGII (B), p. 1509).

During the past decades, unusual extreme weather events have affected Latin America and the Caribbean, contributing to the vulnerability of human systems to natural disasters (WGII (B), p. 1504). Central America has experienced a steady increase in extreme events, including storms, floods and droughts; during the 2000–2009 period, 39 hurricanes occurred in the Caribbean basin compared with 15 and 9 in the 1980s and 1990s, respectively (WGII (B), p. 1508). Furthermore, in Central America and South America together, 613 climatological and hydro-meteorological extreme events have "occurred in the period 2000–2013, resulting in 13 883 fatalities, 53.8 million people affected, and economic losses of US$52.3 billion" (WGII (B), p. 1504).

The coastal states of Latin America and the Caribbean have a human population of more than 610 million, three-fourths of whom live within 200 km of the coast (WGII, p. 1524). Countries in Central America and northern South America – the Republic of El Salvador, the Republic of Nicaragua, the Republic of Costa Rica, the Republic of Panama, Colombia, Venezuela (Bolivarian Republic of) and the Republic of Ecuador – are exposed to climatic events such as SLR and weather extremes, as more than 30 percent of the population live in coastal areas (ibid.). The SLR due to climate change and human activities on coastal and marine ecosystems poses threats to fish stocks, corals, mangroves and recreation (WGII (B), p. 1543). Changes in weather extremes and climatic patterns are affecting human health in the whole region; for example, the outbreaks of vector- and water-borne diseases that were triggered in Central America by Hurricane Mitch in 1998, and the 2010–2012 Colombian floods that caused hundreds of deaths and displaced thousands of people (WGII (B), p. 1535). The AR5 predicts that extreme flooding events might become more frequent with urban coastal areas in the eastern coast being particularly affected (WGII (B), p. 1525).

Observational studies from global and regional models suggest changes in temperature extremes: increases in warm days and heat waves and decreases in cold nights have been identified with medium confidence in Central America, northern South America, northeast Brazil, southeast South America, and the west coast of South America (WGII (B), p. 1505). Low confidence regarding long-term increase in tropical cyclone activity persists (WGII (B), p. 1511).

According to the AR5, South America and, especially, Central America face significant challenges in terms of environmental sustainability and adaptability to the changing climate. These challenges are strongly associated with inequality in access to water, sanitation and adequate housing for the most vulnerable groups – e.g. indigenous people, Afro-descendants, children and women living in poverty (WGII (B), p. 1516). In order to improve the resilience of natural systems and dependent communities to climate change and variability, the AR5 emphasizes the importance of ecosystem-based adaptation by referring to schemes such as payment for environmental services (PES) and community-based management (WGII (B), p. 1540). According to the AR5, PES schemes are relatively well developed, adapted and implemented in Central America and South America when compared with other regions (WGII (B), p. 1523).

The AR5 believes PES schemes are also applicable to coastal and marine areas, although only a few cases have been reported. The rather low application of PES schemes in fisheries is presumed by the AR5 to be attributed to three factors: "origin (the mechanism was originally designed for forests), monitoring (marine resources such as fish are more difficult to monitor than terrestrial resources), and definition of resource boundaries in offshore water" (WGII (B), p. 1541). One example of applied PES cited by the AR5 in the region is the so-called *defeso* in Brazil. The *defeso* consists of a period (reproductive season) when fishing is forbidden by the government and fishers receive a financial compensation. It applies to shrimp, lobster, and both marine and freshwater fisheries (ibid.).

Referring to marine and coastal environments, the AR5 highlights, in addition to early warning systems and climate forecasts for fisheries in the eastern Pacific, MPAs as one major climate change adaptation strategy employed in Central America and South America (WGII (B), p. 1526). By 2007, more than "700 MPAs were established in LA [Latin America] and the Caribbean covering around 1.5 percent of the coastal and shelf waters, most of which allow varying levels of extractive activities" (ibid.). Significant financial and human resources are expended annually in the marine reserves to support reef management efforts. These actions, including the creation of marine reserves to prevent overfishing, improvement of watershed management, and protection or replanting of coastal mangroves, are noted by the AR5 as proven tools to improve ecosystem functioning (ibid.). In the Mesoamerican Reef, such actions may also increase the thermal tolerance of corals to bleaching stress (WGII, p. 1527). In relation to mangroves, coastal planning to facilitate mangrove migration with SLR and better management of non-climate stressors are recommended by the AR5 as appropriate adaptation strategies (ibid.).

In Brazil, a protected area type known as "Marine Extractive Reserves" currently benefits 60 000 small-scale fishers along the coast (WGII (B), p. 1526). Examples of fisheries' co-management, a form of a participatory process involving local fisher communities, government, academia and non-governmental organizations, are reported by AR5 to favour a "balance between conservation of marine fisheries, coral reefs, and mangroves on the one hand and the improvement of livelihoods, as well as the cultural survival of traditional populations on the other" (ibid.). A comparative study from the forestry sector on different management types of natural resources found that protected areas have higher deforestation rates than areas under community management, thus underlining the importance of community involvement (WGII (B), p. 1524).

As outlined above, some countries in Central America and South America have made efforts to adapt to climate change and variability through the conservation of key ecosystems (MPAs) and community-based management. The AR5 notes that location-appropriate adaption will “demand effective and enforceable regulations and economic incentives, all of which require political will as well as financial and human capital” (WGII (B), p. 1504).

The AR5 states that improving the understanding of the physical oceanic processes in the region, in particular of the Humboldt Current system flowing along the west coast of South America, which is one of the most productive ecosystems worldwide, will be of local and global importance (WGII (B), p. 1541).

Europe

Evidence exists that climate change is affecting the productivity of “freshwater, and marine ecosystems” in Europe (WGII (B), p. 1303). It has been observed that changes in temperature have impacted the distribution of fisheries in all European (semi-enclosed) seas during the past three decades (WGII (B), p. 1295). The relative magnitude of these changes will vary temporally and spatially (ibid.).

To date, little academic research appears available regarding the implications of climate change for employment and/or livelihoods of Europeans. However, changes in employment opportunities by subregion and by sector are likely to occur (WGII (B), p.1291). One study conducted in the United Kingdom of Great Britain and Northern Ireland found that vulnerability to climate change in coastal communities is likely to be increased by social deprivation (WGII (B), p. 1292). Furthermore, indigenous populations in the European Arctic region (e.g. Nenets reindeer herders) are affected by climate change impacts (ibid.).

Most southern European countries have access to semi-enclosed seas, such as the Tyrrhenian and the Mediterranean Seas (the Kingdom of Spain, the French Republic, the Italian Republic, the Republic of Slovenia, the Republic of Croatia, Bosnia and Herzegovina, Montenegro, the Republic of Albania, and the Hellenic Republic) or the Black Sea (the Republic of Bulgaria, Romania and Ukraine). Semi-enclosed seas, due to their shallow structure, are especially at risk under climate change with implications for traditional flora and fauna that are sensitive to increasing temperatures, lower oxygen levels and increasing acidification (WGII (B), p. 1680).

As global mean sea surface water temperature increases, invasive tropical species will contribute to the alteration of trophic dynamics and the productivity of coastal marine ecosystems in southern Europe’s semi-enclosed seas (WGII, (B), p. 1295). For example, in the Mediterranean basin, it has been observed that invasive aquatic species have arrived in recent years at the rate of one introduction every four weeks (ibid.). Most of these invasive species have migrated northward by an average of 300 km since the 1980s, resulting in an “area of spatial overlap with invasive species replacing natives by nearly 25 percent in 20 years” (ibid). The northward expansion of marine species is predicted to contain benefits for certain countries along the western coastline of the European continent (WGII (A), p. 458).

The east coast of the United Kingdom of Great Britain and Northern Ireland faces the North Sea, an ocean basin that borders with the Kingdom of Belgium, the Kingdom of the Netherlands, the Federal Republic of Germany, the Kingdom of Denmark, the Kingdom of Sweden and the Kingdom of Norway. The North Sea is warming at rates 2–4 times faster than the global mean rate with implications for the whole food chain. For example, SST-related changes in the timing and location of phytoplankton and zooplankton are affecting North Sea cod larvae (WGII (B) p. 1295). A possibly SST-related observed steep decline in boreal species was, however, compensated for by the arrival of southern (Lusitanian) species (WGII (B), p. 1290). The number of endemic diseases of (farmed) salmonids in the area is likely to become more prevalent and threats associated with exotic pathogens may rise (ibid.).

Many central and northern European countries (Germany, the Republic of Poland, the Republic of Lithuania, the Republic of Latvia, the Republic of Estonia, the Republic of Finland, Sweden and Denmark) border with the semi-enclosed Baltic Sea in which the SSF temperature is also warming up at rates 2–4 times higher than the global mean (WGII (B) p. 1295). Even though some new species would be expected to immigrate because of an expected increase in SSF temperature, only a few of them would be able to successfully colonize the Baltic Sea because of its low salinity (WGII (B), p. 1290). Sea ice is expected to decrease over all the Baltic Sea, resulting in increased exposure of coastal areas to storms (WGII (B) p. 1295).

The AR5 underlined that overfishing is an important key driver for reduced catches of traditional European stocks as it amplifies the effects of climate change (WGII (B), p. 1290). The economic implications of climate change related impacts on marine fisheries profits range from negative for the sardine fishery in the Iberian Atlantic fishing grounds to non-significant for the Bay of Biscay and positive along the Portuguese coast, since most of the immigrant fish species are marketable (ibid.). However, there is limited and diverging evidence on climate change impacts on “net fisheries economic turnover and local economic impacts attributable to climate change will depend on the market value of (high temperature tolerant) invasive species” (WGII (B), p. 1272).

Aquaculture could be affected by climate change, as the areal extent of habitats suitable for aquaculture production is likely to be reduced by sea level rise (WGII (B), p. 1290). Evidence exists that higher water temperatures have adversely affected both wild and farmed freshwater salmon production in the southern part of the distribution areas (ibid.). Ocean acidification may adversely impact shellfish production systems (ibid.). In the Iberian Atlantic, the harvesting season for the mussel aquaculture industry was reduced due to harmful algal blooms. These algal blooms resulted from changes in phytoplankton communities linked to a weakening of the Iberian upwelling (ibid.). Toxic algae, likely linked to climate warming and direct anthropogenic stressors, may affect oyster production in France (ibid.).

Certain algal blooms might be harmful to the extent that they cause the production of phycotoxins, which causes the uptake of marine biotoxins in seafood and, hence, endangers food safety (WGII (B), p. 1291). Concrete implications of climate change for post-harvest mycotoxin production are yet unclear, but could be addressed through controls of storage facilities (ibid.).

As the risk of extreme sea level events increases with climate change, coastal flood risk will “remain a key challenge for several European cities, port facilities, and other infrastructure” (WGII (B), p. 1280). Extreme sea level events such as storm surges are expected to vary along the European coasts with significant increases being projected for the eastern North Sea and west of the United Kingdom of Great Britain and Northern Ireland and Ireland. Medium agreement is expressed by the

AR5 that the south of the North Sea and the Dutch coast will experience increasing storm surges in the future (ibid.). Direct costs from sea level rise "in the EU27 without adaptation could reach €17 billion per year by 2100" (ibid.). The highest absolute damage is predicted for the Netherlands, Germany, France, Belgium, Denmark, Spain and Italy (ibid.).

The frequency of river flood events and annual flood and windstorm damages have increased over recent decades, but these changes are not clearly attributable to climate change. Climate projections show "an increase in high temperature extremes (high confidence), meteorological droughts (medium confidence), and heavy precipitation events (high confidence), with variations across Europe, and small or no changes in wind speed extremes (low confidence) except increases in winter wind speed extremes over Central and Northern Europe (medium confidence)" (WGII (B) p. 1270). Storm hazards in northwest Europe are projected to result in an overall increase in economic losses (WGII (B), p. 1280).

To adapt to the climate change impacts on fisheries, the AR5 states that European countries will need to "adapt their fishery management thresholds as the ecological basis on which existing thresholds have been established changes, and new thresholds will have to be developed for immigrant species" (WGII (B), p. 1290). These changes of the ecological basis may, on the one hand, lead to productivity losses. On the other hand, new fishing opportunities may occur. Potential consequences of the ecological shifts include: (i) the need to adjust fishing regulations; (ii) price changes of fish products and operating costs; and, ultimately (iii) changes in the economic performance of the fleets (ibid.).

North America (United States of America, Canada, Mexico)

Canada and the United States of America are relatively food secure, although households living in poverty are vulnerable. On the contrary, a total of 17.6 percent of Mexicans are classified as food insecure (WGII (B), p. 1462). Indigenous communities are especially strongly dependent on climate-sensitive sectors, such as fisheries, for livelihoods and food across the region (WGII (B), p. 1471).

The estuaries, coastal marshes and mangrove forests along the Gulf Coast and the East and West Coasts of North America are highly productive ecosystems and strongly exposed to human stressors such as overfishing, tourism and urban development (WGII (B), p. 1459). Human stressors interact and are often exacerbated by climate drivers, such as acidification, SLR, increasing water temperatures, altered upwelling systems and storms. Flooding and the loss of coastal ecosystems, including dunes and wetlands, mangroves, seagrasses and oyster beds along the coastline of North America, are directly related to SLR (ibid.). Projected increases in SLR, particularly along the coastlines of Florida, Louisiana, North Carolina and Texas, is likely to threaten coastal plant ecosystems (WGII (B), p. 1460). Where "landward shifts are not possible, a 1 metre rise in SLR will cause the loss of wetlands and mangroves of up to 90 per cent in Veracruz, for example" (ibid.).

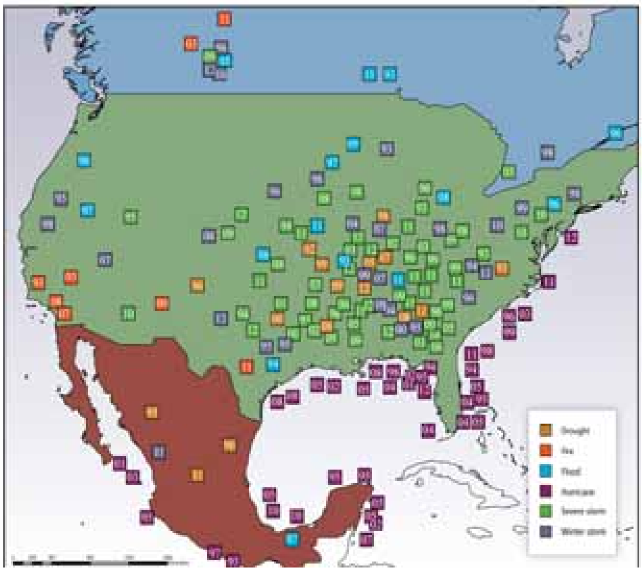
In estuaries, increases in sea surface temperature threatens the diversity of species. Coldwater fish are especially affected as evidenced by the fact that historically warm periods "have coincided with low salmon abundance and restriction of fisheries in Alaska" (ibid.). On the contrary, it is projected that increases in sea surface temperature will expand the habitat suitable for warm-water species (WGII (B), p. 1469). However, the expansion of habitats suitable for warm-water species is likely to "increase the presence of invasive species that threaten resident populations" (ibid.). In that context, Chinook salmon in the Pacific Northwest may decline by 20 to 50 percent by 2040–2050. According to the AR5, "habitat restoration and protection particularly at lower elevations may help mitigate declines in abundance" (WGII (B), p. 1460).

The observed shifts in the Pacific Northwest marine ecosystems, which have restricted fisheries and thus affected fishing communities, have been attributed to anthropogenic climate change. In fact, 30 communities and 25 000 families in British Columbia were identified to be adversely impacted by these shifts (WGII (B), p. 1469). According to the AR5, fishing contributes to economic and food security, and the implications of climate change are posing a threat to livelihoods dependent on fisheries, particularly among women (WGII (B), p. 1471).

North Atlantic cetaceans and tropical coral reefs in the Gulf of California and the Caribbean have been affected by increases in the incidence of diseases associated with warm waters (WGII (B), p. 1459). Continuing ocean acidification in combination with temperature increases is likely to lead to increased risk of coral bleaching, and increasingly unfavourable conditions for colonial mussel beds, and thus for ecosystem biodiversity (WGII (B), p.1460). Evidence exists that oyster larvae in the Chesapeake Bay grew more slowly when reared with CO_2 levels between 560 and 480 ppm compared with current environmental conditions (WGII (B), p. 1459).

According to the AR5, it is very likely that the mean annual temperature has increased over the past century over most of North America (WGII (B), p. 1452). Observations show a rise in hot seasons for northern Mexico, the United States of America, and parts of eastern Canada during the twentieth century (ibid.). The increase in hot days has been accompanied by a decrease in cold nights (ibid.). Furthermore, it is likely that annual heavy precipitation has increased over the past decades over wide areas of northern America. Observations on severe thunderstorms and tropical cyclones remain limited (WGII (B), p. 1452). The most robust evidence exists for an increasing frequency of extratropical cyclones over the Northern Canadian Arctic, and for a decrease in frequency and intensity of strong storms over the south-eastern and south-western area of Canada (WGII (B), p. 1454). Hurricanes and cyclones appear to occur increasingly along the east coast of the United States of America and Mexico (Figure 7). The persistence of the observed regional sea level rise is unknown to date (ibid.). All three countries have suffered economic losses from extreme weather events such as hurricanes, droughts and floods during the past few decades (WGII (B). p. 1448).

Figure 7: Significant weather events taking place during 1993–2012



Source: IPCC AR5WGII (B), p. 1450.

Water withdrawals are already exceeding stressful levels in many regions of North America (e.g. south-western United States of America, northern and central Mexico, southern Canadian prairies). The AR5 notes that climate change and population growth will add further stress to the already scarce freshwater resources. Currently, observed changes in drought frequency cannot clearly be attributed to anthropogenic climate change (WGII (B), p. 1456). Strategies employed to improve water management include, for example, the reduction of leaks from water systems and the implementation of green infrastructure for capturing rainwater (WGII (B), p. 1458).

According to the AR5, fisheries' managers should select activities that are more adapted to new climatic conditions in order to sustainably organize fisheries resources (WGII (B), p. 1466). Moreover, early warning and response systems could be developed to provide protection against storms, floods and droughts (ibid.). In areas of high risk regarding weather extremes, insurance prices have gone up, but have gone down again where adaptation measures to changes have been put in place (WGII (B), p. 1469). However, according to the AR5, few municipalities had moved into the climate change adaptation plan implementation stage, and most programmes were yet in the stage of identifying the problem and defining solutions (WGII, p. 1473). At the federal and subnational level, climate change adaptation initiatives appear "to be preliminary and relatively little has been done to implement specific measures" (WGII (B), p. 1475). The AR5 expresses high confidence that, *inter alia*, urban floods in riverine and coastal areas, the disruption of social systems, supply chains, ecosystems, SLR and cyclones are future key risks for Northern America. The AR5 suggests the conservation of wetlands including mangroves to reduce the intensity of floods (WGII (B), p. 1477).

Small Island States

The small island states considered in the AR5 are located within the tropics of the southern and western Pacific Ocean, central and western Indian Ocean, the Caribbean Sea, the eastern Atlantic off the coast of West Africa, and the Mediterranean Sea (WGII (B), p. 1618). According to the AR5, the key climate and ocean drivers affecting small island states include "variations in air and ocean temperatures, ocean chemistry, rainfall, wind strength and direction, and sea levels and wave patterns" (WGII (B), p. 1619). Small islands are often economically dependent on a limited number of climate-sensitive sectors such as fisheries and tourism, and thus vulnerable to climate change, variability and extreme events such as tropical cyclones, drought and storm swells (WGII (B), p. 1626, p. 1619). Therefore, the well-being of many coastal island communities is directly dependent on the services provided by healthy and productive ecosystems, such as:

- Coral reefs for: (i) dissipating wave energy and hence reducing shore erosion; (ii) habitat provision for marine species; (iii) the provision of food for subsistence; and (iv) the attraction of reef-based tourism (WGII (B), p. 1621). However, thermal stress, often in combination with reduced calcification rates due to elevated CO_2 levels and human stressors, triggers the frequency of intense coral bleaching events in various small island states (ibid.). The capacity of corals to recover from bleaching events increases in the absence of human drivers (ibid.). Box 2 provides an overview of a number of coral reef bleaching events in small island states.

  Coral reef fish and thus fisheries are also affected by rising SST, as higher temperatures in and around corals reefs have been observed to negatively affect the spawning of adult reef fish. A lag of larval supply of coral reef fish such as at Rangiroa Atoll, French Polynesia, (1996–2000) has been associated with rising SST (ibid.). Coral and sponge ecosystems are also threatened by invasive fauna, as shown by recent research on the invasion of the Caribbean Sea by the Indo-Pacific lionfish. The preference of this lionfish, a highly efficient predator, for herbivorous coral reef fish has contributed to the decline of coral reef fish communities, which has translated into an increase in algal dominance in coral and sponge communities (WGII (B), p. 1633). There is no evidence that the invasion of the Indo-Pacific lionfish is climate related; however, the concern is that its presence enhances the effects of climate-related drivers and thus further reduces coral reef resilience (ibid.). The AR5 suggests that the removal of invasive species can contribute to the recovery of the traditional flora and fauna (ibid.).

- Mangroves for: (i) providing services that can be used commercially or for subsistence; and (ii) providing coastal protection from erosion and storm events (WGII (B), p. 1621). The survival of mangroves is particularly threatened by the rising SLR, as mangroves find it difficult to tolerate increasing water depth (ibid.).

- Seagrass environments, which have been observed to be adversely impacted by temperature stress (ibid.).

Box 2: Coral reef bleaching events in small island states

Location	**Year**	**Coral mortality due to bleaching (%)**	**Comments**
Phoenix Islands (Kiribati)	2002–2003	100 62	In the lagoon of Kanton Atoll. On the outer leeward slopes of Kanton Atoll.
Phoenix Islands (Kiribati)	2009	Not specified	Temperature-induced coral bleaching in Palmyra. Atoll during ENSO event.
Maldives, Seychelles and Chago Islands	1998	Not specified	Most impacted regions of the severe El Niño bleaching event.
Barbados	2005	70	Caribbean bleaching event.
Belize	1998	Not specified	Coral mortality enhanced by reduced water quality related to human coastal development.
Madagascar	Study (1960–2008)	Not specified	Severe degradation is mostly attributable to direct human drivers in spite of temperature increase of 1 ºC over this period.
Tarawa and Abaiang atolls (Kiribati)	2004	Not specified	Recovery from coral reef bleaching was improved due to absence of human drivers.

Source: IPCC AR5, WGII (B), p. 1621.

Tuna fishery		Change in catch (%)		
		2035: B1/A2	2100: B1	2100: A2
Skipjack tuna	Western fishery	+11	−0.2	−21
	Eastern fishery	+37	+43	+27
	Total	+19	+12	−7
Bigeye tuna	Western fishery	−2	−12	−34
	Eastern fishery	+3	−4	−18
	Total	+0.3	−9	−27
Country		Change in government revenue (%)		
		2035: B1/A2	2100: B1	2100: A2
Federated States of Micronesia		+1 to +2	0 to +1	−1 to −2
Solomon Islands		0 to +0.2	0 to −0.3	0 to +0.8
Kiribati		+11 to +18	+13 to +21	+7 to +12
Tuvalu		+4 to +9	+4 to +10	+2 to +6

Box 3: Summary of projected percentage changes in tropical Pacific tuna catches by 2036 and 2100 relative to 1980–2000 for SRES scenarios A2 and B1, and the estimated resulting percentage changes to government revenue.

Source: IPCC AR5 (WGII (B), p. 1629).

With regard to food safety, the AR5 emphasized the link between rising SST and the presence of the organism responsible for producing the toxin that causes Ciguatera fish poisoning (CFP), which occurs in tropical regions (WGII (B), p. 1624). CFP is among the most common non-bacterial foodborne illness associated with the consumption of fish, and rising rates have been observed in the Lesser Antilles and in the Pacific in Tokelau, Tuvalu, the Republic of Kiribati, the Cook Islands, the Republic of Vanuatu (WGII (B), p. 1625), and the Mediterranean (WGII, p. 1634). To note, aquatic pathogens such as ciguatoxins may be dispersed by currents across boundaries of subtropical and tropical waters (ibid.). Aquatic pathogens that cause mass mortality events of aquatic resources can spread quickly through the oceanic current system, as observed in the 1980s, when the mass mortality event of the Black Sea urchin spread from the Caribbean Basin to Bermuda (4 000 km east) within only 13 months (WGII (B), p. 1633). Besides emphasizing the importance of coastal ecosystems for the well-being of coastal communities dependent on these ecosystems for, *inter alia*, subsistence fisheries and food security, the AR5 also provides information on projected percentage changes in commercially valuable tropical Pacific tuna catches (skipjack and bigeye) by 2016 and 2100 under two different emission scenarios: A2 (high emissions) and B1 (low emissions) (Box 3). The changes in geographical catch potential are reflected in government revenue changes of the Federated States of Micronesia, Solomon Islands, Kiribati and Tuvalu (Box 3). Large international fishing fleets might benefit from these changes as they “can shift operations over large distances compared to local, artisanal fishers” (WGII (B), p. 1629).

Sea level rise poses a particular threat to many small island states, as the majority of human communities are often located in low-lying coastal areas and relocation opportunities are limited (WGII (B), p. 1623). Global and regional patterns of SLR differ widely, with the SLR in the tropical western Pacific, where many small island states are located, having experienced SLR up to four times the global mean value (reported between 1993 and 2009) (WGII (B), p. 1619). These elevated SLR rates are, however, most likely attributable to climate variability events such as ENSO. Strong interannual variability has also been observed in the SLR of the Indian Ocean, though not for the Caribbean region where SLR has been similar to the global mean development over the last 60 years (ibid.).

Sea level rise is often associated with the inundation and the erosion of coastal areas and subsequent consequences for freshwater reserves, agriculture activities and human infrastructure (WGII (B), p. 1619). However, the AR5 has identified a variety of other drivers that can contribute to coastal inundation and erosion events: (i) beach aggregate mining (the Comoros, Indian Ocean); (ii) rapidly expanding settlements and agriculture in low-lying areas; and (iii) swell waves (WGII (B), p. 1620). In 2008, the severity of flooding in the Independent State of Papua New Guinea and the Solomon islands increased with the combination of swell waves and high regional sea levels linked to ENSO. Around 63 000 people were displaced in these two locations alone (ibid.).

Large deep ocean swells that are generated by extratropical cyclones in the mid and high latitudes from distant sources can travel some 6 000 km before they meet an island and cause flooding, erosion of beaches, destruction of sea defences and damage to property (WGII (B), p. 1631). Well-known events and observations of large deep ocean swells and their potential effect on small island states include, for example, the Caribbean (seasonal damage by northerly swells recognized since 1950); the Republic of Maldives (1987); Maldives and several other small island groups in the Indian Ocean (most notably in 2007); the Republic of Guyana on the South American mainland (2005); the Hawaiian Islands (related damage to coral growth has been observed, 2008); and the Republic of Fiji (2011) (ibid.). In addition to large ocean swells generated in mid- and high-latitude regions, large waves can also be generated by tropical cyclones and wander to high- and mid-latitude regions, as observed in St. Helena Islands in 1999. An increase in wave height activity is predicted for the Southern Ocean (WGII (B), p. 1632).

According to the AR5, supporting appropriate adaptation strategies of small island states to climate change and variability is challenging, as research on these regions of the world highlights that change is occurring but does not yet quantify these changes (WGII (B), p. 1634). Furthermore, island vulnerability assessments are still challenging by the heterogeneity of island ecosystems and communities and the general paucity of vulnerability indicators for island states (WGII (B), p. 1635). Data (for example, tropical cyclones, wind speed and direction, SLR and ocean acidification) required to apply island vulnerability indicators are often missing. Responding to that lack of data and thus the absence of certainty in model-based scenarios, an increasing emphasis is put on participatory approaches that link scientific knowledge with local visions of vulnerability (ibid.).

Nevertheless, there are many options in which climate adaptation can be undertaken: reducing socio-economic vulnerability, building adaptive capacity, enhancing disaster risk reduction, or building long-term climate resilience. Given that resources on small islands are often limited and the per capita investment for implementing adaptation projects is relatively high, "recognising the starting point for action is critical to maximize the benefits from adaptation" (WGII (B), p. 1637). More research is needed on how to address and adapt to future extreme events (ibid.).

The AR5 suggests three available approaches to help small island states to adapt to SLR: (i) protection of people, property and infrastructure through "hard" protection measures (e.g. seawalls) and/or "soft" protection measures (e.g. enhancing coastal vegetation, reducing coastal erosion, maintaining the coast as a barrier to storms through applying an ecosystems-based approach); (ii) retrofitting buildings and infrastructure to make them more resistant to SLR; and (iii) managed retreat of people away from the coast (WGII (A), p. 387, p. 392).

In the case of natural systems, the AR5 suggests that risks can be spread though enhancing representation of habitat types and replication of species through, for example, the introduction of MPAs, and notes that "local MPAs – which involve the local community in the management and protection of their local marine environment – have proven to be effective in increasing biodiversity, and in reducing poverty in areas dependent on marine resources in several Pacific islands" (WGII (B), p. 1638). The AR5 suggests that in order to address the decline of coral reef systems through thermal stress and acidification, negative impacts of anthropogenic stresses should be minimized (e.g. destructive fishing practices, water quality change) (WGII (B), p. 1635). Also, improved management of freshwater resources, restoration of coastal landforms, and appropriate buildings such as traditional construction methods in the Solomon Islands will increase the resilience of small island state communities to high-water level events (ibid.).

The AR5 emphasizes the importance of community-based adaptation, as this approach allows for active participation of local stakeholders in the adaptation process and takes into consideration a community's unique perception of its adaptive capacities, which is important to identify useful solutions that cut across sectors and technological, social and institutional processes as "technology itself is only one component of successful adaptation" (WGII (A), p. 390).

Polar Regions

Indigenous populations in the Arctic are considered especially vulnerable to climate change impacts due to their strong dependency on natural resources for their livelihoods (WGII (B), p. 1582). In 2010, between 400 000 and 1.3 million indigenous inhabitants were estimated to live in the Arctic (ibid.). Livelihoods are, *inter alia,* affected by decreased sea ice thickness and extent, less predictable extreme weather events such as severe storms, sea level rise (WGII (B), p. 1583), and climate drivers triggering spatial redistribution of aquatic resources and thus hunting/harvesting opportunities (ibid.). According to the AR5, under climate change, hunting and fishing have become a riskier undertaking for many communities in the Arctic (WGII (B), p. 1594).

Approximately 11 percent of the Arctic Ocean experienced a trend towards earlier phytoplankton blooms between 1997 and 2009 – this advanced timing coincided with decreased sea ice concentration in early summer triggered, *inter alia,* by rising temperatures (WGII (B), p. 1574). Responding to increasingly longer periods without ice, a 20 percent increase in annual net primary production was observed in the Arctic Ocean between 1998 and 2009 (ibid.). It has to be noted that regional differences in zooplankton reaction to warming and thus production patterns exist; for example, *Calanus finmarchicus* production remained relatively stable during the relatively warm period from 1984 to 2010 in the Barents Sea, whereas *C. marshallae* in the southeast Bering Sea was more abundant in the colder years compared with the warmer years of the recent decade (WGII (B), p. 1575).

Evidence exists that the timing of spawning, hatching and larval emergence of some fish and shellfish is matched with fluctuations in prey availability (WGII (B), p. 1574). Larval and juvenile mortality of certain species might increase where this synchrony is disrupted (ibid.). Even though certain species evidently adapt their distribution range to the changing environmental conditions, limitations appear to exist to the movement potential of other species. For example, the movement of subarctic species, fish as well as shellfish, might be restricted by water temperatures below their thermal tolerance spectrum (ibid.). In fact, scientific estimations with respect to the future movement of aquatic species are mixed. Certain studies predict an increase in biomass in the Arctic, whereas other studies indicate that the migration of subarctic species to the poles might be restricted due to the persistence of cold seawater temperatures on the shelf regions (WGII (B), p. 1588).

Harmful algal blooms, influenced directly by climatic drivers, are predicted to increase in the Arctic Ocean with potentially serious implications for human and animal health (WGII (B), p. 1582). Increasing SST has already caused the occurrence of a cholera-like disease in Alaskan Oysters (ibid.). In general, incidences of aquatic parasites, bacteria and viruses – some zoonotic[19] – are predicted to increase with implications for human health (ibid.). In addition, the reduction and redistribution of marine resources have been observed to reduce traditional food supply, resulting in indigenous people abandoning their (nomadic) lifestyle and becoming increasingly dependent on unhealthy "western"

[19] Animal to human transmission is possible.

diets (WGII (B), p. 1583). Traditional food processing such as drying of fish is affected by increasingly wet conditions (ibid.).

In the Southern Ocean, changing productivity and food web dynamics are observable in the form of increasing abundance of benthic sponges and their predators and regionally declining krill stocks (e.g. as observed in the Scotia Sea since the 1980s) (WGII (B), p. 1576). Regional declines in krill populations are very likely the result of multiple stressors, such as changes in sea ice thickness and temperature linked to increasing metabolic costs (WGII (B), p. 1577). Fisheries in Antarctica, consisting mostly of krill, amount to approximately 6 percent of total capture fisheries production (WGII (B), p. 1585). The Commission for the Conservation of Antarctic Marine Living Resources identified the need to include climate change concerns into ecosystem-based management for Antarctic krill, but had still to define procedures for doing so in 2010 (WGII (B), p. 1586).

Freshwater ecosystems are predicted to be affected by climate change in the Arctic and Antarctic. In the Arctic, alterations to ice duration are projected to go hand in hand with changing patterns of species abundance and diversity, with increased open water periods favouring the development of new "trophic levels, colonization of new aquatic species assemblages, (…) and a decrease in winter kill of resident fish with cascading effects on lower tropic levels" (WGII (B), p. 1586). In the Antarctic, warming of once cold freshwater habitats will allow for an invasion of sub-Antarctic species (WGII (B), p. 1587).

The effects of ocean acidification on polar marine ecosystems are likely to have considerable implications. Small planktonic molluscs exposed to acidification and temperature conditions as projected for the Arctic started showing dissolution marks in their shells (WGII (B), p. 1587). Juvenile walleye pollock in the Gulf of Alaska and the Bering Sea appeared to be resilient to the direct effects of decreasing pH levels (ibid.). In the Southern Ocean, shell dissolution has been observed in the Atlantic Basin, a result of both atmospheric changes in CO_2 and upwelling systems (ibid.). The red king crab appears to react to elevated CO_2 concentrations with increased "hatch durations, decreased egg yolk, increased larval size, and decreased larval survival" (ibid.). Some species will be able to adapt to changing conditions through shifting key life-cycle events and diets, while the capacity of other species to cope with changes is, in fact, uncertain (WGII (B), p. 1588). The AR5 emphasizes the need for additional studies to be able to upscale ocean acidification observations to the regional level. Also, more studies are needed on other species potentially replacing Arctic pteropods (WGII (B), p. 1587).

Until today, commercial fishing activity is relatively absent in the Arctic Ocean due to a combination of "fisheries policy, the abundance of the resource, the lack of infrastructure for capturing and processing fish, and the difficulties in accessing fishing grounds, especially during winter" (WGII (B), p. 1584). According to the AR5, recently observed changes in the spatial distribution and abundance of mackerel (*Scomber scombrus*) has "challenged existing international agreements for shared resources in the North Atlantic and, although loss of sea ice in summer is allowing greater access to fisheries resources in the Arctic Ocean, some nations have prohibited commercial fishing within their exclusive economic zones (EEZ) until there is sufficient understanding of stock status to ensure that proposed fisheries would be managed sustainably" (ibid.). The AR5 emphasizes that – given uncertainty in biological responses as well as how harvesters will respond to changing economic, institutional and environmental conditions under climate change – "the future of commercial fisheries in the Arctic Ocean is uncertain" (WGII (B), p. 1590). According to the AR5, if fisheries open in the Arctic Ocean, adoption of sustainable management practices will have to be a high priority (WGII (B), p. 1591).

Relying on a combination of their extensive traditional and modern scientific knowledge, some indigenous communities have started to develop long-term adaptation plans (WGII (B), p. 1593). Indigenous adaptation strategies include, but are not limited to, a changing resource base, shifting settlement area, changing timing and location of fishing areas, improving communication, and education. Moreover, as fishing has become a riskier undertaking, GPS navigation, taking more supplies when hunting, constructing permanent shelters on land as storm protection, synthetic aperture radar to provide estimates on sea ice condition, the use of larger vehicles, and avoiding dangerous terrain have proven to be useful practices (WGII (B), p. 1594).

7. SUMMARY KNOWLEDGE GAPS

This summary of knowledge gaps in the IPCC AR5 with regard to capture fisheries, aquaculture, dependent human systems and suitable adaptation strategies is non-exhaustive. However, this section seeks to highlight the most urgent areas of additional research needed to prevent and reduce the risks (and benefit from opportunities) resulting from the interaction of climate-related hazards with the exposure and vulnerabilities of aquatic ecosystems and societies directly and indirectly dependent on these systems for food security, nutrition and livelihoods.

- The AR5 greatly advances global knowledge of the climate change implications to the aquatic systems, especially the oceans, coastal systems and low-lying areas. Because of the often-lacking long time-series data, uncertainty in biological responses to change, and the combined impacts of climate and human drivers, the AR5 information on the "combined effects" of chemical and physical drivers of climate change on the aquatic environments is yet limited. Consequently, "regional and subregional predictions" on climate change effects are difficult to be made with certainty. However, the AR5 provides information on (possible) changes in individual fish stock movements, regional capture potential and aquaculture productivity that are likely influenced by climate drivers (sections 3 and 6 of this report contain more detailed information on this topic).
- To note, more information is needed on the effects of climate change on "aquatic inland systems", which provide food security and livelihoods for millions around the globe. Inland systems, alongside coastal systems, also require special attention as these systems are under the double pressure of climate change and human stressors. More information on impacts is needed for inland aquatic systems, especially in the context of indigenous communities and small-scale fisheries in tropical countries.
- Future IPCC reports would also benefit from additional research on the observed and potential "social and economic impacts" on coastal, riparian and lacustrine communities and risks to infrastructure in order to guide decision-making and strategic planning within relevant sectors at different scales, such as fisheries and aquaculture. Increased effort on understanding the "risks and vulnerabilities" within the multitude of social-ecological (fisheries and aquaculture) systems to support adaptation planning will also strengthen future IPCC reports.
- The implications for "post-harvest systems and trade" in the context of fisheries and aquaculture under climate change remains limited, and improved collective knowledge of impacts along the value chains and options for both adaptation and mitigation in the face of change is needed.
- More guidance will be needed for the sector to help understand when a given system may rely on "incremental change" to adapt successfully, when "major shifts" within production/post-harvest systems will be needed, and when "transition away" from the sector will be needed.
- The AR5 highlights that the mismanagement of aquatic resources is still a major contributor to the unsustainable development of capture fisheries. However, the AR5 also acknowledges that climate drivers are certainly enhancing the negative consequences of the mismanagement. The suggested structural, physical, social and institutional "adaptation strategies" would ideally be further contextualized for fisheries, aquaculture and dependent communities in the AR6. Practical information (e.g. case studies) are yet widely missing on how to design, implement and finance most AR5 adaptation options for fisheries and aquaculture systems in a way that suit local conditions within continental subregions.

- Adaptation strategies to enhance the ability of aquatic ecosystems to cope with climate change and variability (i.e. ecosystem-based adaptation) would ideally be placed into a socio-economic context as well. The AR5 strongly refers to the importance of co-management (involving all stakeholders) as a favourable approach for balancing environmental and socio-economic sustainable development objectives. More practical examples on that would be of interest to the sector.
- Further IPCC reports will also benefit from a more detailed understanding of how to "monitor and evaluate" adaptation and mitigation efforts from within fisheries and aquaculture systems.

Table 4 highlights some areas of additional knowledge that would support future IPCC reports.

Table 4: Fisheries and aquaculture knowledge gaps in the AR5

1. Chemical and physical drivers of change
Oceanic systems • More data are needed on trends in ocean circulation, surface winds, waves and extreme events such as storms to improve the understanding of climate change and variability impacts on the oceanic environments. • The information on the combined effect(s) of all chemical and physical drivers is limited; further downscaling of models to understand regional and local implications of these drivers is needed. **Coastal systems** • More data are needed on the intensity and frequency of storms, projections on flood magnitude and extreme winds for subregions. • Further regional downscaling of the individual and combined effect(s) of chemical and physical drivers is needed. **Freshwater systems** • More data are needed on hydrological and meteorological hazards in regional and local contexts. • More information is needed on the potential implications of water quality and quantity changes (e.g. effects of temperature, rainfall and acidification) for freshwater systems.
2. Effects on ecosystems, capture fisheries and aquaculture systems
Shifting ecosystems and migration of species • More research is needed on the evolutionary adaptation potential of marine and freshwater species to observed and predicted changes in the physical and chemical environment. • More research is needed on the biogeographical adaptation potential of species and possible implications for marine and freshwater food webs to make reliable and comprehensive predictions on changes in catch potential (risks and opportunities). **Observed and predicted implications of aquatic species** • More data and models are needed to understand the combined acidification, climate change and climate variability implications (risks and opportunities) for individual habitats, fish and other fisheries species globally and within the six ocean systems. • More research is needed on inland fisheries and aquaculture systems under climate change and variability. **Capture fisheries** • More data and models are needed to understand the risks and opportunities arising in the capture fisheries social-ecological systems due to the migration of aquatic species under climate change and how these link with other drivers of change. • More concrete information is needed on the implications of climate change on the post-harvest sector.

Aquaculture

- The impacts to freshwater, brackish and marine aquaculture systems need to be separated, as these systems will face different drivers of change and will thus require specific adaptation strategies suitable for different species and regions.
- More research is needed on how to sufficiently substitute aquaculture and mariculture feed derived from capture fisheries. Fisheries yields from EBUEs – a main source for feed – might be reduced under climate change.
- The implications of increasing droughts and changing precipitation patterns on aquaculture production need to be further contextualized (also in the light of competition between sectors for freshwater).
- More research is needed to understand individual shellfish and fish species ability to cope with chemical and physical changes in different farming systems.
- More concrete information is needed on the implications of climate change on the post-harvest sector.

3. Adaptation options within fisheries and aquaculture

- More information is needed to improve the understanding of social, economic and governance impacts and vulnerabilities specific to fisheries and aquaculture systems (coupled social-ecological systems) under climate change.
- WG II refers to general structural, physical, social, technical and institutional adaptation options across sectors. More concrete information is required on these adaptation options in the context of fisheries, aquaculture and dependent communities and human systems.
- A wider range of adaptation options needs to be investigated within different (cross-sectoral) contexts and their efficacy *vis-à-vis* acidification and climate change documented.
- Information is, in particular, required on prioritizing and financing proposed adaptation options within fisheries and aquaculture.
- More detailed information is needed on alternative livelihood strategies in regions predicted to experience a decline of capture fisheries or that become increasingly unsuitable for farming aquatic species.
- More detailed information is needed on how the processing of aquatic products can be adapted to improve the resilience of livelihoods dependent on such products.
- Marine protected areas (MPAs) certainly contain a huge potential for maintaining and improving the resilience of aquatic systems. However, more information is needed on how to design and implement MPAs in a way that responds to environmental and biological variability and change, as well as how different MPA types will respond to these changes. More concrete information is needed on how to integrate the needs of communities directly and indirectly dependent on the aquatic resources when designing and implementing MPAs.
- Farming systems (marine, brackish, freshwater) will be one key strategy to meet increasing demand in the future. More information is needed on how to design and where to operate such systems sustainably.

4. Fisheries and aquaculture information by continent

- The quantity of AR5 information provided on the different continents varies substantially with regard to climate change implications for food security, nutrition and livelihoods of those directly and indirectly dependent on capture fisheries and aquaculture. Adaptation strategy examples for the different continents – and countries within these continents – are provided but need to be expanded with regard to fisheries and aquaculture. In addition, little information is provided on related design and implementation processes and associated costs and benefits to guide adaptation planning. Hardly any information is provided on the implications of climate change and variability in the post-harvest sector (e.g. traditional food processing strategies and trade impacts for aquatic products).

- Given that many aquatic systems are subject to “open access”, aquatic resources might be at risk of becoming the resource of last resort when other sectors deteriorate – either due to poor management or climate change and variability. The moving of people between sectors for finding alternative livelihood opportunities should certainly receive more attention when assessing climate change implications for the fisheries sectors.
- The sections below present a short summary of the key information missing with respect to the different continents:

  Africa: The importance of fisheries and aquaculture for food security, nutrition and livelihoods is highlighted. However, in a text box outlining food security on the African continent, fish is not referred to. Given that many people depend on inland fisheries, more concrete information is needed on climate change implications for these fisheries and how to support the adaptation of dependent communities.

  Asia: The importance of fisheries and aquaculture for food security, nutrition and livelihoods is highlighted. However, more information in inland systems (besides the Mekong Delta) is needed to identify risks, opportunities and adaptation strategies for dependent communities.

  Australasia (Australia, New Zealand): More information is needed on the total number of those directly and indirectly dependent on fisheries and aquaculture systems, especially with regard to indigenous communities. Hardly any information and concrete practical cases are provided on how to support adaptation to climate change and variability for indigenous communities.

  Central America and South America: The example of MPAs, in combination with PES schemes, as a key adaptation strategy is best illustrated for Central America and South America. The AR5 refers to the *defeso* (Brazil), which consists of a period when fishing is forbidden and fishers receive compensation payments. However, challenges for PES schemes remain and require further research to improve this tool (which was initially designed for forests) for fisheries management under climate change.

  Europe: Data on climate change and variability implications on employment opportunities and livelihoods dependent on fisheries and aquaculture is hardly provided. Information on capture fisheries in inland systems (other than semi-enclosed seas) is widely missing.

  North America (United States of America, Canada and Mexico): Dependency of rural and indigenous communities on fisheries resources for food security and livelihoods is highlighted. More information on climate change implications for inland systems is needed.

  Small Island States: Climate change and variability associated risks, especially for fisheries dependent coastal communities are highlighted. More data are needed on different island types and various levels of exposure to climatic drivers for understanding risks and opportunities and suitable adaptation strategies.

  Polar Regions: More information is needed on Arctic and Antarctic inland systems with regard to climate change impacts. Information on indigenous communities and their adaption strategies is referred to the strongest compared with the other continents. Nevertheless, more detailed information is needed on adaptation strategies for the post-harvest sector.

8. CONCLUSIONS

The information in the AR5 is a vast resource for understanding the implications of climate change variability, climate change and ocean acidification implications on fisheries, aquaculture and dependent communities and economies. The AR5 recognizes that oceanic, coastal and freshwater resources and the fisheries and aquaculture sectors that derive services from these are tremendously important for food security, nutrition, cultural identities and livelihoods around the globe.

The AR5 notes, however, that these natural systems and the communities and economies that depend on them are already feeling the impacts of climate change and are likely to face further risks and opportunities for their fisheries and aquaculture sectors. These risks and vulnerabilities are not only dependent on the predicted physical, chemical and biological changes, but also on the vulnerability contexts in which they occur. For example, small-scale fisheries in developing countries, coral-reef dependent fisheries and small island states are recognized as particularly vulnerable due to their direct and indirect exposure to climate change and acidification, their high dependency on ecosystems that support capture fisheries and the farming of fish and their low capacities to adapt.

Concrete effects of these physical and chemical changes on habitats and species of importance to fisheries and aquaculture production systems are investigated within the AR5, and the report provides a vastly improved understanding of potential changes in species ranges and biological processes and how these changes translate into different risks and opportunities for food security, food safety, economic and social costs, and governance issues in different regions. The AR5 also provides a look into how coastal communities and infrastructure are directly exposed to effects such as sea level rise, storms, floods and other extreme climate events.

Adaptation and risk reduction options of relevance to the aquatic systems, fisheries and aquaculture production systems, and at-risk coastal communities are also presented within the AR5, such as improved environmental monitoring of aquatic systems, disaster-risk management, ecosystem-based adaptation, livelihood alternatives, and adaptive management of aquatic resources.

The AR5 also reminds the sector that poor governance and mismanagement of natural resources remain key obstacles to the sustainability of fisheries and aquaculture, and that the negative implications of human stressors (ranging from pollution to overfishing) are being enhanced by climate change and variability.

Future IPCC reports will benefit from continued research and downscaling of physical and bio-climatic models within the aquatic systems, especially within the inland systems. The reports will also benefit from documented experiences in the understanding of social, economic and governance risks, vulnerabilities and context-specific disaster-risk management, and adaptation options for the coupled social-ecological fisheries and aquaculture systems at different scales and all along the value chains and across governance regimes. Defining how to measure resilience and adaptation to climate change in fisheries and aquaculture systems will assist the sector and countries in monitoring the effectiveness of their adaptation efforts in support of the most vulnerable.

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GLOSSARY

Definitions retrieved from AR5 glossary

Adaptation – the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Adaptive capacity – the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.

Biomass – The total mass of living organisms in a given area or volume; dead plant material can be included as dead biomass. Biomass burning is the burning of living and dead vegetation.

Capacity building – The practice of enhancing the strengths and attributes of, and resources available to, an individual, community, society or organization to respond to change.

Carbon dioxide (CO_2) – A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal, of burning biomass, of land use changes, and of industrial processes (e.g. cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.

Climate change – Climate change refers to a change in the state of the climate that can be identified (e.g. by 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. Climate change may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate variability – Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also Climate change.

Climatic driver (Climate driver) – A changing aspect of the climate system that influences a component of a human or natural system.

Community-based adaptation – Local, community-driven adaptation. Community-based adaptation focuses attention on empowering and promoting the adaptive capacity of communities. It is an approach that takes context, culture, knowledge, agency and preferences of communities as strengths.

Contextual vulnerability (Starting-point vulnerability) **–** A present inability to cope with external pressures or changes, such as changing climate conditions. Contextual vulnerability is a characteristic of social and ecological systems generated by multiple factors and processes.

Coral bleaching – Loss of coral pigmentation through the loss of intracellular symbiotic algae (known as zooxanthellae) and/or loss of their pigments.

Dead zones – Extremely hypoxic (i.e. low-oxygen) areas in oceans and lakes, caused by excessive nutrient input from human activities coupled with other factors that deplete the oxygen required to support many marine organisms in bottom and near-bottom water.

Ecosystem-based adaptation – The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. Ecosystem-based adaptation uses the range of opportunities for the sustainable management, conservation and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. It aims to maintain and increase the resilience and reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change. Ecosystem-based adaptation is most appropriately integrated into broader adaptation and development strategies.

Extreme weather event – An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g. drought or heavy rainfall over a season).

Food security – A state that prevails when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development, and an active and healthy life.

Sensitivity – The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea level rise).

SRES scenarios – SRES scenarios are emission scenarios.

Vulnerability – The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. See also Contextual vulnerability.

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