Impacts of climate change on fisheries and aquaculture

Synthesis of current knowledge, adaptation and mitigation options

FAO
FISHERIES AND
AQUACULTURE
TECHNICAL
PAPER

627

Edited by
Manuel Barange
Director
FAO Fisheries and Aquaculture Department
Rome, Italy

Tarûb Bahri
Fishery resources officer
FAO Fisheries and Aquaculture Department
Rome, Italy

Malcolm C.M. Beveridge
Acting branch head: Aquaculture
FAO Fisheries and Aquaculture Department
Rome, Italy

Kevern L. Cochrane
Department of Ichthyology and Fisheries Science
Rhodes University
Cape Town, South Africa

Simon Funge-Smith
Senior fishery officer
FAO Fisheries and Aquaculture Department
Rome, Italy

and

Florence Poulain
Fisheries officer
FAO Fisheries and Aquaculture Department
Rome, Italy

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2018

Chapter 1: Climate change and aquatic systems

Tarûb Bahri, Manuel Barange and Hassan Moustahfid
FAO Fisheries and Aquaculture Department, Rome, Italy

KEY MESSAGES

- The warming of the climate system is unequivocal. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished and sea level has risen. The uptake of additional energy in the climate system is caused by the increase in the atmospheric concentration of carbon dioxide (CO_2) and other greenhouse gases (GHGs).
- CO_2 concentrations have increased by 40 percent since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. It is thus extremely likely that human influence has been the dominant cause of the observed warming since the mid-twentieth century.
- The ocean has absorbed 93 percent of this additional heat and sequestered 30 percent of the emitted anthropogenic CO_2. Over the period 1901 to 2010, global mean sea level also rose by 0.19 m.
- Aquatic systems that sustain fisheries and aquaculture are undergoing significant changes as a result of global warming and projections indicate that these changes will be accentuated in the future.
- A range of scenarios for atmospheric concentrations of GHGs are used to model and project future climates; most of these scenarios indicate that a large fraction of anthropogenic climate change is irreversible for centuries to come even after complete cessation of anthropogenic CO_2 emissions.
- In many regions, climate change is affecting precipitation and melting of snow and ice, altering hydrological systems and affecting water resources in terms of quantity and quality. Projections show that rainfall can be expected to increase in equatorial areas and decrease elsewhere.
- Temperature of water bodies is increasing across the globe, which results in more pronounced stratification of the water column, with more dramatic consequences for freshwater systems than for oceans because of their shallowness and lower buffering capacity.
- Dissolved oxygen levels decrease with increased temperature, and oxygen minimum zones in the oceans have expanded over the last decades, both in coastal and offshore areas. This trend is expected to continue.
- Global and local ocean circulation is changing, with a weakening of patterns such as the Gulf Stream and the California Current upwelling, and an increase in upwelling in other areas, such as in the Canary, the Humboldt and the Benguela Current systems. Responses are still heterogeneous and predictions have low confidence.
- The absorption of increasing amounts of anthropogenic CO_2 by the oceans results in acidification of waters, with potentially detrimental impacts on shell-forming aquatic life; water acidity has increased by 26 percent since the industrial revolution and this trend will continue, especially in warmer low- and mid-latitudes.

- Primary production in the oceans has been projected to decrease by three percent to nine percent by 2100; in freshwater systems observations vary depending on the area, but overall, forecasts are highly uncertain for both marine and freshwater systems because primary production is an integrator of changes in light, temperature and nutrients.

1.1 INTRODUCTION

Since 1988 the Intergovernmental Panel on Climate Change[1] (IPCC) has been providing regular, evidence-based updates on climate change and its political and economic impacts. These updates comprehensively synthesize the internationally accepted consensus on the science of climate change, its causes and consequences. Based largely on the 5th IPCC Assessment Report (AR5), and recent scientific literature, this chapter provides an overview of the major impacts of climate change on the dynamics of aquatic systems (oceans, seas, lakes and rivers), and particularly on the aspects that relate to aquatic food production, i.e. fisheries and aquaculture. While more detailed information on the impacts of climate change on these food production systems is available in subsequent chapters of this publication, this chapter focuses specifically on providing basic information on the underlying drivers of climate change and on how they translate into biophysical changes in aquatic systems. Its purpose is to contextualize the different chapters and set up a knowledge baseline that avoids the need for repetition in subsequent chapters.

1.2 OBSERVED CHANGES IN THE CLIMATE SYSTEM

Information on the climate system is based on multiple lines of evidence, which include direct and indirect observations and historical reconstructions going back thousands of years as well as more recent instrumental observations, conceptual and numerical models, including radiative and heat budgets. Based on analysis of these data, and notwithstanding the uncertainties associated with knowledge and data gaps, the IPCC AR5 concluded that the warming of the climate system was unequivocal, and that many of the observed changes since 1950 are unprecedented compared with preceding decades to millennia. At the global level, the Earth's average surface temperature has increased by more than 0.8 °C since the middle of the nineteenth century, and is now warming at a rate of more than 0.1 °C every decade (Hansen *et al*., 2010). Heat waves are more frequent now, even though the reliability of data and level of certainty vary across continents (Hartmann *et al*., 2013).

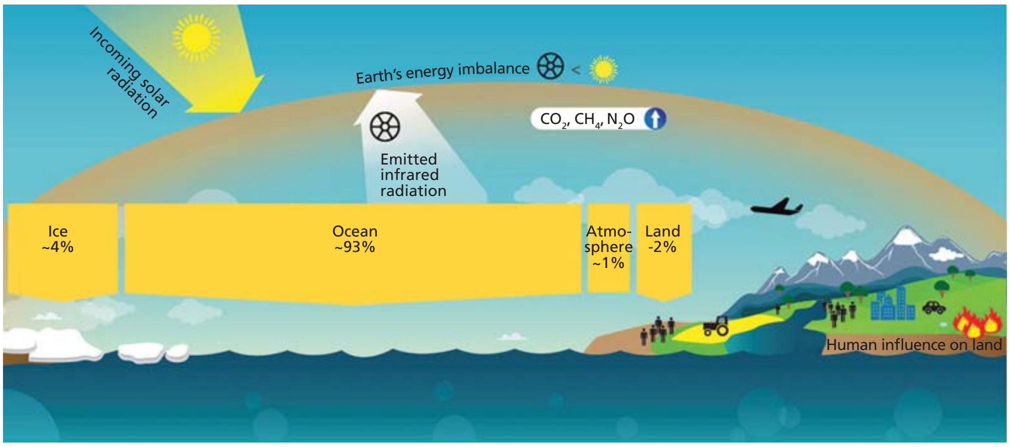
The largest contribution to this warming is believed to be from the increase in atmospheric concentration of GHGs, such as CO_2, methane CH_4 and nitrogen dioxide NO_2. GHGs act like a thermal blanket around the planet and are responsible for allowing life on Earth to exist (IPCC, 2014). The exponential increase in the emission of GHGs since the industrial revolution has resulted in atmospheric concentrations of these gases that are unprecedented in the last 800 000 years. For example, atmospheric CO_2 concentrations increased from 278 ppm in the middle of the eighteenth century to around the current level of 400 ppm (See Figure 6.25 in Ciais *et al*., 2013). The IPCC AR5 has also concluded that it is extremely likely that humans have been the dominant cause of the observed warming since the mid-twentieth century, through

[1] The IPCC is the international body for assessing the science related to climate change, set up in 1988 by the World Meteorological Organization and the United Nations Environment Programme. The IPCC periodically issues special reports on specific themes, as well as global assessment reports based on published scientific information and taking stock of the most recent scientific evidence of climate impacts and proposed adaptation and mitigation responses. These reports are intended for policymakers and constitute the scientific basis for the international negotiations within the United Nations Framework Convention on Climate Change (UNFCCC). http://www.ipcc.ch

the association of GHG emissions with gas and oil combustion, deforestation, and intensive agriculture.

Only one percent of the additional heat caused by anthropogenic climate change is retained in the atmosphere, whilst 93 percent has been absorbed by the global ocean. The remaining three to four percent is absorbed by the melting of ice and snow (Figure 1.1). The ocean's heat buffer is thus enormous and any small change in the balance of heat between ocean and atmosphere would have huge impacts on global air temperature (Reid, 2016). In addition to its thermal capacity, the ocean has also sequestered about 25 percent of the CO_2 released as a result of anthropogenic activities (Le Quéré *et al.*, 2018), playing a crucial role in the regulation of the Earth's climate.

FIGURE 1.1
Flow and storage of energy in the Earth's climate system



Source: Reid, 2016.

BOX 1.1
El Niño Southern Oscillation

The El Niño-Southern Oscillation, or ENSO, is the interaction between the atmosphere and ocean in the tropical Pacific that results in three to seven year periodic oscillations in the temperature of surface waters of the equatorial Pacific, between particularly warm and cold temperatures, referred to as El Niño and La Niña respectively. The release of heat from the ocean to the atmosphere during El Niño events is known to cause changes in global atmospheric circulation, cyclone and hurricane patterns, monsoons, and heat and precipitation patterns, with associated drought and flooding episodes (Reid, 2016). The effects are felt worldwide, with consequences for marine and freshwater systems throughout the food web, including species sustaining fisheries.

The interactions between anthropogenic climate change and ENSO cycles have challenged scientists for decades. Since the publication of the IPCC AR5, there have been a number of modelling studies that have shown an increasing frequency of extreme El Niño events as a result of climate change (e.g. Cai *et al.*, 2014, 2015; Wang *et al.*, 2017). It is significant, in this context, that the 1982/83, 1997/98 and most recent 2015/16 El Niño events were not just the most intense in the modern observational record but also the most peculiar, exhibiting unusual characteristics distinct from any other observed events (Santoso, Mcphaden and Cai, 2017).

1.3 FUTURE CHANGES IN THE CLIMATE SYSTEM

In order to assess and forecast future possible changes in the climate system, the IPCC uses a hierarchy of climate models that simulate changes based on a set of scenarios of anthropogenic forcing. These scenarios take the form of representative concentration pathways (RCPs), which simulate possible ranges of heat or radiative forcing values in the year 2100, relative to pre-industrial values (+2.6 W/m^2, +4.5 W/m^2, +6.0 W/m^2, and +8.5 W/m^2, respectively[2]). The four RCPs are based on certain socio-economic assumptions (possible future trends e.g. population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy), which provide flexible descriptions of possible futures. RCP2.6 is consistent with an emissions pathway that leads to very low GHG concentration levels and is thus a "peak-and-decline" scenario. RCP4.5 and RCP6.0 reflect two stabilization scenarios in which total radiative forcing is stabilized shortly after 2100 with differential speed, while RCP8.5 is characterized by increasing GHG emissions over time, representative of scenarios in the literature that lead to high GHG concentration levels (van Vuuren *et al*., 2011).

It is estimated for all RCP scenarios except for RCP2.6 that global atmospheric temperature change for the end of the twenty-first century is likely to exceed 1.5 °C relative to the average of the 1850 to 1900 period. It is likely to exceed 2 °C for RCP6.0 and RCP8.5, but more likely not to exceed 2 °C for RCP4.5. Warming is forecast to continue beyond 2100 under all RCP scenarios except RCP2.6, although there will be interannual-to-decadal variability and regional heterogeneity (IPCC, 2014). A large fraction of anthropogenic climate change is considered to be irreversible for centuries to come, and possibly even millennia, even after a complete cessation of anthropogenic CO_2 emissions (IPCC, 2014; Solomon *et al*., 2009) (Figure 1.2).

1.4 IMPLICATIONS FOR AQUATIC SYSTEMS

1.4.1 Hydrological cycle and rainfall patterns

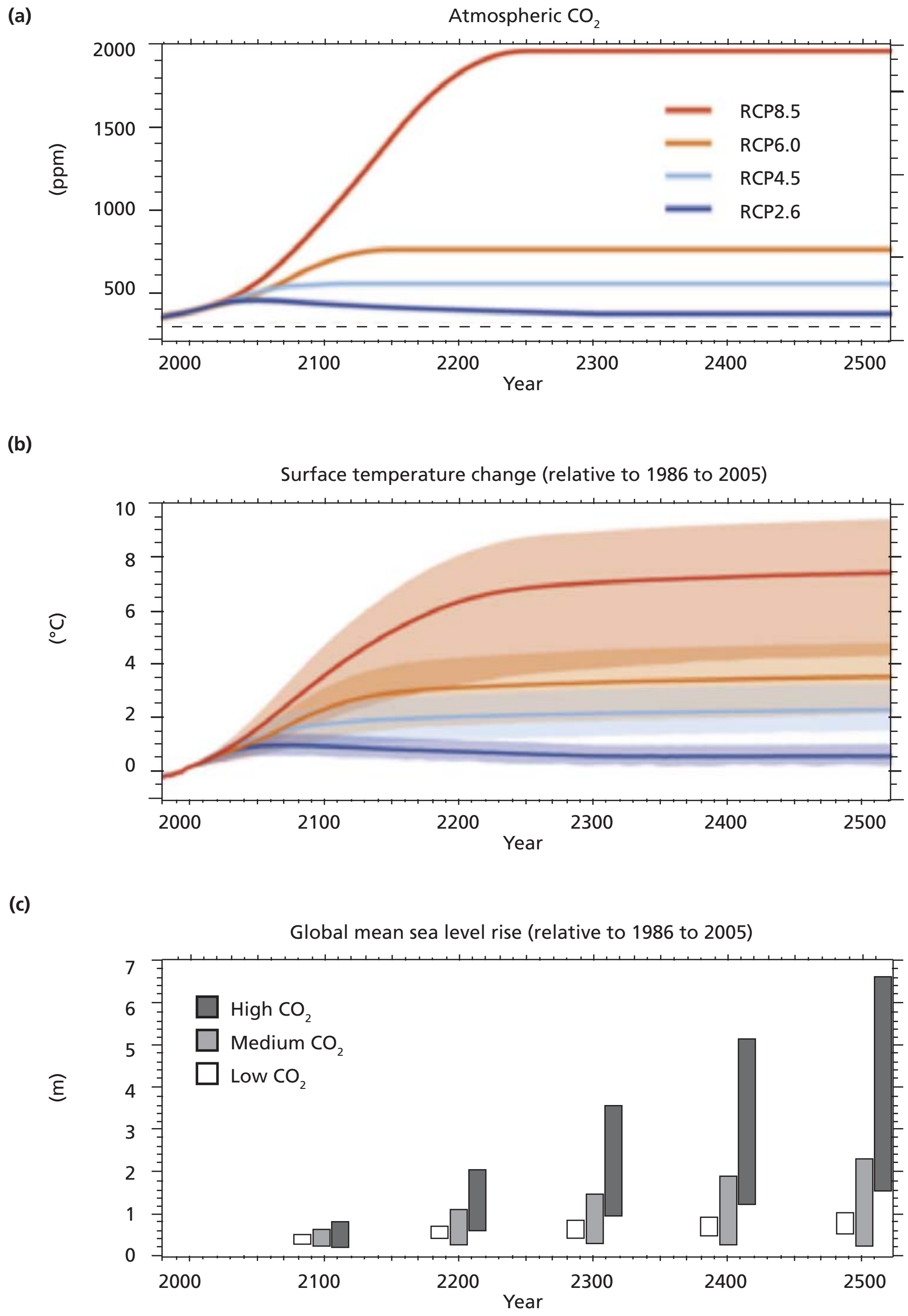
The warming of the climate has significant implications for the hydrological cycle. Changing precipitation, temperature and climatic patterns and the melting of snow and ice affect the quantity, quality and seasonality of water resources, leading to inevitable changes in aquatic ecosystems. Climate change is already causing permafrost warming and thawing in high-latitude regions, and in high-elevation regions it is driving glacier shrinkage, with consequences for downstream water resources (IPCC, 2014 – AR5 synthesis report p. 51). In the marine systems, the melting of the Arctic sea ice has the potential to disrupt or slow down the global ocean conveyor belt (Liu *et al*., 2017; also see ocean circulation section below).

Observed precipitation changes since 1901 vary across regions with some such as the mid-latitude land areas of the Northern Hemisphere showing likely increases while others have shown decreases, but with low confidence (Hartmann *et al*., 2013). However, models indicate that zonal mean precipitation is very likely to increase in high latitudes and near the equator, and decrease in the subtropics (Ren *et al*., 2013). In California, in the Mediterranean basin, as well as in the already arid zones, droughts are expected to be longer and more frequent, and there will be reductions in river flows. As discussed in Chapter 19, precipitation changes at the regional scale will be strongly influenced by natural variability.

[2] W/m^2= Watts per square metre

FIGURE 1.2

(a) Atmospheric CO_2 and (b) projected global mean atmospheric (surface) changes for the four RCPs up to 2500 (relative to 1986 to 2005). The dashed line on (a) indicates the pre-industrial CO_2 concentration. (c) Sea level change projections according to GHG concentrations (low: below 500 ppm as in RCP2.6; medium: 500 ppm to 700 ppm as in RCP4.5; high: above 700 ppm and below 1500 ppm as in RCP6.0 and RCP8.5). The bars represent the maximum possible spread



Source: IPCC, 2014

In the twentieth century, global river discharges have not demonstrated changes that can be associated with global warming. However, as most large rivers have been impacted by human influences such as dam construction, water abstraction and regulation, it is difficult to be conclusive. Despite uncertainties, it is expected that the contribution of snowmelt to river flows will increase in the near future (Jha *et al.*, 2006; Pervez and Henebry, 2015; Siderius *et al.*, 2013). Changes in precipitation will substantially alter ecologically important attributes of flow regimes in many rivers and wetlands and exacerbate impacts from human water use in developed river basins.

The frequency and intensity of heavy precipitation events over land are also likely to increase in the short-term, although this trend will not be apparent in all regions because of natural variability. There is low confidence in projections of changes in the intensity and frequency of tropical cyclones in all basins to the mid-twenty-first century (Kirtman *et al.*, 2013).

1.4.2 Water temperature

Anthropogenic forcing has made a substantial contribution to the upper ocean warming (above 700 m) that has been observed since the 1960s (Cheng *et al.*, 2017), with the surface waters warming by an average of 0.7 °C per century globally from 1900 to 2016 (Huang *et al.*, 2015). Ocean temperature trends over this period vary in different regions but are positive over most of the globe, although the warming is more prominent in the Northern Hemisphere, especially the North Atlantic. The upper ocean (0 m to 700 m) accounts for about 64 percent of the additional anthropogenic energy accumulated in oceans and seas. Upper ocean warming is expected to continue in the twenty-first century, especially in the tropical and Northern Hemisphere subtropical regions, whereas in deep waters the warming is expected to be more pronounced in the Southern Ocean. The trend in sea surface temperature already exceeds the range in natural seasonal variability in the subtropical areas and in the Arctic (Henson *et al.*, 2017). Best estimates of mean ocean warming in the top 100 m by the end of the twenty-first century are about 0.6 °C (RCP2.6) to 2.0 °C (RCP8.5), and about 0.3 °C (RCP2.6) to 0.6 °C (RCP8.5) at a depth of about 1 000 m compared to the 1986 to 2005 average (IPCC, 2014).

For freshwater systems, an increase of water temperature is expected to occur in most areas, as a result of an increase of air temperature. This is linked to the relatively shallow nature of surface freshwaters and their susceptibility to atmospheric temperature change. Harrod *et al.* (Chapter 18, this volume) analysed a set of river basins on all continents and found that an increase of up to 1.8 °C in water temperature is expected, with geographical heterogeneities, including areas where the increase is expected to be minor, such as in the Lower Mekong river basin. There is a high confidence that rising water temperatures will lead to shifts in freshwater species' distributions and exacerbate existing problems in water quality, especially in those systems experiencing high anthropogenic loading of nutrients (IPCC, 2014).

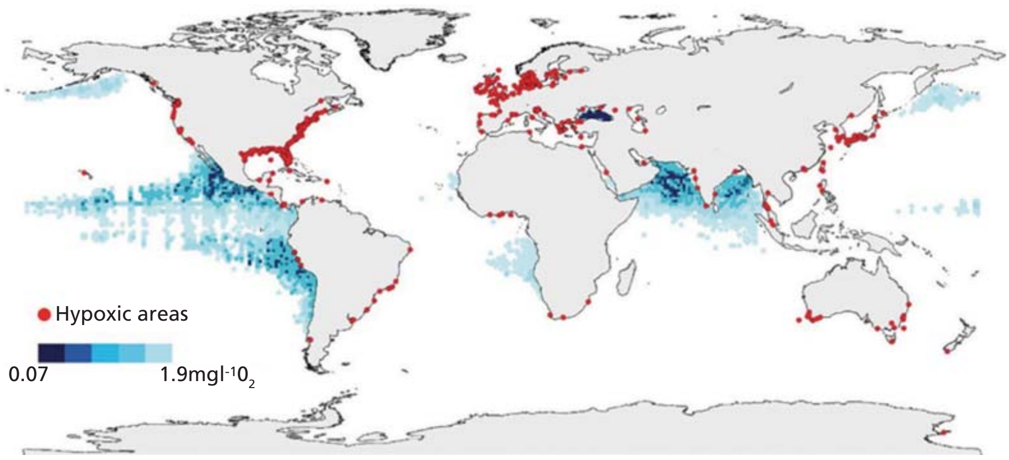
1.4.3 Oxygen content

Dissolved oxygen is an important component of aquatic systems. Changes in its concentrations have major impacts on the global carbon and nitrogen cycles (IPCC, 2014). The average dissolved oxygen concentration in the ocean varies significantly, ranging from super-saturated Antarctic waters to zero in coastal sediments where oxygen consumption is in excess of supply over sufficient periods of time. A large variety of such systems exist, including the so-called oxygen minimum zones (OMZs) in the open ocean, coastal upwelling zones, deep basins of semi-enclosed seas, deep fjords, and other areas with restricted circulation (Figure 1.3), but the discovery of widespread decreases in oxygen concentrations in coastal waters since the 1960s, and the expansion of the tropical OMZs in recent decades (IPCC, 2014) has raised concerns. GHGdriven global warming is the likely ultimate cause of this ongoing deoxygenation in many parts of the open ocean (Breitburg *et al*., 2018). Ocean warming, which reduces the solubility of oxygen in water, is estimated to account for approximately 15 percent of current total global oxygen loss and more than 50 percent of the oxygen loss in the upper 1 000 m of the ocean. Intensified stratification is estimated to account for the remaining 85 percent of global ocean oxygen loss by reducing ventilation. Modelling simulations show that the global volume of OMZs is expected to increase by 10 percent to 30 percent by 2100, depending on the oxygen concentration threshold considered. Beyond 2100, the trend could reverse with a decrease of global volume of OMZs (Fu *et al*., 2018). However, modelling results are associated with a high uncertainty because of the discrepancy between observations and modelled trends (Bopp *et al*., 2013).

Oxygen influences biological and biogeochemical processes at their most fundamental level, but the impacts are very dependent on widely varying oxygen tolerances of different species and taxonomic groups. In particular, the presence and expansion of low oxygen in the water column reduces vertical migration depths for some species (e.g. tunas and billfishes), compressing vertical habitat and potentially shoaling distributions of fishery species and their prey (Eby and Crowder 2002; Chapter 12, this volume).

FIGURE 1.3

Coastal sites where anthropogenic nutrients have exacerbated or caused O_2 declines to <2 mg/litre (<63 µmol/litre) (red dots), as well as ocean oxygen minimum zones at 300 m of depth (blue shaded regions)



Source: Breitburg *et al*., 2018.

1.4.4 Ice coverage

Over the period 1979 to 2012 the average annual extent of Arctic sea ice decreased at a rate of 3.5 percent to 4.1 percent per decade, and the extent of perennial sea ice (summer minimum) decreased by 11.5 percent ± 2.1 percent per decade. It is also very likely that the average annual extent of Antarctic sea ice increased by 1.2 percent to 1.8 percent per decade over the same period (Vaughan *et al*., 2013). Almost all glaciers worldwide have shrunk: between 2003 and 2009, most of the ice loss was from glaciers in Alaska, the Canadian Arctic, the periphery of the Greenland ice sheet, the Southern Andes and the Asian Mountains (Vaughan *et al*., 2013). In the near future, as global mean surface temperature continues to rise, it is very likely that there will be further shrinking and thinning of Arctic sea ice cover and decreases in the northern high-latitude springtime snow cover and near surface permafrosts. On the other hand, there is low confidence in projected short-term decreases in the Antarctic sea ice extent and volume (Bindoff *et al*., 2013).

Melting of ice and snow coverage and reduction of mountain glaciers contribute to water levels and flows in aquatic systems. Sea level rise is a direct consequence of ice melting and, as discussed below, is expected to have impacts in the long-term, whereas the reduction of mountain glaciers will have an impact on river flow and lake levels over the short term, until their likely disappearance in the medium-term.

1.4.5 Sea level

In the recent past, sea level has increased by an average of 3.1 mm/year as a result of climatic and non-climatic factors (Dangendorf *et al*., 2017). The rate of increase shows a high variability across regions, with values up to three times the global average in the Western Pacific or null or negative values in the Eastern Pacific. Sea level has already risen by a global mean of 0.19 m over the period 1901 to 2010. It is estimated that between 2000 and 2100, the projected global mean sea level rise (SLR) will very likely (90 percent probability) reach between 0.5 m and 1.2 m under RCP8.5, 0.4 m to 0.9 m under RCP4.5, and 0.3 m to 0.8 m under RCP2.6 (Kopp *et al*., 2014). There is a high certainty that the sea level will rise in 95 percent of the ocean area; however, there will be a significant regional heterogeneity in the SLR and thus in its consequences (IPCC, 2014).

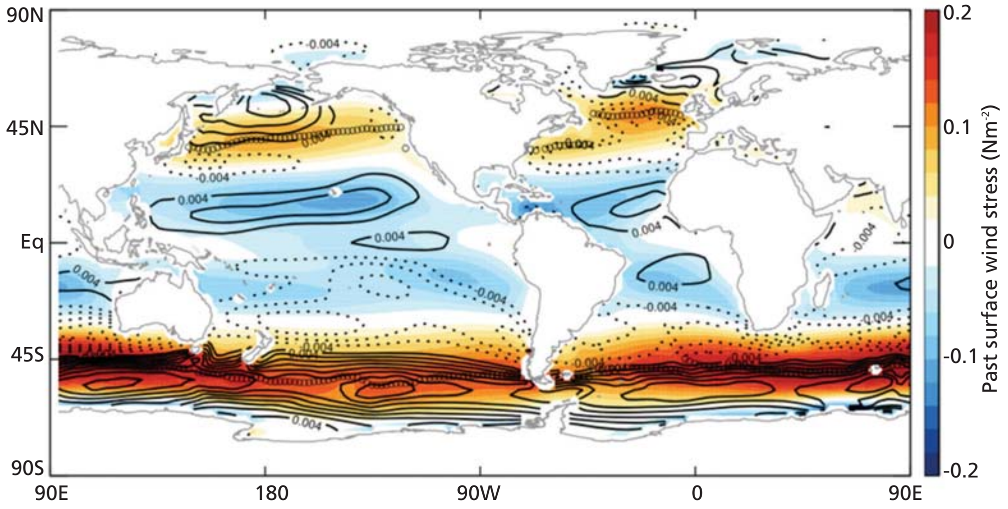
1.4.6 Ocean circulation

Ocean circulation redistributes heat and freshwater across the globe, influencing local climates. A significant part of this redistribution is done by the meridional overturning circulation (MOC), responsible for much of the ocean's capacity to carry excess heat from the tropics to middle and high latitudes, and for the ocean's sequestration of carbon. While the timing of changes is still under debate, partially because of its observed short-term variability (Cunningham *et al*., 2007), it appears clear that the Atlantic meridional overturning circulation (AMOC) is progressively weakening, resulting in a cooling of sea surface temperature in the subpolar Atlantic Ocean and a warming and northward shift of the Gulf Stream (Caesar *et al*., 2018; Thornalley *et al*., 2018). While it is very likely that the AMOC will overall continue to weaken over the twenty-first century, with significant inter-decadal variability, the rate and magnitude of weakening is very uncertain. This is mostly because the predictability of the AMOC varies among models and their realism cannot be easily judged in the absence of a sufficiently long record of observation-based AMOC values. Whether the AMOC will undergo an abrupt transition or collapse after the twenty-first century is an open question and a strong candidate for further research and understanding of the dynamical behaviour of coupled climate models; their predictability, inherent biases, improved parameterizations and confidence of validation of their results against past and continuing observations (Collins *et al*., 2013; Liu *et al*., 2017; Sgubin *et al*., 2017). There is also low confidence in assessing the evolution of the AMOC beyond the twenty-first century because of the limited number of analyses and equivocal results. The consequences of the AMOC weakening would include a disruption of climate patterns in the subtropical Atlantic that would translate into an increased storminess and frequency of heat waves, as well as a warming of tropical Atlantic waters.

Western boundary currents transporting heat poleward from the tropics (Gulf Stream, Kuroshio Current and Somali Current in the Northern Hemisphere; Agulhas Current, Brazil Current and East Australia Current in the Southern Hemisphere) and formed in response to large-scale wind forcing have a strong influence on regional climate and storm tracks. Apart from the Gulf Stream, which is expected to weaken together with the AMOC, all the western boundary currents are likely to intensify as a result of wind shifts and tropical atmospheric changes in connection with GHG concentrations (Figure 1.4). This would favour the formation of severe storms and would affect the climate of the coastal areas in the vicinity of these currents (Yang *et al*., 2016).

FIGURE 1.4

The historical (shading) and projected change (contours) from 1979 to 2005 to 2070 to 2099 in annual mean surface zonal wind stress evaluated as the multimodel mean of CMIP5[3] historical simulations and projections with the RCP8.5 high emissions scenario

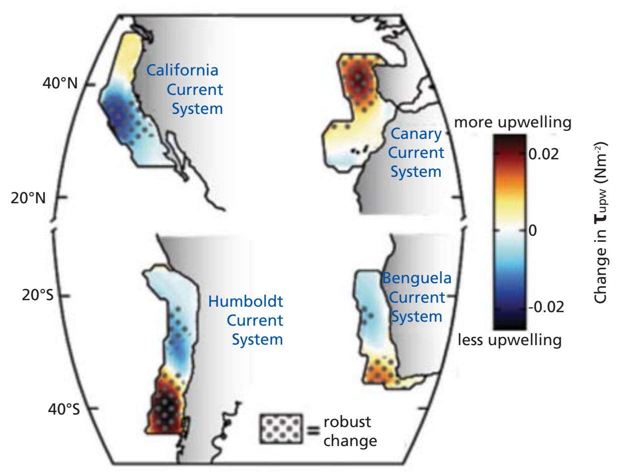


The black circles denote the location of the maxima in climatological wind stress at each longitude in the historical period. The contours represent anomalies, i.e. projections minus historical data: the bold lines represent positive anomalies with an interval of 0.004 N/m^2 (Newtons per square metre, pressure unit) with the zero line omitted, whereas the dashed lines represent negative anomalies with an interval of -0.004 N/m^2. The models used are as in Simpson et al. (2014). *Source:* Simpson, Shaw and Seager (2014).

FIGURE 1.5

Illustration of upwelling intensification hypothesis. Change in coastal upwelling-favourable winds (τ_{upw}) between two periods: 2071 to 2100 average minus 1861 to 1890 average

Change in coastal upwelling–favourable wind (2071 to 2100 mean minus 1861 to 1890 mean)



Source: Rykaczewski *et al*., 2015.

[3] The Coupled Model Intercomparison Project (CMIP) is a standard experimental protocol for studying the output of coupled atmosphere–ocean general circulation models. CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. CMIP5 refers to the fifth phase of the project. https://cmip.llnl.gov/index.html

BOX 1.2

Eastern boundary upwelling systems: global pattern and patchy responses

Major coastal upwelling zones exist along the edges of eastern boundary currents of the Pacific and Atlantic Oceans (Figure 1.5). In these eastern boundary upwelling systems (EBUS), alongshore winds interact with the earth's rotation to force surface waters offshore. These waters are then replaced with nutrient-rich deeper waters (upwelled), making EBUS some of the most productive of the world's marine ecosystems. According to a widely debated theory, under global warming coastal upwelling would generally strengthen as a result of differential warming between land and ocean, which would intensify upwelling-favourable winds (Bakun, 1990). However, the warming of the global ocean surface is also expected to increase thermal stratification, which would limit the depth from which water is upwelled, and thus the amount of nutrients brought to the near surface (Jacox and Edwards, 2011). How the impacts of climate change on wind and stratification interact, and their relative importance in different regions and times, remains uncertain and yet remarkably important for the future of a significant portion of global fisheries.

The processing of decades of data indicates that over the past 60 years, winds have intensified in the California, Benguela, and Humboldt upwelling systems and weakened in the Iberian system. In the Canary Current system, the trend is equivocal. Intensification was more evident in higher latitudes, which is consistent with the warming pattern associated with climate change (Sydeman *et al.*, 2014). While in general, results of recent projections corroborate Bakun's 1990 upwelling intensification theory (Wang *et al.*, 2015), there are regional differences in terms of upwelling intensity and duration, as well as spatial heterogeneity between low and high latitudes and in Northern and Southern Hemispheres (Rykaczewski *et al.*, 2015) (Figure 1.5).

In the Humboldt and the Benguela Currents, the duration and intensity of the upwelling is expected to increase with latitude, meaning that subtropical areas will experience more intense and longer upwelling events in the future. In the Canary Current, the same pattern is expected in terms of intensity, with an increase in high latitudes and a decrease in low latitudes. Contradictory information is found on the California Current as regards intensification of the upwelling; recent modelling results indicate that the upwelling might become more intense in spring and less intense in summer (Brady *et al.*, 2017). Contradicting theories on the California Current are probably because of the fact that it is strongly influenced by regional processes and natural variability (i.e. El Niño, Pacific Decadal Oscillation, North Pacific Gyre Oscillation).

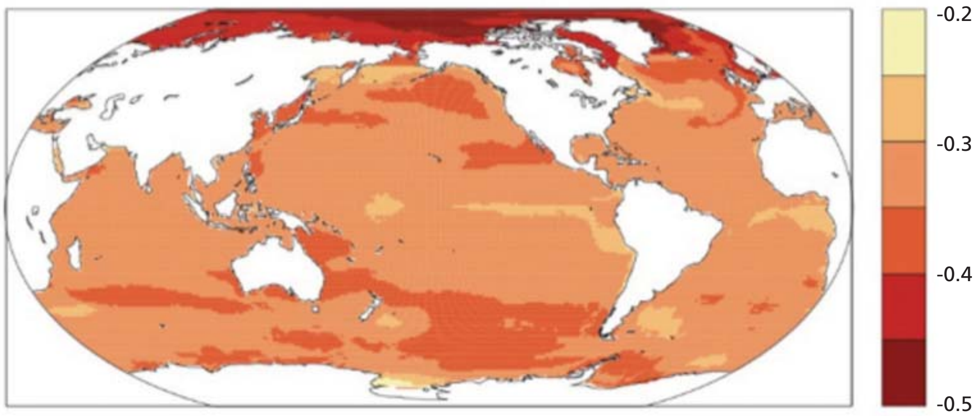
Regarding ocean productivity, the dynamics of the upwelling areas and their interactions with regional processes need to be better understood. On the one hand, upwelling intensification could have a positive impact on nutrient inputs and primary production, while on the other hand it could increase the presence of low oxygen waters in shelf habitats (Bakun *et al.*, 2015)

1.4.7 Ocean acidification

Ocean acidification refers to a reduction in the pH of the ocean over an extended period (typically decades or longer) caused primarily by the uptake of atmospheric CO_2. It can also be caused by other chemical additions to or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity. As atmospheric CO_2 concentrations increase, the oceans absorb more CO_2. This causes an increase in the partial pressure of CO_2 (pCO_2) at the ocean surface and a decrease in water pH and in the saturation state of mineral forms of calcium carbonate ($CaCO_3$), referred to as Ωar[4], which is important for all shell-forming aquatic life (Pörtner *et al*., 2014). Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in increasing acidification of the ocean; the pH of ocean surface water has decreased by an average of 0.1, corresponding to a 26 percent increase in acidity (IPCC, 2014; Jewett and Romanou, 2017). Variability in coastal pH, pCO_2 and Ωar is higher in coastal waters than in the open ocean. Lower salinity (resulting from ice melt and/or excess precipitation) exacerbates water acidification by diluting the concentration of substances acting as buffers. There are regional variations in the rate of acidification of surface waters: acidification is already 50 percent higher in the Northern Atlantic than in the subtropical Atlantic, and Arctic waters are acidifying faster than the global average because cold water can absorb more CO_2. In the California Current, corrosive conditions events (in terms of Ωar state) have increased in frequency, severity, duration and spatial extent (Harris, DeGranpre and Hales, 2013).

While oceanic pH is subject to natural variability, especially near sources of freshwater input like rivers and heavily tidal environments, observed trends in global ocean pH already exceed the range in natural seasonal variability over most of the oceans (Henson *et al*., 2017), and are expected to exceed it further in coming years (Gattuso *et al*., 2015). Projections indicate that the volume of ocean water supersaturated in aragonite (where Ωar is greater than 1) will decrease by half (RCP2.6) or even disappear (RCP8.5) by the end of the century. The volume of undersaturated waters (where Ωar is less than 1), which are corrosive to calcium carbonate shells and skeletons, are forecast to increase by 10 percent to 20 percent depending on the scenario considered. Future projections show that this decrease in pH will occur throughout the world oceans, with the largest decreases in surface waters occurring in the warmer low- and mid-latitudes. However, it is the already low Ωar waters in the high latitudes and in the upwelling regions that are expected to become aragonite unsaturated first (Figure 1.6).

FIGURE 1.6
Median model's change in surface pH from 1850 to 2100 resulting from projected changes in ocean acidification of 11 CMIP5 Earth System Models under RCP8.5



Source: Ciais *et al*., 2013.

While the nature and speed of the acidification process are well understood and predicted with high confidence, its consequences over the next few decades are still

[4] If Ωar is less than 1 (Ωar<1), conditions are corrosive (undersaturated) for aragonite-based shells and skeletons. When Ωar>1, waters are supersaturated with respect to calcium carbonate and conditions are favourable for shell formation. Coral growth benefits from Ωar≥3 (IGBP, IOC & SCOR, 2013).

unclear. The type and magnitude of ocean acidification impacts on marine organisms vary with their physiological abilities to adapt to these new conditions, on top of the multiplicity of other stressors the organisms are exposed to. Ocean acidification research is still in the early stages of development and so far, mainly short-term responses in laboratory conditions have been investigated and provide information only on the sensitivity of organisms to a single stressor (McElhany, 2017). There is an emerging trend of scientific research that explores long-term responses and adaptive capacity of marine organisms (Munday, 2017), as well as the impact of combinations of stressors, such as temperature and acidification, or oxygen content and acidification (Gobler and Baumann, 2018). This will yield more insight into likely impacts.

1.4.8 Primary production

Phytoplankton production is the process at the base of the marine food web, controlling the energy and food available to higher tropic levels and ultimately to fish. Earth system model projections of global marine primary production as a result of climate change are uncertain, with models projecting both increases (Taucher and Oschiles, 2011) and declines of up to 20 percent by 2100 (Bopp *et al*., 2013; see also Chapter 4, this volume). This is partly because primary production is an integrator of changes in light, temperature and nutrients, but also because of the uncertainty in the sensitivity of tropical ocean primary production to climate change. Specifically, how climate change will affect El Niño events in the tropical Pacific remains uncertain (Chapter 15, this volume). However, based on the most recent understanding of tropical ocean primary production, it is estimated that global marine primary production will decline by 6 percent ± 3 percent by 2100 (Kwiatkowski *et al*., 2017). Primary production in freshwater lakes has been observed to increase in some Arctic (Michelutti *et al*., 2005) and boreal lakes, but to decrease in Lake Tanganyika in the tropics (O'Reilly *et al*., 2003). In both cases the changes were attributed by the authors to climate change (IPCC, 2014).

1.5 CONCLUSION

This chapter summarizes thematic information on climate change and its consequences for aquatic systems in order to provide the background and to set the context for the chapters that follow. Considering that aquatic systems represent more than two-thirds of the Earth surface, the current level of available information on climate change impacts is relatively low and many of the theories and assumptions are still under debate. However, it is a certainty that oceans play a critical role in climate regulation and in absorbing heat and the increased amounts of CO_2 resulting from anthropogenic activities. Model projections agree that ocean warming, increased stratification and increasing emissions will reduce the ocean's future capacity to absorb CO_2 (Gattuso *et al*., 2015).

Freshwater systems are also strongly connected to climate, as they may influence climate-related atmospheric processes and also be indicators of climate change. The IPCC considered freshwater systems to be among the most threatened on the planet because of the multiple anthropogenic impacts they are subject to. Hydropower infrastructure, water use for irrigation and agricultural land-use result in the fragmentation of water bodies, modification of flow regimes and a progressive disconnection of floodplains and wetlands from the rivers that sustain them. It is expected that these stressors will continue to dominate as human demand for water resources grows, together with urbanization and agriculture expansion (Settele *et al*., 2014), in addition to climate change.

Whether positive or negative, the evolution of aquatic systems under climate change will have implications for the fisheries and aquaculture sector, throughout the value chain. Species productivity and fish growth are already changing with consequences for fishing and farming yields, as a result of shifts in the distribution of fish, alteration of larval transport or thermal tolerance of farmed fish. Operations of fishing and farming activities are also expected to be affected, whether by short-term events such as extreme weather events or medium to long-term changes such as lake levels or river flow that could affect the safety and working conditions of fishers and fish farmers. Food control procedures will undergo major reshaping to protect consumers from potential increase in contaminants and toxin levels resulting from changes in water conditions. These examples of potential implications are further developed in more comprehensive analyses in the subsequent chapters, which examine the evolution of the fisheries and aquaculture sector in the context of climate change, but also in relation to the multiple stressors that it is currently experiencing, whether related to environmental or to anthropogenic activities. The chapters also explain the implications of these changes for fisheries and watershed management and, more importantly, they provide a set of potential solutions, both to adapt to the expected changes and to contribute to climate change mitigation.

1.6 REFERENCES

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science*, 247(4939): 198–201. (also available at https://doi.org/10.1126/science.247.4939.198).

Bakun, A., Black, B.A., Bograd, S.J., García-Reyes, M., Miller, A.J., Rykaczewski, R.R. & Sydeman, W.J. 2015. Anticipated effects of climate change on coastal upwelling ecosystems. *Current Climate Change Reports,* 1(2): 85–93. (also available at https://doi.org/10.1007/s40641-015-0008-4).

Bindoff, N.L., Stott, P.A., AchutaRao, K.M., Allen, M.R., Gillett, N., Gutzler, D., Hansingo, K. *et al.* 2013. Detection and attribution of climate change: from global to regional. *In* T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P.M. Midgley, eds. *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* pp. 867–952. Cambridge, UK and New York, USA, Cambridge University Press. (also available at http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter10_FINAL.pdf).

Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M., Halloran, P. *et al.* 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences,* 10(10): 6225–6245. (also available at https://doi.org/10.5194/bg-10-6225-2013).

Brady, R.X., Alexander, M.A., Lovenduski, N.S. & Rykaczewski, R.R. 2017. Emergent anthropogenic trends in California Current upwelling. *Geophysical Research Letters,* 44(10): 5044–5052 (also available at https://doi.org/10.1002/2017GL072945).

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V. *et al.* 2018. Declining oxygen in the global ocean and coastal waters. *Science,* 359(6371): eaam7240 [online]. [Cited 28 April 2018]. https://doi.org/10.1126/science.aam7240

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. & Saba V. 2018. Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature,* 556: 191–196. (also available at https://doi.org/10.1038/s41586-018-0006-5).

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change,* 4: 111–116. (also available at https: doi:10.1038/nclimate2100).

Cai, W., Santoso, A., Wang, G., Yeh, S.-W., An, S.-I., Cobb, K.M., Collins, M. *et al.* 2015. ENSO and greenhouse warming. *Nature Climate Change,* 5: 849–859. (also available at https://doi.org/10.1038/nclimate2743).

Cheng, L., Trenberth, K.E., Fasullo, J., Boyer, T., Abraham, J. & Zhu, J. 2017. Improved estimates of ocean heat content from 1960 to 2015. *Science Advances,* 3(3): e1601545 [online]. [Cited 24 May 2018]. https/doi.org/10.1126/sciadv.1601545