Addressing Climate Change Impacts on Fisheries and Aquaculture

Changes in the climate system are generating a diversity of impacts on ocean ecosystems, creating novel challenges for the sustainability of marine fisheries and aquaculture production. These include marine heatwaves, ocean acidification, deoxygenation, and rising sea levels and temperatures, the severity of which depends on future trajectories of global greenhouse gas emissions. Yet advances in monitoring, modeling and projections are helping to inform management strategies that can help to mitigate these risks and contribute to "climate-smart" seafood production.

Introduction

Since 1988, the Intergovernmental Panel on Climate Change (IPCC) has been the world's authority on the scientific basis for understanding human-induced climate change, its associated risks, and the potential for addressing these. Drawing on input from thousands of scientists and over 100 governments, the IPCC concluded in 2013 that:

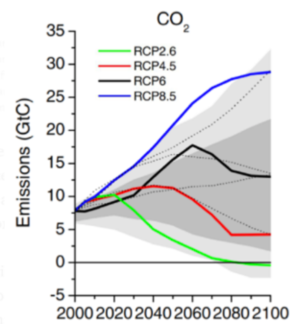
> *"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased."* [1]

Yet these changes are affecting different communities, regions and industries in very different ways. In addition, future impacts will depend on how successful humanity is at reducing greenhouse gas emissions and adapting to climate change impacts.

To understand future changes to the Earth's systems, it has been useful to develop a range of forward-looking scenarios. The most frequently used set of scenarios are referred to using the acronym RCP[i]. Four RCPs have been defined, and these correspond to a range of potential trajectories of greenhouse gas emissions (Figure 1). Such scenarios depend on historical data and continuous observations of Earth's systems (Figure 2).

[i] Formally, Representative Concentration Pathways (RCPs) denote projected levels of radiative forcing per square meter in year 2100 relative to 1750: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (2.6, 4.5, 6.0 and 8.5 Watts per square meter, respectively). The RCPs were adopted by the IPCC for its Fifth Assessment Report (2013)

Scenario names	Global action with regard to greenhouse gas emissions	Temperature increase* by 2100
RCP 2.6	Emissions peak around 2020, and rapidly decline due to global mitigation and carbon capture efforts	1.6° Celsius
RCP 4.5	Emissions peak around 2040 and start to decline	2.5° Celsius
RCP 6.0	Emissions peak around 2080 and start to decline	2.9° Celsius
RCP 8.5	Continued increase in global greenhouse gas emissions throughout the 21st century	4.3° Celsius



* Rough estimates of increase in planetary surface temperature – see IPCC (2019) for full ranges.

Figure 1: Common scenarios of future global trajectories of greenhouse gas emissions (RCPs), and graphical representation.[2,3]

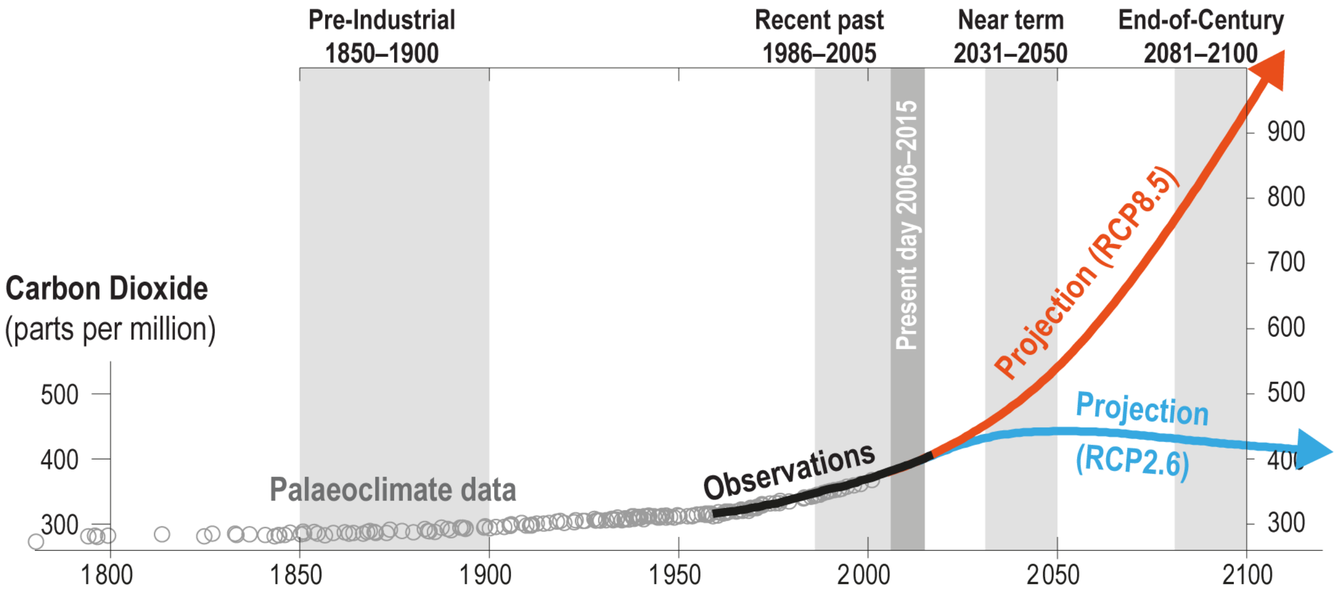


Figure 2: Example of CO_2 measurements/data used to understand climate change. An increasingly global set of observational data has become available since the 1960s. In the "Present Day" (2006-2015), globally representative data is available. Looking forward, different projections are used to understand the range of possibilities for future carbon dioxide levels based on current and future efforts to reduce greenhouse gas emissions.[4]

Climate Change Impacts on the Ocean (Current and Projected)

The impacts of climate change on the ocean can be split into four main categories:

- Changes to the ocean climate
- Changes to ocean chemistry
- Changes to ocean circulation
- Changes to sea level and ice distribution

Each of these four categories is described in more detail in the following sections, but it is important to note that there are interactions among these different impacts, with some reinforcing and amplifying the impacts of others, although many of these interactions remain poorly understood.[3,5,6]

Changes to the ocean climate

The ocean has acted as a reservoir or a buffer for the impacts of climate change, by absorbing approximately 93% of the extra heat generated by climate change.[7] As a result, global average sea surface temperatures have increased by 0.7°C since 1908.

Warming has also been identified at greater depths (below 700 meters) and has been increasing for the past four decades.[7] Under the RCP 8.5 scenario, a five-fold to seven-fold increase in ocean temperatures is expected by 2100, compared with observed change since 1970, while even the RCP 2.6 scenario would see a two-fold to four-fold increase.[4] Warming is not uniform across the ocean, and a high degree of regional variability is expected (See Figure 3). Marine hotspots have been identified, where warming is faster than average, and many impacts have been documented from these locations.[9]

Another increasingly common feature of oceans in the context of climate change is a change in the frequency, duration, or extent of extreme events. Increasingly frequent, long and intense marine heatwaves, extended periods of extreme regional ocean warming, have been observed in the historical record.[11] Marine heatwaves have resulted in largescale coral bleaching, with successive mass bleaching events in 2016 and 2017 resulting in the loss of nearly half the corals in the Great Barrier Reef.[12] A 2013-2015 marine heatwave (known as "the Blob") in the northeastern Pacific resulted in mass

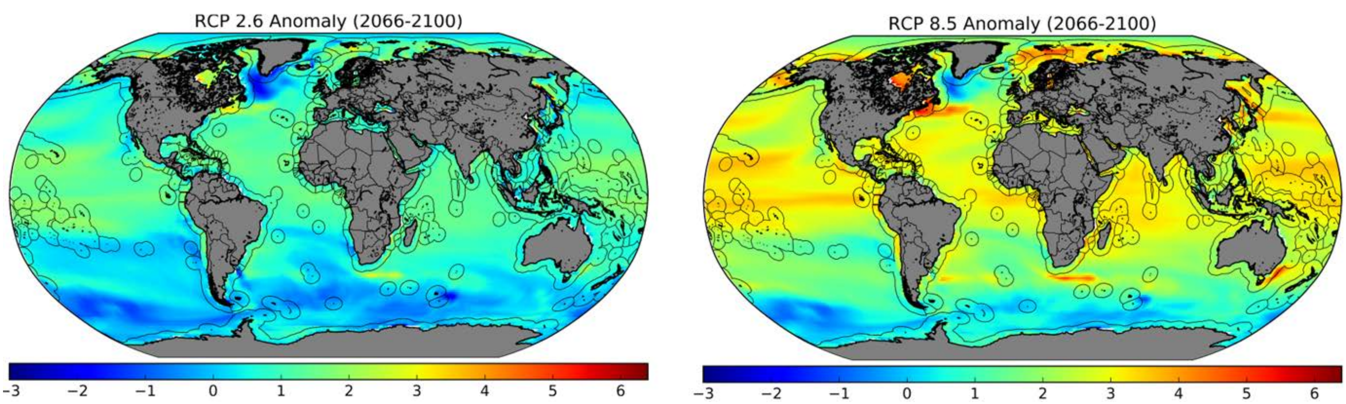


Figure 3: Changes in global sea surface temperature by 2100 under RCP 2.6 and RCP 8.5 with overlaid exclusive economic zone boundaries.[10]

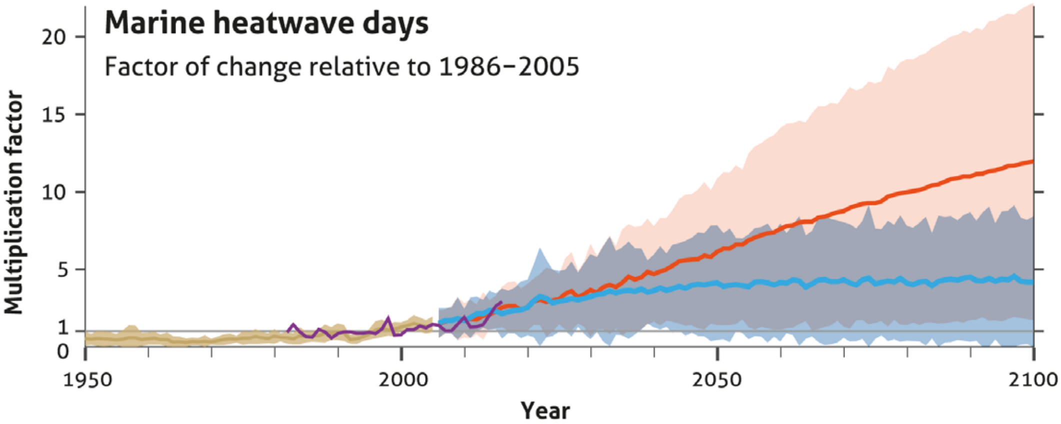


Figure 4: Increasingly frequent marine heatwaves expected under both mild (RCP 2.6 – blue line) and severe (RCP 8.5 – orange line) climate change scenarios by 2100.[4]

mortality of seabirds and marine mammals, closure of fisheries, and disruption of aquaculture[13] (Figure 4). By the end of the century, an up to twelve-fold increase in the frequency of marine heatwaves is predicted, relative to 1986-2005, depending on future climate change scenarios.[4]

Changes to ocean chemistry

The increase in carbon dioxide emissions from burning of fossil fuels and other human activities is the main driver of climate change, and much of this carbon dioxide (CO_2) is absorbed by the ocean[ii]. The result has been an increasingly acidic ocean, with acidity levels increasing by 26% since the 1900s, with some regional variation.[4,15]

Corals and many other marine organisms with shells (e.g. sea urchins, snails) depend on availability of carbonate ions in ocean water to form their shells. Increasingly acidic waters not only have lower concentrations of such ions, but the high acidity levels cause their shells to slowly dissolve, requiring them to expend extra energy on shell formation (See Figure 5).

Some parts of the ocean are seeing lower oxygen levels (deoxygenation), as a result of lower gas solubility and higher interior respiration of organic matter in a warmer and more stratified ocean. As a result, the oxygen minimum zones (OMZ) are growing in size, particularly in the tropics, and are characterized by substantial decadal variability.[4] Globally, the oxygen content in the ocean is projected to decline by 3.2-3.7% by 2100 relative to the current status (2006-2015) under RCP 8.5.[4] Deoxygenation poses a threat to the growth and survival of both fish and invertebrates through the reduction in body size and contraction of suitable environmental conditions.[16,17]

Changes to ocean circulation

Currents are an important feature of the ocean, affecting local weather patterns, ocean chemistry, and the productivity of the ocean. Constantly moving, ocean currents are described as the "global conveyor belt", as they slowly redistribute heat and freshwater from polar ice melt.

Climate change is altering ocean circulation, causing the global conveyor belt to slow down. This is primarily a result of large-scale melting of glaciers and sea ice, which feed massive amounts of freshwater into the ocean, resulting in lower levels of sea ice formation and sinking of cold salt water. The intensity of currents is also an important factor for the productivity of upwelling zones, which result in some of the most productive fishing areas in the world.

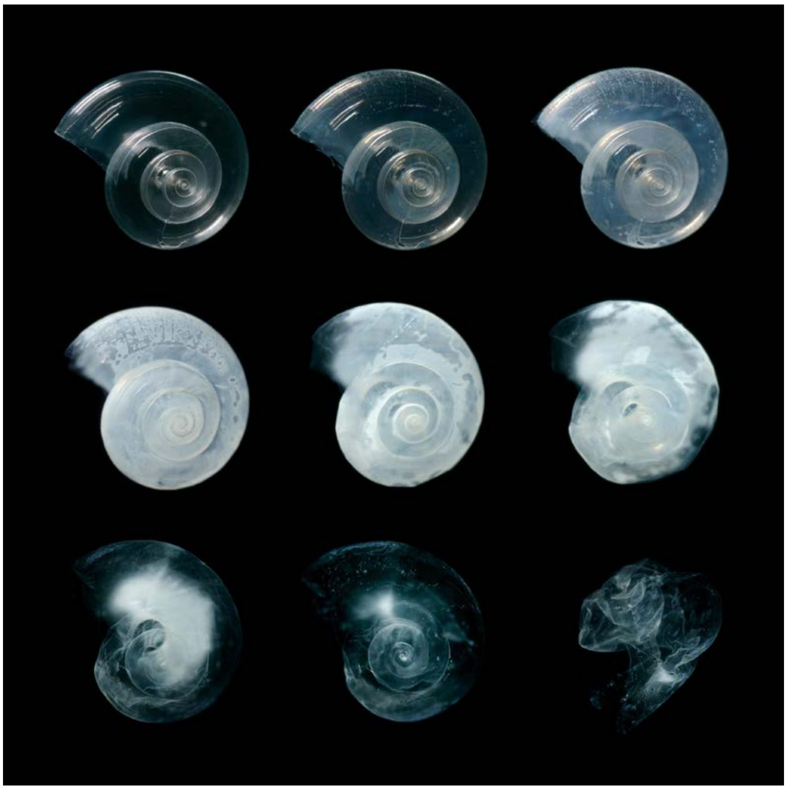


Figure 5: Pteropods are eaten by organisms ranging in size from tiny krill to whales and are a food source for North Pacific juvenile salmon. Under projected ocean chemistry conditions in 2100 (increased acidity and lowered carbonate ion levels), pteropod shells dissolve within weeks. (Photo: David Liitschwager, reproduced with permission)

[ii] When the ocean absorbs CO_2, concentrations of bicarbonate and hydrogen ions increase, resulting in a drop in pH, alongside a drop in carbonate ion concentrations, and increased levels of dissolved inorganic carbon[14]

Changes to sea level and ice distribution

The "cryosphere" (the parts of the Earth's surface covered in ice) has experienced some of the most striking shifts due to climate change. The decline in Arctic sea ice cover over the past decades (see Figure 6) has resulted in the opening of new shipping routes and the possibility of ice-free summers. Melting of the Greenland Ice Sheet doubled in scale from 2007-2016, while the loss of the Antarctic Ice Sheet tripled over the same period.[4,14] These trends are expected to increase throughout the remainder of the 21st century.[4]

On average, sea levels have risen globally by 16 cm from 1902 to 2015 due to the melting of ice sheets and glaciers, and receding snow cover. Under RCP 2.6, a further 29-59 cm of sea level rise is expected by 2100; under RCP 8.5, 61-110 cm is expected.

Main impacts of climate change on capture fisheries

Shifts in distribution and abundance of fish populations

Changing ocean conditions (most notably rising temperatures) are already resulting in changes in the distribution and abundance of fish populations. One study found that fish and other animals are moving into new territories at an average rate of 72 km per decade[18], and a continuation or acceleration of this trend is expected.[19,20]

One challenge for fisheries managers is that shifts in distribution are happening at different speeds for different species and in different parts of the world. Long-term trends are also difficult to understand over short time periods, so changes from one year to the next may be considered part of a long-term trend by some observers, or simply natural variability by others. A well-publicized example of this is the "mackerel war" that started in 2007 when a mackerel stock in the northeastern Atlantic seemingly shifted from areas under management by the European Union, Norway and the Faroe Islands into waters managed by Iceland and Greenland. Disagreements over the stock's distribution and responsible catch allocations led to overfishing.[19,21]

The "mackerel war" also highlights another risk: the challenges of designing fisheries agreements and institutions that can react flexibly in the context of uncertainty. This is particularly challenging in the case of transboundary stocks that enter into the exclusive economic zone (EEZ) of multiple countries.[22] Climate model projections and information about current fish distributions have been used to predict future movement of stocks: between 46 and 60 stocks are expected to become transboundary by 2060 (under RCP 2.6 and 8.5, respectively).[19]

Regionally, some general changes are expected to becoming increasingly apparent. In tropical regions, fisheries will generally become less productive, with associated impacts on food security and associated livelihoods. More stability is expected in temperate regions in terms of overall productivity, although the composition of stocks will change. However, climate change impacts on tropical fisheries also affect sustainable development in non-tropical regions through seafood trade and distant-water fishing.[23] In polar regions, expected increases in productivity carry some risks, as governance mechanisms are still inadequate to ensure sustainable management of fisheries.[3]

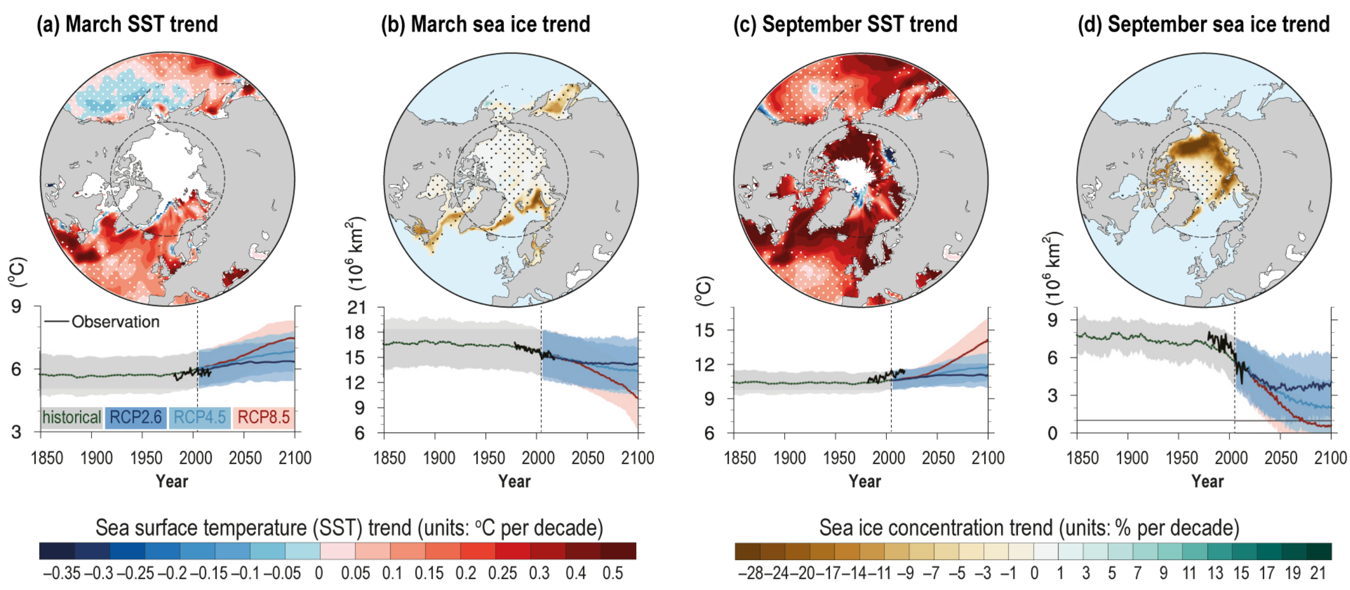


Figure 6: Historical and projected sea surface temperature (SST) and sea ice trend in the Arctic (1850-2100).[4]

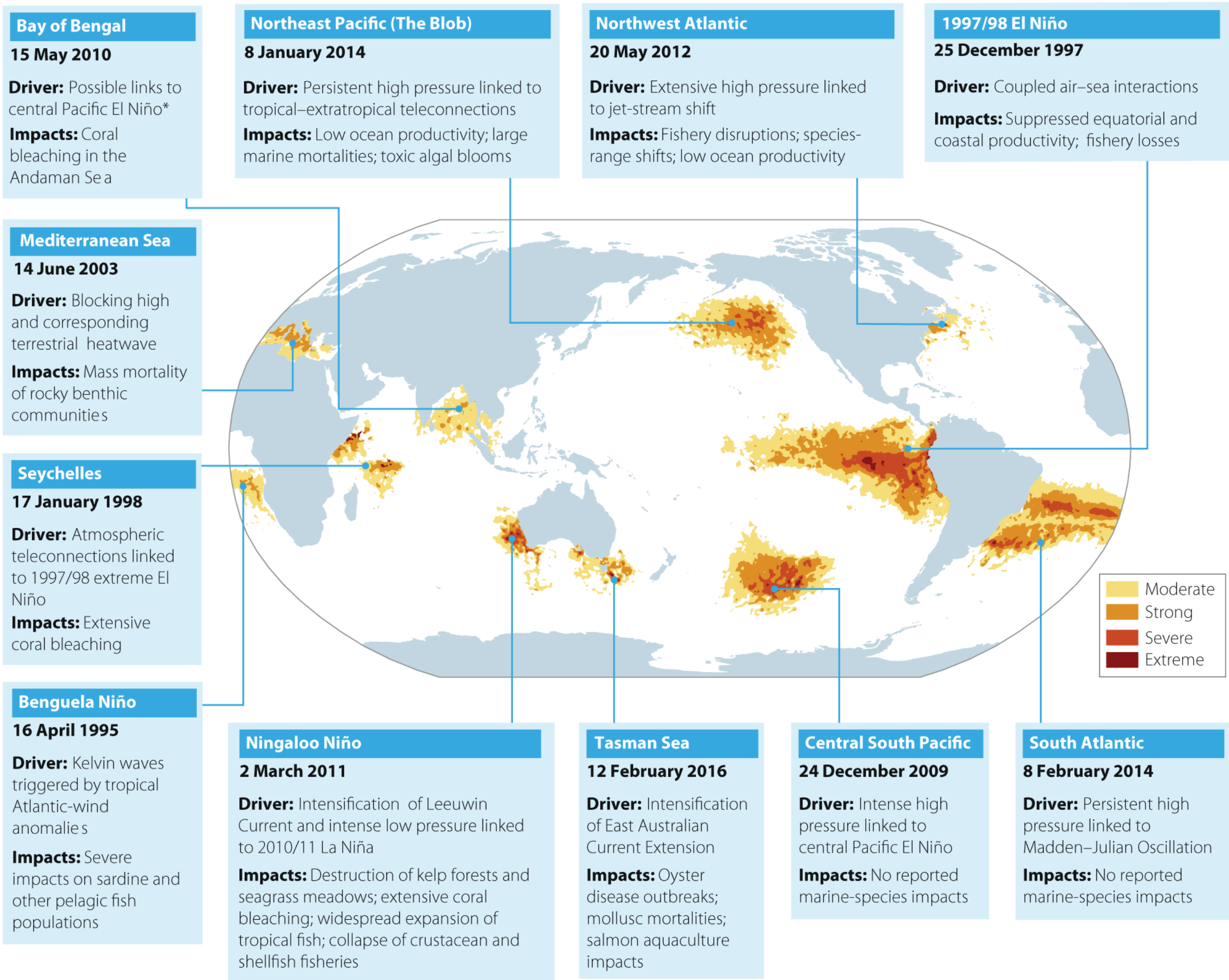


Figure 7: Drivers and ecological impacts of a subset of major marine heatwave events since 1995.[11] Reprinted by permission from Nature Reviews Earth & Environment (Keeping pace with marine heatwaves, Holbrook et al. 2020)

Less productive fisheries

On a global level, changing ocean conditions are making fisheries less productive, and have caused maximum sustainable yield to have fallen by an estimated 4.1% over the past 80 years.[24] Changes in productivity due to climate change, however, are very regional. Some regions are growing more productive, while others (e.g. in East Asia and the North Sea) are growing less productive.[24]

Significant changes in productivity are expected in fisheries in major upwelling areas. The most important of these are the Benguela Current (southwestern coast of Africa) the California Current (west coast of North America) the Canary Current (northwestern Africa) and the Humboldt Current (western coast of South America). All four of these "eastern boundary currents" support major fisheries. Globally, climate change-related shifts in ocean circulation and upwelling are expected to reduce primary productivity by 7-16% by 2100 under RCP 8.5.[4] Elsewhere, the loss of coral reefs to warming waters and marine heatwaves is resulting in declining fish populations, with one study linking the loss of corals to at least a 35% loss in fisheries productivity.[25]

The Gulf of Alaska marine heatwave of 2014-16 has been linked to a 71% decline in abundance in Pacific cod (*Gadus macrocephalus*), a fishery worth over $100 million per year.[26] Although increased mortality likely led to the decline in the Pacific cod population, historically low recruitment concurrent with the heatwave portends a slow recovery for the stock and gives a preview of impacts facing this region due to climate change. Such impacts are becoming widely reported from marine heatwaves around the world (Figure 7).

Risks to fisheries operations and infrastructure

Climate model projections are particularly clear on the increased severity of tropical cyclones, and associated storm surges, with differences between RCP 2.6 and 8.5 becoming evident by 2050.[4] Rising sea levels and increasing frequency and intensity of storms are expected to combine with extremely costly impacts for both onshore and offshore infrastructure, making it likely the most expensive and disruptive of the climate change impacts on the ocean.[14] Annual costs of up to USD 14 trillion have been estimated just for flooding damage from sea level rise.[27] Storms pose a safety risk for fisheries operations, and increase the likelihood of lost gear (see below for impacts on aquaculture production).

Main impacts of climate change on aquaculture production

Similar to capture fisheries, the impacts of climate change on aquaculture production will vary depending on region and species. Both finfish and bivalve production, for instance, are expected to be negatively impacted on a global scale due to climate change, but will likely become more productive in polar and sub-polar regions.[28]

Mariculture, however, is significantly more reliant on shore-based and ocean-based infrastructure than capture fisheries. This makes such production particularly vulnerable to sea level rise[29] and storms of increasing frequency and severity.[30] Periods of intense rainfall over land have resulted in higher levels of agricultural runoff, subsequent nutrient overloads in rivers and streams, and more frequent harmful algal blooms (HABs).[31,32] Rising sea levels can also lead to coastal areas characterized by brackish waters (mixing of freshwater and seawater) to become increasingly salty. This can cause the area of habitat available for brackish-water aquaculture to shrink.[29] Changes in environmental variables such as temperature, oxygen, and chlorophyll also affect the areas that are suitable for marine aquaculture[28,33] and climate change impacts can lead to an average of 10-40% decline in the number of species being potentially suitable to be farmed in tropical and subtropical regions by mid-century.[34]

Ocean acidification poses a risk to commercial shellfish production, as it interferes with the growth of calcium carbonate shells and skeletons.[35] Associated impacts include a decline in recruitment levels, greater vulnerability to disease and parasites, and higher overall mortality.[36,37] Pathogens and parasites are also expected to become increasingly potent risks to aquaculture production as water temperatures rise,[38] enabling the spread of pathogens and parasites into new areas and amplifying the toxicity of chemical pollutants.[14,39] Countries most vulnerable to climate change are expected to face the highest risks of antimicrobial resistance.[38]

Strategies for ensuring climate-resilient seafood production

Promote effective fisheries management measures

Historical data as well as future projections suggest that some of the most important tools for promoting climate-proof fisheries are already in our toolbox: science-based catch limits, using the precautionary principle, protection of essential fish habitats, accountability and traceability measures, and regional flexibility to match local conditions. All of these tools are elements of well-managed fisheries, which have historically been more resilient to anomalous conditions[24] and are projected to be crucially important for reducing climate risk (Figure 8).[4]. One study[3]

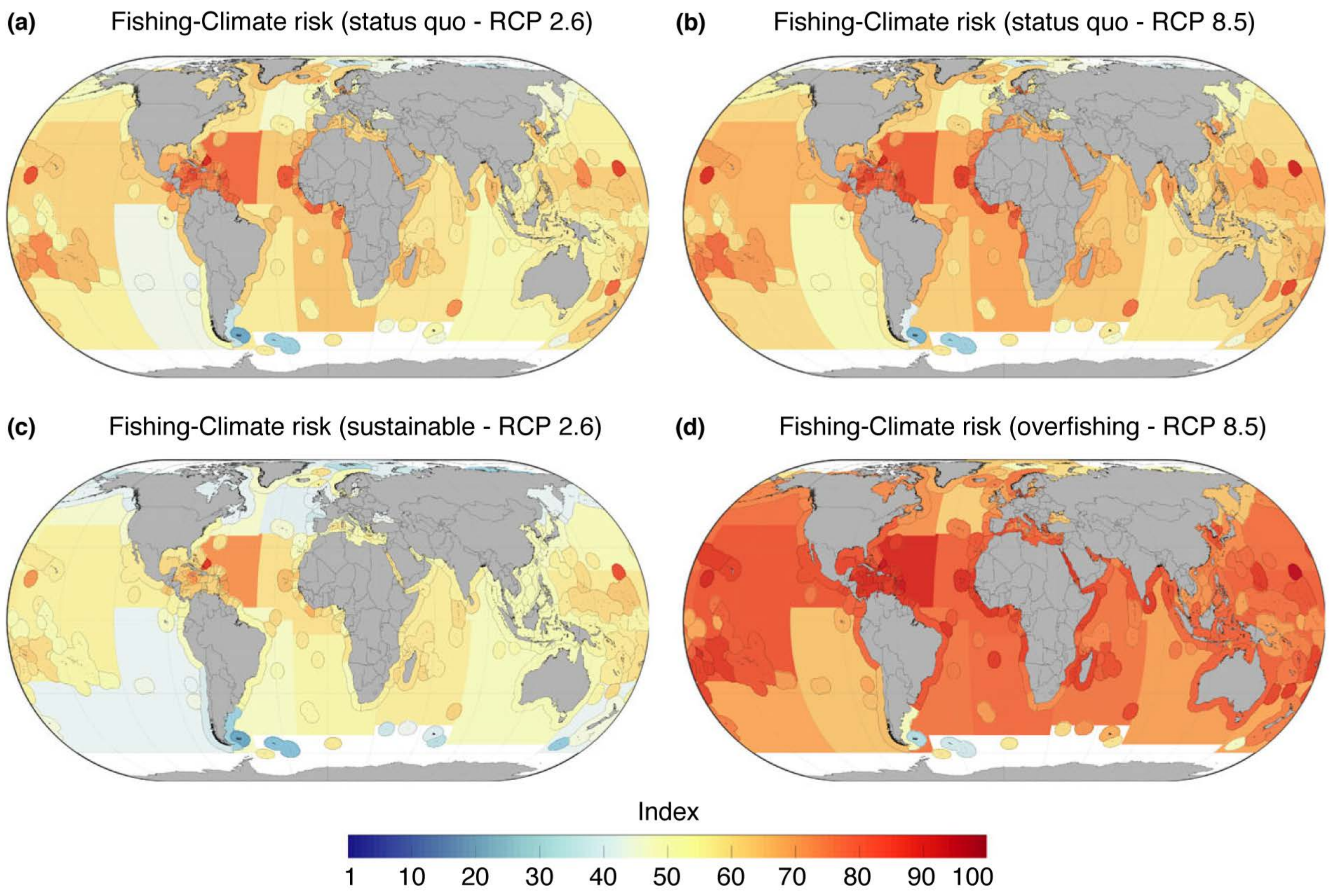


Figure 8: Estimated climate risk to 825 exploited fish species under different fishing and climate scenarios. A movement from status quo (a) to sustainable global fisheries (c) shows decreased risk by 2050 despite continued climate change (RCP 2.6), and the impact becomes clearer when considered a high emissions scenario (RCP 8.5) under status quo management (b) and overfishing (d) (adapted from Cheung et al.).[40]

estimates substantial gains in biomass, harvests and profits from adopting climate adaptive management measures that account for both productivity changes and range shifts. Studies have also found that effective community-based fisheries management may help to increase climate resilience.[41,42]

Promote effective institutions and governance mechanisms

Jurisdictional boundaries mean nothing to ocean currents, fish populations, pathogens, or disease. Regional and international coordination will therefore be a crucial component of addressing climate change impacts on seafood production. Regional bodies need to be supported by states and their decisions need to be informed by science.[14] In the special case of transboundary fish stocks that are shifting due to climate change, or experiencing unpredictable interannual fluctuations in distribution and abundance, there is a need for fisheries agreements with built-in flexibility and trigger mechanisms allowing for rapid response before overfishing or conflict emerges.[19]

Anticipate and plan for future change

A range of tools are available to fisheries and aquaculture managers to plan for the future.[14] These include use of forecasts and scenarios to envision and prepare for alternative futures.[43,44] More and more real-time (or near real-time) data is available to managers in order to react quickly to changing conditions. This could include adjusting management decisions, for instance by introducing spatial or temporal closures to avoid bycatch of endangered species.[45] Management measures including harvest control rules, which aim to stop the risk of overfishing, also need to be continuously tested and adjusted to ensure that they continue to function well under increasingly unpredictable conditions caused by climate change.[46]

Engage with financial institutions and governments to ensure resources for climate smart seafood production

Looking towards the future, a growing interest among financial institutions to protect themselves against climate risk presents an opportunity for seafood companies focused on climate-proofing their operations. Companies that can demonstrate a responsible strategy and strong commitment to reducing their own carbon footprint, combined with a risk-based approach to future seafood production and sourcing could be incentivized by financial institutions with more advantageous credit and insurance terms. Pilot research has already shown that insurance schemes focused on vulnerable small-scale aquaculture and fisheries operations have been a sound investment.[15]

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