Chapter

08

Impacts of Climate Change on Coastal and Marine Ecosystems

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Introduction

The global climate has changed since the preindustrial period. A number of evidences are now available that these changes have a few positive ad many negative impacts on organisms and ecosystems, as well as human systems and wellbeing. The global mean surface temperature (GMST), which increased by 0.87°C in 2006-2015 relative to preindustrial period of 1850-1900, will increase further to 1.5°C or higher by 2030-2040 with increased magnitude of impacts on natural and human systems (IPCC, 2014). Until recently, information on evidence-based impacts of climate change were available for a global warming of 0.87°C or less. After the release of Special Report of the Intergovernmental Panel on Climate Change (IPCC) in October 2018, direct information and predictions on the impacts of global warming of 1.5°C and up to 2°C are now available.

In its Fifth Assessment Report (AR5), the IPCC (2014) evaluated the changes to natural systems, and the impact on human communities and industry. While impacts varied substantially between systems, sectors and regions, many changes over the past 50 years were attributed to human-driven climate change and its impacts. Risks were observed to be increasing for natural ecosystems as climate extremes increase in frequency and intensity. In association with the changes with the natural ecosystems, the associated fauna and flora will be shifting their biogeographical ranges to higher latitudes and altitudes. This will have consequences for ecosystem services and human dependence. AR5 also reported increasing evidence of changing patterns of disease, invasive species as well as growing risks for coastal communities and industry, especially in the context of sea level rise and human vulnerability.

For assessing possible impacts on natural and managed systems at 1.5ºC and above, the IPCC (2018) used the following approaches: (i) Identifying impacts of global 0.5°C warming in the observational record of previous decades, assuming that the impacts would scale linearly for higher levels of warming; (ii) Using conclusions from past climates combined with e modeling of the relationships between climate drivers and natural systems; and (iii) More complex approach on laboratory or field experiments which provide useful information on the causal effect of a few factors (which can be as diverse as climate, greenhouse gases (GHG), management practices, biological and ecological factors) on specific natural systems. The major conclusions arrived by IPCC (2018) for marine ecosystems are given here.

Oceans systems

The Ocean plays a central role in regulating atmospheric gas concentrations, global temperature and climate. It is also provides habitat to a large number of organisms and ecosystems that provide goods and services that are worth trillions of USD per year (e.g., Costanza et al., 2017). Together with local stresses, climate change poses a major threat to an increasing number of ocean ecosystems (e.g. coral reefs) and consequently for many coastal communities who depend on marine resources for food, livelihoods and a safe place to live. Changes in the ocean include rapid increases in ocean temperature down to at least 700 m depth. It is *virtually certain* that the surface temperature of the upper layers of the ocean (0–700 m) have warmed over the period 1950–2016 by 0.11°C, 0.07°C, and 0.05°C per decade for the Indian, Atlantic and Pacific oceans, respectively with the greatest changes occurring at high latitudes. There is also evidence of significant increases in the frequency of marine heatwaves, consistent with changes in mean ocean temperatures. Increasing climate extremes in the ocean are associated with the general rise in global average surface temperature as well as more intense patterns of climate variability (e.g., climate change intensification of ENSO). Increased heat in the upper layers of the ocean is also driving more intense storms and greater rates of inundation, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas.

Ocean chemistry is also changing with the global temperature increase of 1.5°C. Projected changes in the upper layers of the ocean include pH, oxygen content, as well as sea level. Seawater is slightly basic (meaning pH > 7), and ocean acidification involves a shift towards pH-neutral conditions rather than a transition to acidic conditions (pH < 7). Anthropogenic carbon dioxide has decreased the pH, as well as affected the concentration of ions (such as carbonate) in seawater. About 30% of CO_2 emitted by human activities, for example, has been absorbed by the ocean where it has combined with water to produce a dilute acid that leads to ocean acidification. Ocean pH has decreased by 0.1 pH unit since the Pre-Industrial Period, which is unprecedented in the last 65 to 300 million years. Experimental manipulation of CO_2, temperature and consequently acidification indicate that these impacts will continue to increase in size and scale as CO_2 and SST continue to increase in tandem. As CO_2 concentrations continue to increase along with other GHGs and SST increase of 1.72°C, the pH will decrease linearly to 0.22 pH unit (relative to the preindustrial period). These changes are likely to continue given the linear correlation of SST and pH.

Increasing surface water temperatures have reduced the oxygen concentration in the ocean by 2% since 1960. Changes to ocean mixing and metabolic rates (due to increased temperature and supply of organic carbon to deep areas) have increased the frequency of 'dead zones', areas where oxygen levels no longer support oxygenic life.

Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e. evaporation and inundation). Some regions (e.g. northern oceans and Arctic regions) have decreased salinity (i.e. due to melting glaciers and ice sheets) while others are increasing in salinity due to higher sea surface temperatures and evaporation. These changes in salinity (density) are also potentially driving changes to large scale patterns of water movement.

Increased ocean temperature has intensified the storms. Storms, wind, waves and inundation can have highly destructive impacts on ocean and coastal ecosystems as well as the human communities that depend on them. The intensity of tropical cyclones across the world's ocean has increased although the overall number of tropical cyclones has decreased. The direct force of wind and waves associated with larger storms, along with changes in storm direction, increase the risks of physical damage to coastal communities as well as ecosystems such as mangroves and tropical coral reefs. These changes are associated with increases in maximum wind speed, wave height and inundation, although the trends vary from region to region. In some cases, this can lead to increased exposure to related impacts like reduced water quality and sediment run-off. More intense storms have the potential (along with other factors such as disease, food web changes, invasive organisms and heat stress mortality) to offset the capacity for natural and human systems to recover from disturbances. Observations on precipitation show that there are more areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation.

Importantly, changes in the response to climate change act synergistically and rarely operate in isolation (Fig. 1). Hence, the effect of global warming at 1.5°C must be considered in the light of multiple, interactive factors that may produce complex risks and impacts on human and natural systems.

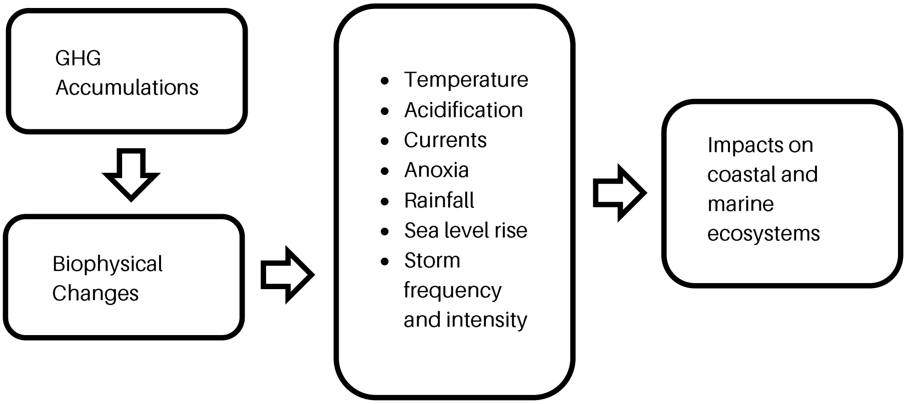

Figure 1. The pathway by which climate change impacts coastal and marine ecosystems

Impact on marine ecosystems

The developmental rates of poikilotherms, where body temperatures vary with the environment, increase exponentially with temperature, with important consequences including larval dispersal, population connectivity, local adaptation, and speciation. Marine organisms are already responding to climate change by shifting their biogeographical ranges to higher, cooler latitudes, at rates that range from 0 to 40 km per year. This has affected the structure and function of the ocean, along with its biodiversity and food webs. Movements of organisms do not necessarily result in movement of entire ecosystems. For example, the oil sardine has been observed to expand its geographic ranges to the northern latitudes along the Indian coast, but this has not resulted in the expansion of entire coastal ecosystems from the southern latitude to the northern latitude. In the case of 'less mobile' ecosystems (e.g. coral reefs, kelp forests, intertidal communities), shifts in biogeographical ranges may be limited with mass mortalities and disease outbreaks increasing in frequency as the exposure to extreme temperatures increases. These trends will become more pronounced at 1.5°C, and even more at 2°C and are likely to result in decrease in marine biodiversity at the equator and increase in biodiversity at higher latitudes.

While the impacts of relocating species are mostly negative for human communities and industry, there are instances of short-term gains. Fisheries, for example, may expand temporarily to the northern latitudes. One example, as mentioned in the previous paragraph, is the latitudinal expansion of oil sardine from southern latitudes to northern latitudes along the east and west coasts of India (Vivekanandan, 2011). Fisheries in temperate waters and in high latitudes are influenced by the temperature on Net Primary Productivity (NPP) as well as on fish and fisheries. Low and mid latitudes, on the other hand, increase in sea temperature is driving decrease in NPP due to the direct effects of elevated temperatures and/or reduced ocean mixing from reduced ocean upwelling (increased stratification). Reduced ocean upwelling has implications for millions of people and industries that depend on fisheries for food and livelihoods.

Changes in ocean circulation also can have profound impacts on marine ecosystems. Ocean circulation connects regions and facilitates the entry and establishment of species in areas where they were unknown before (e.g., 'tropicalization' of temperate ecosystems) as well as the arrival of novel disease agents. For example, the sea urchin, *Centrostephanus rodgersii*, a herbivore, has been able to reach Tasmania, where it was previously unknown, from the Australian mainland due to strengthening of East Australian Current. As a consequence, the distribution and abundance of kelp forests has rapidly decreased with implications for fisheries and other ecosystem services.

Numerous risks have been identified associated with ocean acidification. Changes in pH of seawater are having, and are likely to have, fundamental and substantial impacts on a wide variety of organisms. Organisms with shells and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a broad number of organisms and processes such as de-calcification. Some taxa do not show the same sensitivity to changes in CO_2, pH and carbonate concentrations. Moreover, these risks vary with latitude (maximum changes at high latitudes) and depths. While many risks have been identified through laboratory and mesocosm experiments as the result of acidification, there is a growing list of impacts from the field that includes community scale impacts on bacterial assemblages and processes, coccolithophores, pteropods and polar food webs, phytoplankton, benthic ecosystems, seagrass, macroalgae, as well as sponges, endolithic microalgae, and reef-building corals.

As the number of ‘dead zones’ (areas where oxygenic waters have been replaced by hypoxic conditions) has been growing strongly since the 1990s, some impacts related to deoxygenation include expansion of Oxygen Minimum Zones (OMZ), physiological impacts, and mortality and/or displacement of oxygenic organisms such as fish and invertebrates. Deoxygenation interacts with ocean acidification to present substantial and combined challenges for fisheries and aquaculture. The number of hypoxic areas continues to increase and is likely to have greater impacts as ocean warming and acidification increases.

Sea level increases are interacting with other factors such as strengthening storms, which together are driving greater storm surge, infrastructure damage, erosion and habitat loss. Coastal wetland ecosystems such as mangroves, seagrasses and salt marshes are under pressure from rising sea level as well as a wide range of other non-climate change related risks and impacts. The loss of wetlands due to sea level rise has been recently estimated at approximately 1% per annum across a large number of countries. While some ecosystems (e.g. mangroves) may be able to shift shoreward as sea levels increase, coastal development (e.g. coastal building, seawalls, and agriculture) can often interrupt shoreward shifts of mangroves. The response to sea level rise include reducing the impact of other stresses such as those arising from tourism, fishing, coastal development and reduced sediment supply. In some cases, restoration of coastal habitats and ecosystems may be a cost-effective way of responding to changes arising from increasing levels of exposure from rising sea levels, intensifying storms, coastal inundation, and salinization.

Framework organisms (tropical corals, mangroves and seagrass)

Marine framework organisms (‘ecosystem engineers’), such as seagrass, kelp, oysters, salt marsh species, mangrove and corals build physical structures or frameworks (i.e. seagrass meadows, kelp forests, oyster reefs, salt marshes, mangrove forests and coral reefs) which form the habitat for large numbers of species. These organisms in turn provide food, livelihoods, cultural significance, and services such as coastal protection.

Coral dominated reefs are found between latitude 30°S and 30°N along coastlines where they provide habitat for over a million species. The food, income, coastal protection, cultural context, and many other services for millions of people along tropical coastal areas are provided by corals. More recently, climate change has emerged as the greatest threat to coral reefs. With temperatures of just 1°C above the long-term summer maximum remaining for 4-6 weeks, the corals undergo mass coral and mortality. Tropical coral reefs face very high risks of becoming unsustainable if warming exceeds 1.5°C. Even with warming until today (0.87°C), a substantial proportion of coral reefs have experienced large scale mortalities (Vivekanandan et al., 2009). In the last 3 years alone, large coral reef systems such as the Great Barrier Reef (Australia) have lost as much as 50% of their shallow water corals.

On a global scale, the distribution and abundance of coral reefs has decreased by approximately 50% over the past 30 years as a result of pollution, storms, overfishing and unsustainable coastal development. Ocean warming and acidification can also slow growth and calcification, making corals less competitive to other benthic organisms such as macroalgae. As corals disappear, so do fish stocks, and many other reef-dependent species, directly impacting industries such as tourism and fisheries, as well as coastal livelihoods for many. These impacts are exacerbated by increasing intensity of storms, which physically destroy coral reefs, and by ocean acidification which can weaken coral skeletons, contribute to disease, and slow the recovery of coral communities.

Predictions of bleaching events and decline of coral abundance is possible now. Recent models are capable of predicting large-scale loss of coral reefs. These predictions indicate large-scale loss of corals by mid-century under even low emission scenarios. Even if emission reduction is achieved and the temperature is increase is restricted to 1.5°C, there will be further loss of 90% of reef-building corals compared to today. If the temperature increases to 2°C or more above the pre-industrial period, 99% of corals will be lost.

Tropical coral reefs are found down to depth of 150 m and are dependent on light, as distinct from the cold deep-water reef systems that extend down to depths of 2000 m or more. Due to difficulty in accessing deep-water reef systems, the literature on impacts of climate change is limited compared to that of tropical coral reefs.

Risks of climate change impacts for seagrass and mangrove ecosystems have recently been assessed by an expert group led by Short et al. (2016). Impacts of climate change were similar across a range of submerged and emerged plants.

Submerged plants such as seagrass were affected mostly by temperature extremes and indirectly by turbidity, while emergent communities such as mangroves and salt marshes were most susceptible to sea level variability and temperature extremes. If the global warming reaches 1.8°C above the preindustrial period, seagrasses are projected to reach moderate to high levels of risk due to sea level rise, erosion, damage from extreme temperatures and storm damage. Projection of the future distribution of seagrasses suggest that tropical, low latitude seagrass communities will reduce due to increasing stress levels and there will be a poleward shift. For mangroves, recent assessments suggest that climate change risks are moderate, i.e., moderate risks start at 1.3°C due to sea level rise and more frequent heat stress mortality.

Strategies for reducing the impact of climate change on framework organisms include reducing non-climate change stresses (e.g. coastal pollution, overfishing, destructive coastal development) in order to increase ecological resilience in the face of accelerating climate change impacts. A full understanding of the utility and feasibility of the role of refugia in reducing the loss of ecosystems has yet to be developed. There is also interest in *ex situ* conservation approaches involving restoration of corals via aquaculture and 'assisted evolution' to help corals adapt to changing sea temperatures. However, there are numerous challenges for these approaches, which have to be cost effective.

Integrating coastal infrastructure with ecosystems dependent on mangroves, seagrasses and salt marsh is necessary such that they are able to shift shoreward as sea levels rise. Maintaining sediment supply to coastal areas will enable mangroves keep pace with sea level rise. In addition, integrated coastal zone management should recognize the importance of using natural ecosystems such as mangroves and tropical coral reefs to protect coastal human communities. High levels of adaptation will be required to prevent impacts on food security and livelihoods in general. Adaptation options include developing alternative livelihoods and food sources, ecosystem-based management/adaptation such as ecosystem restoration, and constructing coastal infrastructure that reduces the impacts of rising seas and intensifying storms. Clearly, these options need to be carefully assessed in terms of feasibility, cost and scalability, as well as in the light of the coastal ecosystems involved.

Ocean food webs

Ocean food webs are interconnected systems that transfer solar energy and nutrients from phytoplankton to higher trophic levels (including apex predators) as well as through other food web interactions. Animal metabolism is temperature-dependent, and consequently ecological processes such as predator-prey interactions are likely to be altered as warming occurs. Global warming and ocean acidification are forecast to exert significant impacts on marine food webs. Using a sophisticated mesocosm experiment, Ullah et al (2018) modelled energy flows through a species-rich multilevel food web, with live habitats, natural abiotic variability, and the potential for intra- and intergenerational adaptation. They have shown experimentally that the combined stress of acidification and warming reduced energy flows from the first trophic level (primary producers and detritus) to the second (herbivores), and from the second to the third trophic level (carnivores). Warming in isolation also reduced the energy flow from herbivores to carnivores, the efficiency of energy transfer from primary producers and detritus to herbivores and detritivores, and the living biomass of detritivores, herbivores, and carnivores. Whilst warming and acidification jointly increased primary producer biomass through an expansion of cyanobacteria, this biomass was converted to detritus rather than to biomass at higher trophic levels, i.e., production was constrained to the base of the food web. The results show how future climate change can potentially weaken marine food webs through reduced energy flow to higher trophic levels and a shift towards a more detritus-based system, leading to food web simplification and altered producer–consumer dynamics, both of which have important implications for the structuring of benthic communities. However, greater focus on incorporating predation and competition interactions into models will significantly improve the ability to identify species and industries most at risk from climate change.

As with many risks associated with impacts at the ecosystem scale, most adaptation options focus on the management of non-climate change stresses from human activities. Reducing non-climate change stresses such as pollution and habitat destruction will be important in efforts to maintain these important food web components. Fisheries management at local to regional scales will be important in reducing stress on food web organisms, as well as helping communities and industries adapt to changing food web structure and resources. One strategy is to maintain higher population levels of fished species in order to provide more resilient stocks in the face of challenges driven by climate change.

Table 1. Summary of projected risks to marine ecosystems at 1.5°C above pre-industrial level (IPCC, 2018)

Driver	**Risk**	**Risk level**	**Regions of high risk**	**Adaptation potential**
Warming & Stratification	Loss of corals	High	Tropical/ Subtropical	High
	Loss of seagrass	Medium	Tropical/ Subtropical	Medium
	Loss of mangroves	Medium	Tropical/ Subtropical	Medium
	Disruption of food webs	Low	Global	Medium
	Migration	Medium	Global	Medium
	Loss of fisheries	Medium/High	Global	Medium
Acidification & Elevated temperature	Loss of coastal ecosystems	Low/Medium	Tropical/ Subtropical	Medium
	Loss of bivalves	Medium	Temperate upwelling regions	Medium/High
	Changes to physiology of species	Low/Medium	Global	Low
Deoxygenation	Increased hypoxic zones	Low	Global	Low
	Change in upwelling productivity	Low	Most upwelling regions	Low
Intensified storm	Loss of coastal ecosystems	High	Tropical/ Subtropical	Medium
	Destruction of properties & loss of livelihood	High	Global	Medium
Sea level rise	Areas exposed	High	Asia	Medium
	Population exposed	High	Asia	Medium

Conclusion

Refugia or Marine Protected Areas may play an important role in terms of conservation of marine ecosystems, especially if they are protected from non-climate change risks. Given the marine ecosystems to heat stress, even short periods of temperature increase will be very challenging. Reduction in the services provided by marine ecosystems will increase poverty levels, highlighting the key issue of equity for the millions of people that depend on these valuable ecosystems. Addressing these challenges related to coastal and marine ecosystems is increasingly becoming important. Given the scale and cost of these interventions, implementing them earlier rather than later is necessary.

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