OCEANS: THE NEW FRONTIER

The human community insistently pushes the oceans' limits, seeking to exploit all of its varied resources – fisheries, fuels, minerals and genetic material – now at the centre of the world economy. All of these developments draw oceans closer to the heart of contemporary human societies.

International governance is challenged by the blurring frontier between the mainland and the ocean, constantly redefined by new technologies, scientific discoveries, industrial demands and most recently, by ecological imperatives. No sea escapes these onslaughts.

This volume takes the reader straight to the heart of how human-ocean interactions, work, and identifies contemporary trends, mechanisms and tools that can influence current strategies and choices.

FEATURING

- Papers by leading international experts and scholars
- New perspectives through in-depth analyses
- Multiple maps, charts, tables
- A wealth of ideas for specialists and non-specialists alike (policy-makers, administrators, concerned citizens, development professionals, entrepreneurs, journalists, students, and others).
The ocean plays a crucial role in the planet’s climate system and its ability to sustain life. Human-caused climate change affects the ocean, preventing it from functioning properly. This poses serious threats to marine and coastal ecosystems, as well as to human societies along the coastlines – and everywhere.

**CHANGING CLIMATE, CHANGING OCEAN, CHANGING PLANET**

Over the next several decades, human-driven climate change will profoundly affect the sea and the marine resources upon which so many depend for food and livelihood. As we move into a more uncertain future, we require a much better scientific understanding of the complex ocean climate system to inform adaptation and mitigation strategies. The ocean plays a critical role in Earth’s climate system and in the planet’s ability to sustain life. It helps to regulate global cycles of heat, freshwater and carbon, as well as the magnitude and regional patterns of land temperature and precipitation. However, this ability is threatened by increasing anthropogenic carbon dioxide in the atmosphere and the resulting changes to global and regional climate patterns (Meehl et al. 2007). Observations show that climate change is already affecting the ocean in significant ways, diminishing its capacity for further climate change mitigation and imposing some unavoidable constraints upon marine biodiversity, ecosystem services, and human societies in the future (Allsopp et al. 2009).

Satellite data and in-situ measurements over the last several decades provide clear evidence that surface and subsurface waters are warming, ice shelves are disintegrating, sea-ice and glaciers are retreating in both the Arctic and along the Antarctic Peninsula, and freshwater is being redistributed on basin-wide scales. Climate change also affects river discharges to the ocean and alters global wind and ocean circulation patterns—all of which will have untold additional impacts on the planet’s interlinked physical, chemical and biological systems. Sea-level rise and associated impacts, such as submersion, salinization and so forth, also pose major threats to coastal natural and human systems.
All projections of Earth’s future climate rely on an accurate understanding of how the ocean will respond to warming. It presently removes about a quarter of all the carbon dioxide released by the burning of fossil fuels and deforestation and slows the rate of warming in surface temperature. However, the ocean also provides the largest reservoir for storing the excess heat generated by greenhouse gases. Globally, the average temperature of the surface ocean has already warmed by about 0.4 degrees Celsius since the 1950s; substantial warming clearly penetrates through the upper 750 metres of the water column and has even been found in bottom waters (Arndt et al. 2010). Under future climate scenarios, the ocean may prove less effective in removing excess atmospheric carbon dioxide and heat, resulting in an acceleration of already-observed atmospheric warming.

This chapter will examine these threats. It starts by exploring the two main direct consequences of atmospheric changes on the ocean – beyond simply warming – namely sea level rise and ocean acidification. It then shows how these changes will impact ecosystems and human systems, focusing in particular on polar regions, coral reefs, coastal areas and biodiversity. It concludes by highlighting some crucial challenges in both research and implementation.

CLIMATE CHANGE INCREASES SEA LEVEL AND ACIDIFICATION

SEA LEVEL RISE There is a growing scientific consensus that global sea level will rise by 0.5 to 1 metre by the end of this century, given current projections of future atmospheric greenhouse gas levels and climate warming. At the global scale, ongoing glacial melting and the thermal expansion of warming seawater drive rising sea level; it may rise even more if there is substantial melting of the ice sheets in either Greenland or west Antarctica. At the local scale of coastal ecosystems and human communities, a range of additional factors such as storm surge and land use will further affect coastline inundation rates.

THERMAL EXPANSION AND LAND SUBSIDENCE CONSEQUENCES ON LOCAL SEA LEVEL RISE Roughly speaking, two types of causes influence local sea level: those that actually raise water levels, and those that lower land levels. Oceanic thermal expansion and exchanges of water between the ocean and other reservoirs are the two main factors raising water levels. Thermal expansion occurs when water is heated and its volume expands, elevating the surface level – a phenomenon influenced, obviously, by the increased average ocean temperatures that climate change brings. The second factor, water exchange, leads to sea level rise when the amount of water entering the ocean exceeds the amount lost through evaporation. Warmer average air temperatures lead to partial melting of the main reservoirs of freshwater, e.g. glaciers and ice sheets (primarily those in Greenland and the Antarctic). The two principle causes
of altered land levels are rising or subsiding tectonic plates and human-caused land subsidence, or sinking – a phenomenon resulting from groundwater extraction and/or the weight of built-up urban areas.\footnote{For example, in Venice, Italy, a combination of several factors, e.g. geology, groundwater extraction and sea level rise have led to a subsidence of approximately 23 centimetres (9 inches) during the twentieth century.}

Sea level changes and impacts are not (and will not be) the same around the globe. In the first place, factors affecting surface elevation have differing local effects. Secondly, other local phenomena, such as ocean currents and atmospheric pressure, also change sea levels. Finally, the causes of land subsidence are highly local. Consequently, both global and local factors should inform assessments and adaptation strategies for coastal ecosystems and human-built infrastructure.

**AN OLD PHENOMENON POSES NEW RISKS** Rising sea levels are not a new phenomenon. For example, at the end of the last glacial period 25,000 years ago, the average sea level elevation measured 120 metres lower than at present. Ten thousand years ago, sea levels rose approximately two metres per century, or two to four times more than twenty-first century projections, if one excludes the prospect of substantial ice sheet melting. While projected sea levels for the coming century remain controversial, the amplitude or the speed of changes now appears less noteworthy than human societies’ vulnerability to them, due to development and urbanization along the coasts. We also note that progressive increases in average ocean elevation may worsen the effects of extreme weather events (e.g., hurricane generated storm surge), whose frequency and intensity may increase due to climate change.

Sea-level rise combined with climate change will have many negative effects on ecosystems and human societies. These will vary according to local conditions – beach erosion, groundwater salinization, heavier coastal flooding, and receding or disappearing deltas, estuaries and mangroves. In such cases, the effects of rising sea levels and climate change add to existing stresses. Deltas, for example, suffer from human activity: urbanization, agriculture and dam construction have had and probably will continue to have as destructive effects than those expected from climate change.\footnote{In the 1970s, construction of the Aswan Dam in Egypt blocked the flow of delta-building sediments normally carried by the Nile to the coast. The result has been intense coastal erosion that is not due to climate change, but that climate change will probably worsen.}

**ACIDIFICATION** The chemical composition of seawater strongly influences the distribution of marine life and the productivity of the sea. For example, ocean phytoplankton require nutrients and inorganic carbon to grow, and animals need oxygen for respiration. However, human activities are changing ocean chemistry, often in fundamental ways (Doney 2010). Fossil-fuel combustion increases the level of carbon dioxide gas in the atmosphere, and about a quarter of this excess carbon dioxide subsequently dissolves into the ocean. The uptake of anthropogenic (human-caused)
carbon dioxide alters ocean chemistry, causing seawater to become more acidic; this makes it harder for some corals, mollusks and other marine life to build shells and exoskeletons from carbonate minerals (Doney et al. 2009). The current rate of ocean acidification is roughly 100 times higher than natural trends over at least the past several million years, and the extent to which marine organisms can adapt to such rapid change is unclear. Based on recent data, Figure 1 illustrates the extent of ocean acidification expected by 2050.

The biological effects of ocean acidification have been studied in the laboratory and through short-duration experiments at sea. The results suggest that ocean acidification may directly harm some ocean microbes, plants and animals while benefiting others. Less is known, at present, about how natural populations will respond or adapt to rising carbon dioxide levels in the wild or how this will alter marine communities. Key questions involve possible feedbacks through marine food webs, impacts on commercially important fisheries, and local and regional differences in the timing and intensity of effects. Nevertheless, the potential for acidification damage, to ocean life and ecosystems and coastal and marine biodiversity in general, remains highly troubling in light of the compounding anthropogenic pressures: pollution, overfishing, physical degradation (mechanical destruction of habitats) of coastal ecosystems due to erosion, loss of wetlands, and trawling. Coral reef ecosystems may be especially at risk. Finally, the combined impacts of acidification,
climate change and more local human activities may prove far worse than each threat in isolation.

**ECOSYSTEMS AND HUMAN SYSTEMS IN JEOPARDY**

**COASTAL AND MARINE BIODIVERSITY** Coastal and open-ocean ecosystems provide a range of services vital to societies and to the planet. Key services include (but are not limited to) providing food, cleansing and recycling water, supplying nutrients and chemicals to plants and animals, supporting recreation and tourism, regulating climate, and protecting infrastructures and populations against erosion and flooding.

The climate change impacts outlined above (rising sea levels, warming temperatures, ocean acidification, and altered ocean circulation) threaten and degrade ocean ecosystems – as do other human impacts (including enhanced coastal erosion, excess nutrient inputs, overfishing, and pollution). These changes can dramatically affect the growth, reproduction or distribution of marine species; this in turn may destabilize the structure of ocean biological communities, disrupt food chains, diminish the production of harvestable living resources, and reduce the biodiversity that plays a fundamental role in maintaining a healthy ocean.

Climate change effects are already observed in historical fish survey data. For coastal regions such as the North Sea and the east coast of North America, the geographical ranges of individual marine species have moved poleward and offshore to deeper waters over the last several decades, apparently in response to warming (see e.g. Nye et al. 2009). Most commercial fisheries species around the globe will probably see further and even more rapid poleward shifts over the 21st century, with the ranges of fish living in the water column more likely to change than those of bottom-dwelling fish (Cheung et al. 2010). This may result in significant changes in community structure and marine biodiversity; the Arctic and Southern Ocean may see an invasion of warm-water species, while the tropics and subpolar domains may experience high local extinction rates. Predicting the effect of climate change on fish population size is more challenging because warming and altered circulation patterns influence many factors – food supply, growth rates, disease, predation, seasonality or phenology – sometimes in opposite directions. Marine parasites and diseases are spreading poleward with warming waters. Moreover, the productivity of phytoplankton, the base of the marine food web, is projected to decline in the tropics and subtropics and remain constant or increase somewhat at higher latitudes (Steinacher et al. 2010).

**CORAL REEF ECOSYSTEMS MAY BE ESPECIALLY AT RISK**

**POLAR REGIONS** Earth’s polar regions appear to be some of the most sensitive ecosystems to the effects of climate change (ACIA 2004; Meehl et al. 2007), and understanding the role of the ocean in these regions is crucial. The evidence of dramatic recent environmental changes in the Arctic and Antarctic Peninsula is now widely
acknowledged: Arctic air temperatures are rising about twice as fast as the planetary average; sea ice and land-based glaciers are melting, in some cases more quickly than models project, and permafrost on surrounding land areas is thawing (Arndt et al. 2010; National Research Council 2010). Strikingly, the amount of sea-ice in the Arctic during late summer has shrunk by 30-40% in the last three decades (Fig. 2); computer models now suggest that the Arctic will be ice-free in summer by the middle of this century. On the Antarctic Peninsula, several large marine ice shelves (including the Larsen and Wilkins shelves) have collapsed either partially or fully, opening up large regions of new open water.

Such changes have already had startling and profound effects on marine and terrestrial ecosystems, and inevitably, on human populations (Anisimov et al. 2007). Changes in the distinctive marine ecosystems of the high latitudes have already been observed, with ramifications for such iconic species as polar bears, walruses and penguins, as well as for important commercial fisheries that feed millions of people worldwide. Many polar animals depend on sea-ice for food, habitat and breeding during part or all of their life cycles. The rapid disappearance of sea-ice has substantially reduced some populations, in some cases leading to local extinctions and replacement by species from more sub-polar environments (Ducklow et al. 2007). Climate change and retreating sea ice were key factors in polar bears’ “threatened” status listing under the U.S. Endangered Species Act.
At the same time, a decrease in Arctic summer sea ice may lead to a greatly expanded human presence in the Arctic, to wider exploitation of polar marine resources such as fisheries, oil and gas reserves, and the expansion of shipping routes into these fragile and poorly-understood areas. Evaluating the impact of these activities poses key challenges for the research community: it will need to develop improved observation systems and greater insight into polar climate and ecosystem dynamics. In particular, better information is needed on the sensitivity of polar ecosystems to increased human perturbations to better anticipate and evaluate their impacts.

**Coral Reefs** Coral reefs cover nearly 600,000 square kilometres (373,000 sq. miles) of the planet; they are among the richest ecosystems in terms of biodiversity, and provide shelter to juvenile fish in particular. Beyond this intrinsic value, the thousands
FIGURE 4. THREATS WEIGHING ON CORAL REEFS

Present
- High coral cover
- High structural complexity
- Diversity
- Low coral cover
- Few sensitive species
- Low structural complexity
- Reduced biodiversity
- Local species extinctions

Future
- Acidification
- Irradiance reduction
- Temperature increases
- Cyclones increase
- Drought
- Floods
- Reduced calcification
- Increased erosion
- Reduced coral recruitment
- Low coral cover
- Low structural complexity
- Few sensitive species
- Macro-algae dominance
- Crown-of-thorns population explosion
- Few coral-dependent species
- Few herbivores
- Reduced biodiversity
- Local species extinctions

* A coral parasite.

Source: Based on data from Wilkinson (2008)
According to a 2008 European Union report (Billé and Rochette 2008) on coping with rising sea levels, three main types of adaptation are usually favored, over and above non-action: protection, “accommodation” and strategic retreat. Table 1 summarizes some of the advantages and drawbacks. On this basis, we further explore examples of strategies to promote the conservation of coastal ecosystems and the protection of human installations.

Two examples of protective strategies for the conservation of coastal ecosystems: (1) Allow environments to adapt on their own, i.e. do not let present or future infrastructure create irreversible pressures on the local environment; this would require moving some existing infrastructure and avoid building new infrastructure by creating buffer zones (no buildings or other structures allowed). Climate change should also be integrated into environmental impact studies and into land-use and town-planning documents.

(2) Strengthen the ability of coastal habitats and species to adapt on their own: climate threats exacerbate existing phenomena (fragmentation of ecosystems, pollution, over-exploitation, etc.). This increases the need for protected areas that are larger, better located, better managed, and more interconnected (networks of protected areas, corridors, greenbelts, etc.), as well as the need to reduce or move sources of occasional pollution (urban and industrial), diffuse pollution (agricultural) and habitat degradation (dredging, bottom trawling). Four examples of strategies for protecting human installations: (1) Plan the strategic retreat: move coastal installations inland to protect them from coastal hazards, i.e. make the coastal zones less artificial. Of course, it may be difficult to get the different players involved to accept this, but experience shows they can understand the process and rationale, at least when the stakes are quite low. (2) Manage the risk by introducing risk prevention plans, town planning programmes, and regulations to limit or prohibit building on strips near the coast. The size of such “buffer zones” will depend on local topography, subsidence rates, erosion rates and projected sea-level rise over some time horizon (e.g., for 100 years, 2 metres altitude, etc.). (3) Use insurance and compensation mechanisms, which are sometimes more effective and less costly than other types of measures. Use the price of insurance and even the impossibility to insuring property to create economic incentives for relocation. (4) Use strong defenses to protect the coast when there is no other alternative (an environment that is highly urbanized, a very active economy that cannot be moved, critical infrastructure with long lifetimes such as power plants, etc.). Finally in certain contexts, artificially replacing sand on beaches may be less expensive than other options, but once again it must be thought through according to the specificities of the local context (size of the grains, the area where to put new sands, erosion patterns and downstream effects, etc.).

### Table 1. Advantages and Drawbacks of Different Adaptation Options

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection Freeze coast line (dikes, rock armor) or deal with causes of erosion (breakwaters, jetties, re-depositing sand)</td>
<td>Efficiently solves local problems Very socially acceptable</td>
<td>High cost The erosion phenomenon is simply moved to other sectors Disruption of sediment function</td>
</tr>
<tr>
<td>“Accommodation” (adjustment of natural or human systems to a new or changing environment)</td>
<td>A gain of space and conservation of natural shore condition Local policy Low cost Compensation and extra cost of protecting shore are avoided</td>
<td>Local measures and inconsistent applications Measures do not meet long-term imperatives</td>
</tr>
<tr>
<td>Strategic retreat Move the objects threatened further inland</td>
<td>More efficient in the short and long-term No maintenance No impact on sedimentary function</td>
<td>A need for space inland and land where infrastructures and activities can be moved to Difficult to implement in zones where socio-economic interests are important or infrastructures and urbanization are extensive Not very socially acceptable</td>
</tr>
<tr>
<td>Non-action Decide to take no action</td>
<td>Preserve natural functions</td>
<td>Implementation limited to low-interest natural spaces</td>
</tr>
</tbody>
</table>

Source: Adapted from Paskoff (2001) and according to Carreno et al. (2008) in Billé and Rochette (2008: 2-3)
of reef species provide a primary food source for about thirty million people. In addition, coral reefs have several other functions – primarily, protecting coastlines by buffering them from ocean swells. They also possess substantial economic value, for example from tourism. Today, coral ecosystems face serious threats from human activities as well as from climate change and ocean acidification.

Coastal communities frequently overfish the reefs, taking larger catches than the ecosystem can naturally replenish. Land-based pollution – from deforestation, sediment erosion and/or urban, industrial and agricultural waste – degrades water quality, affecting the highly sensitive coral polyps that build the reefs. These stresses have already considerably harmed marine biodiversity; they exacerbate the impact of climate warming and of natural phenomena, such as the episodic warming of surface ocean waters in the eastern tropical Pacific known as the El Niño Southern Oscillation or ENSO. In 2008, the Global Coral Reef Monitoring Network estimated that 20% of the world’s reefs were definitively destroyed; nearly 50% were in threatened to very threatened condition, and only 30% were not yet at risk (Figs. 3-4) (Wilkinson 2008).

The trend toward urban development along coastlines worldwide suggests that pressure on coral reefs will not lessen: global climate-change effects only add to the local and regional threats. Beyond possibly intensifying storm activity, climate change’s three primary processes will also affect reefs’ survival: higher surface water temperatures, increased ocean acidification and rising sea levels. Coral animals (polyps) are very sensitive to temperature variations: coral bleaching – the loss of color from symbiotic algae under stressful conditions – has been linked with unusually high water temperatures. The zooxanthellae (tiny single-celled algae that live in symbiosis with polyps) abandon the polyps, depriving them of needed nutrients and causing their colors to bleach out. The polyps may also die because of changes in the ocean’s chemistry, resulting in bleaching as well. Seawater becomes more acidic as levels of dissolved carbon dioxide increase, harming the polyps’ ability to construct their limestone structures. Rising sea levels force coral to either grow taller or die since their zooxanthellae need to be near surface light to photosynthesize. No one knows precisely how coral will react to rising ocean levels, but three hypotheses have been advanced: (1) they will grow at the same rate the water rises; (2) they will go through a relatively agonizing period and then catch up to the higher levels; (3) they will not be able to keep up and will die.

**COASTAL AREAS** Over and beyond their menace to reefs, climate change and the growing local and regional human footprint also threaten the coastal environments...
upon which we depend for so many resources. Rising sea levels caused by climate change threaten low-lying coastlines and communities (Nicholls et al. 2007), and further projected rises this century will have wider socio-economic and environmental impacts. Half of Earth’s people live near the coast, on less than one-fifth of its land mass. Two-thirds of the world’s largest cities are on the coast. Low-lying regions and island nations are threatened with inundation and are more vulnerable to storm surges and flooding.

In coastal areas, as elsewhere, climate change is clearly not the only threat, but rather adds to other existing human stresses. For instance, the combination of coastal development, pollution, climate change and sea-level rise can destroy valuable salt-marsh, estuarine, sea-grass and mangrove ecosystems that serve as key marine nurseries for large commercial fisheries. Likewise, excess nutrient runoff from land-based agriculture is a particular problem for many coastal and estuarine regions, producing low-oxygen hypoxic zones (“dead zones”) that harm fish and marine invertebrates. In some coastal upwelling regions, shifts in ocean circulation and wind patterns also enhance the frequency and severity of coastal hypoxia (Doney 2010). The burden of adapting to such coastal changes will fall disproportionately on poor and lesser-developed countries (See Box 1).

CHALLENGES
The urgency of climate change threats, especially those exacerbated by other human activities and natural processes, calls for immediate action to mitigate further change and reduce other environmental pressures on the ocean and coasts – overfishing, nutrient eutrophication, and wetland destruction. The prospect of future progress in ocean science should not be an excuse for postponing decisive political action. It seems clear now that we have committed the planet to a substantial level of climate change – whatever action is taken to reduce both current and future greenhouse gas emissions – and decisions made in the next several decades will affect Earth’s climate for centuries or even millennia (Solomon et al. 2009; National Research Council 2010). Human populations across the globe will thus have to adapt to impacts that will grow in magnitude with time, particularly if the will to pursue mitigation measures remains as low as it does today. Coastal areas and communities are clearly vulnerable to changing environmental conditions and will have to prepare for and adapt to their effects.

Some important adaptation options already exist: developing well-managed aquaculture in specific areas instead of increasing the harvest of wild stocks; building resorts and housing relatively far inland instead of destroying coastal dunes; developing consumer awareness about fish and fisheries. More generally, three main factors are crucial when developing adaptation strategies. First, it is important to consider how climate change will affect human society in the future and not simply the present, even if this adds to the complexity. This will require long-term integrated projections, for example in population growth, coastal urbanization, and food demands. Second, every solution is relevant only within the context in which
it is developed. A “good practice” for climate adaptation under one specific set of conditions could prove detrimental under another; it could create irreversibility or reinforce non-climate related stresses. Third, climate adaptation strategies must also fit within both economic and (geo)political constraints; they must account for incentives driving the actions of individuals, businesses, organizations and governments that could either advance or undermine the adaptation strategy’s objectives.

At the same time, a network of global, regional and national institutions is desperately needed to support a climate services program. Such an effort would gather and synthesize climate and ocean information, data products and services, and would foster dialogue between providers and users. Most importantly, however, politicians, policy-makers and an informed public must show a willingness to act on the best information that the ocean science community has to offer. Enhancing scientific knowledge should thus be a priority.

This commentary is partly based on a white paper prepared by the Marine Biological Laboratory and Woods Hole Oceanographic Institution for the Oceans Day held at the UNFCCC COP-15 in Copenhagen, December 2009. See http://www.woodsholeconsortium.org for more information about the Woods Hole Consortium. It is also based on the main results of the CIRCE research project (“Climate change and impact research: the Mediterranean environment”) funded by the European Union (DG Research). For more details, see http://www.circeproject.eu/
WORKS CITED


The human community insistently pushes the oceans’ limits, seeking to exploit all of its varied resources—fisheries, fuels, minerals and genetic material—now at the centre of the world economy. All of these developments draw oceans closer to the heart of contemporary human societies.

International governance is challenged by the blurring frontier between the mainland and the ocean, constantly redefined by new technologies, scientific discoveries, industrial demands and most recently, by ecological imperatives. No sea escapes these onslaughts.

This volume takes the reader straight to the heart of how human-ocean interactions, work, and identifies contemporary trends, mechanisms and tools that can influence current strategies and choices.

**F E A T U R I N G**
- Papers by leading international experts and scholars
- New perspectives through in-depth analyses
- Multiple maps, charts, tables
- A wealth of ideas for specialists and non-specialists alike (policy-makers, administrators, concerned citizens, development professionals, entrepreneurs, journalists, students, and others).