Coastal Zones and Climate Change

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Impacts of Climate Change on Coastal Ecosystems in the Indian Ocean Region

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The Indian Ocean region is highly diverse geomorphologically. It consists of littoral and island states and spans an area between the African, Asian, and Australian continents, reaching to the Antarctic landmass.[1] The Indian Ocean forms the natural border to the South Asian subcontinent (Bangladesh, India, and Pakistan) and encompasses many large islands, such as Java, Madagascar, Sri Lanka, and Sumatra; many smaller island groups, such as the Comoros islands, the Maldives, and Seychelles; and numerous atolls and archipelagos. The littoral countries of this vast ocean also include the Persian Gulf states; the East African coast states from Somalia, Kenya, Tanzania, and Mozambique to South Africa; and the Southeast Asian nations of Brunei, Cambodia, Indonesia, Malaysia, Myanmar, the Philippines, Singapore, Thailand, East Timor, and Vietnam.

This paper provides a general account of the coastal zone ecology of the Indian Ocean region and the known and potential impacts of climate change on the region's ecosystems. Ecosystems are complex entities consisting of living beings, the physical environment they inhabit, and the interactions within and between these two components.[2] The three basic levels of biodiversity are genes, species, and ecosystems/communities/habitats. The goods and services that ecosystems provide, such as food, fuel, and materials, are essential for human survival. Oceans and their constituent ecosystems form essential elements of the chemical, biological, and physical processes of life on Earth. Climate, driven by the solar energy that warms the Earth and causes the circulation of the atmosphere and oceans, is defined according to meteorological parameters (e.g., air temperature, rainfall, and humidity); and exhibits natural variability. Climate is one of the two most important physical factors (the other being topography) determining the survival and nature of all living beings, from individuals and communities to populations and entire species, by heavily influencing the natural systems on which they depend.[3]

Two things need to be kept in mind. First, the characteristics of ecosystems vary over time and space. Scale is an important variable in the definition and measurement of any ecological system. Except in a very few instances, organisms and the environmental factors that

determine their survival are distributed as gradients that blend into one another at the edges of the space they occupy. Most coastal and marine ecosystems display important characteristics specific to the region; despite the common types of stresses exerted on coastal regions globally, the specific aspects of particular ecosystems should not be ignored, even as microclimates are exceptions to the effects of climate systems over very large scales. There is much we do not know about the interactions of ecosystems with their surroundings, especially in coastal and marine environments, and many indirect effects of global change on ecosystem functioning will likely reveal themselves as gradual impairments rather than as readily apparent losses of ecosystem integrity.

Second, ecology cannot deal only with nature. Humans are part of the ecology of any place on this planet. They and their constructed systems have to be included in any analysis of ecology. Thus the term *social-ecological system* is often applied in the analysis of human impacts on ecosystems. In this paper, only a few salient socioeconomic, cultural, and political factors relevant to coastal climate change can be highlighted.

What Is the Coastal Zone?

The coastal zone, where land meets ocean, is one of the most dynamic natural systems. Here, the three main components of our planet—the hydrosphere, the lithosphere, and the atmosphere—meet and interact, forming interconnected systems. Coastlines are formed by morphological changes governed by climatic and geological processes.[4] They constitute a transition zone where land and freshwater meet saline water, and across which the effects of land on the ocean, and vice versa, are transferred and modified. Coastal zones are a crucial battleground in the current fight against climate change.

This paper follows the definitions of coastal zones adopted in two key publications. For the Millennium Ecosystem Assessment (2005), "the inland extent of coastal ecosystems is defined as the line where land-based influences dominate up to a maximum of 100 kilometers from the coastline or 50-meter elevation (whichever is closer to the sea), and with the outward extent as the 50-meter depth contour. Marine ecosystems begin at the low water mark and encompass the high seas and deepwater habitats."[5] For the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), "coastal systems are considered as the interacting low-lying areas and shallow coastal waters, including their human components…This includes adjoining coastal lowlands, which have often developed through sedimentation during the Holocene (past 10,000 years), but excludes the continental shelf and ocean margins [and inland seas]."[6] Coastal systems also form part of the larger marine ecosystems that include coasts and open ocean areas.

Coasts are of great ecological and socioeconomic importance. They sustain economies and provide livelihoods through fisheries, ports, tourism, and other industries. They also provide ecosystem services such as regulating atmospheric composition, cycling of nutrients

and water, and waste removal.[7] These areas have been centers of human settlement since perhaps the dawn of civilization, and have cultural and aesthetic value as well. Coastal ecosystems are among the most productive because they are enriched by land-based nutrients and nutrients that well up into the coastal waters from deeper levels of the ocean. Coastlines are also among the most populated regions. Nearly half the world's major cities are located within 50 kilometers of a coast, and coastal population densities are 2.6 times greater than those of inland areas.[8]

Changing Coastal Zone Ecology

Coastal ecosystems are repositories of biological diversity and provide a wide range of goods and services. The major habitats of the coastal zone are coral reefs; seagrass beds/meadows; coastal or barrier islands; rocky coasts; cliffs; intertidal rocky, mud, or salt flats; rock pools; sandy, pebble, or rocky beaches; dune systems; saline, brackish, and freshwater lagoons; estuaries and coastal river floodplains; salt marshes; and mangrove forests—all of which have been highly modified over millennia by human activities. The Indian Ocean region is particularly rich in marine biodiversity. For example, the diversity of a number of marine taxa, including corals, fishes, lobsters, and snails, peaks in the so-called East Indies Triangle (Indonesia, Malaysia, New Guinea, and the Philippines) and (though declining in the central Indian Ocean) shows another lower peak in East Africa and Madagascar.[9]

Ecosystem services can be broadly grouped into three types:[10]

- *Provisioning*—e.g., food species, water for agricultural and industrial use, timber, fibers, fuel, and genes
- *Regulating*—e.g., climate regulation; influencing hydrological flows and cycles; regulation of erosion; removal of excess nutrients and wastes; and mitigation/amelioration of natural hazards such as floods, storm surges, landslides, and high winds
- *Cultural and religious*—e.g., recreational, aesthetic, educational, and scientific opportunities; and spiritual and symbolic values

The current widespread decline of regulating services is most worrying as, without these, the other two types of services are not possible.

Coasts are affected by two main types of influences, terrestrial and marine, that are considered external to the coastal zone. *Terrestrial influences* are mostly anthropogenic in nature. They include land use changes and all the consequences of changing hydrological regimes, and nutrient loading from sediment transport, runoff, and reduction of sediments through rivers (for example, from dam and channel construction and extraction of river sand upstream). *Marine influences* are mostly natural phenomena such as weather events (storms and cyclones), tsunamis, and wave patterns and coastal and ocean currents that affect the processes of nutrient, material, and heat transfer and mediate geomorphological changes.

Loss and degradation of ecosystems are affected by a suite of interacting factors that can be divided into two groups: direct drivers and indirect drivers. The *direct drivers* (also known as *proximate causes*) of loss and degradation of coastal zone ecosystems are as follows:

- *Loss, fragmentation, and degradation of habitats*, primarily by land use changes such as conversion to agriculture
- *Overexploitation of resources* for livelihoods and commercial purposes
- *Pollution*, mostly by nutrient enrichment by land-based use of chemical fertilizers and sewage but also from toxins such as pesticides and hazardous chemicals
- *Introduction of alien invasive species* and their rapid and uncontrolled spread (this is also considered a form of biological pollution)
- *Anthropogenic climate change*, which interacts with the previous factors listed, generally reinforcing their impacts

Following are the main *indirect drivers* (sometimes referred to as *ultimate or root causes*) that underlie the proximate causes:[11]

- *Population expansion*—increase of populations is followed by increased demands for resources
- *Distribution of wealth and social inequalities*—the poor often must emphasize survival over sustainability, while the wealthy are far removed from the consequences of overexploitation of resources, leading to degradation of natural systems
- *Policy failure*—policies that do not take into account the inherent characteristics of ecosystems permit their unsustainable exploitation (e.g., policies on land tenure are especially responsible for changing the manner in which land and biological resources are used)
- *Market failure/distortions*—ecosystem goods and services mostly bypass markets and thus are often undervalued and underpriced, so the costs of environmental destruction are not reflected in the market
- *Globalization*—trade and market liberalization have created a global system in which commodities and their prices are highly influenced by international pressures that do not usually take local and regional environmental impacts of production into account
- *Poor development model*—a development model that equates increased consumption rates with growth and advancement

These drivers, both direct and indirect, are also agents of global change. Their impacts contribute to widespread trends on local, regional, and global scales and across socioeconomic strata. These drivers do not operate singly but form an interacting and often synergistic complex. Coastal and marine ecosystem goods and services are highly undervalued, as

are ecosystems and biodiversity in general. This undervaluation results in unsustainable patterns of resource exploitation, highly degraded ecosystems, and weak attempts at conservation. Communities that directly depend on these goods and services bear the heaviest economic and social costs of such decline and loss. Often they are among the poorest segments of society.[12]

All told, human stressors have significant implications for coastal ecosystems and biodiversity. Anthropogenic pressures are leading to the disappearance, fragmentation, and outright destruction of habitats. Decreases in individual populations or in the number and types of species can result in decreasing ecological richness and degradation of communities and ecosystems. Loss or reduction of ecosystem goods and services or loss of biodiversity beyond certain limits can impair the natural functioning of ecosystems. Reduction of ecological resilience (the natural capacity to recover or revitalize from damage or disturbance) beyond certain levels may lead to ecosystem collapse. Ecosystems already highly affected by anthropogenic activities may in some cases prove unable to withstand the additional effects of climate change and may suffer irreversible loss of function.[13]

Global assessments of trends over the past century and the impacts of proximate drivers on coastal zone wetland biodiversity can be summarized as shown in table 1.[14]

Table 1: Assessment of Ecosystem Degradation

Driver	Degree of impact	Trend
Habitat change	Very high	Increasing impact
Overexploitation	High	Increasing impact
Pollution (nutrient loading by nitrogen and phosphorus)	Very high	Very rapidly increasing impact
Invasive species	High	Increasing impact
Climate change	Moderate	Very rapidly increasing impact

Climate Impacts on Ecosystems

Climate change is the predominant challenge of this century. Increased concentrations of greenhouse gases, mostly carbon dioxide (CO_2) in the atmosphere from anthropogenic influences, have led to increasing global mean surface air temperatures, increased climate and weather variability (including the occurrence of extreme events), and changes in precipitation patterns and seasonal cycles such as monsoons.[15] The main climate variables of interest to ecology are mean surface air temperature, rainfall, humidity, wind speeds, and the frequency and intensity of extreme climate/weather events such as storms and

droughts. These affect fundamental physiological processes and the survival of living systems. However, many other measures are used to study and monitor the consequences of climate change in oceans and coastal areas, including sea levels, sea surface temperatures, intrusion of saltwater into freshwater, rates of evapotranspiration from oceans and other water bodies, snow and ice cover, and changes to polar ice sheets and glaciers.

As living systems, ecosystems often exhibit nonlinear responses brought on by crossing thresholds that alter their composition and key processes—changes that in turn affect ecosystem stability, resilience, and functions. Studies of several types of ecosystems, including coral reefs, kelp forests, and oceans, show that pressures from human activities can bring about dramatic changes where functioning is severely impaired.[16] Once some critical threshold is passed, even relatively small stresses may trigger rapid ecosystem degradation and loss of integrity. Climate change may very likely be the factor pushing some ecosystems over the limit.

Climate change is a global change driver that interacts with and exacerbates the impacts of already existing environmental and human drivers on the natural world.[17] Changes in climate will affect biodiversity at all levels: genes, species, habitats, and ecosystems. Temperature increase, change in rainfall patterns, drought, sea level rise, coastal flooding, damage from cyclones, and change in salinity can affect habitat suitability. Populations and species can respond in several ways to large-scale environmental change. They may benefit or remain unchanged; they may continue in the original distribution range, adapt, disperse to new regions, decline in numbers, or become extinct. As species respond individually and collectively, chain reactions will take place in the food webs of coastal and marine areas. Changes in the physiology or survivorship and reproduction of a species will affect any other species—including humans—that depend on it.

There will be species loss if flora and fauna cannot adapt to climate change or migrate to suitable habitats fast enough. The species composition of communities and ecosystem services will be affected, which in turn risks severely reducing productive functions and diminishing ecosystem resilience. The implications for humans include negative impacts on food security; the spread of diseases and vectors into new regions; loss of productive agricultural lands and water bodies; changes in seasonal cycles; plant and animal life cycle variations; and changes in ecosystem functions that disturb the provision of food, water, and essential environmental services.

There may be some benefits from climate change. These include increased precipitation over some areas that are currently water scarce and increased production from some types of ecosystems as a result of increased temperatures. Some species that are currently restricted by temperature regimes may expand their range. Growing and breeding seasons for species of the higher latitudes may be longer. However, a climate variable that favors

one species or ecological community may be detrimental to another. While it is safe to say that all regions will experience the impact of climate change and that positive as well as negative effects will likely take place in the same large areas, the magnitude of any positive effects, the ways species might be able to adapt to them, and the possibility of unforeseen negative consequences are largely unknown at present.

Major Consequences of Climate Change and Ocean Acidification for Coastal Zone Ecosystems

The IPCC Fourth Assessment Report states with high confidence that, globally, coasts are undergoing adverse consequences from climate change, such as sea level rise, inundation, erosion, and ecosystem loss.[18] The report also states that coasts are highly vulnerable to extreme events such as cyclones, extreme waves, storm surges, altered rainfall and runoff patterns, and ocean acidification. The data show strong regional and local variations in the impacts of climate change on coasts as a result of nonclimate factors. Even so, the overall impacts of climate change are "virtually certain to be overwhelmingly negative."[19] Climate change and its associated effects pose serious risks to coastal biodiversity.[20]

Climate change contributes to accelerated sea level rise by the thermal expansion of near-surface ocean waters and the increased melting of glaciers and ice sheets. Sea level rise in turn has numerous impacts. Flooding of coasts, estuaries, and river deltas can alter the physical structure of habitats and lower habitat availability and suitability, compromising the biota on which organisms higher up on food webs depend. Increased coastal erosion can reduce or remove beach areas and protective barrier islands and interfere with near-shore currents and their physical transport patterns. Subsequent changes in drainage and irrigation patterns and modifications of fluvial flows can reroute sediment transport nutrient runoff into coastal waters. Saltwater intrusion into coastal wetlands, especially estuaries, can negatively affect these ecosystems and contaminate groundwater and other inland freshwater sources. Higher sea levels can also intensify storm surges.

The IPCC predicts a sea level rise of 0.6 meters or more by 2100 and an increase of sea surface temperature by 3°C, but recent work suggests that these may be underestimates. It is important to note that there is significant regional variation in the coastal impacts of sea level rise. Sea levels can also vary naturally through the geological processes of subsidence and uplift or through human processes such as extraction of water, oil, and gas. Similarly, shoreline retreat, flooding, and saltwater intrusion can occur through natural phenomena such as changes in ocean currents, transport of sediments to coasts, and wind patterns.

Climate change is projected to affect climate variability, increasing the frequency and severity of storm/tidal surges, tropical cyclones, hurricanes, etc. These phenomena also cause coastal flooding, erosion, saltwater intrusion into freshwaterways, salinization of

soils, and destruction of coastal infrastructure. Global warming will also increase sea surface temperatures as surface waters absorb heat from higher air temperatures. Such altered temperature regimes can significantly affect the reproduction and survival of species unless they can adapt quickly enough.[21]

In addition to heat, the oceans absorb CO_2 from the atmosphere. Approximately a quarter of all the CO_2 released into the atmosphere by human activities is absorbed by the oceans.[22] This process also creates carbonic acid in the seawater. Ocean acidification has a corrosive effect on the corals and shelled organisms that form the basis of marine and coastal food webs. In a glimpse of the potential future implications of ocean acidification, Orr et al. report that coastal and marine locations with naturally occurring high CO_2 levels show a high number of invasive species and low biodiversity.[23]

Climate Change Impacts on the Coastal Zone Ecosystems of the Indian Ocean Region

The Indian Ocean coastal region is a key area of vulnerability. Several of its component subregions have consistently been identified as among the most vulnerable to climate change now and in the future.[24] All coastal areas in Asia and Africa are facing an increasing range of stresses and shocks, the scale of which now poses a threat to the resilience of both human and environmental coastal systems, and which are likely to be exacerbated by climate change. Summaries of the ecosystems of major concern follow, along with the known and predicted impacts of climate change.

Coral Reefs

Coral reefs support nearly 25 percent of all marine species.[25] They are among the world's most diverse and productive ecosystems. Yet they are also among the most threatened and perhaps the most high-profile "ecosystem victims" of climate change in the oceans.[26] Coral reefs occur mainly in the relatively nutrient-poor waters of the tropics, but because very efficient nutrient cycling and complex biological interactions transfer energy through the system, their ecological productivity is high. Cold-water, deep-sea corals are important breeding grounds for many species of marine organisms, including commercially important fish. Reefs provide food to humans, habitat to plants and animals, and protection of coasts from storm and wave damage by acting as natural breakwaters. They are also important for tourism, particularly in developing countries.

When coral, already threatened by overexploitation and coastal development, suffers from bleaching (a process attributed to increasing ocean temperature), the zooxanthellae that live within the coral in a symbiotic arrangement die—and finally, in turn, so does the coral. Over 34 percent of the vast and diverse coral reefs of Asia are reported to have been lost in

1998, largely as a result of coral bleaching induced by the 1997–98 El Niño event. Further increases in sea temperature are predicted to cause widespread coral collapse. The final blow to corals may yet come from the ocean acidification that is corrosive to coral growth. Recent data indicate that, by the middle of the next century, the process of coral calcification will decrease to the level where erosion will be greater than new growth.[27]

The 2008 report of the Global Coral Reef Monitoring Network sums up the status of, threats to, and trends concerning the coral reefs of the Indian Ocean.[28] Around the Indian Ocean, reefs are either highly degraded or degraded to a medium degree. Loss of habitat, sedimentation, overfishing, and pollution remain major threats for all coral reefs. A few that are highly protected as nature preserves of French territory islands remain relatively intact, but even they have undergone some amount of coral bleaching over the past 10 years. Reefs in South Asia were subject to the massive bleaching event of 1998, with attendant dramatic reduction of coral cover, but are recovering, albeit patchily. Reefs of the western atoll chain of the Maldives and the Bar Reef of Sri Lanka show relatively good recovery, but there is little or no recovery in other reefs near Sri Lanka and the eastern atoll chain of the Maldives.

Seagrass Beds

Seagrass beds are formed by unique groups of species of flowering plants that grow completely submerged in shallow coastal waters. These beds are very productive and provide a host of ecosystem services, ranging from filtering and trapping sediments to nutrient cycling. They are an important nursery habitat for fish and invertebrates and a source of food for many coastal organisms in tropical areas. In tropical waters, seagrasses often occur in proximity to coral reefs or mangroves, suggesting interactions that benefit the organisms inhabiting both types of habitat. Seagrasses can be considered "coastal canaries." Because they need high levels of light, they reflect changes in turbidity and water depth far more rapidly than comparable species in coastal waters. In all regions, sediment or nutrient inflows are the greatest stressors leading to seagrass loss and degradation.[29] Climate change factors such as increased coastal water temperatures, sea level rise, and extreme events such as storms and storm surges can contribute to increasing these stresses on seagrass meadows.

Mangroves and Coastal Wetlands

Asian wetlands have been increasingly threatened by a warmer climate in recent decades. Droughts and declining precipitation in most delta regions of Bangladesh, China, India, and Pakistan have caused wetlands to dry up and have severely degraded their ecosystems.[30] Reduction of freshwater flows and saltwater intrusion in the Indus Delta and Bangladesh have seriously compromised these regions' mangrove forests. About one-third of the world's mangroves have reportedly been lost during the last 50 years of the 20th century, likely as a result of human activities. Mangroves in developing countries are projected

to decline another 25 percent by 2025, with key countries such as Indonesia estimated to lose 90 percent or more of their mangroves in some areas.[31]

Wetlands, such as intertidal zones and floodplains, and vegetated ecosystems, such as mangroves, can be critical to the buffering of flooding and erosion arising from climate change. Maintaining these ecosystems' integrity is an important adaptation strategy. Coastal wetlands, including mangroves, are likely to respond to climate change and sea level rise through accretion, migration inland, or else habitat loss.[32] Reconstructions of ancient coastal geomorphological changes indicate that mangroves can respond to shifts in sea level. Vertical accretion by sediment accumulation may allow mangroves to keep up with mounting sea levels up to some limits. Where sea level rise exceeds the rate of accretion, habitat loss can result, but the wetland types can also migrate or shift inland. Where migration is not possible or is prevented by human interventions such as converting coastal zones to other types of land use, habitat loss will be the inevitable result. This phenomenon is called "coastal squeeze," the restriction of coastal ecosystems to ever-decreasing zones between advancing seas and inland development. Many mangrove localities are experiencing subsidence and therefore higher relative rates of sea level rise. Other climate change drivers, such as shifts in rainfall patterns, increased CO_2 levels, and changes in storm and wave actions, will affect mangroves in different ways, sometimes positively.[33] It is also possible that mangroves may not respond as a single entity, but that constituent species will adapt in different ways, leading to changes in distribution as well as composition of forest community and structure.

Challenges and Opportunities

The key challenge in addressing the climate threat to coastal zones is timely adaptation to global warming, for too much delay means that the option of adaptation no longer exists. Nevertheless, serious socioeconomic, technical, political, and ecological problems hamper the planning and implementation of adaptive strategies. Governments of the Indian Ocean region have joined the international treaty regime, produced National Communications required under the UN Framework Convention on Climate Change, and taken some steps toward addressing the issues of climate change, but there is little real national-scale action. In contrast to more developed regions of the world, national-scale awareness of the impending climate risks, special vulnerabilities of particular populations, and responsibilities of individuals and groups in mitigating climate change and reducing vulnerability remain very low. Forecast patterns for energy needs, water use, and natural resource consumption suggest pressures on ecosystems and ecosystem services in the Indian Ocean region will be exacerbated by climate change, yet a survey of the literature shows that interest in economic development of the coastal zone has overridden concerns regarding climate change, natural disasters, or environmental quality.

The Asian and African regions of the Indian Ocean share characteristics that make them more likely to be affected by climate change. In many countries, lack of effective governance structures, high rates of population growth and urbanization, poor land use planning, and myriad other development pressures add to the challenges posed by environmental degradation. A significant proportion of the population is either poor or low income and already vulnerable to malnutrition, ill health, and limited access to drinking water and sanitation. Climate change tends to disproportionately affect the more vulnerable segments of society, such as the poor and the marginalized, as they are already living in locations that have high vulnerability.[34] At the same time, developing countries have comparatively little capacity to adapt, given the speed with which climate change is taking place. Indeed, poverty has been identified as the most significant barrier to adaptation to climate change.[35] The costs of adaptive responses will be highly site-specific within a country, but will be greater in low-income economies in coastal zones of developing countries.

Both policymakers and the public display a lack of willingness to act, which is partly fueled by a lack of sufficient awareness of the effects of national-scale climate change. Insufficient regional models are available for analyses and vulnerability assessments, and downscaling from global scenarios remains problematic. Only a few global and crude regional-scale analyses are available for Indian Ocean coastal zones, with the exception of the megadeltas and a few selected localities of the Indian subcontinent, Southeast Asia, and East Asia. The uncertainties associated with climate change projections, and a general perception that climate change is of such overwhelming reach that it is beyond the capacity of individual countries to make a difference, further impede policy efforts. Despite slowly increasing levels of awareness among the general public, the level of debate and discussion is woefully inadequate.

Several difficulties beset attempts to gather information on how climate change affects the ecology of the Indian Ocean coastal zone. First, there is insufficient published information of the required type and quality on these ecosystems (with the status of coral reefs being an exception) and on economic, social, and other aspects of climate change. The underlying causes for this lack are mostly underresourced institutions and insufficient numbers of professional scientists. Second, there is a mismatch between the scales at which scientists typically study individual ecosystems and the conceptual scales of understanding needed to connect climate change with ecologically meaningful changes in populations and communities. Present understanding of most ecological processes largely derives from individual species, sites, or smaller regions studied over shorter time scales (a few decades), whereas many important climatological processes take place at global or regional scales and evolve over longer time frames. This makes it difficult to connect specific processes taking place in populations and communities with broader climate changes affecting whole regions and their constituent ecosystems.[36]

Another barrier to action arises from the problem of multiple scales across the natural, administrative, socioeconomic, and political realms. Political considerations at one level—local, regional, national—often ignore effects on other levels and in other domains, such as the social or environmental. This contributes to conflicts over governance, management, and responsibilities for adaptive responses. To protect the integrity of ecosystems, remedial action has to take place at several scales, often simultaneously.

More generally, governments in Asia and Africa are already overburdened trying to address pressing socioeconomic issues such as poverty, inequality in access to health care and education, the need for infrastructure development, and security issues such as terrorism. It will be very difficult or impossible for most developing countries to divert resources from these problems to combat global warming. Many will focus on climate change only when it causes natural disasters and emergencies. Governments and the public alike seem ready to respond to sudden, large-scale catastrophes but will ignore slow, cumulative processes such as climate change and sea level rise. Although the ultimate impacts of climate change could be calamitous, they are not easily recognizable over short periods and are frequently indistinguishable from the natural pattern of climatic events.

The Indian Ocean tsunami of December 2004 is a case in point. It caused unprecedented loss of human lives and damage to coastal infrastructure, but its aftermath created awareness of the power of natural events, especially in societies where tsunamis were very rare, such as Sri Lanka and southern India. Most Sri Lankans previously did not even know the term "tsunami." Since then, there has been a large increase in awareness, and the potential hazards of living in the coastal zone are better recognized. Responses by the affected governments included establishing tsunami early-warning systems, community-level programs to reduce risks, and national disaster management policies. These programs will also serve to reduce loss of life from flooding and other types of climate-related events affecting coastal zones. Assessments of the environmental vulnerabilities of coastal areas after the tsunami highlighted the importance of maintaining the integrity of coastal ecosystems. Mangroves and coral reefs buffered the impact of the waves that hit the coastlines. Nevertheless, the potential lessons to be drawn from the tsunami for undertaking better coastal zone management appear not to have been learned, except in some countries such as India. There, authorities seized the opportunity to develop coastal zone management guidelines that include reducing the risks of coastal flooding from climate change–related drivers.

Perhaps governments will prove able to leverage such opportunities to take action on climate risks. Numerous studies demonstrate the vulnerability of coastal zones in the region. At the same time, maintenance of coastal ecosystems is growing in importance as buffers against climate impacts and for sustaining coastal livelihoods. Indeed, multilateral donor agencies such as the World Bank, the Asian Development Bank, and the African Development Bank

increasingly include climate change in their development lending strategies. As public understanding of the consequences of environmental degradation rises, some governments have begun to take steps—however small—toward reducing greenhouse gas emissions. Sri Lanka, for example, has ended the use of chlorofluorocarbons (CFCs) in its refrigeration and tea industries. It would be far better if popular awareness and political foresight could engender timely and effective measures to avert the high human costs of global warming than for society to respond only belatedly to climate calamity.

We are just beginning to understand the changes that we have wrought on the massive and highly complex system that is the climate of our planet. We do not completely understand its workings and therefore are beset with the uncertainties of climate science, specifically how accurate our climate projections will prove. Even though it is commonly agreed that more accurate regional climate models would enable better decision making, dissenting views insist that we do not have to wait to adopt meaningful strategies to cope with climate change.[37] For most countries of the Indian Ocean region, there seems little choice but to attempt to reduce the exposure to climate risks of the most vulnerable populations, build resilience where possible, and salvage what we can of our ecosystems to prevent further degradation and extinction.

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