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WICKED CHALLENGES AT LAND'S END: Managing Coastal Vulnerability under Climate Change

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■ **Abstract** With continuing influx of large numbers of people into coastal regions, human stresses on coastal ecosystems and resources are growing at the same time that climate variability and change and associated consequences in the marine environment are making coastal areas less secure for human habitation. The article reviews both climatic and nonclimatic drivers of the growing stresses on coastal natural and human systems, painting a picture of the mostly harmful impacts that result and the interactive and systemic challenges coastal managers face in managing these growing risks. Although adaptive responses are beginning to emerge, the adaptation challenge is enormous and requires not just incremental but also transformative changes. At the same time, such "wicked" problems, by definition, defy all-encompassing, definitive, and final solutions; instead, temporary best solutions will have to be sought in the context of an iterative, deliberately learning-oriented risk management framework.

Keywords wicked problems, extreme events, sea-level rise, nonclimatic stressors, adaptation, transformative change

1. PRESENT CHALLENGES AND FUTURE PRESSURES ON COASTAL REGIONS

Coastal regions of the world face wicked challenges. In a nutshell, with continuing influx of large numbers of people into coastal regions, human stresses on coastal ecosystems and resources are growing at the same time that climate variability, climate change, and associated changes in the marine environment are making coastal areas less secure for human habitation. Wicked problems (1) are ones that defy complete definition and easy or final solutions owing to the inherent and constantly evolving complexity of the system at stake. Every intervention in such problems generates further challenges, suggesting that wicked problems do not have unambiguously good or bad solutions, only temporary best answers. Wicked problems---even in a relatively static environment---may continue to plague managers with diabolic challenges, but adding global climate change with all its ramifications, deep-seated causes, and systemic uncertainties will guarantee them (2, 3).

This review aims to frame these wicked challenges as emerging at the interface of the impacts of climate change on already vulnerable, already stressed coastal environments (**Figure 1, see color insert**). We begin below with a brief sketch of the proximate and deeper causes underlying the current trends at "land's end" to set the stage for the exploration of coasts and global environmental change. We then turn to a review of global climate change, its causes and impacts, including a discussion of the potential implications of projected impacts on human systems and the natural systems on which they depend. We conclude with a discussion of the wicked challenges involved in coastal zone management and adaptation in the context of converging stresses.

Figure 1 Climate change will impact the coastal system---made up of a natural and a societal subsystem---via changes in sea level, storms and wave regimes, temperature, precipitation and runoff, atmospheric and seawater concentrations of carbon dioxide, and

pH. These drivers of change will interact with preexisting conditions and vulnerabilities at land's end to create changing climate-related risks.

1.1. Human Pressures on Coastal Environments

About 40% of the world's population lives in the 5% of the world's land area located within 100 km of the coastline, and there, population growth is continuing (4). Population concentration in this relatively narrow strip of land thus serves as a simple first indicator of human pressure on coastal air, waters, and ecosystems. Population concentration goes hand in hand with ongoing extraction of economic value from these productive ecosystems and attractive environments through high-intensity land development and construction; tourism and recreation; fishing and aquaculture; agriculture and fuelwood; shipping, transportation, and trade; energy and minerals development; waste disposal; military uses; and other industrial economic activities (5). Although not new, these pressures are continuing or accelerating the observed degradation of coastal ecosystems despite various national and more localized efforts to halt habitat or species loss, water and air quality declines, shoreline hardening, and threats to human health and security (6, 7).

Positive feedback effects among population growth, economic growth and securing viable livelihoods, globalization, food production, energy, resource and land use, the growing gap between rich and poor, and escalating consumption make sustainable development difficult anywhere on Earth, but particularly in urban concentrations. The majority of near-coastal populations still live in relatively densely populated rural areas and small- to medium-sized cities (8), but almost two-thirds of urban settlements with populations greater than 5 million are, at least partly, in areas less than 10 m above sea level (4, p.17). Indeed, 15 of the current 26 megacities (>10 million people) are in the immediate coastal zone (8a, 9, 10). Such concentrations of people require an influx of external resources and place enormous demands on local resources and ecosystem services to support human needs, economic activities, and accommodate disposal of waste and emissions. Demographic trends in coastal areas suggest that rapid population growth will continue through in-migration and reproduction, as well as with temporary visitation by tourists.

1.2. Coastal Ecosystem Degradation and Human Vulnerability

Over the past decade and more, there have been improvements in tracking and assessing the effects of human disturbance on coastal ecosystems (11). The Millennium Ecosystem Assessment (7, 12) used available data and indicators to conclude that coastal and island ecosystems are already among the most highly threatened systems in the world. As all coastal ecosystems are downstream of upland land uses and pollution sources, some of the most vulnerable ecosystems---such as coral reefs, estuaries, wetlands, and mangrove forests---are greatly degraded, and their ecosystem services (e.g., fisheries, water filtering, flood protection, carbon capture in wetlands, and aesthetic value) are already compromised.

Ecological degradation has been the price or unintended consequence of continued human development in the coastal zone. The wealth generated has not been shared equally. In many developing nations in particular, exposure of the poor and disadvantaged segments of urban populations to flooding and storm surge hazards, lack of sanitation, and access to only the most marginal resources and degraded ecosystems is all too common (7). Even in developed nations like the United States, wealth is not distributed equally in coastal areas, leading to significant differences in social vulnerability (13). When combined with the exposure to physical threats, such as climate change (14) and the degradation of local environments, complex pictures of social-ecological vulnerability can arise (15). A particular challenge lies in the cross scalar connections between the drivers of social-ecological vulnerability and resilience which, therefore, makes it difficult to identify effective levers to affect systemic change (16, 17).

1.3. The Emerging Threat of Global Climate Change

The unequivocal global temperature increase (18) and other climatic changes are already beginning to add pressures on coastal environments. Global sea-level rise (SLR), a major long-term and---on human timescales---permanent effect of climate warming is impacting coasts now and will have increasingly significant social and economic impacts on coastal and low-lying regions worldwide (19--21). The effects of SLR on coasts are not uniform, however, but vary considerably regionally and over a range of temporal scales (19, 21). The effects will be greatest on low-relief, low-elevation coasts, such as deltas, coastal plains, and islands, many of which are also subsiding, as well as on densely populated and vulnerable urbanized coasts (10). Thus, the ~600 million people in coastal regions below 10 m elevation are increasingly at risk from the interactive hazards of SLR, storms, flooding, rising temperatures, reductions in sea ice, changes in freshwater runoff, increasing variability and extremes in weather, and acidification of coastal waters that are being exacerbated by global climate change (4, 9, 10, 22).

Understanding and predicting with confidence how these global environmental changes will affect coastal regions is a major challenge for scientists and engineers. Meanwhile, policy makers together with affected stakeholders must determine how society chooses to address these emerging challenges in addition to those already faced, ideally in ways that are cost-effective and sustainable. Yet, deep-seated drivers behind the draw of humans to the coast, the inherent complexity of coastal systems, the plethora of environmental challenges affecting the coasts, and their synergistic and cumulative effects on humans make place-specific, decision-relevant forecasts difficult. Such limits to understanding combined with a relative lack of awareness among decision makers and the public of the growing threats from climate change to coastal populations, ecosystems, and resources; the insufficiency of compartmentalized solutions; and differing perspectives among stakeholders on them make global environmental change in coastal areas truly a wicked problem (23).

2. CLIMATE CHANGE: GLOBAL TRENDS AND REGIONAL VARIABILITY

2.1. Temperature Increases

2.1.1. Observed and projected coastal water temperatures. Global climate change is being driven predominantly by the accumulation of carbon dioxide (CO_2) and other greenhouse gases (principally methane, nitrous oxide, halocarbons, and tropospheric ozone) in the atmosphere. For example, the concentration of CO_2 has increased by more than 40% since the start of the Industrial Revolution. The heat-trapping characteristics of these greenhouse gases result in increasing temperatures in Earth’s lower atmosphere and oceans. Analyses of temperature data collected on land, at sea, and via satellite sensors demonstrate that average land and ocean temperatures warmed by 0.8°C from the first decade of the twentieth century to the first decade of the twenty-first century, with the most pronounced warming over the past three decades (24). This warming was not geographically uniform, with greater warming in northern latitudes. Nor has the warming been monotonic, with the El Niño/Southern Oscillation (ENSO), volcanic aerosols, and solar variability playing important roles in year-to-year variations. Once these are accounted for, the various surface and satellite-based records agree remarkably, indicating a warming trend of 0.14°C to 0.18°C per decade for the period 1979--2010 (25).

Surface ocean waters have warmed slightly less than the lower atmosphere over land; still, the oceans have accumulated most of the heat generated during this warming period, with heat penetrating to the ocean depths (26). The warming trend in the ocean has also not been uniform (e.g., the northern Indian Ocean warmed more than the central North Pacific). The few coastal regions from which reliable, long-term temperature records are available also show consistent warming trends: 0.4°C per decade between 1970 and 2002 at Woods Hole, Massachusetts (27); 0.35°C per decade between 1970 and 2005 in Chesapeake Bay, United States (28); and an average of 0.28°C per decade between 1965 and 2009 at 13 sites on the North Sea coast of Great Britain (28a).

Coastal water temperature is influenced by local air temperature, but it may also be affected by the temperature of the source of coastal ocean water. For example, Shearman & Lentz (29) attributed the rapid warming of coastal surface temperatures in the Gulf of Maine and Middle Atlantic Bight to the warming of the Arctic and Labrador source waters rather than to the local air-sea exchange of heat.

Projections for future coastal water temperatures can be made from the general circulation models used to project global changes in temperature and other climate parameters; however, these global models do not resolve coastal currents well. Nonetheless, inferences can be made on the basis of the surface air temperature changes projected from the models used in the Intergovernmental Panel on Climate Change's (IPCC's) *Fourth Assessment Report* (30). As is the case with recent temperature trends, warming is projected to be substantially greater toward the Arctic and in inland areas of land masses than in near-coastal areas and on the surface of ocean waters. Increases in coastal air temperatures are likely to exceed an additional 1°C by midcentury and 3°C by the end of the century, depending on the greenhouse gas emissions trajectory. Greater warming is expected in polar regions, with much geographic variability elsewhere.

2.1.2. CONSEQUENCES OF TEMPERATURE CHANGES ON COASTAL AND MARINE ECOSYSTEMS.
The consequences of this level of warming on coastal ecosystems are numerous and profound

(31). One of the direct consequences is the reduction in the extent and duration of near-shore sea-ice coverage in polar and subpolar regions. This is already occurring, leading to increased wave exposure of shorelines and substantial changes in sea-ice-dependent ecosystems (32, 33), including shifts in food chains that support seabirds and mammals, as well as challenges for walruses and polar bears that use ice floes. These changes are happening at the same time that greater ice-free conditions allow expansion of maritime transportation and Arctic nations increase their exploitation of oil and gas resources.

At the other end of the latitudinal spectrum, reef-building corals are known to be particularly sensitive to temperatures that only slightly exceed mean summer maximum temperatures, wherein stressed corals release most of their pigmented microalgal symbionts in a phenomenon known as coral bleaching (34). If the thermal stress is severe and persistent, corals may die. As the climate warms, the thresholds for bleaching are likely to be exceeded more substantially and frequently. There is considerable variation in tolerance among coral species, and some adaptation to the warmer temperatures may occur (35). As a consequence, coral reefs are expected to change in composition and distribution rather than disappear as a result of warming alone. However, warming in combination with other human stressors and, as discussed below, ocean acidification present more formidable challenges to the continued existence of coral reefs (36).

Temperature increases and shifts in seasonal temperature patterns will affect important physical processes, such as the density stratification of the water column, that have substantial consequences for organisms and biogeochemical cycling. Increased sea surface temperatures have been implicated in declining phytoplankton biomass in the major ocean basins, probably by increasing water column stability, which limits nutrient supply from below (37). Biological processes and structure can be affected by increased temperature in terms of physiological responses, population and community dynamics, and ecosystem structure and function (32). As temperatures increase, organisms are challenged to adapt in place or move to track changes in the environment in space and time. Burrows et al. (38) found that both the velocity of thermal change and the shift in seasonal timing observed over the past 50 years were higher in the ocean than on the land at some latitudes, despite the slower ocean warming. Areas of high marine biodiversity often had greater velocities of change and seasonal shifts, raising conservation concerns. Some species will shift ranges faster than others, which will result in new species combinations, trophic structures, food-web dynamics, changes in biogeochemical cycling, species invasions, and increased prevalence of marine diseases (32). These changes have substantial implications for ecosystem-based fisheries management and conservation and restoration of coastal ecosystems (22).

2.2. Precipitation Changes and Their Consequences for Coastal Areas

Precipitation is substantially affected by the warming of Earth's atmosphere and ocean. Warmer temperatures increase evaporation from ocean and land surfaces, resulting in increased precipitation elsewhere to balance the water cycle (39). IPCC projections indicate increased precipitation along the equator and at higher latitudes and decreased precipitation along lower to midlatitudes (30)---changes that seem to be occurring more rapidly already than predicted (40). Several semienclosed seas with important coastal zones fall within the zone of projected decreases in precipitation, including the Gulf of California, Gulf of Mexico, Caribbean Sea, and Mediterranean Sea. Changes in precipitation within the catchments draining to coastal waters have substantial consequences for coastal ecosystems, affecting salinity, density stratification, and the delivery of sediments and nutrients. However, it is not straightforward to translate increases or decreases in precipitation into changes in delivery of freshwater into coastal waters. Warmer temperatures increase evapotranspiration and affect whether precipitation falls as rain or snow, thus altering the timing of delivery; and in many regions, precipitation is expected to come in more intense events, separated by longer dry periods (14, 41).

Changes in freshwater discharge and temperature in coastal systems will interact with changes in other atmospheric and oceanic conditions and sea level to create new sets of conditions that alter coastal ecosystems as we know them. These new conditions require adjustments to how these systems are being managed. Modeling the effects these interactive forces over this century for California's San Francisco Bay-Delta-River System has demonstrated how key indicators of hydrology and habitat quality can change substantially (42).

2.3. Sea-Level Rise

Coastal landforms are modified by a variety of dynamic processes with cumulative effects, which exhibit great regional variability. The driving forces that influence the evolution that coasts undergo include the geologic framework and character of the area, relative sea-level change, major tropical and extratropical storms, coastal oceanographic processes (i.e., wind, waves, currents), sediment supply, and effects of human activity altering sediment movement (43).

2.3.1. OBSERVED TRENDS. Sea-level change is a dominant driving force of coastal change as observed in the geologic record of coastal landforms and experienced in historic times. Sea-level rise is likely to increase in importance as a hazard for all coastal regions because of predicted acceleration in rise rates and increased risk to vulnerable coastal regions, such as cities, deltas, islands, and low-lying coastal plains. As the global climate continues to warm and ice sheets melt, coasts will become more dynamic, and coastal cities and low-lying areas will be increasingly vulnerable.

The geologic record shows that sea levels have been highly variable with levels 6 to 8 m higher than present during the last interglacial warm period and about 120 m lower during the Last Glacial Maximum period (44, 45). Regional to local-scale land subsidence, owing to geologic processes and human activities, and uplift often contribute significantly to relative SLR, affecting local erosion, accretion, and changes to sediment budgets. These processes are complex, cumulative, and often difficult to distinguish but typically result in increased human vulnerability to hazards.

The global sea level has been rising at variable rates in concert with warming and glacier and ice-sheet melting since the end of the Last Glacial Maximum. The average rate of rise has been modest for the past several millennia with evidence of both accelerations and decelerations on timescales of several decades or longer, but large increases are projected by AD 2100 and beyond. The complexity of methods for studying SLR has been reviewed by several researchers (44, 46, 47). Analyses of tide-gauge records worldwide indicate that the twentieth-century global rate averaged 1.7 mm/year (48), with decadal fluctuations (49). Since the early 1990s, both satellite altimeter (**Figure 2**) and tide-gauge observations indicate that SLR increased to more than 3 mm per year (48, 50). There is now emerging evidence of acceleration in SLR caused by climate warming (51), with the increase likely the result of equal contributions from ocean thermal expansion and glacier and ice-sheet melting and long-term shifts in ocean circulation along the US mid-Atlantic region (47, 51). Regional and local effects of the recent rise are becoming increasingly evident by more frequent flooding of urban roadways, docks, storm drains, and coastal lands during routine astronomical spring high tides.

<COMP: PLEASE INSERT FIGURE 2 HERE>

Figure 2 The highly variable spatial distribution of the rates of sea-level change, plotted about the globally averaged rate of rise for the period 1992 to 2011, as measured from satellite altimeter data in mm/year. Source: NOAA Laboratory for Satellite Altimetry (180).

Church et al. (47) examined global sea-level change and energy budgets from 1961 to 2008 and showed that of the 1.8 mm/year observed rise, ocean expansion accounts for 0.8 mm/year, melting glaciers and ice caps account for 0.7 mm/year, and the ice sheets of Greenland and West Antarctica account for 0.4 mm/year. Over the same time period, ice melt contributions increased as did thermal expansion, but less rapidly. Groundwater depletion increases SLR, whereas water retention behind dams decreases SLR over decadal time periods; together these affect the global sea level by –0.1 mm/year (47, 52).

2.3.2. Projections of future sea-level rise. A fundamental and important question is whether there is evidence of SLR acceleration, and if so, whether it can be linked to observed global warming? Credible analyses suggest global acceleration started in the mid-nineteenth century to a current rate of more than 3 mm/year, a 50% increase in the past two decades (53--56). In contrast, Houston & Dean (57) claim to have found evidence of deceleration; however, subsequent papers by Rahmstorf & Vermeer (58) and Rignot et al. (59) have essentially discredited those claims.

The IPCC's *Fourth Assessment Report* (18) included model-based projections of SLR by the end of the twenty-first century. It reported that sea level could rise 18 to 59 cm but did not include potential additional rise owing to the melting of major land-based ice masses on Greenland or West Antarctica because of the limits in modeling capability at the time. The fifth IPCC climate assessment will include refined model results of ice-sheet dynamics and change, and it may report higher SLR projections on the basis of improved model results and more observations.

As shown in **Figure 3,** many studies since the *Fourth Assessment Report* (10, 21, 58--67) suggest that SLR in decades ahead is likely to be considerably greater than the IPCC's 59 cm upper limit. Ice-sheet melting in Greenland and West Antarctic is likely to be more rapid than assumed in the IPCC projection (46, 67a). Average global SLR is thus expected to be in the range of 0.5 to 2 m (**Figure 3**) by AD 2100; however, the rates of rise will have high regional and temporal variability. For example, some modeling studies conclude that gravitational effects and shifts in ocean currents are likely to result in nonuniform rise in sea levels, possibly with an additional 30 to 51 cm rise along the northeast coast of the United States and Canada (46, 51).

<COMP: PLEASE INSERT FIGURE 3 HERE>

Figure 3 Graphic summary of the range of average global sea-level rise (SLR) projections by end of century (2090--2100) from the peer-reviewed literature (60--63, 67, 182, 184) as compared to the National Research Council's (181) and Intergovernmental Panel on Climate Change's (IPCC's) (30) projections. Notations B1, A2, and A1Fi refer to IPCC emissions scenarios (18). Details on the methods used and assumptions are in the original references.

With continued warming, accelerated melting of the Greenland and West Antarctic ice sheets could lead to SLR of ~6 to 8 m over several hundred years on the basis of the levels recorded from the last interglacial warm period (68). Jevrejeva et al. (62) suggest SLR of 1.8 to 5.5 m is possible by AD 2500. At the extreme, a maximum rise of up to 70 m is possible, but unlikely, if global warming continues such that all ice sheets melt. Total melting has happened in the geologic past, but this would require centuries of global temperatures higher than present. However, temperatures at such levels (4°C or more) are within the range projected by IPCC (18).

2.4. Changing Storminess and Effects on Coasts

Although SLR will bring increasing risk to vulnerable coastal regions by itself, major storms (i.e., cyclones) have more immediate impacts to both landforms and human development. Storms, by means of waves, currents, wind, and elevated surge, provide the kinetic energy to transport sediment, thereby causing erosion and land loss. These coastal changes may be temporary for natural coasts that are able to recover during fair weather; however, for highly developed coasts, storms can be devastating in terms of loss of life and property damage (69).

Data on storm impacts to coastal regions are limited. Historic records go back a century, and the geologic storm record goes back several centuries, but the best records cover just the past 50 years. In the United States, weather events caused more than $500 billion in damages from 1980 to 2005, and storms account for approximately 35% of these damages (70). Since then, storm damages have increased greatly. The U.S. National Oceanic and Atmospheric Administration reported that in 2011 there were 12 billion-dollar disasters for a total loss of about $53 billion in the United States. Several were coastal storms, and the 2011 losses were greater than in 2008, the previous record year (70a).

Climate change also affects storm characteristics such as intensity, frequency, and tracks, as well as changes in precipitation patterns, including seasonal and annual amounts, and variability. In turn, they affect runoff, flooding, erosion, sedimentation, water quality, vegetation, navigation, and many other factors important to coastal ecosystems and human welfare. According to IPCC (14), there is high confidence that, in some places, climate change has the potential to substantially affect the risk of flooding and associated impacts to human health, infrastructure, and agriculture.

Moreover, the IPCC (14) concluded that because hurricanes are powered by the release of moisture and heat from warm oceans, increases in sea temperatures are expected to result in stronger storms. Acknowledging that warmer temperatures can trigger a shift toward weak El Niño-like conditions, which reduce hurricane activity, the IPCC expects increases in average tropical cyclone maximum wind speed and a possible decrease or no change in global frequency of cyclones, confirming earlier findings (18, 71, 72). The IPCC (14) also noted that storms can be expected to continue to shift north, exposing higher-latitude regions to more coastal erosion, flooding, and property damage, and lower-latitude regions to less.

In addition to the direct impacts on physical landforms and human development, major storms can also cause ecosystem changes superimposed on those resulting from nonclimatic stressors. Salt marsh wetlands, mangrove swamps, and coral reefs are particularly vulnerable to impacts of major coastal storms (73, 74).

2.5. The Changing Ocean

Coastal ecosystems are influenced by the conditions in the adjacent ocean as well as on land and along the coast. Climatic oscillations (such as ENSO) will be affected in ways that are presently poorly understood yet can have profound consequences for marine ecosystems and fish populations (75). Along the coast, climate change will affect thermal gradients, water column stratification, winds, precipitation, boundary currents, and upwelling. Warming intensifies pressure gradients between land and sea; thus, upwelling winds are expected to intensify in Eastern Boundary Current systems (76), and coastal upwelling intensity seems to have increased already during the late twentieth century (77). Since 2002, changes in wind forcing along the northwestern United States coast have resulted in an upwelling regime that moves water severely depleted in dissolved oxygen onto near-shore habitats, resulting in mass mortalities (78). Changes in wind forcing that modify coastal currents, upwelling intensity, and surface temperature also influence the recruitment of marine species that utilize estuaries as nursery habitat in San Francisco Bay, California (79).

The pH and calcium carbonate saturation are being reduced as the rising atmospheric CO_2 concentrations equilibrate with surface ocean waters (80). This decline in pH of ocean surface waters during the past 30 years and an overall decrease from the preindustrial period of 0.1 pH units is already well documented. The pH is projected to decrease further by 0.3--0.4 units by the end of the century if CO_2 emissions continue to grow at recent rates (81). In short, the process of ocean acidification will continue unless atmospheric CO_2 concentrations are stabilized through dramatic reduction of emissions.

Ocean acidification undermines the formation of shells and skeletons by planktonic and benthic organisms, including mollusks and corals (80). In coastal ecosystems, the effects on shellfish production are of direct human concern. Decreased calcification rates for mussels and oysters exposed to higher CO_2 have been demonstrated (82), and upwelling of deep CO_2-enriched waters have been implicated in mortalities of oyster larvae in Washington, United States (83). Similarly, declining pH in waters in the lower Chesapeake Bay could reach levels that limit calcification and increase shell dissolution (84). Reef-building corals are particularly susceptible to ocean acidification (36). Declining calcification rates have been observed for corals on the Great Barrier Reef coincident with the reduction in pH, although thermal and additional stresses may also have played a role (85). Evidence to date indicates that ocean acidification will severely affect reefs by midcentury and will have reduced many of them to ecologically collapsed carbonate platforms by century’s end if atmospheric CO_2 concentrations are not soon stabilized (86). The tremendous biodiversity and ecosystem services associated with coral reefs are at serious risk, but not all marine organisms are negatively affected by ocean acidification. Some sea grasses increase in biomass and reproductive output if provided more dissolved CO_2 (87), although the stress of warmer temperatures may counteract this stimulatory effect.

Coastal ecosystems experience more widely fluctuating pH levels than open ocean systems mainly because of the high rates of photosynthesis that deplete CO_2 and raise pH, and because of the high rates of decomposition of organic matter that release CO_2 and lower pH (88). The oxygen-poor bottom waters of the Gulf of Mexico "Dead Zone" thus experience even lower pH than the open waters of the Gulf (89). Moreover, inputs of the dissociation products of strong acids (nitric and sulfuric acid) and bases (ammonia) resulting from fossil-fuel combustion and agriculture can also decrease pH (80).

3. CHANGES IN LAND-SEA INTERACTIONS

The rich and productive coastal ecosystems and population centers at the interface between land and ocean are largely the result of abundant living opportunities for humans and other organisms along the coast and of the fluxes of materials and energy across this interface. For human societies these fluxes are mediated by maritime commerce, food supplies, and the flux of people. Coastal ecosystems in turn are greatly influenced by the fluxes of water, sediments, and dissolved substances from the land, as well as stimulating intrusions from the sea, such as coastal upwelling of nutrient-rich waters.

3.1. Dynamic Fluxes at the Land-Sea Interface

The fluxes from the land into coastal ecosystems have been greatly affected by human activities (see Section 3.2). Freshwater flows have often been reduced, and soils have eroded. Moreover, the land-based loads of important chemical constituents, ranging from toxic manufactured chemicals to nutrient elements essential to life, have often increased (Section 3.3). Where changes in these fluxes have resulted in too little freshwater, too much or too little sediments, or water pollution entering estuaries and coastal waters, they have become critical concerns for coastal management.

As climate change alters patterns and amounts of precipitation and river discharge, the amounts of sediment and dissolved substances carried into coastal areas will add additional complexity to the management challenge. Two pervasive management challenges are considered here: alterations of sediment transport and nutrient over enrichment.

3.2. Changes in Sediment Transport to and along the Coast

Human activities, particularly land clearing and cultivation, the construction of dams for flood control and freshwater retention, and levee construction and other river alterations have greatly altered the delivery of sediments by rivers to the coast with substantial consequences to estuaries, shorelines, and deltas (90). Human-induced soil erosion increased the sediment transport through global rivers by about 2.3 billion metric tons per year, yet the flux of sediment reaching the world's coasts from land has been reduced by about 1.4 billion metric tons per year because of retention within reservoirs (91). Both sediment erosion and retention present coastal management challenges. Historically, erosion filled in estuaries and bays, resulting in the loss of valuable ecosystems and abandonment or relocation of ports. Some coastal systems still receive far more sediment loads than they did before pervasive human alteration of their catchments.

At the other end of the sediment transport spectrum are regions experiencing rapid shoreline retreat and land loss because of the deficiency of sand-size sediments in rivers carrying sediment to the coast or deficiencies in the coastal alongshore sediment transport system. These sediment deficits have increased over the past century and result from a variety of human activities, such as sand mining in rivers and at the coast, sediment trapping by dams and reservoirs, loss of coral reefs, and coastal engineering structures that disrupt transport processes and cut off natural sediment sources.

The challenges are even more substantial for coastal deltas, which are low-lying and rely on periodic sedimentation from river floods. As most of the world's deltas experience further SLR, their vulnerability is heightened because of continued land subsidence owing to sediment compaction and consolidation; the removal of oil, gas, and water from underlying geologic formations; the trapping of sediments in upstream reservoirs; and floodplain engineering that constrains river flooding and alters tidal exchange. Syvitski et al. (92) found that over a decade 85% of the world's deltas experienced severe flooding, resulting in the temporary submergence of 260,000 km^2. They also conservatively estimated that such vulnerable delta surface area would increase by 50% as sea level rises during the twenty-first century. Only by alleviation of the capture of sediments upstream or their entrainment within the delta, and cessation of other human activities causing local land subsidence, could this inundation of the world's deltas be lessened.

A particular case is the Mississippi River Delta, United States, where 4,900 km^2 of coastal land (mostly wetlands) has been lost since 1900, and ambitious efforts are underway to stem the losses and, where possible, restore the landscape both for natural resources and protection from storm surges (93). Sediment loads have been reduced by more than 50% through dam construction and Blum & Roberts (94) estimated that the present sediment load of the river is less than the historical rate of sediment storage in the delta, when the sea level was rising at a third of the present rate. Even so, very little of the present sediment load escapes the flood-control levees that confine the lower river. They estimated that an additional 10,000--13,500 km^2 of wetland area would be submerged by AD 2100, but some of this landscape could be sustained with strategic diversions of much of the remaining sediment load in the river through engineered breaks in the levee system.

3.3. Nutrient Enrichment

Human activities have also greatly increased the availability of plant nutrients, particularly forms of nitrogen and phosphorus, in coastal ecosystems. This is not only the result of direct disposal of wastes into coastal waters, but also because of diffuse source runoff from agricultural and urban systems and, in the case of nitrogen, atmospheric deposition of fossil-fuel combustion by-products. Although increasing nutrient loads enhance primary production, there are often deleterious consequences that result from increasing the supply of organic matter (eutrophication) of coastal ecosystems. These include decreased water clarity often resulting in the loss of bottom vegetation; alteration of food chains supporting desired species and some toxic or otherwise harmful algal blooms; and depletion of dissolved oxygen in bottom waters, or hypoxia (95). The frequency, extent, and severity of these deleterious effects of eutrophication virtually exploded after the 1960s, commensurate with the rapid increase in the use of manufactured nitrogen fertilizers, the intensification of livestock production, and the generation of nitrogen oxides through combustion of fossil fuels (95). Known areas of recurrent hypoxia that develop as a result of the degradation of excess production in stratified bottom waters have grown dramatically (96). Nutrient over enrichment has been an important cause of the accelerating loss of sea grass across the globe, contributing to a 29% reduction of their known areal extent (97).

Reversing the effects of eutrophication through reducing land-based nutrient inputs is one of the major objectives of coastal environmental management in the developed world, while symptoms of eutrophication are increasingly being observed in the developing world. Commitments to reversing eutrophication have been made, and substantial resources are being directed to reduce nutrient inputs into large coastal ecosystems, such as the Chesapeake Bay (98), the northern Gulf of Mexico (99), and in many smaller systems. However, climate change is likely to transform conditions in the catchments and in coastal waters that make the alleviation of the effects of eutrophication more challenging. Increased precipitation and runoff expected in temperate regions are likely to increase the delivery of nutrients and sediments during the spring, intensify density stratification of receiving waters, and exacerbate hypoxia (28, 100).

Climate change may be intensifying the effects of eutrophication already. Carstensen et al. (101) found for several coastal ecosystems in Europe and North America that phytoplankton biomass decline with decreasing nutrient loading was slower than the pace of biomass growth when loadings were increased. They suggested that these shifting baselines were possibly a result of global climate change and increasing human stress on coastal ecosystems.

4. COMPOUNDING IMPACTS OF CLIMATE CHANGE ON HUMAN SYSTEMS

4.1. Overview

The combined impacts of SLR, changing coastal storm regimes, ocean acidification, saltwater intrusion in coastal aquifers, air and water quality degradation, and changing interactions between upland and downstream regions will add to the stresses confronting coastal ecosystems and human population centers (**Figure 1**) (101). Climate disruptions, shifts in species abundance and distribution, as well as direct and indirect impacts on the economic resource base of coastal regions will in many instances further degrade ecosystems and the services they provide, undermining locally viable, sustainable economies and posing significant challenges to human health, well-being, and security (10, 21, 102--104).

Studies of climate change impacts on coastal regions to date have generally not considered the interacting global and more localized environmental changes in an integrative fashion, nor have they fully accounted for the existing state of environmental degradation and human vulnerability (22, 105). Most existing studies instead have focused on individual impacts (e.g., sea-level rise, acidification, storms, or saline intrusion in groundwater) rather than the sum of interacting climate change--driven stressors (for an interesting exception see Reference 69). Different assumptions about climate scenarios, demographic changes, and economic development produce ranges of projected impacts that are insufficient for smaller-scale coastal planning or decision making (106). Moreover, studies have taken either a global or megaregional focus (107--109) or a smaller-scale and local focus (110--113). Different approaches and methodologies make such assessments difficult to integrate. Although these limitations are easily explained by data limitations, methodological and computational challenges, and knowledge gaps, existing impact assessments possibly underestimate the actual severity of future impacts on coastal environments, communities, and economies when viewed synergistically.

These limitations notwithstanding, a synthetic reading of existing studies suggests a very challenging future for coastal regions. The effects seem predominantly negative. Of course, the exact pace and ultimate severity of local impacts very much depend on regional climatic changes, feedbacks, threshold crossings, and also on the interactions with the geological processes, the nature and health of ecosystems, the intensity of human development, and whatever adaptive strategies are taken to minimize these effects.

4.2. Synthesis of Impacts

Overarching findings include the following:

- Coastal erosion, inundation, and flooding from the combined impacts of SLR and storms will become even more pervasive along most of the world's coastlines. Increasing impacts from more frequent and intense extreme weather on coastal infrastructure, services, and particularly harbors and ports are expected (114, 115). Heavier rainfall, combined with SLR and storm surge, is expected to substantially increase the frequency of flooding in major metropolitan areas around the world (19, 116--121).

- Examining the changing global flood risk under the IPCC's emissions scenarios (not accounting for any changes in storminess), Nicholls & Lowe (108) found that SLR increases the flood impacts under all climate change scenarios, with significant impacts becoming apparent later in the century when large additional numbers of people (2--50 million annually) could be flooded during storms. A more recent analysis found that if the increase in global mean temperature exceeds 4°C the associated SLR of up to 2 m by 2100 could lead to the forced displacement of up to 187 million people (~2.4% of global population) from at-risk areas (10).
- Low-lying coastal environments dominated by rapid subsidence (deltas, estuaries, coastal floodplains, islands) are not only often the most heavily settled but also the most vulnerable to abrupt and extensive impacts from SLR and coastal storms (122--124).
- As coastal populations are increasingly subjected to more frequent or extensive coastal hazards, demands for basic necessities will increase, and populations may be displaced from low-elevation regions. There is considerable debate in the scientific and practitioner communities as to whether such disruptions and displacements will create political destabilization and thus raise security concerns (24).
- The only coastal regions exempted from growing impacts and stresses from SLR and related coastal hazards are those that experience uplift at rates faster than the expected SLR or fewer coastal storms in the future (e.g., resulting from a poleward shift of extratropical storms), and regions that have abundant sediment along the coast.
- Coastal groundwater resources are threatened universally from saline intrusion by the encroaching sea and landside withdrawal (often overdraft) of water for human uses (125--127).
- Studies of the economic impacts of SLR impacts vary widely by region, climate scenario, and differences in coastal development (108, 128). Recent economic assessments have found that shoreline protection can be cost-effective (129). Finer-resolution studies reveal that economic costs of protecting coastlines against the growing risks from climate change tend to be significantly higher than coarser resolution studies suggest. For example, in a study of the cost of adaptation to SLR for

the full coastline of the continental United States, Neumann et al. (130) found that the economic cost of SLR is much larger than prior studies suggested: The cumulative cost was more than $63 billion (discounted at 3%) (or $230 billion undiscounted) for a rather modest SLR scenario of 68 cm by 2100. This added cost, however, amounted to only a quarter of the total value of low-lying property that would be at risk without protective measures.

- Although the coastlines of developed nations have more infrastructure and economic assets at risk in absolute terms, and thus are expected to experience significant losses from future combined impacts of SLR and coastal storms, the relative socioeconomic vulnerability to current and future coastal impacts is likely greater in developing nations (14, 122).
- In the United States, extreme weather events caused more than $500 billion in damages from 1980 to 2005, and storms account for approximately 35% of these damages (70), with economic impacts in coastal regions dominated by recent hurricanes.
- Ecosystem services will change and often become further diminished (7). Provisioning services, such as the production of seafood, will face shifts in species composition, food chains, and productivity as well as diminution of critical habitats, such as coral reefs, mangroves, and coastal marshes. Regulating services, for example, the control of climate, will be influenced by changes in the pressure gradients between land and ocean that moderate regional climate, and by the ability of wetlands and other coastal ecosystems to sequester carbon. Supporting services, such as nutrient cycles, will be affected by changes in river flows and increased stratification. Cultural, spiritual, and recreational benefits will be affected by shoreline retreat and loss of historical coastal landscapes and habitats. However, a lack of understanding of the connections between ecosystem services and human well-being inhibits clear quantification and conclusions (131).

This unsettling picture is not a future that should be fatalistically accepted. Rather, humans have always and will continue to adapt and change their behavior, modify, and---where possible---minimize coastal risks. The concentration of wealth and brain power in coastal areas may well assist in finding adaptive solutions to climate change. Many of past interventions in coastal problems, however, have led precisely to the situation we find ourselves in at present: increasing human concentration and lucrative economic activity in coastal areas, albeit at the expense of extensive ecosystem loss and degradation. An added challenge at present is that global population is above seven billion and continuing to grow, with many migrating to vulnerable coastal areas. To address the wicked challenges that coastal areas will face under global climate change, a more integrated, forward-looking, and comprehensive management of coastal risks is necessary if coastal occupancy and sustainable coastal resource use are to be achieved. At the same time, it will be impossible---as with all wicked problems in dynamic environments---to wait for perfect, fully thought-out solutions. Instead, a deliberately learning-oriented, adaptive governance approach that supports iteration and works with temporary best solutions is needed as management interventions are determined.

5. MORE SYSTEMIC AND ADAPTIVE COASTAL MANAGEMENT

5.1. Adaptation Approaches and Options

Given the growing challenges expected in coastal areas under climate change, we see a clear imperative to successfully prepare for and minimize the growing risks: Coastal management must better account for the cumulative, synergistic, and mounting stresses arising from climate change and concurrent human activities. Adaptation to these interacting changes will occur mainly in the context of existing governance and social-ecological systems.[1] It is unrealistic to think that adaptation would begin outside of these historical institutional arrangements; at best, these institutions will be modified themselves as part of adaptation. Thus, this governance context and any legacies of past management both enable and constrain the possibilities for future human responses to climate change.

The key issues for policy makers, planners, and engineers are to identify how, where, and when to adapt to the changes resulting from SLR and other climate changes using methods that minimize impacts to both the natural environment and human populations, or create benefits for them.

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[1] Coastal governance involves the legal and institutional context of coastal management, disaster management, resource management, and species and water protection; the ownership rules related to coastal land and resources (e.g., private property versus public trust); a wide range of actors and stakeholders involved in coastal decisions; as well as the social norms, rules, power dynamics, and personal relationships that guide their interactions (185).

For adapting to the impacts of SLR, a common distinction is made between (*a*) hard (e.g., seawalls, revetments, and breakwaters) or soft structural protection measures (e.g., beach replenishment); (*b*) nonstructural measures that accommodate coastal risks while continuing coastal occupancy and land use (e.g., flood insurance, stricter building codes, elevating structures, and diverting river sediments to enhance wetlands); and (*c*) relocation away from the coastal fringe (planned retreat using construction setbacks, buy-outs, and active relocation from the shoreline) (122). Decisions on which means are employed depend on the rate of SLR, the value of development, and the total cost-benefit of the adaptation method over the long term.

In most countries, shore protection policies have been developed in response to shoreline retreat that threatened property or coastal wetland losses. Although it is often recognized that SLR is an underlying cause of these changes, there is limited policy and regulation to date in the United States that explicitly addresses or incorporates accelerating SLR into the decision-making process (74, 132). Assessments of alternative coastal policies, such as planned retreat, coastal easements, buy-outs, ecosystem restoration, and others, are now being investigated in the United States (133, 134), the United Kingdom (135, 136), Canada (137), and Australia (138) among others. These illustrate the growing need for management alternatives that go beyond historic approaches to managing coastal hazards (139--141).

Along highly developed shorelines, structural protection has historically been the preferred option, given the amount of investment at stake. However, hardening of erosive shorelines typically involves the loss of beaches and wetlands in front of protective structures (e.g., seawalls, groins, bulkheads), thus negatively affecting ecosystem services, such as fish nurseries, bird habitat, recreation and tourism, storm buffers, and water filters (74, 142). In the short term (10 to 50 years), an acceleration of SLR may simply increase the cost of current shore protection practices (143). For longer-term (>50 years) planning, policy makers will have to evaluate whether current approaches and justifications for coastal protection need to be modified to reflect increasing vulnerabilities (74). The use of rolling easements (144) to both accommodate SLR and maintain public access to the coast might have application for regions where development is limited and open space is available to accommodate marine transgression.

More generally, whether or not structural protection (including repeated beach replenishment, which tends to be only a short-term solution, albeit one with temporary recreational benefits) will be financially or physically feasible will depend on society's competing priorities, cost-benefit analyses, the ability of various governance levels to finance continued protection, and managers' consideration of broader impacts (e.g., ecological or aesthetic impacts). Additional strategies are needed to address saltwater intrusion into coastal aquifers, inundation of wetlands, and other habitat changes.

Coastal management strategies to adapt to the consequences of climate change beyond SLR and acidification are less well developed. One common suggestion is to ensure the resilience of present ecosystems by alleviating other anthropogenic stresses (e.g., those caused by overfishing, pollution, and habitat loss) that have degraded them. This amounts to a "no regrets" management strategy that would produce benefits in any case (31). Similar suggestions have been made for management of coral reefs as they confront both warming and acidification (35, 36). Noting that both eutrophication and land-based acidic inputs presently lower pH in coastal ecosystems, Kelly et al. (145) argue that enforcement of water and air pollution laws, controlling coastal erosion, and managing land use can provide some level of protection from acidification resulting from increased atmospheric CO_2 concentrations. Fisheries managers also have a variety of risk-averse and adaptive strategies that can improve resilience and help fisheries adjust to climate variability and change. It is unclear, however, whether concerns about climate change and acidification are sufficient to help overcome existing obstacles for implementing such no regrets strategies. Other adaptation strategies, such as providing warnings to oyster hatcheries when low pH waters are upwelled (83), may have to be pursued. Finally, networks of marine protected areas are being assessed for their ability to preserve biodiversity under a changing climate, including considerations of size, spatial layout, spreading risk, critical areas, and connectivity (146).

Thus, a variety of adaptation approaches should be considered and integrated at the local and regional level as indicated by coastal sediment and water dynamics, bringing together managers from heretofore often separately operating departments and agencies (e.g., land-use planning, public health, natural resource management, emergency management, transportation, water management, and economic development). Future coastal management approaches would benefit from acknowledging that coastal environments are dynamic and involve uncertain, long-term trends and shifting baselines. This would involve recognizing and accounting for the long time horizons of decisions, longer time frames for planning (typically >30 years), time lags in the climate and ocean systems, potential physical and ecological thresholds or tipping points, and the long lead times often required for effecting socioeconomic responses. Such shifts in thinking and practice would go a long way toward improving adaptive coastal management.

5.2. Barriers to Adaptation and Sustainability

There is emerging evidence from all regions of the world that coastal communities are beginning to adapt (122). Even case examples from highly developed nations and some of the richest communities there suggest, however, that adaptation is still in the very early stages (132, 147, 148). The reason is that communities face considerable obstacles to adaptation, both in developed and developing nations (122), and our understanding of these barriers has significantly improved in recent years (22, 149--152).

Social, economic, institutional, informational, cultural, and other barriers---those mutable obstacles that delay adaptation or make it less cost-efficient or effective but that can be overcome with concerted effort, creative management, change of thinking, and prioritization, as well as with related shifts in resources, land uses, and institutions (153)---have been examined specifically in the coastal sector (154--157).

Among the most important challenges repeatedly found are intra- and cross institutional or governance barriers, impediments related to the attitudes of involved actors (policy makers, planners, and affected stakeholders), values, and motivations, and budgetary constraints. Informational, communicational, political, and public support barriers also play important roles (155). Although information is clearly important, it matters differently at certain times in the adaptation process. Studies of lay individuals and unplanned, reactive adaptation show a predominance of psychosocial (place attachment, social support, social norms, identity), cultural-cognitive (beliefs, worldviews, values, awareness, education), and economic (livelihood, job mobility, investment) barriers (158).

Another common finding is that barriers occur not alone but in “bundles.” Lack of staff time is related to an overall lack of resources for planning and implementation, and lack of awareness is often related to a lack of experience and lack of communication or education (156, 159). Social resistance to certain adaptation options is influenced by attitudes, worldviews, cultural norms, place attachment, historical investments, and available adaptation options (160).

Some factors act as either enablers or barriers, depending on circumstances (155, 161, 162). For example, strong leadership can help motivate and advance adaptation in some cases (the efforts of London, New York City, and the Southeast Florida Regional Climate Change Compact are leading examples), while hindering broad ownership of the challenges and responsibilities to plan and implement adaptation in others (162). Thus, barriers are not absolute but are context-specific obstacles, and their importance varies accordingly.

5.3. Improved Decision Support for Adaptive Coastal Risk Management

To facilitate adaptation decisions over time, policy makers at certain times in the adaptation planning and implementation process need credible scientific information. Predicting SLR impacts, such as shoreline changes, wetland losses, and other ecosystem consequences, with a high degree of confidence and place-based accuracy is still limited, although the general direction of change is well understood. Other effects of climate change add to the difficulty of providing place-specific, accurate, and reliable information. This lack of reliable information and forecasts has led to the general call for an adaptive approach to managing and reducing climate change--related risks (24, 132). Such an adaptive risk management approach typically entails (*a*) careful risk identification; (*b*) vulnerability assessment and evaluation; (*c*) systematic development and assessment of adaptation strategies; (*d*) iterative decision making combined with deliberate learning; (*e*) decisions with long time horizons that maximize flexibility, enhance robustness, and ensure durability; and (*f*) a portfolio of approaches rather than single technological fixes or market mechanisms (24). Frequently, adaptive decision making for an uncertain future also involves investments in no regrets and "low-hanging fruit" options that are beneficial to society and the environment regardless of future climate change but are useful for reducing climate risks, relatively easy to implement, and may not cost much. In addition, many communities have begun the adaptation process by building their adaptive capacity through developing a better understanding of the problem, educating and building awareness among stakeholders, establishing collaborative ties with scientists and various levels of government, improving data sharing and communication, or developing funding mechanisms (155).

To improve the scientific basis for iterative decision making, predictive models can be used to forecast where erosion hazards are highest. Existing models that forecast shoreline response to SLR include geometric models, such as the Brunn Rule, empirical models based on historical water level data, or more simply extrapolation of historic shoreline change rates. These methods provide deterministic predictions, but they often do not account for the potential acceleration of trends, the spatial and temporal variability of coastal processes, or the fact that erosion is episodic and does not necessarily respond immediately to forcing. Furthermore, the response may depend on the influence of previous events. The use of semiquantitative geomorphic models to predict coastal change (163) offers promise as does incorporating probabilistic methods, such as Bayesian Networks (164, 165), to account for the complexity of coastal change.

6. TOWARD A SUSTAINABLE COEXISTENCE AT LAND'S END

Coastal management in many countries has been successful in ameliorating or adapting to stresses, even multiple stresses. Eutrophication has been reduced and significant ecosystem recovery has been achieved in some places, e.g., Boston Harbor, Massachusetts (166), and Tampa Bay, Florida (167). Depleted fish stocks are being managed for recovery (168). Coastal hazards, such as SLR, storms and tidal flooding, are increasingly recognized as significant risks, and in North America, Europe, Asia, and in many other regions, planning is underway to assess vulnerability and develop adaptation plans. Effective hazard mitigation is well understood in principle (169), and best-practice examples for improving community resilience to coastal hazards are being implemented selectively (170).

However, this review of environmental changes already underway and further expected as a result of anthropogenic climate change interacting with local stresses clearly illustrates the enormous challenges ahead. The wicked nature of problems facing coastal areas lies in the fact that they are virtually impossible to solve once and for all owing to incomplete, sometimes contradictory, and changing conditions, and---given the wide range of affected stakeholders involved---the always contested understanding of causes and preferences for solutions (23, 171). Coastal management under climate change is bound to become even more formidable in the future: More people flock to the coast, and climate change makes coastal habitation more dangerous, and climatic and nonclimatic changes further undermine the health of coastal waters and ecosystems.

A variety of overlapping coastal management approaches have been offered and tried over the past several decades to meet these growing challenges, including integrated coastal zone management, ecosystem-based management, adaptive management, disaster risk management, community-based adaptation, and others (141, 172--174). Fundamentally, these approaches focus on improvements in various aspects of governance (175--177).

The above-cited reviews of these approaches show that a far greater effort has to be made to realize their potential in practice. This requires both changes in science (e.g., more truly transdisciplinary science) and in practice (e.g., effective cross scale and cross sector integration, meaningful stakeholder education and engagement, longer decision-making horizons, stronger legal and institutional arrangements to manage coasts sustainably, better science-practice interactions, and sustained political will) (178). In short, “tinkering on the margins” is unlikely to be insufficient to meet the challenges of the twenty-first century. Instead, truly transformative change is required (179).

Such transformative change would certainly involve improvements in the scientific basis for decision making but more importantly would require a shift toward actually using science more effectively in the decision-making process. Moreover, science is only one input into coastal decision making and frequently not the most important one. Thus, changes are equally needed in the political and organizational cultures of coastal decision making and in public understanding of the risks unfolding and the response options available and necessary for continued safe and prosperous occupation of coastal areas.

As economic, cultural, and population centers in some of the most beautiful and resource-rich environments on Earth, coasts will continue to attract people. In those parts of the world where this aggregation along the coastal margins occurs in largely uncontrolled ways, the transformative change involves, at minimum, building governance systems that can direct the flow of people toward less hazardous areas, construct and maintain functional infrastructure, and thus better protect coastal environments and support economic activity. In parts of the world where more effective governance systems are in place, the transformative change involves, at minimum, reorientation toward ecosystem protection and restoration, and (re)development out of harm’s way. Involving stakeholders in scenario planning and visioning of a desirable future, fostering the political will to invest in hazard mitigation now rather than pay for losses and damages later, strengthening legal instruments for protection of the commons and market instruments (e.g., insurance) to better reflect the true and growing risks are just some of the available tools. Nowhere, however, are there clear, unambiguous, or simple solutions. Instead, in a complex and highly dynamic environment, these solutions will necessarily be temporary and partial, but they can be significantly better than the narrowly sectoral ones sought in the past. Financial and institutional commitment to ongoing observation, a systems approach in science and governance, vigilance, an institutionalized ability to reflect and learn, and a far greater will to change than evident in the past constitute crucial prerequisites for remaining alert to unsuspected problems and unimagined solutions that may well come.

SUMMARY POINTS

- Coastal regions of the world face “wicked” problems as a result of the interactions among continuing influx of large numbers of people into coastal regions, human stresses on coastal ecosystems and resources, and the growing threats from climate variability and change.
- Continued ecological degradation, differential social vulnerability, and exposure to physical threats create a complex picture of social-ecological vulnerability in coastal regions of the world.
- Climate change poses growing threats too coastal areas from air and coastal water temperature increases, precipitation and runoff changes, possibly significant sea-level rise, uncertain changes in coastal storminess, changing ocean currents, acidification, changing freshwater and sediment flows to the coast, and nutrient enrichment of coastal streams and waters.
- The resulting impacts on natural and human systems on the coast will require that individuals, businesses and communities find creative ways to adapt and change their behavior so as to modify, and---where possible---minimize coastal risks.
- In the course of developing adaptation strategies, coastal management must better account for the cumulative, synergistic, and mounting stresses arising from climate change and concurrent human activities.

- The wicked nature of coastal management problems under climate change lies in the fact that they are virtually impossible to solve once and for all owing to incomplete, sometimes contradictory, and changing conditions, and the always contested understanding of causes and preferences for solutions.
- Transformative changes in science and in practice are required for remaining alert to unsuspected problems and unimagined solutions that may well come, and thus for continued safe and prosperous occupation of "land's end."

FUTURE ISSUES

Sample research needs to support coastal management in a rapidly changing climate include the following:

1. **Improved monitoring of coastal environments through expanded networks of basic observing systems, developing time series data on environmental and landscape changes, and assembling baseline data for the coastal zone.**
2. **Improved understanding of natural and human-influenced coastal systems through use of historic and geologic records of coastal change that increase knowledge of SLR and coastal change over the past few millennia, identifying thresholds or tipping points, and more closely relating past changes in climate to coastal change.**
3. **Increases in predictive capabilities through improved quantitative assessment methods and integration of the past and present data into predictive models.**
4. **Improved place-based understanding of the societal drivers of vulnerability and impacts of SLR and related coastal changes through improved data collection and integration and communication with decision makers.**
5. **Research on adaptation, hazard mitigation, and avoidance measures (cost, feasibility, side effects, barriers, and acceptability) to support adaptation planning and decision making.**
6. **Improved access to data, resources, and integrated assessments for decision makers, thus facilitating the transfer of knowledge about risks, vulnerabilities, and adaptation choices, and education of the public about consequences and alternatives (24, 74, 178).**

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