REVIEW

Sea-Level Rise and Its Impact on Coastal Zones

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Global sea levels have risen through the 20th century. These rises will almost certainly accelerate through the 21st century and beyond because of global warming, but their magnitude remains uncertain. Key uncertainties include the possible role of the Greenland and West Antarctic ice sheets and the amplitude of regional changes in sea level. In many areas, nonclimatic components of relative sea-level change (mainly subsidence) can also be locally appreciable. Although the impacts of sea-level rise are potentially large, the application and success of adaptation are large uncertainties that require more assessment and consideration.

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) projected that global sea level will rise by up to ~60 cm by 2100 in response to ocean warming and glaciers melting (*1*). However, the recently identified accelerated decline of polar ice sheet mass (*2*–*5*) raises the possibility of future sea-level rise (SLR) of 1 m or more by 2100 (*6*, *7*). Today, low-elevation coastal zones below 10-m elevation contain ~10% of the world population (*8*). Here, non–climate-related anthropogenic processes (such as ground subsidence due to oil and groundwater extraction, or reduced sediment supply to river deltas caused by dam building) often amplify local vulnerability associated with climate-related SLR. The extent of future SLR, the resulting impacts on low-elevation coastal zones, and the ability of society to cope via adaptation remain uncertain. Here, we review current knowledge on the magnitude and causes of contemporary SLR, examine future projections and their uncertainties, and discuss SLR impacts. These impacts are sensitive to how societies prepare for and adapt to SLR.

What Are the Causes of Contemporary Sea-Level Rise?

Although mean sea level remained nearly stable since the end of the last deglaciation [~3000 years ago; e.g., (*9*)], tide gauge measurements available since the late 19th century indicate that sea level has risen by an average of 1.7 ± 0.3 mm/year since 1950 (*10*). Since the early 1990s, SLR has been routinely measured by high-precision altimeter satellites. From 1993 to 2009, the mean rate of SLR amounts to 3.3 ± 0.4 mm/year (Fig. 1) (*11*), suggesting that SLR is accelerating.

Two main factors contribute to SLR: (i) thermal expansion of sea water due to ocean warming and (ii) water mass input from land ice melt and land water reservoirs (*1*). Ocean temperature data collected during the past few decades indicate that ocean thermal expansion has significantly increased during the second half of the 20th century [e.g., (*12*)]. Thermal expansion accounts for about 25% of the observed SLR since 1960 (*13*) and about 50% from 1993 to 2003 (*1*). Since then, upper-ocean warming has been smaller [e.g., (*12*, *14*)], and on average over the satellite altimetry era (1993 to 2009), the contribution of ocean temperature change to the global mean sea level may be ~30% (*15*).

Numerous observations have reported worldwide retreat of glaciers and small ice caps during recent decades, with an appreciable acceleration of this retreat during the 1990s (*1*, *16*). The glacier contribution to SLR from 1993 to 2009 may be ~30% (*1*, *17*). Change in land water storage, due to natural climate variability and human activities (e.g., underground water mining, irrigation, urbanization, and deforestation), contributes little (<10%) to current sea-level change (*18*). By contrast, intensive dam building along rivers during the second half of the 20th century lowered sea level by ~ −0.5 mm/year (*19*).

Since the early 1990s, different remote-sensing tools [airborne and satellite radar and laser altimetry; synthetic aperture radar interferometry (InSAR); and, since 2002, space gravimetry from the Gravity Recovery and Climate Experiment (GRACE) mission] have provided good data on the mass balance of the polar ice sheets. These data indicate that Greenland and West Antarctica mass loss is accelerating [e.g., (*2*)]. Between 1993 and 2003, <15% of the global SLR was due to the ice sheets (*1*). However, since about 2003, their contribution has nearly doubled (*3*–*5*, *20*); increasing glacier and ice sheet mass loss has compensated for reduced ocean thermal

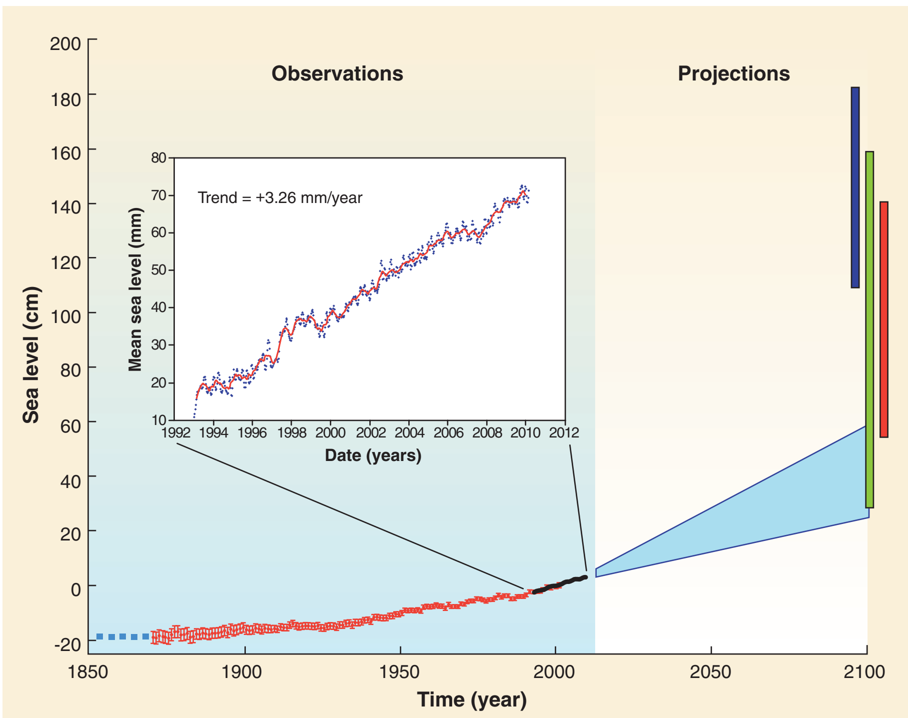

Fig. 1. Global mean sea level evolution over the 20th and 21st centuries. The red curve is based on tide gauge measurements (*10*). The black curve is the altimetry record (zoomed over the 1993–2009 time span) (*15*). Projections for the the 21st century are also shown. The shaded light blue zone represents IPCC AR4 projections for the A1FI greenhouse gas emission scenario. Bars are semi-empirical projections [red bar: (*32*); dark blue bar: (*33*); green bar: (*34*)].

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expansion, such that SLR continues at almost the same rate (Fig. 1). Although not monotonic through time, we estimate that on average over the altimetry era (1993 to 2009), total land ice mass loss explains ~60% of the rate of SLR (*15*).

Accelerated loss of ice sheet mass partly results from rapid outlet glacier flow along some margins of Greenland and West Antarctica where the grounding line is below sea level, and further iceberg discharge into the surrounding ocean [e.g., (*21*–*23*)]. Recent observations suggest that warming of subsurface ocean waters triggers coastal ice discharge (*22*, *24*, *25*). Although surface mass processes (snow accumulation versus surface melting) also contribute to Greenland mass loss (*26*), in West Antarctica mass loss essentially results from ice dynamics [e.g., (*2*, *3*)].

Satellite altimetry shows that sea level is not rising uniformly (Fig. 2). In some regions (e.g., western Pacific), sea level has risen up to three times faster than the global mean since 1993. Spatial patterns in sea-level trends mainly result from nonuniform ocean warming and salinity variations (*1*, *27*), although other factors also contribute, including the solid Earth response to the last deglaciation and gravitational effects and changes in ocean circulation due to ongoing land ice melting and freshwater input (*28*, *29*). Spatial patterns in ocean thermal expansion are not permanent features: They fluctuate in space and time in response to natural perturbations of the climate system (*1*); as a result, we expect that the sea-level change patterns will oscillate on multidecadal time scales. IPCC AR4 projections suggest appreciable regional variability around the future global mean rise by 2100 in response to nonuniform future ocean warming (*1*), but agreement between the models is poor. However, accurate estimates of future regional sea-level changes are required for coastal impact and adaptation assessment.

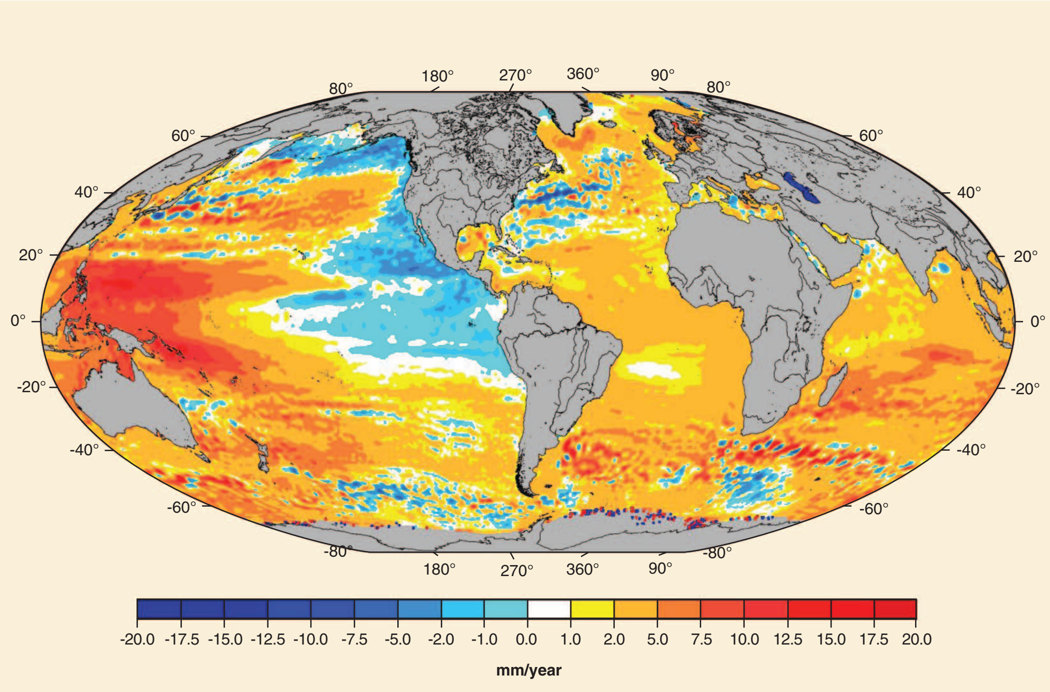

Fig. 2. Regional sea-level trends from satellite altimetry (Topex/Poseidon, Jason-1&2, GFO, ERS-1&2, and Envisat missions) for the period October 1992 to July 2009 (*48*).

How Much Will Global Sea-Level Rise in the 21st Century?

The rapid changes observed in polar regions suggest that the ice sheets respond to current warming on much shorter time scales than previously anticipated [e.g., (*1*)]. However, it is unknown whether these processes will continue into the future, resulting in a partial collapse of the ice sheets after a few centuries, or whether a new equilibrium will be reached (*30*, *31*). For the near term (next decades), the largest unknown in future SLR is the behavior of the ice sheets. Although IPCC AR4 projections did not account for dynamical changes of large ice sheets, simple kinematics and observations of current velocities of marine-terminated glaciers in Greenland and West Antarctica suggest that future ice-dynamics discharge could lead to SLR of about 80 cm by 2100 (*6*). Several groups have developed semi-empirical approaches in which a simple relation between past sea-level rate and temperature or radiative forcing is determined, and then extrapolated through the 21st century using IPCC temperature or forcing projections [e.g., (*32*–*34*)]. Depending on some model variants, these studies yield SLR between ~30 and 180 cm by 2100 (Fig. 1). The upper limit of these estimates is well above IPCC AR4 SLR projections [of ~60 cm for the business-as-usual A1FI greenhouse gas emissions scenario (*1*)].

What Are the Main Impacts of Sea-Level Rise?

The physical impacts of SLR are well known (*35*). The immediate effect is submergence and increased flooding of coastal land, as well as saltwater intrusion of surface waters. Longer-term effects also occur as the coast adjusts to the new conditions, including increased erosion and saltwater intrusion into groundwater. Coastal wetlands such as saltmarshes and mangroves will also decline unless they have a sufficient sediment supply to keep pace with SLR. These physical impacts in turn have both direct and indirect socioeconomic impacts, which appear to be overwhelmingly negative (*35*). Although climate-induced SLR is important, coastal impacts also result from relative (or local) SLR (e.g., from geological processes such as subsidence). For example, relative sea level is presently falling where land is uplifting considerably, such as the northern Baltic and Hudson Bay—the sites of large (kilometer-thick) glaciers during the last glacial maximum. In contrast, relative sea level is rising more rapidly than climate-induced trends on subsiding coasts. In many regions, human activities are exacerbating subsidence on susceptible coasts, including most river deltas [e.g., the Ganges-Brahmaputra, Mekong, and Changjiang deltas (*36*, *37*)]. The most dramatic subsidence effects have been caused by drainage and groundwater fluid withdrawal; over the 20th century, coasts have subsided by up to 5 m in Tokyo, 3 m in Shanghai, and 2 m in Bangkok (*38*). To avoid submergence and/or frequent flooding, these cities now all depend on a substantial flood defense and water management infrastructure. South of Bangkok, subsidence has led to substantial shoreline retreat of more than 1 km, leaving telegraph poles standing in the sea.

These and other human-induced changes in coastal areas (such as coastal defenses, destruction of wetlands, port and harbor works, and reduced sediment supply due to dams) obscure the impacts of climate-induced SLR during the 20th century (*39*, *40*). The nonclimate components of SLR receive much less attention than climate components, because they are considered a local issue. However, they are so widespread that they amount to a global problem warranting more systematic

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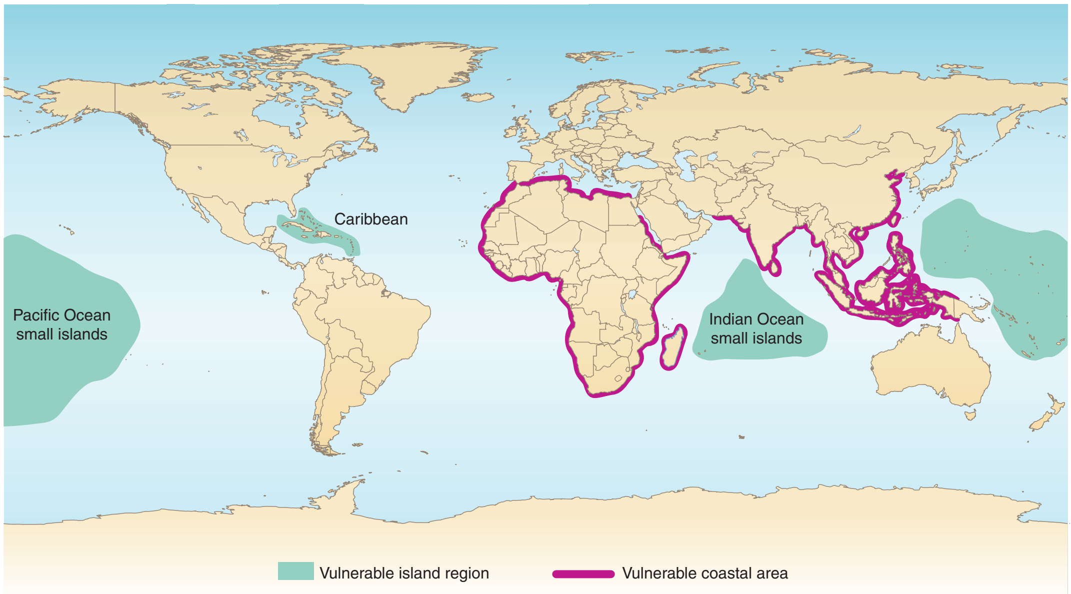

Fig. 3. Several regions are vulnerable to coastal flooding caused by future relative or climate-induced sea-level rise. At highest risk are coastal zones with dense populations, low elevations, appreciable rates of subsidence, and/or inadequate adaptive capacity.

study, including appropriate mitigation (of human influence) as well as adaptation options.

As the magnitude of climate-induced SLR increases, the impacts will become more apparent (*35*), especially in certain low-elevation coastal zones (Fig. 3). Most countries in South, Southeast, and East Asia appear to be highly threatened because of the widespread occurrence of densely populated deltas, often associated with large growing cities (Fig. 3). Africa also appears highly threatened owing to the low levels of development combined with expectations of rapid population growth in coastal area: Egypt and Mozambique are two "hotspots" for potential impacts. However, the small island states experience the largest relative increase in impacts, including regions of high islands like the Caribbean. Low islands such as the Maldives or Tuvalu face the real prospect of submergence and complete abandonment during the 21st century (*41*).

Can Adaptation Help?

Many impact studies do not consider adaptation, and hence determine worst-case impacts [e.g., (*42*)]. Yet, the history of the human relationship with the coast is one of an increasing capacity to adapt to adverse change [e.g., (*43*)]. In addition, the world's populated coasts became increasingly managed and engineered over the 20th century (*35*). The subsiding cities discussed above all remain protected to date, despite large relative SLR. Analysis based on benefit-cost methods show that protection would be widespread as well-populated coastal areas have a high value and actual impacts would only be a small fraction of the potential impacts [e.g., (*44*)], even assuming high-SLR (>1 m/century) scenarios (*45*). This suggests that the common assumption of a widespread forced retreat from the shore in the face of SLR is not inevitable. In many densely populated coastal areas, communities advanced the coast seaward via land claim owing to the high value of land (e.g., Singapore). Yet, protection often attracts new development in low-lying areas, which may not be desirable, and coastal defense failures have occurred, such as New Orleans in 2005. Hence, we must choose between protection, accommodation, and planned retreat adaptation options (*35*). This choice is both technical and sociopolitical, addressing which measures are desirable, affordable, and sustainable in the long term. Adaptation remains a major uncertainty concerning the actual impacts of SLR.

In one of the few strategic plans to respond to SLR, the Netherlands is planning to upgrade protection both for SLR and to provide higher levels of safety (to a nominal chance of failure of 1 in 100,000) by building their North Sea coast seaward using beach nourishment (*46*). The plan stresses how adaptation to SLR must be integrated into wider coastal management and development plans. It also explicitly recognizes that adaptation will continue beyond 2100 (*35*). In most developing countries, the issues are more challenging, and the limits to adaptive capacity will be a key constraint. National development plans will need to address the growing risks of coastal occupancy and identify the most appropriate approaches to coastal management.

Outlook

The extent of future SLR remains highly uncertain—more so than in 2007, when the IPCC AR4 was published. A two-track solution is required to advance the scientific understanding of observed and future climate-induced SLR and develop pragmatic impact and adaptation scenarios that capture the uncertainties of future SLR. The former analysis should focus on understanding the processes that control SLR (e.g., ice sheet instabilities), whereas the latter analysis requires a range of plausible scenarios, including the low probability–high consequence part of the possible SLR range where our understanding is weaker (*7*). More attention must also focus on the nonclimate components of SLR, especially for coasts more susceptible to subsidence, such as deltas. Nonclimate processes tend to be larger where there are high concentrations of people and economic activity, and hence have a high impact potential.

The impacts of SLR can also be divided into two distinct issues: impacts for climate policy, which usually focus on the effects of climate-induced SLR and the incremental benefits of different climate mitigation policies, and impacts for coastal management policy, which must consider all relevant climate and nonclimate coastal drivers. An improved understanding of adaptation is fundamental, because it is one of the biggest determinants of actual rather than potential impacts. Studies such as the World Bank assessment of adaptation costs in developing countries (*47*) are useful starting points to address these problems.

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REVIEW

How Do Polar Marine Ecosystems Respond to Rapid Climate Change?

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Climate change will alter marine ecosystems; however, the complexity of the food webs, combined with chronic undersampling, constrains efforts to predict their future and to optimally manage and protect marine resources. Sustained observations at the West Antarctic Peninsula show that in this region, rapid environmental change has coincided with shifts in the food web, from its base up to apex predators. New strategies will be required to gain further insight into how the marine climate system has influenced such changes and how it will do so in the future. Robotic networks, satellites, ships, and instruments mounted on animals and ice will collect data needed to improve numerical models that can then be used to study the future of polar ecosystems as climate change progresses.

How does a changing physical ocean environment affect regional and local marine food webs? Many regions, especially polar seas (*1*, *2*), are experiencing changes in atmospheric/ocean circulation (*3*), ocean properties (*4*, *5*), sea ice cover (*6*, *7*), and ice sheets (*8*, *9*). These rapid climatic changes are triggering pronounced shifts and reorganizations in regional ecosystems and biogeochemical cycles (*10*, *11*). However, it remains difficult to link these ecosystem changes to shifts in the physical system. Overcoming this gap is a critical step in establishing any level of predictive skill.

The West Antarctic Peninsula (WAP), northwestern North America, and the Siberian Plateau are exhibiting rapid regional warming (*1*), but only the WAP has a maritime climate. Thus, the WAP is an ideal location to monitor and understand the impacts of rapid climate change on marine ecosystems. Other regions of Antarctica are exhibiting much smaller rates of warming—and some, such as the Ross Sea (*12*), are even experiencing trends in the opposite direction—but climate models predict strong warming and circumpolar sea ice retreat around Antarctica over the next century (*13*). Understanding the response of the WAP ecosystems to climate change will thus help to predict further changes in the polar ecosystem as a whole and will provide insight into the planetary-scale changes that are likely as greenhouse gas–driven warming continues.

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Physical Changes in the WAP

Changes in the WAP are profound (Fig. 1). Midwinter surface atmospheric temperatures have increased by 6°C (more than five times the global average) in the past 50 years (*14*, *15*). Eighty-seven percent of the WAP glaciers are in retreat (*16*), the ice season has shortened by nearly 90 days, and perennial sea ice is no longer a feature of this environment (*17*, *18*). These changes are accelerating (*19*, *20*).

Ocean warming has been implicated as a major driver for this deglaciation (*21*). The ocean has become warmer in the WAP (*17*). Most of this heat comes from the warm, saline Upper Circumpolar Deep Water (UCDW) that penetrates onto the WAP shelf from the Antarctic Circumpolar Current (ACC) in the adjacent deep ocean. The increased supply of heat from the UCDW is believed to be associated with the strengthening of winds over the Southern Ocean (*22*, *23*). Enhanced upwelling of heat to the WAP is complemented by rising summertime surface-ocean heating (*24*), which is associated with the strong retreats in the seasonal sea ice cover (*7*, *18*).

This atmosphere–ocean-ice interplay at the WAP results in a positive feedback that amplifies and sustains atmospheric warming. Understanding these feedbacks will require better knowledge of the processes at the shelf edge and in the adjacent deep ocean to determine where and when the UCDW intrudes from the ACC onto the WAP shelf. Although the ACC is a major current in the

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