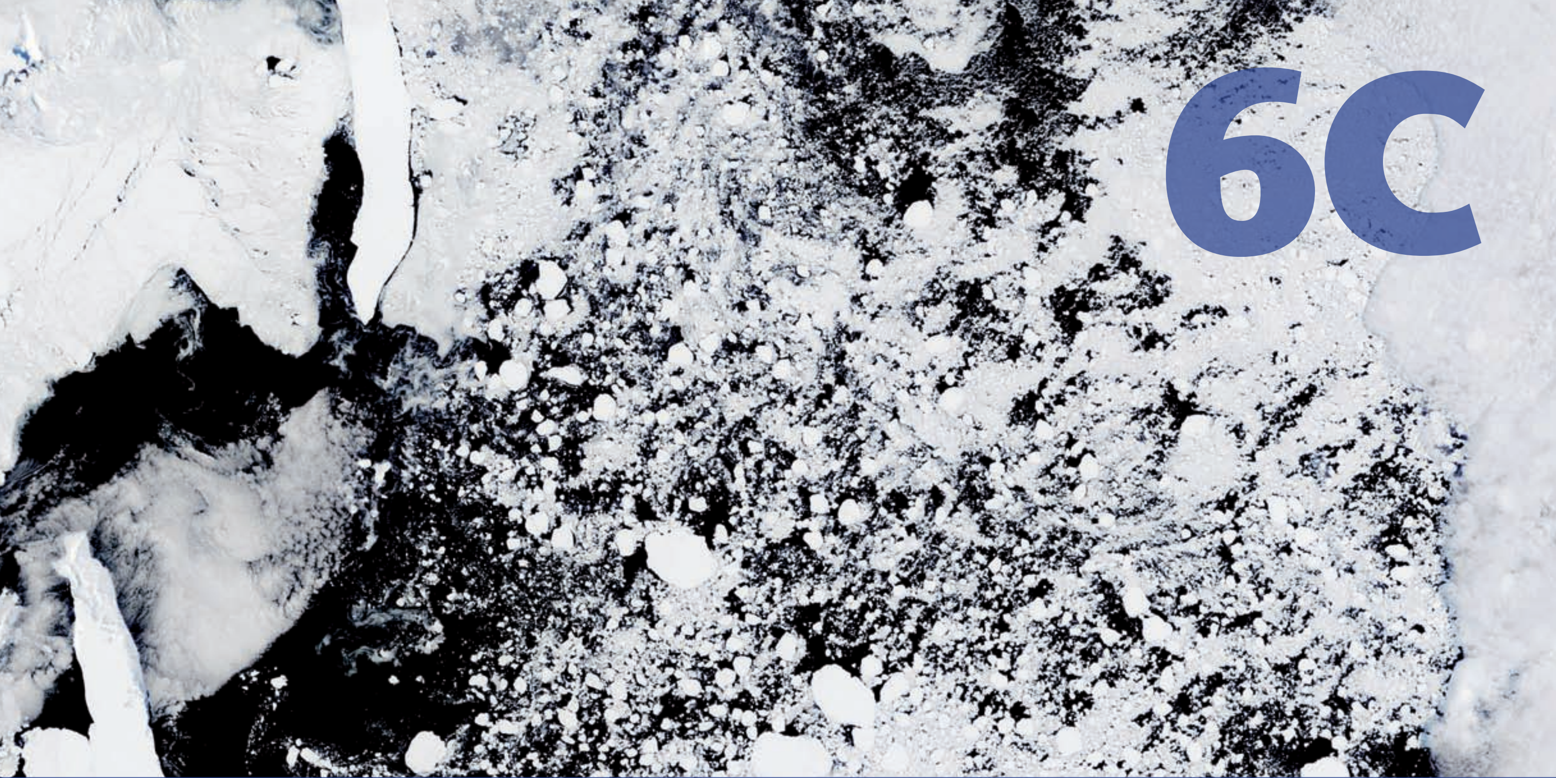

6C

Ice and Sea-level Change

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Ice and Sea-level Change

Summary

Sea-level rise is a major impact of global warming. There is clear scientific consensus that sea level is rising partly in response to past emissions of greenhouse gases from human activity. Melting glaciers and ice sheets are responsible for more than a third of the current rate of sea-level rise and the contribution of meltwater to the oceans can be expected to continue and accelerate as more land ice melts. Over the long term the ice sheets of Greenland and Antarctica have the potential to make the largest contribution to sea-level rise, but they are also the greatest source of uncertainty.

Sea level will rise during the 21st century and after and hence adaptation measures will be required during the 21st century and beyond. The rate and magnitude of sea-level rise, particularly beyond the mid 21st century, depends on future emission of greenhouse gases. Significant and urgent reductions in emissions are essential if we wish to avoid committing future generations to a sea-level rise of metres over centuries. Both adaptation and mitigation strategies need to be seriously considered, as together they can provide a more robust response to human-induced climate change than either can alone. Sea-level rise is both an international and a national issue. Preparation and implementation of adaptation and mitigation plans requires partnerships between nations, as well as between all levels of government, the private sector, researchers, non-governmental organizations and communities. Rising sea level is a mainstream issue in need of urgent and informed decision making and action.

Sea-level change: Sea level can change, both globally and locally, due to changes in the shape of the ocean basins, changes in the total mass of water in the ocean, and changes in ocean water density. Relative sea level is measured by a tide gauge with respect to the land upon which it is situated, and includes land uplift/subsidence. Mean sea level is the average sea level over a period long enough to average out effects from waves, tides and other short term fluctuations.

Components of the Cryosphere	**Potential Sea-level rise (cm)**
Antarctica ice sheet	5660
Greenland ice sheet	730
Glaciers and ice caps *(lowest and [highest] estimates)*	15 [37]
Permafrost (Northern Hemisphere)	~7
Snow on land (Northern Hemisphere) *(annual minimum ~ maximum)*	0.1 ~ 1
Sea ice and ice shelves	0

Source: IPCC 2007[26]

Introduction to sea level issues

Coastal regions, particularly some low-lying river deltas, have very high population densities. It is estimated that in excess of 150 million people live within 1 metre of high tide level, and 250 million within 5 metres of high tide[1,2]. Also, there are billions of dollars invested in coastal infrastructure immediately adjacent to the coast (Figure 6C.1). Sea-level rise

◄ **Figure 6C.1:** Billions of dollars of coastal infrastructure has been built immediately adjacent to the coast, as shown here in Gold Coast, Australia.
Photo: Bruce Miller

▼ **Figure 6C.2:** Low-lying coral atolls are particularly vulnerable to sea-level rise.
Photo: John Hay

contributes to coastal erosion and inundation of low-lying coastal regions – particularly during extreme sea-level events – and saltwater intrusion into aquifers, deltas and estuaries. These changes have impacts on coastal ecosystems, water resources, and human settlements and activities. Regions at most risk include heavily populated deltaic regions, small islands, especially atolls (islands formed of coral, Figure 6C.2), and sandy coasts backed by major coastal developments.

Sea-level rise is a central element in detecting, understanding, attributing and correctly projecting climate change. During the 20th century, the oceans have stored well over 80 per cent of the heat that has warmed the earth. The associated thermal expansion of the oceans, together with changes in glaciers and ice caps, will likely dominate 21st century sea-level rise. However, on longer time scales, the ice sheets of Greenland and Antarctica have the largest potential to contribute to significant changes in sea level.

Past sea-level change

Ice-age cycles and sea level

Sea level varied over 100 m during glacial–interglacial cycles as the major ice sheets waxed and waned as a result of changes in summer solar radiation in high northern hemisphere latitudes[3,4]. Palaeo data from corals indicate that sea level was 4 to 6 m (or more) above present day sea levels during the last interglacial period, about 125 000 years ago[5]. Climate and ice-sheet model simulations[6] indicate that Greenland was about 3° C warmer than today and that the Northern Hemisphere ice sheets contributed 2.2 to 3.4 m to the higher sea level, with the majority of the rise coming from the partial melting of the Greenland ice sheet.

During the last ice age, sea level fell to more than 120 m below present day sea level as water was stored in the

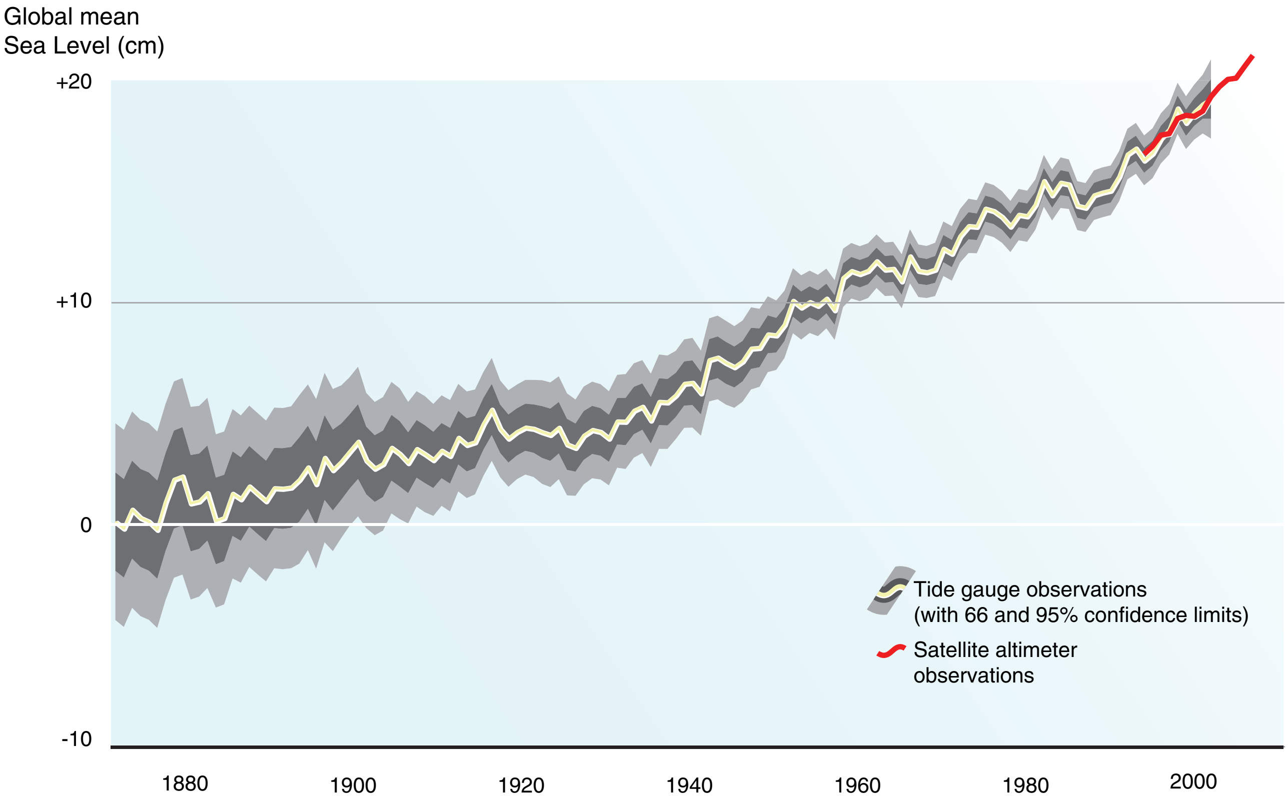


Figure 6C.3: Global averaged sea levels from 1870 to 2006 as inferred from tide-gauge data (white line, with 66% and 95% confidence limits given in dark and light shading) and satellite altimeter data (red line).

Source: Updated from Church and White 2006[13]

North American (Laurentian, Cordilleran and the Greenland), the northern European (Fennoscandia and the Barents region) and the Antarctic ice sheets[3,7]. As the ice melted, starting around 20 000 years ago, sea level rose rapidly at average rates of about 10 mm per year (1 m per century), and with peak rates of the order of 40 mm per year (4 m per century), until about 6000 years ago.

The last few thousand years

Sea level rose much more slowly over the past 6000 years. The sea level 2000 years ago can be deduced by examining fish tanks built by the ancient Romans. Because the tanks had to be at sea level for the sluice gates to function, one can precisely estimate sea level during the period of their use. Comparison of this level with historical records indicates that there has been little net change in sea level from 2000 years ago until the start of the 19th century[8].

Changes in local sea level estimated from sediment cores collected in salt marshes reveal an increase in the rate of sea-level rise in the western and eastern Atlantic Ocean during the 19th century and early 20th century[9–11], consistent with the few long tide-gauge records from Europe and North America[12].

The last few centuries

Coastal and island tide-gauge data show that sea level rose by just under 20 cm between 1870 and 2001, with an average rise of 1.7 mm per year during the 20th century and with an increase in the rate of rise over this period. This is consistent with the geological data and the few long records of sea level from coastal tide gauges[13] (Figure 6C.3). From 1993 to the end of 2006, near-global measurements of sea level (between 65°N and 65°S) made by high precision satellite altimeters indicate global average sea level has been rising at 3.1 ± 0.4 mm per year[14]. This rate is faster than the average rate of rise

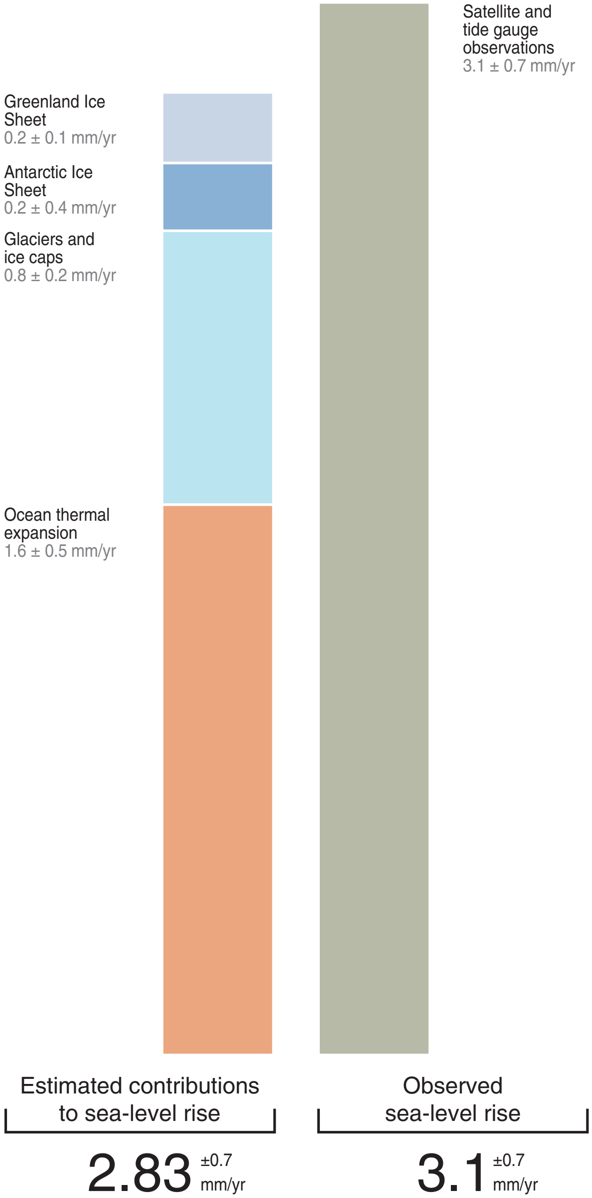


Figure 6C.4: Estimated contributions to sea-level rise from 1993 to 2003 (uncertainty intervals are 5 to 95%).

Source: Based on IPCC 2007[15]

during the 20th century which, in turn, was an order of magnitude larger than the rate of rise over the two millennia prior to the 18th century.

Contributions to sea-level change

The two main reasons for sea-level rise (Figure 6C.4) are thermal expansion of ocean waters as they warm, and increase in the ocean mass, principally from land-based sources of ice (glaciers and ice caps, and the ice sheets of Greenland and Antarctica). Global warming from increasing greenhouse gas concentrations is a significant driver of both contributions to sea-level rise.

From 1955 to 1995, ocean thermal expansion is estimated to have contributed about 0.4 mm per year to sea-level rise[16], less than 25 per cent of the observed rise over the same period. For the 1993 to 2003 decade, when the best data are available, thermal expansion is estimated to be significantly larger, at about 1.6 mm per year for the upper 750 m of the ocean alone[17], about 50 per cent of the observed sea-level rise of 3.1 mm per year. Kaser and others[18] estimate the melting of glaciers and ice caps (excluding the glaciers surrounding Greenland and Antarctica) contributed to sea-level rise by about 0.3 mm per year from 1961 to 1990 increasing to about 0.8 mm per year from 2001–2004.

The ice sheets of Greenland and Antarctica have the potential to make the largest contribution to sea-level rise, but they are also the greatest source of uncertainty (see also Section 6A). Since 1990 there has been increased snow accumulation at high elevation on the Greenland ice sheet, while at lower elevation there has been more widespread surface melting and a significant increase in the flow of outlet glaciers[19]. The net result is a decrease in the mass of the Greenland ice sheet – a posi-

Projections of 21st century sea-level rise

The Intergovernmental Panel on Climate Change (IPCC) provides the most authoritative information on projected sea-level change. The IPCC Third Assessment Report (TAR) of 2001[23] projected a global averaged sea-level rise of between 20 and 70 cm (the limits of the model projections) between 1990 and 2100 using the full range of IPCC greenhouse gas scenarios and a range of climate models. When an additional uncertainty for land-ice changes was included, the full range of projected sea-level rise was 9 to 88 cm[7]. For the IPCC's Fourth Assessment Report (AR4), 2007, the range of sea-level projections, using a much larger range of models, is 18 to 59 cm (with 90 per cent confidence limits) over the period from 1980-2000 to 2090-2100[15]. To allow a margin for the ice sheet uncertainties discussed above, the IPCC AR4 increased the upper limit of the projected sea-level rise by 10 to 20 cm above that projected by the models, but stated that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise."

While the 2001 and 2007 IPCC projections are somewhat different in how they treat ice sheet uncertainties and the confidence limits quoted, a comparison of the projections (Figure 6C.5) shows the end results are similar, except that the lower limit of the 2001 projections has been raised from 9 to 18 cm.

From the start of the IPCC projections in 1990 to 2006, observed sea level has been rising more rapidly than the central range of the IPCC (2001 and 2007) model projections and is nearer to the upper end of the total range of the projections shown in Figure 6C.5[24], indicating that one or more of the model contributions to sea-level rise is underestimated. Rahmstorf[25] developed a simple statistical model that related 20th century surface temperature change to 20th century sea-level change. Using this relationship and projected surface temperature increases, estimated 21st century sea-level rise might exceed the IPCC projections and be as large as 1.4 m.

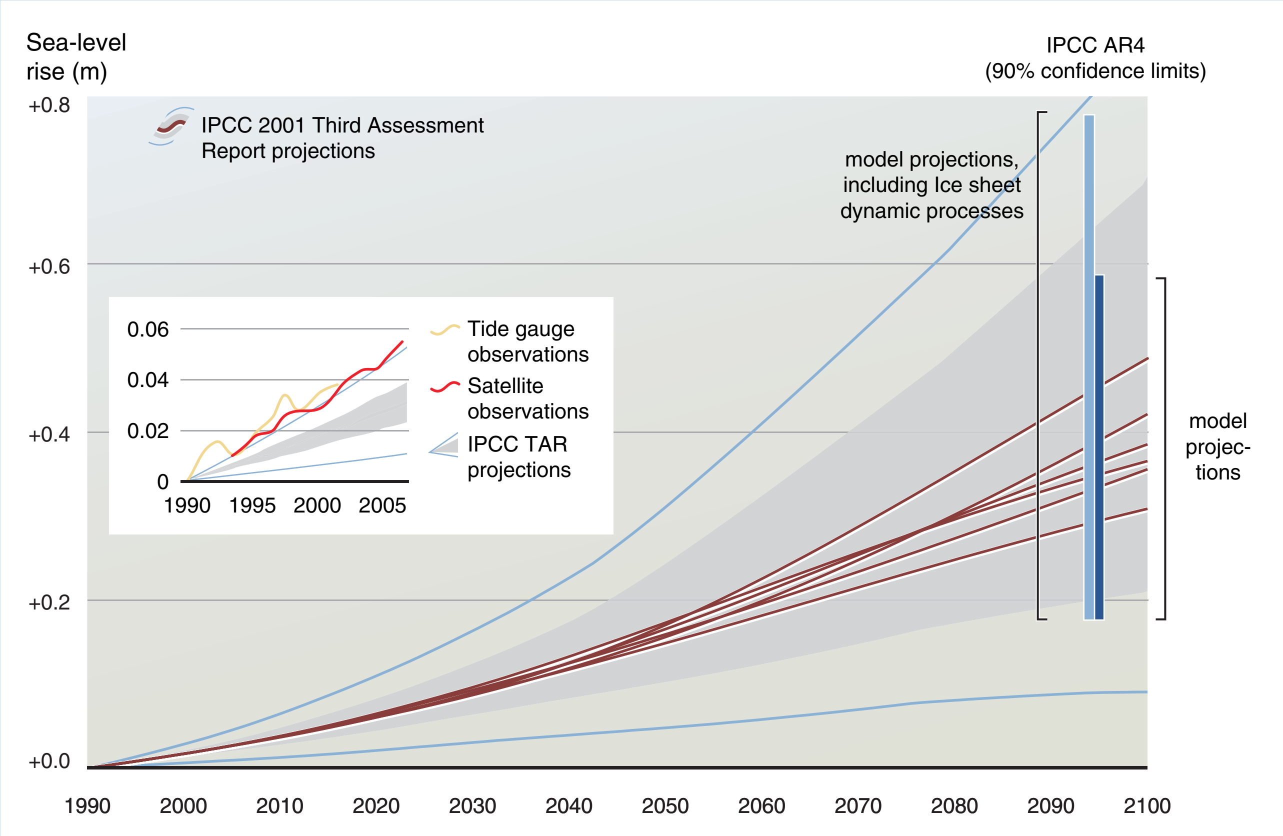


Figure 6C.5: Projected sea-level rise for the 21st century. The projected range of global averaged sea-level rise from the IPCC 2001 Assessment Report for the period 1990 to 2100 is shown by the lines and shading. The updated AR4 IPCC projections made are shown by the bars plotted at 2095, the dark blue bar is the range of model projections (90% confidence limits) and the light blue bar has the upper range extended to allow for the potential but poorly quantified additional contribution from a dynamic response of the Greenland and Antarctic ice sheets to global warming. Note that the IPCC AR4 states that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise." The inset shows the observed sea levels from tide gauges (orange) and satellites (red) are tracking along the upper bound of the IPCC 2001 projections since the start of the projections in 1990.

Source: Based on Church and others 2001[7]; information added from IPCC 2007[15] and Rahmstorf and others[24] tive contribution to sea-level rise. For the Antarctic Ice Sheet, the uncertainty is greater. There are insufficient data to make direct estimates for the preceding decades. At present, the mass gain of the Antarctic Ice Sheet due to increased thickening of the East Antarctic Ice Sheet does not appear to compensate for the mass loss due to the increased glacier flow on the Antarctic Peninsula and the West Antarctic Ice Sheet[20,21]. Modelling studies suggest that the Antarctic Ice Sheet is still responding to changes since the last ice age and that this may also be contributing to sea-level rise.

The difference between the sum of the contributions to sea-level rise and the observed rise from 1993 to the present is smaller than the estimated errors. However during the 1961 to 2003 period, ocean thermal expansion along with the melting of glaciers and ice caps and a reasonable allowance for an ice sheet contribution do not adequately explain the observed rise. Possible reasons for this discrepancy include the inadequate ocean database, particularly for the deep and Southern Hemisphere oceans, leading to an underestimate of ocean thermal expansion, and inadequate measurements of the cryosphere.

Changes in the storage of water on land, including changes in lakes, building of dams (both large and small), seepage into aquifers, and mining of ground water, may also be important – but the extent of these contributions is unclear. Model studies suggest significant variability from year to year of the climate-related components of terrestrial water storage, but little long-term trend[22].

Outlook for sea-level change

During the 21st century, sea level will continue to rise due to warming from both past (20th century and earlier) and 21st century greenhouse gas emissions (see box on projections of 21st century sea-level rise). Ocean thermal expansion is likely to be the dominant contribution to 21st century sea-level rise, with the next largest contribution coming from the melting of glaciers and ice caps.

Recent estimates indicate that non-polar glaciers and ice caps may contain only enough water to raise sea level by 15 to 37 cm[26]. Melting of glaciers at lower altitude and latitude in a warming climate will eventually result in significant reduction of the sizes of the glaciers and reductions in their contribution to the rate of sea-level rise. The most important impact is from large glaciers in regions with heavy precipitation, such as the coastal mountains around the Gulf of Alaska (Figure 6C.6), or Patagonia and Tierra del Fuego in South America. Many of these glaciers flow into the sea or large lakes and melt quickly because the ice is close to melting temperature (see also Section 6B).

For Greenland, both glacier calving and surface melting contribute to mass loss. Over the last few decades surface melting has increased[27] and now dominates over increased snowfall, leading to a positive contribution to sea level during the 21st century. For the majority of Antarctica, present and projected surface temperatures during the 21st century are too cold for significant melting to occur and precipitation is balanced by glacier flow into the ocean. In climate change scenarios for the 21st century, climate models project an increase in snowfall, resulting in increased storage of ice in Antarctica, partially offsetting other contributions to sea-level rise. However, an increase in precipitation has not been observed to date[28].

In addition to these surface processes, there are suggestions of a potential dynamical response of the Greenland and Antarctic ice sheets (see also Section 6A). In Greenland, there was a significant increase in the flow rate of many of the outlet glaciers during the early 21st century[19]. One potential reason for this is increasing surface melt making its way to the base of the glaciers, lubricating their flow over the bed rock, consistent with increased glacier

Figure 6C.6: Glaciers in the Alaskan coastal mountains melt more quickly as air temperatures increase, contributing to sea-level rise. *Photo: iStockphoto* flow during the summer melt season[29] (see Figure 6A.6 in previous section). However, recent work[30] has shown the flow rate of at least two of these glaciers has recently decreased to near their earlier rates, suggesting that there is significant short-term variability in glacier flow rates.

Another potential factor is the role of ice shelves in restraining the flow of outlet glaciers. The rapid break up of the Larsen B Ice Shelf in the Antarctic Peninsula (Figure 6A.4 in previous section) was followed by a significant increase in the flow rate of the glaciers previously feeding this ice shelf[31], suggesting that the ice shelves played a role in restraining the flow of outlet glaciers. However, some modelling studies suggest this is a transient acceleration. Another important consideration is that the West Antarctic Ice sheet is grounded below current sea level. As the ice sheet thins and starts to float, warm ocean water can penetrate beneath and enhance melting at the base.

All of these dynamic ice-sheet processes, in both Greenland and West Antarctica, could lead to a greater rate of sea-level rise than in current projections. However, the processes are inadequately understood and are therefore not included in the current generation of ice-sheet and climate models. It is therefore not possible to make robust quantitative estimates of their long-term contribution to the rate of sea-level rise.

Greenland ice sheet.
Photo: Konrad Steffen

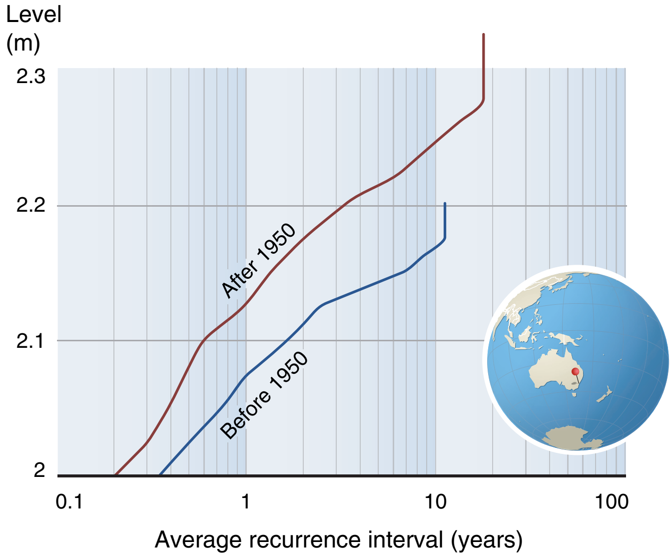


Figure 6C.7: Average Recurrence Interval for sea-level events of a given height at Sydney, Australia. For the second half of the 20th century (red line), the average recurrence interval for a sea-level height of a given value is less than half the value for the first half of the 20th century (blue line).

Sources: Based on Church and others 2006[42]

Longer-term projections

For the next few decades, the rate of sea-level rise is partly locked in by past emissions, and will not be strongly dependent on 21st century greenhouse gas emission. However, sea-level projections closer to and beyond 2100 are critically dependent on future greenhouse gas emissions, with both ocean thermal expansion and the ice sheets potentially contributing metres of sea level rise over centuries for higher greenhouse gas emissions.

For example, in the case of the Greenland Ice Sheet, if global average temperatures cross a point that is estimated to be in the range of 1.9°C to 4.6°C above pre-industrial values[32], this will lead to surface melting exceeding precipitation. The inevitable consequence of this is an ongoing shrinking of the Greenland Ice Sheet over a period of centuries and millennia[15]. This conclusion is consistent with the observation that global sea level in the last interglacial, when temperatures were in this range, was several metres higher than it is today. This threshold (of melting exceeding precipitation) could potentially be crossed late in the 21st century. In addition, dynamic responses of the Greenland and West Antarctic Ice Sheets could lead to a significantly more rapid rate of sea-level rise than from surface melting alone.

Regional patterns of sea-level rise

For the period 1993 to the present, there is a clear pattern of regional distribution of sea-level change that is also reflected in patterns of ocean heat storage[33]. This pattern primarily reflects interannual climate variability associated with the El Niño/La Niña cycle. During El Niño years sea level rises in the eastern Pacific and falls in the western Pacific whereas in La Niña years, the opposite is true. At this stage there is no agreed-upon pattern for the longer-term regional distribution of projected sea-level rise. There are, however, several features that are common to most model projections – for example a maximum in sea-level rise in the Arctic Ocean and a minimum sea-level rise in the Southern Ocean south of the Antarctic Circumpolar Current[34].

In addition, past and ongoing transfers of mass from the ice sheets to the oceans result in changes in the gravitational field and vertical land movements and thus changes in the height of the ocean relative to the land[35–37]. These large-scale changes, plus local tectonic movements, affect the regional impact of sea-level rise.

Withdrawal of groundwater and drainage of susceptible soils can cause significant subsidence. Subsidence of several metres during the 20th century has been observed for a number of coastal megacities[38]. Reduced sediment inputs to deltas are an additional factor which causes loss of land elevation relative to sea level[39].

Extreme events

Sea-level rise will be felt both through changes in mean sea level, and, perhaps more importantly, through changes in extreme sea-level events. Even if there are no changes in extreme weather conditions (for example, increases in tropical cyclone intensity), sea-level rise will result in extreme sea levels of a given value being exceeded more frequently.

This change in the frequency of extreme events has already been observed at many locations[40–43] (Figure 6C.7). The increase in frequency of extreme events will depend on local conditions, but events that currently occur once every 100 years could occur as frequently as once every few years by 2100.

Table 6C.1: The main natural system effects of relative sea-level rise, interacting factors and examples of socio-economic system adaptations. Some interacting factors (for example, sediment supply) appear twice as they can be influenced both by climate and non-climate factors. Adaptation strategies: **P** = Protection; **A** = Accommodation; **R** = Retreat.

Source: Based on Nicholls and Tol 2006[47]

Natural System Effects		Interacting Factors		Socio-economic System Adaptations
		Climate	Non-climate	
1. Inundation, flood and storm damage	a. Surge (sea)	– wave/storm climate – erosion – sediment supply	– sediment supply – flood management – erosion – land use	– dykes/surge barriers [**P**] – building codes/floodwise buildings [**A**] – land use planning/hazard delineation [**A**/**R**]
	b. Backwater effect (river)	– run-off	– catchment management – land use	
2. Wetland loss (and change)		– CO_2 fertilization – sediment supply	– sediment supply – migration space – direct destruction	– land-use planning [**A**/**R**] – managed realignment/forbid hard defences [**R**] – nourishment/sediment management [**P**]
3. Erosion (direct and indirect morphological change)		– sediment supply – wave/storm climate	– sediment supply	– coast defences [**P**] – nourishment [**P**] – building setbacks [**R**]
4. Saltwater Intrusion	a. Surface Waters	– run-off	– catchment management – land use	– saltwater intrusion barriers [**P**] – change water abstraction [**A**/**R**]
	b. Ground-water	– rainfall	– land use – aquifer use	– freshwater injection [**P**] – change water abstraction [**A**/**R**]
5. Rising water tables/impeded drainage		– rainfall – run-off	– land use – aquifer use – catchment management	– upgrade drainage systems [**P**] – polders [**P**] – change land use [**A**] – land use planning/hazard delineation [**A**/**R**]

Overview of sea-level rise impacts and adaptation

Impacts of sea-level rise are determined by the relative sea-level change, reflecting not only the global-mean trend in sea level, but also regional and local variations in sea-level change and in geological uplift and subsidence[44]. Areas that are subsiding are more threatened. The most significant impacts may be associated with changes in interannual variability and changes in extreme sea levels resulting from storms. Given that more intense storms are expected both in the tropics and outside of the tropics[45], extreme sea level scenarios due to changing storm characteristics need to be considered along with mean sea-level rise scenarios, although this information is presently much less developed for most coastal areas[46].

Maintaining and restoring native coastal vegetation in response to sea-level rise

Without stable shorelines, the integrity of infrastructure such as roads, airports, buildings, and residences may be threatened. In addition, significant amounts of salt water may infiltrate the groundwater and degrade drinking-water sources, wetlands, and agriculture.

Intact native vegetation is ideal for stabilizing shorelines. For example, plants indigenous to tropical islands have evolved to tolerate high temperatures and humidity, salt water, extreme sunlight and storms. These vegetation communities function as soil binders and as effective filters, thus maintaining coastal berms and forests. They are part of the dynamic coastal system, well adapted to shifting shorelines. In contrast, seawalls are static, immobile objects that do not conform to the advance and retreat of shorelines. When shorelines shift, sea walls may become undermined and no longer function (Figure 6C.8(a)). Furthermore, seawalls and other similar construction activities often disrupt or displace native vegetation communities. Preserving and restoring this vegetation helps maintain shoreline integrity in the face of rising sea level (Figure 6C.8(b)).

Figure 6C.8: Shoreline integrity in the Fijian village of Yadua.
(a) Part of the degraded seawall protecting the village – storm waves penetrate into the land behind the damaged sea wall and erode the coastal flat on which the village lies.
(b) Mangrove nursery and recent foreshore plantings.
Photos: Patrick Nunn

Relative sea-level rise has a wide range of effects on coastal systems, summarized in Table 6C.1. The immediate effect is submergence and increased flooding of coastal land, as well as saltwater intrusion into surface waters. Longer-term effects also occur as the coast adjusts to the new environmental conditions, including increased erosion, ecosystem changes, and saltwater intrusion into groundwater. These longer-term changes interact with the immediate effects of sea-level rise and often exacerbate them. For instance coastal erosion, which on sandy coastlines occurs at tens to hundreds of times the rate of sea-level rise, will tend to degrade or remove protective coastal features such as sand dunes and vegetation, thereby increasing the risk of coastal flooding (see box on maintaining and restoring coastal vegetation).

Sea-level rise does not happen in isolation (see Table 6C.1 for interacting factors) and it is only one of a number of changes that are affecting the world's coasts. For instance, under a positive sediment budget, coasts may be stable or even grow, while under a negative sediment budget, sea-level rise is exacerbating a situation that is already prone to erosion. Due to increasing human activity in coastal zones and their catchments, sea-level rise impacts are more often exacerbating an adverse situation than not. This emphasizes the need to analyse the impacts of sea-level rise within a framework which addresses multiple stresses.

These natural system changes have many important direct socio-economic impacts on a range of sectors. For instance, flooding can damage key coastal infrastructure, the built environment, and agricultural areas, while erosion can lead to a loss of buildings with adverse consequences on coastal communities and on sectors such as tourism and recreation. As well as these direct impacts, indirect impacts are also apparent, including impacts on human health. For example, mental health problems increase after a flood. Thus, sea-level rise has the potential to produce a cascade of direct and indirect impacts through the socio-economic system. The uncertainties around the actual socio-economic impacts are also large, as impacts will depend on the magnitude of changes to natural systems and on society's ability to adapt to these changes.

Most existing studies examine exposure or potential impacts – few consider the potential impacts while taking into account realistic assumptions about adaptation. This is a complex issue to analyse as it requires integration across the natural, engineering and social sciences. The available analyses all suggest that the high value of many coastal areas would make widespread adaptation to sea-level rise an economically rational response in cost-benefit terms[47,48]. Following this logic, actual impacts would be greatly reduced through adaptation, but

this would require significant investment and planning. Measures instituted to protect human safety may also exacerbate ecosystem impacts, and this needs to be taken into account. For example, building dykes can result in the loss of salt marshes and mudflats[49]. Delivering effective adaptation will be challenging, especially in the poorer countries – and disasters can still occur in rich countries, as shown by Hurricane Katrina in 2005.

◀ Mangrove on Erakor Island, Vanuatu.
Photo: Topham Picturepoint/TopFoto.co.uk

▼ **Figure 6C.9:** Male, Maldives.
Photo: Bruce Richmond, USGS

Vulnerable sectors, systems and localities

Small islands and low-lying coastal areas, such as deltas, have long been considered amongst the areas most vulnerable to sea-level rise[39,50–53]. Low elevation and close proximity to a rising ocean are important collective contributors to this vulnerability. But such a view is overly simplistic. While the interiors of many small islands rise to high elevations, settlements, infrastructure and facilities are usually concentrated around the coastal perimeter. In low-lying areas (such as coastal Bangladesh) the adverse consequences of a rising sea level will be felt at least 100 km inland[54]. Variations in relative sea-level rise also need to be considered, especially in large, geologically-complex features, such as deltas.

In the context of small islands and low-lying areas, the following discussion identifies some of the sectors, systems and localities that are especially vulnerable to sea-level rise. Vulnerability is influenced not only by the nature of the impacts, but also by the capacity to adapt.

Vulnerability of coastal wetlands, mangroves and biodiversity

Since coastal vegetated wetlands are intimately linked to sea level, these ecosystems are sensitive to long-term sea-level change. Modelling of coastal wetlands (excluding sea grasses) suggests that 33 per cent of global wetlands would be lost with a 36 cm rise in sea level from 2000 to 2080 and 44 per cent would be lost with a 72 cm rise in sea level over this period[55]. Losses would be most severe on the Atlantic and Gulf of Mexico coasts of North and Central America, the Caribbean, the Mediterranean, the Baltic and most small island regions, largely reflecting their low tidal range.

A global assessment of mangrove accretion rates[56] indicates that the rate at which mangroves grow in height is variable but commonly approaches 5 mm per year. This is greater than recent, and even many projected, rates of increase in global mean sea level. However, many mangrove shorelines are subsiding and thus experiencing a more rapid relative sea-level rise[57]. Sea-level rise could reduce the current half-million hectares of mangroves in 16 Pacific Island countries and territories by as much as 13 per cent by 2100[58].

Higher relative coastal water levels, and the associated increasing salinity of estuarine systems, will encourage the inland migration of coastal plant and animal communities. However, if such migration is blocked by natural or human-built barriers it will be difficult for these plant and animal communities to survive as sea level rises. Moreover, impacts on one or more 'leverage species' can result in sweeping community-level changes[59].

Vulnerability of sediment processes and coastal zones

Accelerated sea-level rise will exacerbate the problems of coastal erosion which are already widespread globally. But there is not a simple relationship between sea-level rise and the retreat of low-lying coasts[60]. For example, large amounts of sand from the neighbouring open coast can be transported into estuaries and lagoons due to sea level rise. As a result, local erosion rates for these coasts can be an order of magnitude greater than simple equilibrium models would suggest[61].

Changes in sediment supply can influence atoll island morphology to at least the same extent as sea-level rise[62,63]. This is consistent with the view that uninhabited islands of the Maldives are morphologically resilient while those that have been subject to substantial human modification (Figure 6C.9) are inherently more vulnerable[64,65].

Vulnerability of coral reefs

Healthy coral reefs have kept pace with rapid postglacial sea-level rise, suggesting that the projected rates of sea-level rise are unlikely to threaten these reef ecosystems, at least over the next few decades[66]. Some Indo-Pacific reef flats are currently exposed at low tide. Anticipated increases in sea level might well result in their submergence and subsequent recolonization by corals[67]. However, other climate stresses, especially rising sea surface temperature threaten many coral reefs worldwide[46].

Vulnerability of water resources

The water resources of small islands and low-lying coastal areas are very susceptible to sea-level rise. Figure 6C.10 illustrates the direct impacts on the water resources sector, as well as the plethora of higher-order impacts which affect not only that sector but most, if not all, other sectors including health, transport and agriculture.

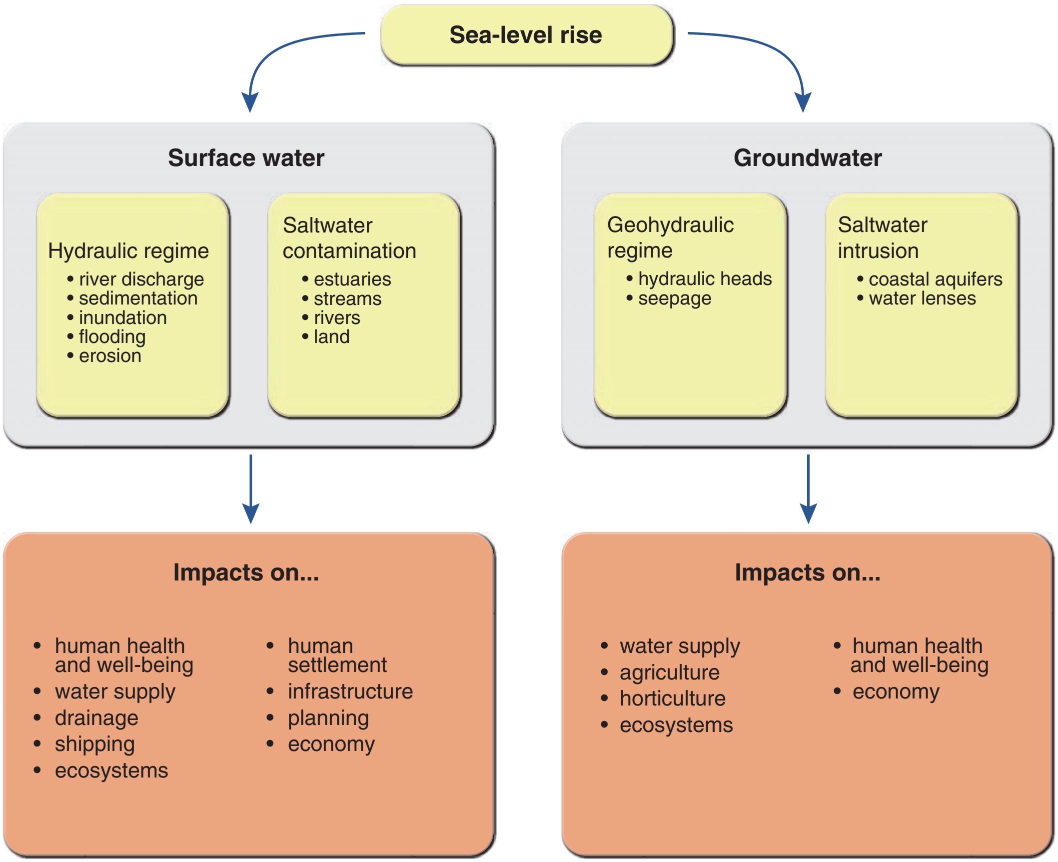


Figure 6C.10: Effects of sea-level rise on water resources of small islands and low-lying coastal areas.

Source: Based on Hay and Mimura 2006[68]

The magnitude of impacts from sea-level rise

Even for today's socio-economic conditions, both regionally and globally, large numbers of people and significant economic activity are exposed to sea-level rise (Figure 6C.11).

With no additional coastal protection a 40 cm rise in sea level by the 2080s (see Figure 6C.5) would result in more than 100 million people being flooded annually, regardless of which socio-economic scenario is adopted (Figure 6C.12). Under this adaptation scenario of no additional protection response, most of these people might be forced to move to higher locations. Upgraded coastal defences can reduce the impacts substantially: in many cases to levels lower than estimated for the baseline (in 1990).

The densely populated megadeltas are especially vulnerable to sea-level rise. More than 1 million people living in the Ganges-Brahmaputra, Mekong and Nile deltas will be directly affected simply if current rates of sea-level rise continue to 2050 and there is no adaptation. More than 50 000 people are likely to be directly impacted in each of a further nine deltas, and more than 5000 in each of a further 12 deltas[39]. Some 75 per cent of the population affected live on the Asian megadeltas and deltas, with a large proportion of the remainder living on deltas in Africa. These impacts would increase dramatically with accelerated sea-level rise.

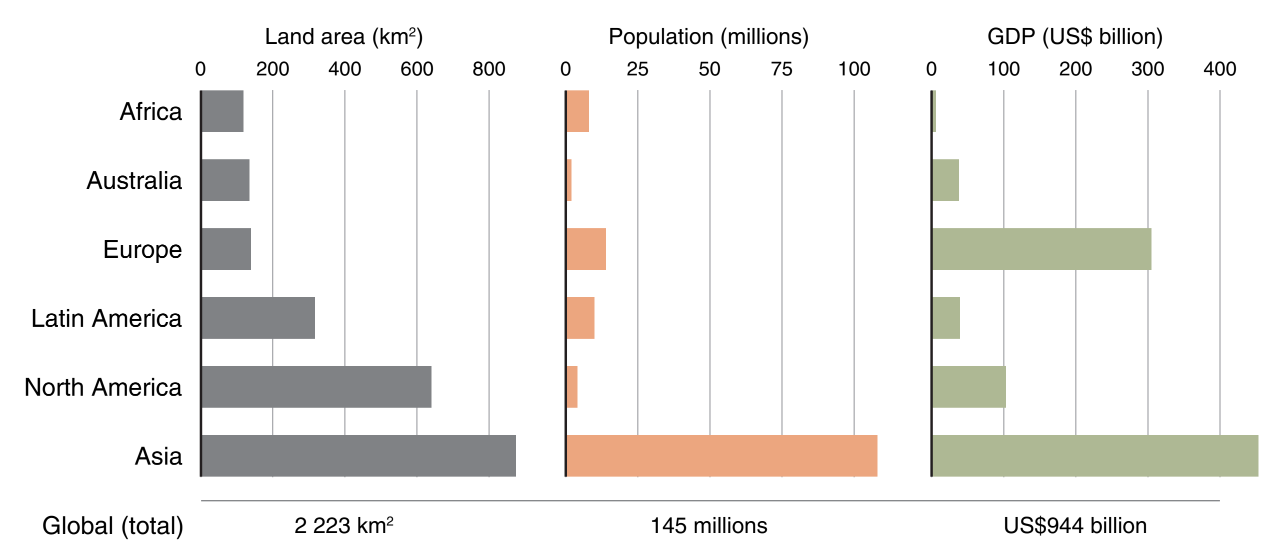


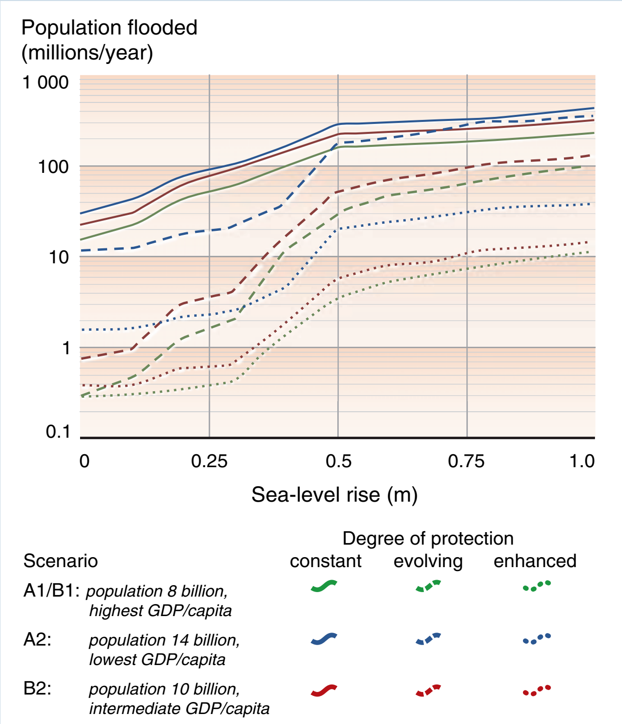
Figure 6C.11: Indicative estimates of regional and global exposure to a uniform 1 m rise in sea level based on today's population and economy.

Source: Based on Anthoff and others 2006[1]

A one-metre rise in sea level would potentially affect more land, people, and value of economic activity in Asia than in any other continent.
Photo: Veer.com

Figure 6C.12: Estimates of people flooded in coastal areas in the 2080s as a result of sea-level rise and for given socio-economic scenarios and protection responses. The lines represent IPCC Special Report on Emissions Scenarios (SRES) based on different world views. The differences in impacts between the SRES scenarios for the same amount of sea-level rise and protection response reflect differences in exposure (population) and ability to adapt (wealth). The solid lines represent a level of 'constant' (no additional) protection response. The dashed and dotted lines represent the addition of protection response to different degrees.

Source: Based on Nicholls and Lowe 2006[69]; Nicholls and Tol 2006[47]



The direct influence of sea-level rise on water resources comes principally from:

- new or accelerated erosion of coastal wetlands;
- more extensive coastal inundation and higher-levels of sea flooding (see box on the magnitude of impacts from sea-level rise);
- increases in the landward reach of sea waves and storm-surges;
- seawater intrusion into surface waters and coastal aquifers (contaminating fresh water); and
- further encroachment of tidal waters into estuaries and coastal river systems.

Sea-level rise, on its own, will not result in seawater contaminating a fresh groundwater lens – it merely raises the height of the interface between the saline and fresh water. But frequently, when one or more of the other direct impacts occurs, seawater will penetrate further into coastal aquifers, including those of small islands. Higher sea levels will, in most cases, result in a local rise in the water table.

The distance inland that a water table will be affected by sea-level rise depends on a range of factors, including elevation and subsurface permeability. In some locations, particularly in deltas such as those in Bangladesh, rising water tables can occur as far as several tens of kilometres inland. Thus, for small islands and even for depressions that are some distance from the coast, sea-level rise may lead to an expansion of the standing body of fresh and brackish water. Drainage and productive use of these and adjacent low-lying areas will often be impeded.

Vulnerability of deltas

Rates of relative sea-level rise can greatly exceed the global average in many heavily populated deltaic areas[39]. This is due to natural subsidence from compaction of sediment under its own weight and human-induced subsidence from water extraction and drainage.

Bangladesh consists almost entirely of the densely populated deltaic plains of the Ganges, Brahmaputra, and Meghna rivers. Here accelerated relative sea-level rise will likely be further compounded by increasing extreme water levels associated with more intense storm surges and monsoon rains. These are in turn related to rising water temperatures in the Bay of Bengal. The vulnerability of Bangladesh is exacerbated by the expansion of aquaculture, involving the conversion of mangroves which provide natural coastal defences[53]. Thus sea-level rise poses a particular threat to deltaic environments, especially with the synergistic effects of other climate and human pressures[70].

Vulnerability of human settlements and activities

Human settlements and activities are preferentially concentrated close to the coasts of both small islands and low-lying areas[71] (Figure 6C.13). This places them at risk from high sea levels, be they associated with extreme events such as storm surges, or increases over the longer term[72]. A few examples:

- The sustainability of island tourism resorts in Malaysia is expected to be compromised by rising sea level causing both beach erosion and saline contamination of the coastal wells that are a major source of water supply for the resorts[73].
- The number of annual rice crops possible in the Mekong delta will decline dramatically with a relative sea-level rise of 20 to 40 cm[74].
- In Hawaii numerous electrical power plants and substations, petroleum and gas storage facilities and lifeline infrastructure such as communications, telephone

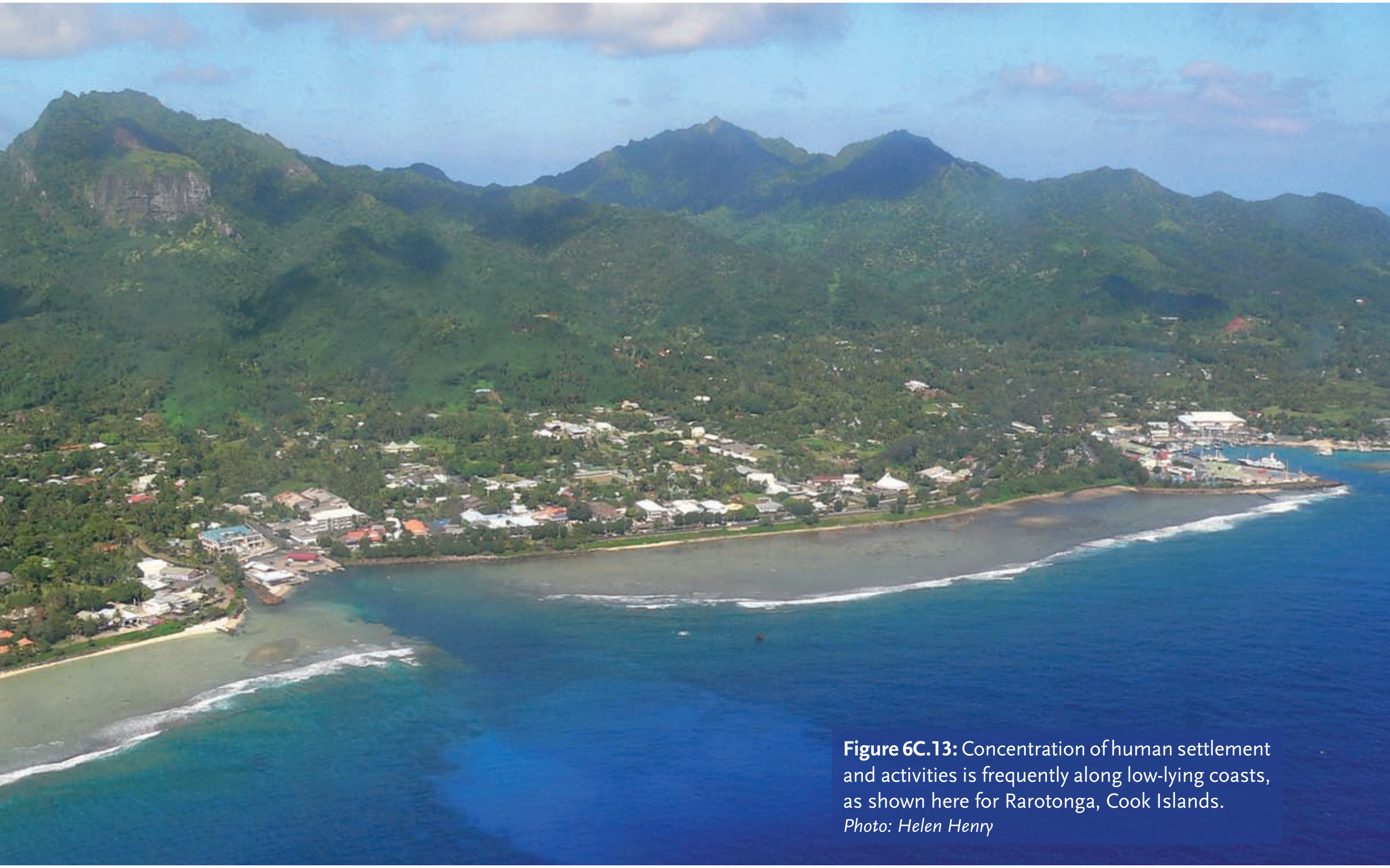


Figure 6C.13: Concentration of human settlement and activities is frequently along low-lying coasts, as shown here for Rarotonga, Cook Islands.
Photo: Helen Henry

offices, fire and police stations are mostly located within coastal inundation zones[75].

- The port facilities at Suva, Fiji and Apia, Samoa would experience overtopping, damage to wharves and flooding of the hinterland if there was a 0.5 m rise in sea level combined with waves associated with a 1 in 50 year cyclone[76].

In addition, most of the world's megacities are in vulnerable coastal regions, some are located on sinking deltaic regions, and are subject to flooding from storm surges as so graphically illustrated by the New Orleans experience of Hurricane Katrina in 2005. See the box on New York City for a case study on vulnerability of megacities to sea-level rise.

Vulnerability of megacities: case study of New York City

New York City faces increasing vulnerability to flooding and storm surges as sea level rises, with extensive damage to infrastructure and buildings, beach erosion, and loss of wetlands. Within the last 45 years, at least three coastal storms have produced widespread inundation and disruption of area transportation systems. Major portions of the city's transportation infrastructure lie at elevations of 3 m or less and have been flooded by severe storms in the past. Regional beaches and coastal wetlands, which provide recreation areas and buffer zones against destructive storm surges, have been eroding, due in part to historic sea-level rise and to the presence of "hard" engineering structures.

Regional 20th century rates of relative sea-level rise (2.1 to 3.8 mm per year) lie above the global mean trend as a result of subsidence caused by ongoing glacial isostatic adjustments. Recent projections of sea-level rise range between 29 and 53 cm for New York City by the 2080s, depending on model and emission scenarios used[77]. Increased ice sheet melting or break up would augment these model projections.

Even modest increases in sea level can exacerbate flood risks. An earlier study found that by the 2080s flood heights of today's 100-year storm (including both hurricanes and powerful nor'easters) would be more likely to recur, on average, as often as once in 60 to once in every 4 years, and that beach erosion rates could increase several-fold, with associated sand replenishment needs increasing 26 per cent by volume[78,79].

New York City is especially vulnerable to major hurricanes that travel northward along a track slightly to its west, since the strongest, most destructive winds to the right of the hurricane's eye would pass directly over the city. Furthermore, the surge would be funnelled toward the near right-angle bend between the New Jersey and Long Island coasts into the New York City harbour. The city and surrounding areas have experienced at least three Category 3 hurricanes during the 20th century. Adding as little as 47 cm of sea-level rise by the 2050s to the surge for a Category 3 hurricane on a worst-case storm track would cause extensive flooding in many parts of the city[80] (Figure 6C.14).

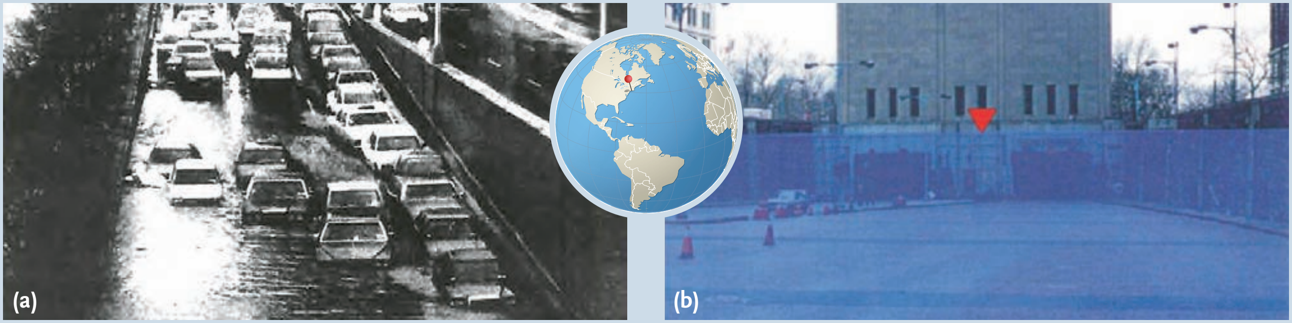


Figure 6C.14: New York City, storms and flooding.
(a) Flooding on the FDR Drive and 80th Street, Manhattan, looking north, during the December 13 1992 extra-tropical cyclone.
(b) Calculated potential surge height (with present day sea level) for a Category 1 (Saffir-Simpson scale) hurricane at Brooklyn-Battery Tunnel Manhattan entrance.

Source: (a) The Queens Borough Public Library, Long Island Division, New York Herald-Tribune Photo Morgue; (b) Rosenzweig and Solecki 2001[79]

Adaptive capacity in small islands and low-lying coastal areas

Adaptive capacity is the ability of a system to adjust to climate change (including variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences[46]. Natural systems have an inherently high ability to adapt to sea-level rise. But this capacity is frequently compromised by human activities stressing or constraining these coastal ecosystems.

The vulnerability of human systems to sea-level rise is strongly influenced by economic, social, political, environmental, institutional and cultural factors[81]. But even a high adaptive capacity may not result in effective adaptation if there is no commitment to sustained action[82]. Importantly, in small island countries such as the Maldives, Kiribati and Tuvalu there is a shortage of the data and local expertise required to assess risks related to sea-level rise. The low level of economic activity also makes it difficult to cover the costs of adaptation[52]. Traditional knowledge is an additional resource to adaptation in such settings and should be carefully evaluated within adaptation planning[76].

Over the years many climate change-related projects have been undertaken in coastal and other low-lying areas. But in most cases these have focused on assessments of vulnerability and on the building of human and institutional capacity. A community-level adaptation project implemented in the Pacific region[83] was one of the first projects world-wide that went beyond the planning and capacity-building stages and included measures to facilitate adequate adaptation. This illustrates that the scale of adaptation for sea-level rise that is required is much larger than the current level of activity.

Need for adaptation

Even if atmospheric concentrations of greenhouse gases could be held constant at today's levels, sea level would continue to rise for decades to centuries. This means adaptation will be required in order to live with the sea-level rise occurring during the 21st century and beyond. Strategies include[84]:

1) **Accommodation** through forward planning and appropriate use of low-lying coastal regions (for example, to ensure escape and emergency routes are available for future flooding events and to increase the resilience of coastal developments and communities). Example: the construction of cyclone storm-surge shelters in Bangladesh, combined with effective warning systems, which has saved many lives.
2) **Protection** via hard measures such as sea walls (Figure 6C.15) for valuable locations and soft measures such as increased beach nourishment. Example: the construction of major dykes and levees to protect the 10 million people who live below sea level in the Netherlands.
3) **(Planned) Retreat** through spatial planning, such as implementation of no-build areas or building setbacks for areas susceptible to flooding and erosion. Example: building setback distances in South Australia that take into account the 100-year erosional trend and the effect of a 0.3 m rise in sea level by 2050.

Adaptation plans must not only consider modern urban development but also allow for the protection of historical sites (such as Venice, Italy or Jamestown, Virginia, USA) and sensitive environmental areas and ecosystems – developing management policies that simultaneously address these potentially conflicting goals presents a major challenge. With proactive planning we can substantially lessen the impact of 21st century sea-level rise.

Figure 6C.15: Examples of accommodation and protection measures.
(a) Sea wall protecting road in the atoll of South Tarawa, Kiribati. The elevated building in background is also a protection measure.
(b) The Thames Barrier. Built 25 years ago, the barrier and associated defences require significant upgrading to protect the City of London from higher sea levels and storm surges, at a probable cost of billions of pounds[85,86].
Photos: (a) John Hay; (b) The Environment Agency

Need for mitigation

The rate and magnitude of sea-level rise, particularly later in the 21st century and beyond, depends on future emissions of greenhouse gases. Indeed, 21st century greenhouse gas emissions could commit the world to a sea-level rise of several metres over hundreds of years as a result of ongoing ocean thermal expansion and contributions from the Greenland and West Antarctic Ice Sheets, as experienced during the last interglacial period. Such a sea-level rise would put huge pressures on society and could result in many millions of environmental refugees[1,87,88].

If we are to avoid these large rises in sea level, a significant reduction in greenhouse gas emissions is essential. Achieving the necessary reduction in emissions will be challenging and requires urgent and sustained commitment.

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