# 13 Sea-Level Rise and Variability: Synthesis and Outlook for the Future

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Coastal zones have changed profoundly during the 20th century with growing populations and economies (Figure 1.2). Increasing urbanization was a major driver of this change. Today, many of the world's megacities are situated at the coast. At the same time, sea level has been rising and is projected to continue to rise further. However, coastal developments have generally occurred with little regard to the consequences of rising sea levels, even in developed regions such as Europe (Tol et al. 2008). An improved understanding of sea-level rise and variability is required to reduce the uncertainties associated with projections for sea-level rise, and hence contribute to more effective coastal planning and management.

The preceding chapters have provided an overview of our understanding of sea-level change. These chapters benefitted from the discussion of position papers at a workshop on sea-level rise and variability held under the auspices of the World Climate Research Programme (WCRP) at the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO) in Paris in 2006. The workshop was attended by 163 scientists from 29 countries representing a wide range of expertise and supported by 34 organizations. The workshop prompted and underpinned new research initiatives. This chapter provides a synthesis of the findings and recommendations from this community discussion, including a summary

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of the contributions to 20th century sea-level rise and a survey of the outlook for the future. It ends with a discussion of the implications for society.

## 13.1 Historical Sea-Level Change

Sea level has changed and continues to change on all timescales. The last era when there were essentially no permanent grounded ice sheets anywhere on the Earth occurred more than 35 million years ago when the atmospheric carbon dioxide concentration was 1250 ± 250 ppm. At that time, the Earth was warmer as a result of larger greenhouse gas concentration in the atmosphere and sea level was about 70 m above present-day values (Alley et al. 2005). About 32 million years ago, carbon dioxide contributions dropped to 500 ± 150 ppm, corresponding with the formation of the Antarctic Ice Sheet and with sea level falling to about 30 m higher than today (Alley et al. 2005). In comparison, the pre-industrial concentration was about 280 ppm and the 2009 concentration was about 387 ppm (and increasing at about 2 ppm/year).

Over the glacial cycles of the last 500 000 years, sea level has oscillated by more than 100 m as the great ice sheets, particularly those of northern Europe and North America, waxed and waned (Chapter 4; Figure 13.1; Rohling et al. 2009).

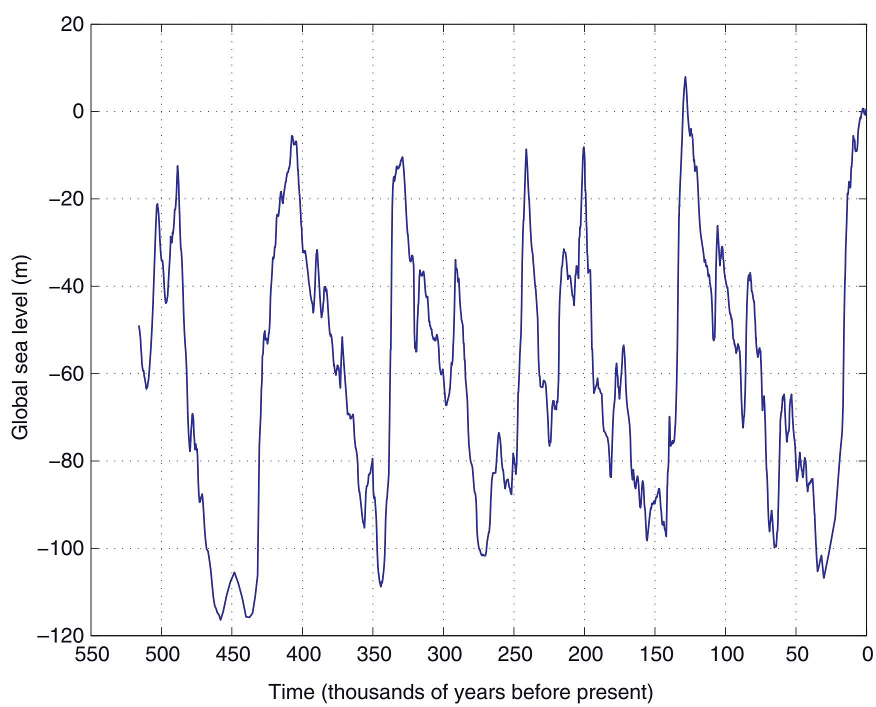


**Figure 13.1** Sea level over the last 500 000 years. This sea-level estimate is from Rohling et al. (2009) and is based on carbonate $\delta^{18}O$ measurements in the central Red Sea rather than a direct measurement of sea-level change.

These changes in sea level and the related global average temperature changes were a direct response to changes in the solar radiation reaching the Earth's surface as a result of variations in Earth's orbit around the sun and feedbacks associated with the related changes in the Earth's albedo and greenhouse gas concentrations that amplified the initial solar radiation changes.

The climatic conditions most similar to those expected in the latter part of the 21st century occurred during the last interglacial, about 125 000 years ago. At that time, some paleodata (Rohling et al. 2008) suggest rates of sea-level rise perhaps as high as $1.6 \pm 0.8$ m/century and sea level about 4–6 m above present-day values (Overpeck et al. 2006; Chapter 4), with global average temperatures about 3–5°C higher than today (Otto-Bliesner et al. 2006). Much of this higher sea level is thought to have come from a smaller Greenland Ice Sheet, but with additional contributions from the Antarctic Ice Sheet (Otto-Bliesner et al. 2006). These conditions serve as a useful analog for the 21st century.

Over the following hundred thousand years, sea level fell to about 130 m below today's values as the northern European and American ice sheets formed (Figures 4.2 and 13.1). From 20 000 years ago to about 7000 years ago these ice sheets collapsed, and sea level rose rapidly at average rates of 1 m/century for many millennia, with peak rates during the deglaciation potentially exceeding several meters per century (Figures 4.2 and 4.3; Fairbanks 1989; Lambeck et al. 2002; Alley et al. 2005). However, these peak rates of sea-level rise during the last deglaciation are not a particularly good analogue to 21st-century conditions because the ice-sheet distribution was very different. From about 6000 to 2000 years ago, sea level rose more slowly, about 2.5 m over 4000 years, and then more slowly again over the last 2000 years up to the 18th century (Figure 4.14). Over this latter period, models of the Antarctic Ice Sheet (Chapter 7) suggest a continuing slow dynamic response to changes in climate since the Last Glacial Maximum (LGM), contributing only about 0.2 mm/year to global averaged sea-level rise, slightly larger than but consistent with the indication of very low rates of sea-level change from paleodata.

Coastal sediment cores and other paleo sea-level data, the few long (pre-1900) tide-gauge records, reconstructions of 20th-century sea levels, and satellite altimetry data all indicate that the rate of sea-level rise has increased by about an order of magnitude: from at most a few tenths of a millimeter per year over previous millennia to about 1.7 mm/year during the 20th century (Figures 5.1 and 5.3), and to over 3 mm/year since 1993 (Figure 5.5). The various estimates of sea level from the late 19th through to the early 21st century are discussed in Chapter 5 and the tide-gauge estimates are summarized in Figure 13.2. The main feature common to all of these estimates is a higher rate of rise during the 20th century compared with the late 19th century. There are also indications of an acceleration during the first half of the 20th century and a deceleration during the 1960s, possibly associated with the volcanic eruptions since 1960, and a substantially faster rate of rise since the late 1980s/early 1990s (about a third or more faster than the rate during any previous 20-year period since 1870; Church et al. 2008). Further

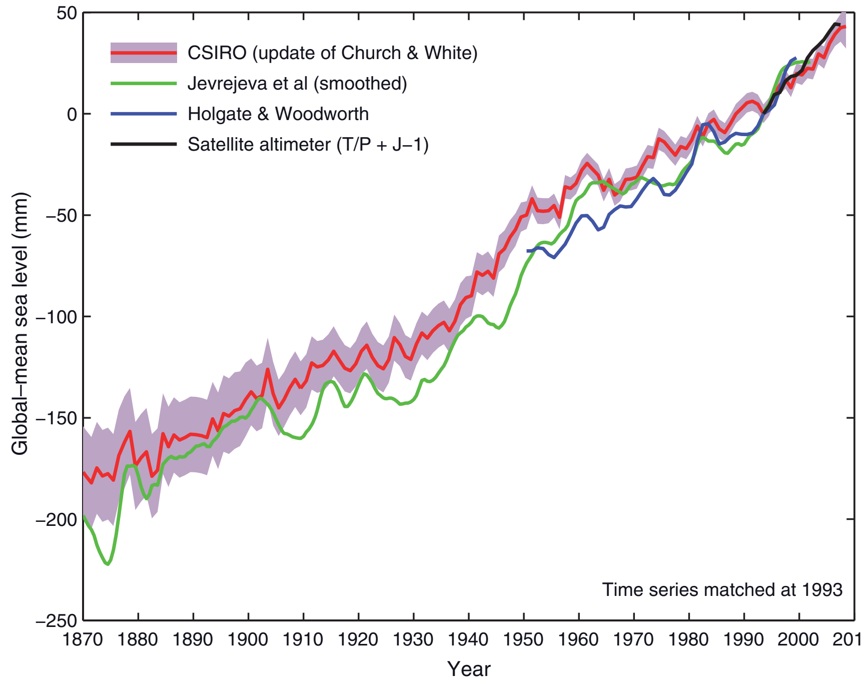


**Figure 13.2** Global mean sea level from 1870 to 2008 with 1 standard deviation error estimates updated from Church and White (2006; red), a low-passed filtered sea level from Jevrejeva et al. (2006; green) and from 1950 to 2000 from Holgate and Woodworth (2004; blue). The TOPEX/Poseidon/Jason-1 and -2 global mean sea level (based on standard processing as in Church and White 2006) from 1993 to 2008 is in black. All series have been set to a common value at the start of the altimeter record in 1993.

investigation, especially given the sparse historical database, is required to better quantify the timing and the magnitude of all these changes.

## 13.2 Why is Sea Level Rising?

A major inadequacy of sea-level science over recent decades, including that in the four IPCC Assessments completed to date, has been the failure to quantitatively explain the observed 20th-century sea-level rise; the observed sea-level rise has been larger than the sum of estimated contributions. Munk (2002) highlighted this discrepancy when he argued that observations of changes in the Earth's rotational parameters (an increase in the length of the day) constrained the possible magnitude of the ice-sheet contributions. The sum of the possible ice-sheet contribution and the estimated contribution from ocean thermal expansion was too small to explain the observed sea-level rise. He called this conundrum "the sea-level enigma".

There has been significant progress in resolving this "enigma" over recent years. Firstly, it is now clear that the observed Earth rotational parameters are not as strong a constraint on ice-sheet contributions as argued by Munk (Chapter 10; Mitrovica et al. 2006). Secondly, revised estimates of ocean thermal expansion

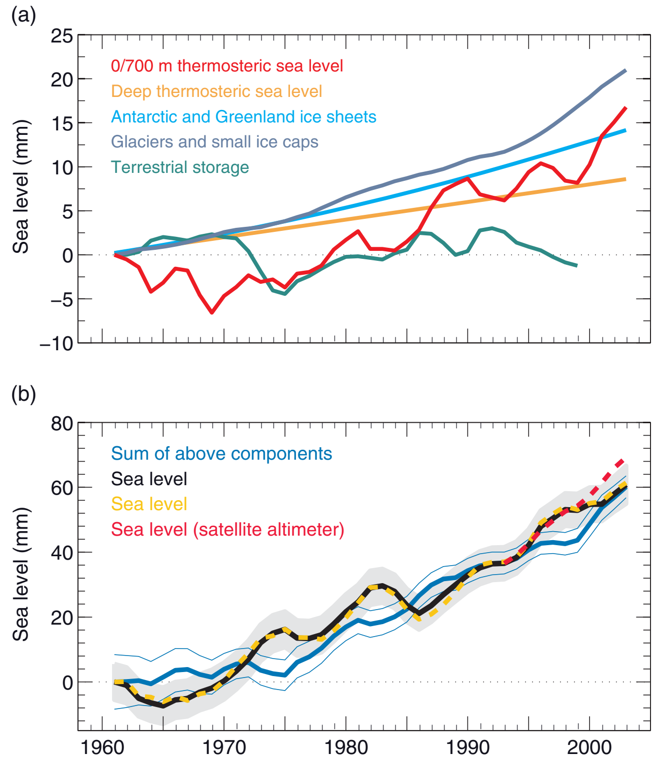


**Figure 13.3** Total observed sea-level rise and its components. (a) The components are thermal expansion in the upper 700m (red), thermal expansion in the deep ocean (orange), the ice sheets of Antarctica and Greenland (cyan), glaciers and ice caps (dark blue), and terrestrial storage (green). (b) The estimated sea levels are indicated by the black line from Domingues et al. (2008), the yellow dotted line from Jevrejeva et al. (2006), and the red dotted line from satellite altimeter observations. The sum of the contributions is shown by the blue line. Estimates of 1 standard deviation error for the sea level are indicated by the grey shading. For the sum of components, the estimates of 1 standard deviation error for upper-ocean thermal expansion are shown by the thin blue lines. All time series were smoothed with a 3-year running average and are relative to 1961 (from Domingues et al. 2008).

and the melting of glaciers and ice caps[1], at least since 1961, are somewhat larger than earlier estimates (Chapters 6 and 7; Domingues et al. 2008; Levitus et al. 2009; Ishii and Kimoto 2009). By combining these revised estimates for upper-ocean thermal expansion and glacier and ice-cap contributions with reasonable but more poorly known estimates of contribution from deep-ocean thermal expansion and the Greenland and Antarctic Ice-Sheet contributions, Domingues et al. (2008) produced an approximate closure of the sea-level budget (Figure 13.3; Table 13.1). On these decadal timescales the dominant contributions are the melting of glaciers and ice caps and upper-ocean thermal expansion, with smaller but significant contributions from deep-ocean thermal expansion and the ice sheets. Over 11 years of the relatively short satellite altimeter era, 1993–2003, the IPCC Fourth Assessment Report (AR4) managed to explain the observed sea-level rise using both satellite and *in situ* data.

[1] Clarification of terminology: two general categories of ice are considered as contributors to global sea-level rise: (1) the ice sheets of Antarctica and Greenland, all of which drain into the surrounding ocean via a number of ice streams or outlet glaciers. Ice sheets are sufficiently thick to cover most of the bedrock topography. (2) Glaciers and ice caps, mostly outside Antarctica and Greenland. A glacier is a mass of ice on the land flowing downhill under gravity and an ice cap is a mass of ice that typically covers a highland area.

**Table 13.1** Contributions to sea-level rise for the period 1961 to 2003, from Domingues et al. (2008).

| Contribution | Amount of rise |
|---|---|
| Ocean thermal expansion for the upper 700 m | 0.5 ± 0.1 mm/year |
| Ocean thermal expansion below 700 m | 0.2 ± 0.1 mm/year |
| Glaciers and ice caps | 0.5 ± 0.2 mm/year |
| Greenland Ice Sheet | 0.1 ± 0.1 mm/year |
| Antarctic Ice Sheet | 0.2 ± 0.4 mm/year |
| Sum of contributions | 1.5 ± 0.4 mm/year |
| Observed sea-level rise | 1.6 ± 0.2 mm/year |

The use of satellite altimetry to measure changes in ocean volume, satellite gravity to measure changes in ocean mass, and Argo profiling floats to measure changes in upper-ocean temperatures and thermal expansion is also leading to improved understanding of the sea-level budget since 2003 (Chapter 6; Willis et al. 2008; Cazenave et al. 2009; Leuliette and Miller 2009). Both Cazenave et al. (2009) and Leuliette and Miller (2009) have closed the sea-level budget within error bars over the short record. However, they had rather different contributions for slightly different periods. Cazenave et al. estimated the mass and thermal-expansion increases were about 2.2 and 0.4 mm/year, respectively, whereas the equivalent estimates of Leuliette and Miller were both about 0.8 mm/year (see Chapter 6 for more detailed discussion). A longer record of these three complementary measurements is likely to lead to significant further progress in understanding 21st-century sea-level rise.

One thing is clear from all of the recent analyses: observations indicate an increasing glacier and ice-cap contribution and also increasing ice-sheet contributions as a result of the flow of ice into the ocean from both Greenland and Antarctica. Of particular concern is the rapid dynamic thinning of the margins of the Greenland and Antarctic Ice Sheets (Chapter 7; Pritchard et al. 2009). However, the record is still short, some discrepancies remain, and physically based quantitative estimates for the 21st century are lacking.

An additional contribution to changing sea level comes from the storage of water on land: in lakes, dams, rivers, wetlands, soil moisture, snow cover, permafrost, and aquifers. These respond to both climate variations and to anthropogenic activities through, for example, the building of dams and the mining of water from aquifers (Chapter 8). Although these terms are important to understanding 20th-century sea-level rise, and hence in improving our projections for the future, their contribution to sea-level change through the 21st century and beyond is likely to be substantially smaller than other changes (continued contribution at the 20th-century rate would alter the projections by centimeters).

This improved understanding of the contributions to sea-level rise is important as it is likely to lead to better observational constraints on the climate models used for projections of sea-level rise in the IPCC Fifth Assessment Report, which has an anticipated completion date of 2013–14.

## 13.3 The Regional Distribution of Sea-Level Rise

The regional distribution of sea-level rise is important as a scientific question, and also because it is the regional or local sea-level change (and local land motion) that impacts society and the environment. Satellite altimeter data show significant regional variations in the rate of sea-level rise (Figure 13.4), with some regions having experienced about five times the global-averaged rate of rise since 1993. However, this regional variation in the relatively short altimeter record is largely a result of climate variability, particularly in the equatorial Pacific Ocean (Chapters 5 and 6). The pattern is associated with the movement of water within the oceans in response to varying wind patterns associated with climate phenomena like the El Niño Southern Oscillation and is largely reflected in regional patterns of ocean thermal expansion (Figure 6.3). During the 21st century, climate variability will continue and coastal communities will be impacted by the combination of the pattern of long-term sea-level rise and the natural variability in sea level.

Changes in the mass of the ice sheets (and glaciers and ice caps) also influence the regional distribution of sea-level rise through corresponding changes in the Earth's gravitational field and the elastic movement of the Earth's crust (Figure 10.5). That is, the contribution from the ice sheets results in a lower relative sea level near decaying ice sheets and a larger than the globally averaged rise (up to

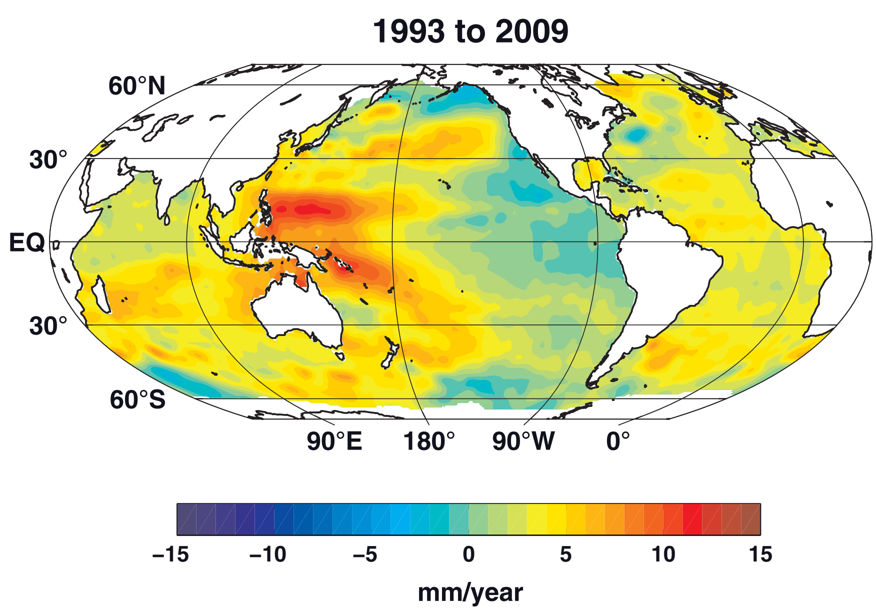


**Figure 13.4** The spatial distribution of the rates of sea-level rise, plotted about the global averaged rate of rise for the period January 1993 to December 2009, as measured from satellite altimeter data (available at http://www.cmar.csiro.au/sealevel/).

about 20%) far from the decaying ice sheets. As a result, ice-sheet contributions to future sea-level rise are likely to have a disproportionate impact in some far-field and potentially vulnerable regions.

## 13.4 Projections of Sea-Level Rise for the 21st Century and Beyond

The IPCC Third Assessment Report (TAR; IPCC 2001) projections of sea-level rise were expressed in the form of globally averaged levels for 2100 compared with 1990 levels (the lines and shaded regions in Figure 13.5), while the AR4 (IPCC 2007) were expressed for the 2090–2100 decade (shown as the bars plotted at 2095 in Figure 13.5) compared with 1980–2000 averages (approximately equal to the 1990 values).

The average of the TAR model projections for the full range of greenhouse gas scenarios is about 30–50 cm (dark shading in Figure 13.5). The range of all model projections over all scenarios is about 20–70 cm (light shading). The full range of projections, including an allowance for uncertainty in estimates of contributions from land-based ice, were for a sea-level rise of 9–88 cm (outer black lines).

The AR4 model projections are composed of two parts. The first part consists of the estimated sea-level rise (with a 90% confidence range) from ocean thermal expansion, glaciers and ice caps, and modeled ice-sheet contributions and is for a sea-level rise of 18–59 cm in 2095 (the magenta bar). This contribution is similar to, but slightly smaller than, the equivalent range from the TAR (the light shaded

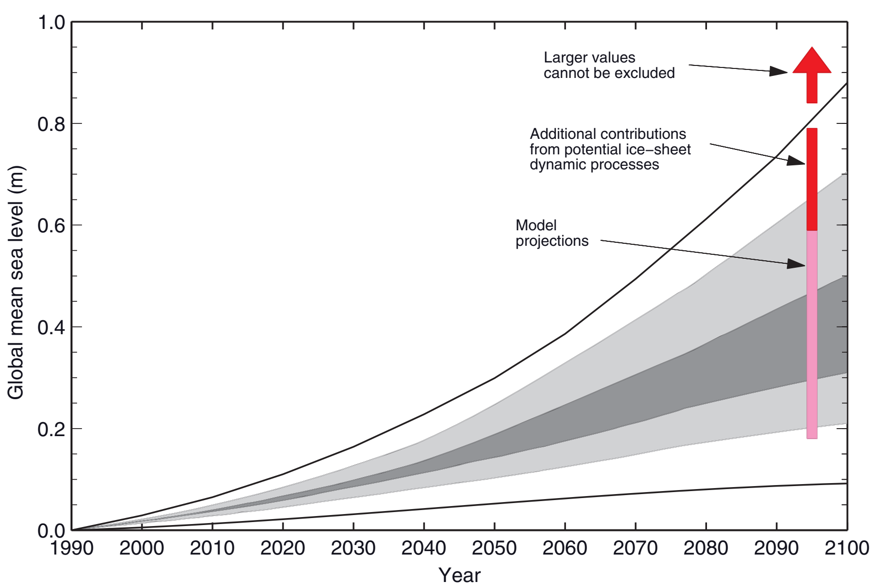


**Figure 13.5** Projected sea-level rise for the 21st century. The projected range of global averaged sea-level rise from the IPCC (2001) assessment report for the period 1990–2100 is shown by the lines and shading (the dark shading is the model average envelope for the range of greenhouse gas scenarios considered, the light shading is the envelope for all models and for the range of scenarios, and the outer lines include an allowance for an additional land-ice uncertainty). The AR4 IPCC projections (90% confidence limits) made in 2007 are shown by the bars plotted at 2095, the magenta bar is the range of model projections, and the red bar is the extended range to allow for the potential but poorly quantified additional contribution from a dynamic response of the Greenland and Antarctic Ice Sheets to global warming. The red arrow indicates 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"; updated from Church et al. (2008).

region). The second part consists of a possible rapid dynamic response of the Greenland and West Antarctic Ice Sheets, which could result in an accelerating contribution to sea-level rise. This additional contribution was not included in the AR4 range of projections noted above because adequate models for quantitative estimates were not available. Recognizing this deficiency, an *ad hoc* allowance for a dynamic response of the ice sheets was made resulting in an additional allowance of 10–20 cm of sea-level rise (the red bar). However, there is currently insufficient understanding of this dynamic response, and IPCC (2007) also clearly stated that a larger contribution cannot be excluded.

When compared in this way, the TAR and AR4 projections of sea-level rise for the 21st century are similar, especially at the upper end of the projected range. However, the wide range of the current projections is a significant hindrance in planning adaptation measures to sea-level rise. It was this wide range that was one of the main motivations that led to the WCRP sea-level workshop underpinning this book.

Another of the main motivations concerned where the observations of sea-level rise lay relative to the IPCC projections. Rahmstorf et al. (2007) demonstrated that sea levels, observed with satellite altimeters from 1993 to 2006 and estimated from coastal sea-level measurements from 1990 to 2001, are tracking close to the upper bound of the TAR projections of 2001, or equivalently as shown above, the upper bound of the AR4 projections of 2007, after the allowance for land-ice uncertainties is included. Recent altimeter measurements indicate sea level is continuing to rise at a rate near the upper bound of the projections since 1993. Updated sea-level reconstructions following the methods of Church and White (2006) also shows the rate of sea-level rise near the upper bound of the projections from 1993. However, the reconstruction also indicates a sea-level fall of about 6 mm between 1991 and 1993 (Figure 13.2), possibly resulting from the explosive volcanic eruption of Mt Pinatubo in the Philippines in 1991. Model simulations indicate that the recovery from the eruption might have resulted in a rate of sea-level rise about 0.6 mm/year higher than what otherwise might have been expected (Chapter 6). The rapid dynamic thinning of the margins of the Greenland and Antarctic Ice Sheets discussed above is likely to be a significant contribution to the observed rapid rate of sea-level rise over the last decade or so. These observations do not necessarily indicate that sea level will continue to track the upper edge of the projections; it may diverge above or below these values.

Recognizing that sea level is currently rising near the upper bound of the IPCC projections, a number of authors (Rahmstorf 2007; Horton et al. 2008; Grinsted et al. 2010) developed relatively simple parameterizations of sea-level rise, based on the relationship between observed historical global sea-level and atmospheric surface temperature records. The processes leading to sea-level rise are not explicitly considered but are represented by a few statistically determined parameters. These models have generally produced higher projections than in the IPCC AR4. While these models are an attempt to overcome the limited understanding of potential future ice-sheet contributions, most of them have been "trained" with observations of 20th-century sea-level rise and some paleo sea-level data, during a period when ocean thermal expansion and glacier melt were the largest contributors to sea-level rise. The Rahmstorf (2007) model has been criticized on statistical grounds and its inability to adequately reproduce observed (Holgate et al. 2007) and modelled (von Storch et al. 2008) sea-level rise.

Sea levels will continue to rise long after 2100. Glaciers and ice caps (outside the polar regions) only contain a limited amount of ice (less than 40 cm of equivalent sea-level rise if they were all to melt), so in the longer term their rate of contribution to sea-level rise will diminish. However, ocean thermal expansion will continue for centuries, even after greenhouse gas concentrations in the atmosphere have been stabilized. The eventual sea-level rise would be dependent on the concentration of greenhouse gases and atmospheric temperatures. Estimates vary but a millennial climate model simulation suggests the order of 0.5 m/°C of global warming (Meehl et al. 2007). The Antarctic and Greenland Ice Sheets are the biggest concern for longer-term sea-level rise. The area and mass of melt from the Greenland Ice Sheet (which contains enough water to raise sea level by about 7 m) is increasing. Model simulations indicate that surface melting of the Greenland Ice Sheet will increase more rapidly than snowfall, leading to a threshold stabilization temperature above which there is an ongoing decay of the Greenland Ice Sheet over millennia. This threshold is estimated as a global-averaged temperature rise of just 3.1 ± 0.8°C (Gregory and Huybrechts 2006) above pre-industrial temperatures. With unmitigated emissions of greenhouse gases, the world is likely to pass this threshold during the 21st century.

In addition, both the Greenland and Antarctic Ice Sheets are showing signs of a dynamic response, potentially leading to a more rapid rate of rise than can occur from surface melting alone (Chapter 7). In an attempt to put bounds on the magnitude of the response, Pfeffer et al. (2008) used kinematic constraints on the potential cryospheric contributions. They estimated that sea-level rise greater than 2 m by 2100 was physically untenable and that a more plausible estimate was about 80 cm, consistent with the upper end of the IPCC estimates and the present rate of rise. This value still requires an acceleration of the ice-sheet contributions. Recent analysis of space-based gravity data (from 2002 to 2009) from the Gravity Recovery and Climate Experiment (GRACE) satellite mission does indicate an accelerating contribution from both Greenland and Antarctica (Velicogna 2009), consistent with the range discussed by Pfeffer et al. (2008). Improved understanding of the processes responsible for ice-sheet changes are urgently required to improve estimates of the rate and timing of 21st-century and longer-term sea-level projections.

Sea-level rise during the 21st century and beyond is not expected to be spatially uniform (as shown in Figures 6.7–6.9). However, there is as yet little agreement in climate models of this regional distribution, indicating systematic uncertainty in the model representation of ocean heat uptake, and transport processes in particular (Chapter 6). This contrasts with quantities relating to surface climate, especially the distribution of projected surface air temperature change, in which current models show reasonable agreement. As discussed above, in addition to this regional distribution of sea-level rise resulting from changes in the coupled atmosphere–ocean climate system, contributions from ice stored on land will also result in changes in the Earth's gravitational field, the shape of the Earth, and hence in the regional distribution of relative sea-level rise (Mitrovica et al. 2009; Bamber et al. 2009).

## 13.5 Changes in Extreme Events

Rising sea levels have been and will continue to be felt most acutely through extreme events (periods of above average sea level). These include the many cyclones and associated storm surges that have resulted in major loss of life over many years in low-lying nations such as Bangladesh and the 1953 and 1962 storm surges in northwest Europe (Figure 11.1). Among the most recent examples are Hurricane Katrina in New Orleans and Cyclone Nargis in Myanmar.

Analysis of 20th-century sea-level extreme events indicates that coastal flooding events of a given height are now happening more frequently than at the start of the 20th century (Chapter 11). This is primarily a response to changes in mean sea level rather than a change in the frequency or intensity of storm events. Indeed, a change in the frequency of flooding when a given level (such as the height of a storm surge barrier or dyke) is exceeded, can be dramatic. Building on the analysis at a number of locations such as San Francisco (Chapter 1; Bromirski et al. 2003) and Sydney (Chapter 11), it is likely that by 2100 the present-day "one in 100 years" flood will be experienced several times per year at many locations. Also, the most severe sea-level events will be higher and thus have a greater impact during the 21st century.

A warmer climate means that the atmosphere can hold more water vapor and projections are for an increase in precipitation during storms. There is also an expectation of more severe winds in storms, leading to larger storm surges and surface waves, but not necessarily an increase in the frequency of storm events (Chapter 11). Each of these phenomena will impact coastal regions.

## 13.6 Sea Level and Society

Variations in sea level have always had an impact on society since *Homo sapiens* evolved in eastern Africa about 200 000 years ago. Initially, the oceans restricted human migration. However, lower sea levels more than 50 000 years ago allowed migration through Southeast Asia and Indonesia to New Guinea and Australia, and during the LGM to North America.

It was only well after the end of the last glacial cycle when climate and sea level stabilized that the precursors of our modern society, with coastal cities, trade, and shipping, began to develop. Indeed, much of the development of our coastal civilization and the occupation of mid-ocean islands occurred when the rate of global averaged sea-level change was only a few tenths of a millimeter per year, and in many regions relative sea level was falling slightly as a result of ongoing glacial isostatic adjustment (GIA) (Chapters 4 and 10). This coastal development accelerated over the last century, particularly over recent decades (e.g. Figures 1.1 and 1.2). With coastal development continuing at a rapid pace, society is becoming increasingly vulnerable to sea-level rise and variability, as Hurricane Katrina demonstrated in New Orleans in 2005.

Climate-change mitigation will be essential to avoid the most severe impacts of sea-level rise, as might occur from ongoing ocean thermal expansion or a collapse of the Greenland or West Antarctic Ice Sheets. While sea-level rise over the next few decades is not sensitive to future greenhouse gas emissions (Church et al. 2001), sea-level projections for 2100 for the highest greenhouse-gas emission scenario (A1FI) considered in the IPCC AR4 (IPCC 2007) are about 50% larger than for the lowest-emission scenario (B1). On the longer term, ocean thermal expansion is roughly proportional to the amount of global warming (see above) and Gregory et al. (2004) indicate that the Greenland Ice Sheet is likely to be eliminated by anthropogenic climate change unless much more substantial emission reductions are made than those considered by the IPCC in either the 2001 or 2007 report.

Even with successful mitigation, adaptation to rising sea levels will be essential (Nicholls et al. 2007b). It is critically important to recognize that during the 20th century global averaged sea level moved outside the range of sea level over previous centuries when much coastal development occurred (shown schematically in Figure 13.6). During the 21st century, sea level will move substantially further outside the range experienced by our society to date. Where coasts are subsiding due to natural and human-induced processes, such as in many densely populated deltas and associated cities, this effect will be exacerbated (Ericson et al. 2006;

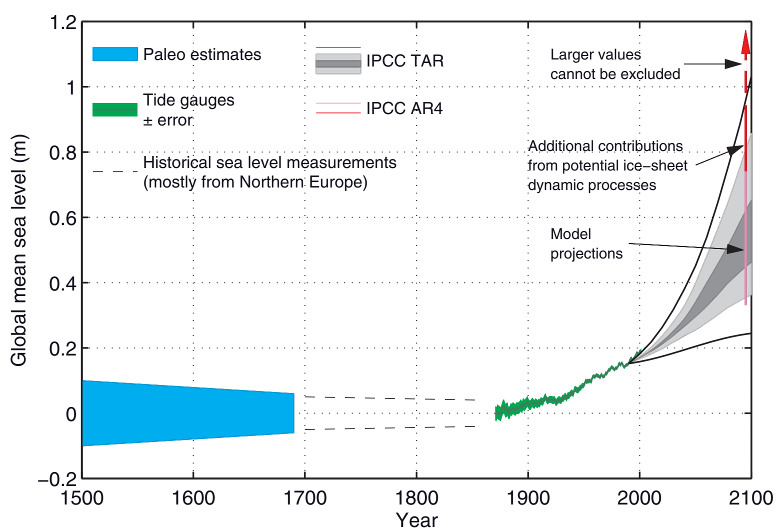


**Figure 13.6** Sea levels from 1500 to 2100. The blue band indicates the range of paleo sea-level estimates from Chapters 4 and 5, the dashed lines from 1700 to 1860 indicate the range of sea levels inferred from a limited number of (mostly European) long sea-level records, the black line from 1870 to 2006 is an estimate of global averaged sea level updated from Church and White (2006), and the curves from 1990 to 2100 are the projections from Figure 13.5 (updated from Church et al. 2008).

Syvitski et al. 2009). As shown in Chapter 2, rising sea levels will result in a number of impacts including (1) more frequent coastal inundation/submergence (Figure 1.12), (2) ecosystem change, such as salt-marsh and mangrove loss, (3) increased erosion of beaches (70% of which have been retreating over the past century with less than 10% prograding; Bird 1993) and soft cliffs (Figure 1.3), and (4) salinization of surface and ground-waters. Low-lying islands and deltaic regions are especially vulnerable. Indicative estimates suggest that about 200 million people, and infrastructure worth several trillion dollars, are threatened by coastal floods today; the actual exposure may be larger (Chapters 2 and 3; Nicholls et al. 2007a). This exposure continues to grow at a rapid rate, primarily due to socioeconomic trends, and in the absence of adaptation, risks are growing as sea levels rise. To effectively manage these increasing risks, appropriate information on how and why sea level is changing and will change during the 21st century and beyond is essential.

Appropriate adaptation can significantly reduce the impact of sea-level rise. Planned adaptation will range from retreat from rising sea levels, through planning and zoning of vulnerable coastal regions (Figure 13.7a), accommodation through modification of coastal infrastructure, and the construction of facilities like the cyclone centers used so effectively in Bangladesh (Figure 13.7b), to protection of highly valued coastal regions through highly sophisticated barriers like the Thames Barrage protecting London and the Maeslantkering storm-surge barrier protecting Rotterdam (Figures 13.7c and d). Planned adaptation is more cost-effective and less disruptive than forced adaptation in response to the impacts of extreme events. For example, the estimated cost of strengthening the levees protecting New Orleans, while large, was substantially less than the cost of the damage caused by Hurricane Katrina.

Science has an important role to play in assisting societies to respond to sea-level rise. Improved understanding and narrowing of the uncertainties of projected rise at both the global and regional/local level and its impacts are critical elements in assisting society. The broad range of current projections of global averaged sea-level rise for the 21st century is primarily the result of model uncertainty, and there is currently inadequate understanding of the factors controlling the global-averaged sea-level rise and its regional distribution. Improving monitoring, understanding, and modeling of the global oceans, of glaciers and ice caps, and of the Greenland and Antarctic Ice Sheets, and detecting early signs of any growing ice-sheet contributions, are critical to informing decisions about the required level of greenhouse gas mitigation and for adaptation planning. Quantifying how the Greenland and Antarctic Ice Sheets will contribute to sea-level rise during the 21st century and beyond is currently the largest single uncertainty.

Today, planning for and early warning of extreme events, through improved storm-surge modeling and its operational application, are important aspects of coastal zone management in some regions. This approach goes hand-in-hand with the building and operation of storm surge barriers and cyclone centers (Figure 13.7b). Coastal planning as well as warning systems need to be improved and applied in regions where they do not currently exist and where substantial

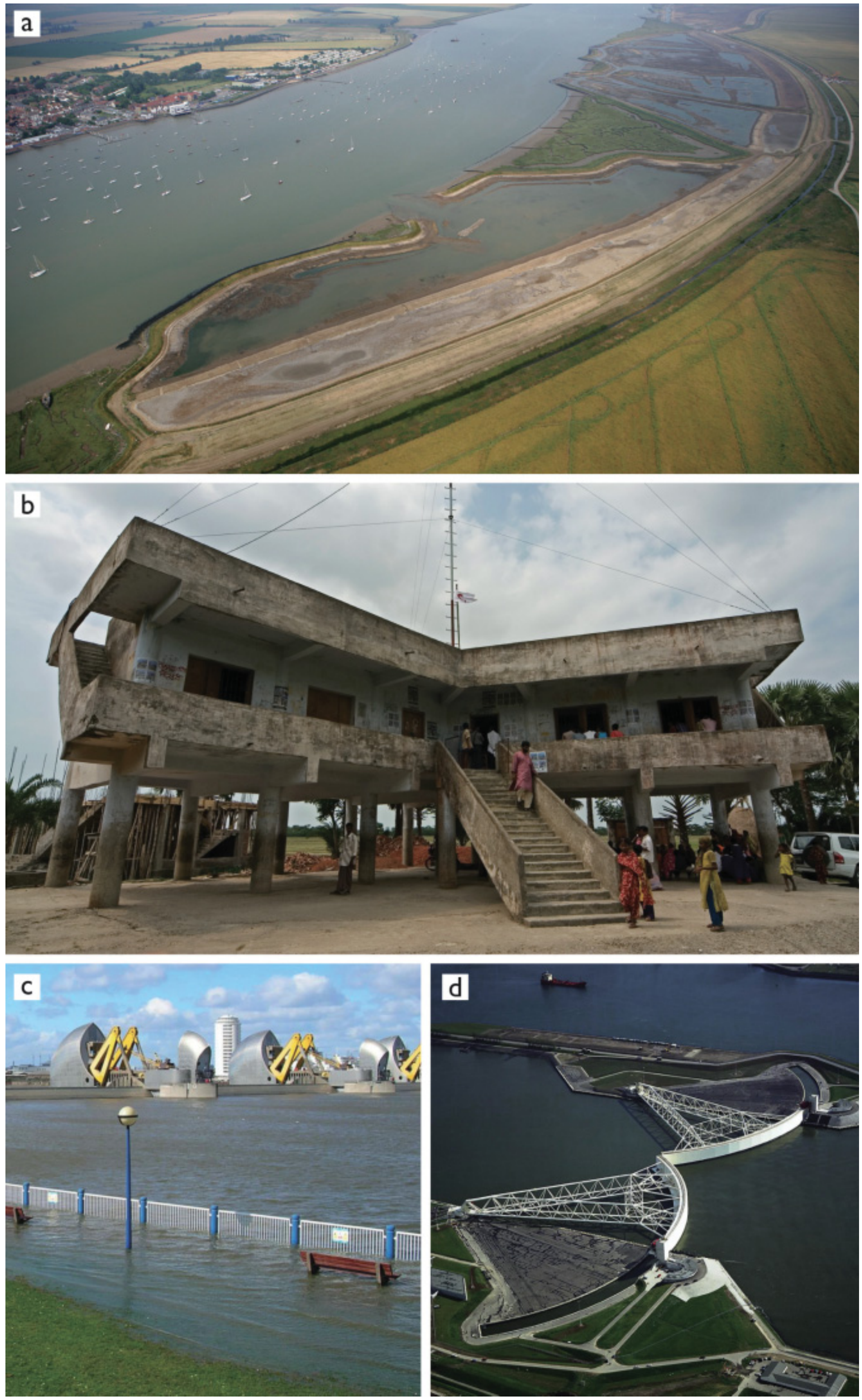


**Figure 13.7** Examples of adaptation to sea-level variability and rise. (a) Retreat. Managed realignment at Wallasea, Essex, UK, on the estuary of the River Crouch where a defense line was deliberately breached in 2006 – a planned retreat of the shoreline often reduces protection costs and also allows the development of intertidal habitat as intended here (www.abpmer.net/wallasea/). This is likely to become a widespread response to sea-level rise across Europe. (b) Accommodate. Khajura Cyclone Center, Kalapara, Patuakhali, Bangladesh, on June 3, 2007. The Cyclone Center is also used as a school building. (c) Protect. The Thames Barrage protecting the City of London from storm surges. (d) Protect. The Maeslantkering storm-surge barrier for protecting the City of Rotterdam from storm surges. (a, © Department of Environment Food and Rural Affairs (DEFRA), London; b, © Shehab Uddin/Drik/Red Cross; c, © UK Environment Agency; d, photo credit: Rijkswaterstaat, Dutch Ministry of Transport, Public Works and Water Management.)

loss of life and damage to infrastructure and the environment has occurred or is likely to occur in the future. As a minimum, the coastal planning effort and the warning systems will require significant improvements in bathymetric, near-shore topographic and forecast meteorological information (including surface waves) for storm-surge modeling and detailed inundation mapping.

The understanding of sea-level rise and variability has progressed considerably over the last decade, largely as a result of dramatically improved *in situ* and satellite observational systems and improved models of the climate system. These observing systems need to be completed, improved and sustained, as described in the plans of the Global Climate Observing System, if we are to continue to reduce uncertainties. Another critical component is the development and maintenance of an accurate International Terrestrial Reference Frame (ITRF) based on an ongoing Global Geodetic Observing System (GGOS; Chapter 9). The 2006 Paris WCRP sea-level workshop which led to this book identified the research and observational needs and they were documented in the summary statement from the workshop (see http://wcrp.wmo.int/AP_SeaLevel.html). These needs are documented in each of the chapters of this book with the observational priorities brought together in Chapter 12.

Ensuring that nations have access to the necessary information for adaptation planning is dependent on continued progress in the implementation of these observing systems and improvement of models of the climate system. This requires implementation of needed local observing systems by individual nations, international cooperation, and exchange of data, including an open-data policy with timely and unrestricted access for all. Finally, the scientific information must be translated into practical adaptation plans and this requires the development and strengthening of partnerships between science, different levels of governments, business, and the public.

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