CHAPTER

5

Sea-Level Rise

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INTRODUCTION

The main goal of this chapter is to briefly describe the current state of knowledge regarding the causes of sea-level rise, summarize recent estimates of how much sea level may rise by the end of the century, and present some of the impacts of sea-level rise on society.

Research on sea-level rise has made very substantial progress in the last few years. It is not my intention to try to provide a very detailed accounting of recent scientific advances. Such a detailed and authoritative summary can be found in Church et al. (2010), chapters of which are referenced extensively here. Another recent reference is Gehrels (2009), which concentrates on the rate of sea-level rise. Here, I will attempt to reflect the recent scientific advances as accurately as I can, while trying to attain a level of detail appropriate for nonspecialists.

CAUSES OF SEA-LEVEL RISE

Changes in mean sea level at any given location are a combination of a number of processes:

- Warming seawater causing a decrease in its density (thermal expansion)

- Adding water to the oceans from the continents through melting or transport of ice from glaciers and ice caps, and transfer of groundwater
- Changes in ocean and atmospheric circulations
- Uplift or subsidence due to tectonic movements or rebound from the loss of glacier ice cover from the last ice age (glacial isostatic adjustment, GIA)
- Natural and human-induced subsidence (often through changes in groundwater levels)

All these processes act together in differing degrees at different locations to alter the relative level between land and sea. For this reason, it is important to distinguish between *absolute* and *relative sea-level change (RSLC)*. *Absolute* sea-level change refers to change measured by satellites relative to the center of the earth. RSLC refers to change measured relative to the land by tide gauges. Both are negative (falling) in some parts of the world and positive (rising) in others. Both are influenced by changes in ocean volume, mass, and mass redistribution but differ locally because of differences in vertical land motion (e.g., land rebound from melted ice sheets, movement along faults, groundwater removal, dams, and reservoirs).

Absolute Versus Relative Sea-Level Change

Given the different processes that influence mean sea level, it is important to keep in mind that changes in sea level at any given location may be very different from the global average. The impacts of changes in sea level will also depend on local conditions, rather than the global mean (Boon, 2012; Sallenger et al., 2012). Figure 5.1 shows measurements of sea level from a number of coastal cities around the world.

Observations for all of the locations show different degrees of variability and different overall trends. Seattle, Honolulu, and Wellington all show a fair amount of interannual variability, but clear upward trends in sea level. In contrast, relative sea level in Stockholm has decreased by roughly 6% over the last century. The fact that the relative sea level in Stockholm (or some other specific locations) is decreasing is not inconsistent with an increase in

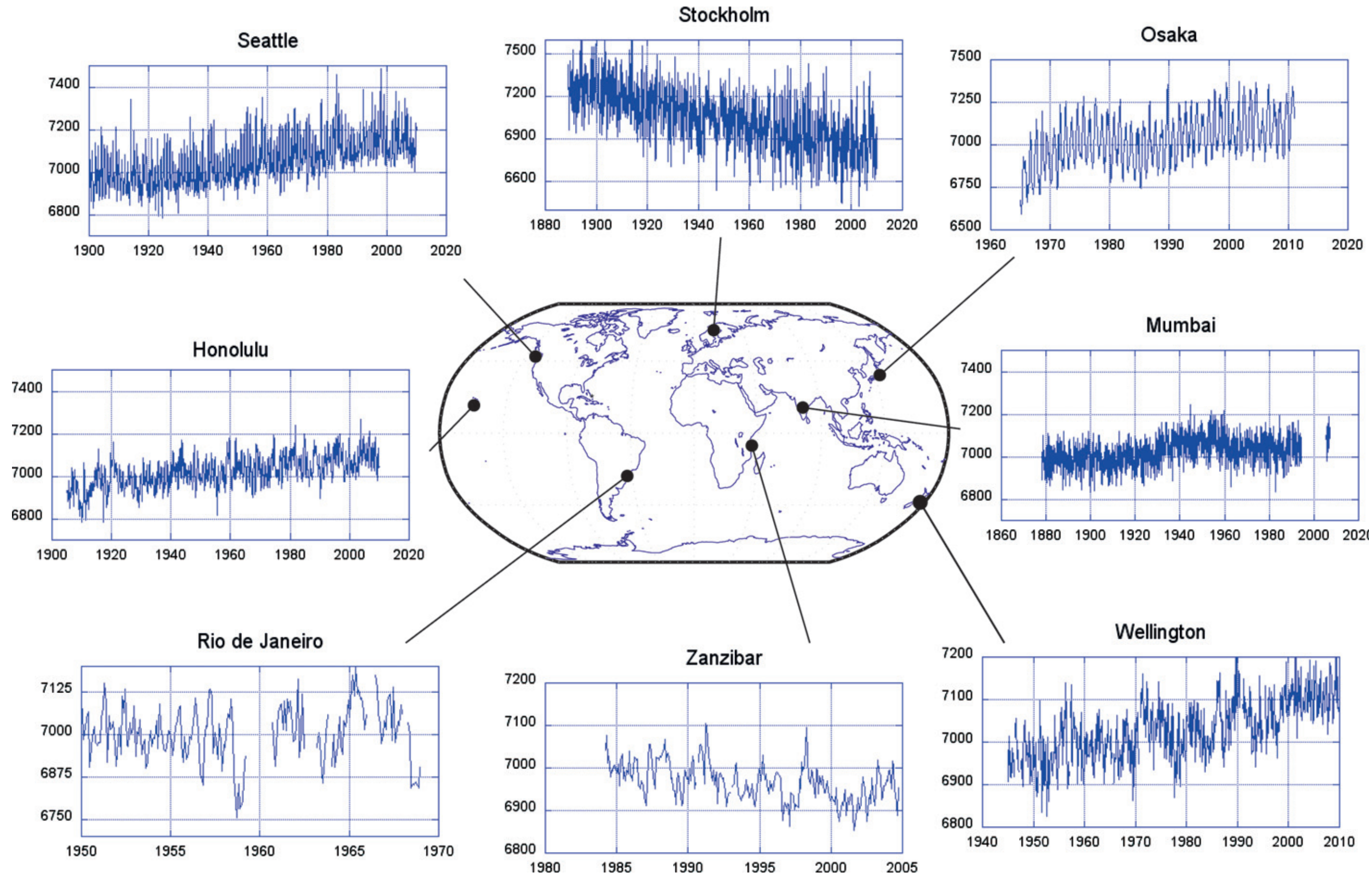

FIGURE 5.1 Observations of relative sea-level change from tide gauges for a number of cities. Note that the measurements at different locations started at different times. *Source: Permanent service for mean sea level (http://www.psmsl.org/) accessed March 2011.*

global sea level. The reason for the decrease in Stockholm is because the land itself has been rising faster than sea level in this period. The Scandinavian Peninsula is still rebounding after the disappearance of the ice sheet that covered it during the latest ice age.

Thermal Expansion/Density Changes

As the surface temperature of the Earth increases, some of the energy associated with the warming is transferred into the oceans. Recent advances in accounting for biases and multiple sources of uncertainty in measurements from *expendable bathythermographs (*XBTs—instruments that measure profiles of temperature in the ocean) have shown a significant warming trend of 0.64 W m^{-2} between 1993 and 2008 (Lyman et al., 2010). This amounts to a substantial increase in the heat content of the oceans, shown in Figure 5.2, taken from Trenberth (2010).

Given the huge volume of water in the oceans, even the small thermal expansion caused by heating water can result in substantial changes in sea level. The uppermost 4 m of the ocean can store as much heat as the entire atmosphere. Because of its large thermal inertia, it will take a very long time for the upper ocean to "lose" the energy now being stored there. Domingues et al. (2008)

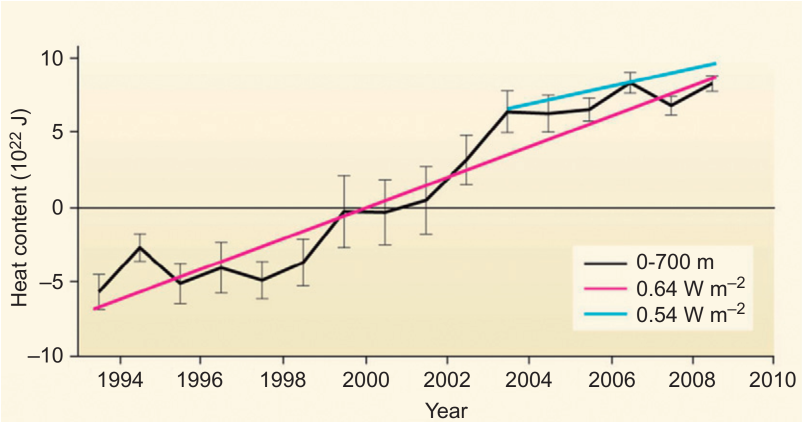

FIGURE 5.2 Time series of oceanic heat content from the surface to 700 m (Trenberth, 2010). *Reprinted with permission from* Nature.

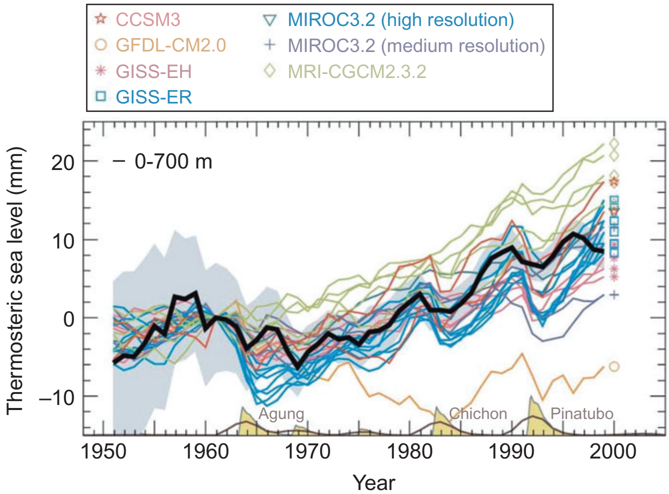

FIGURE 5.3 Observed and modeled global average thermal expansion of the upper 700 m of the ocean. *Adapted from Domingues et al. (2008).*

compared observations of the thermal expansion of ocean water with model calculations over the period 1950-2000 (shown in Figure 5.3).

Figure 5.3 shows changes in the thermosteric sea level (changes due to thermal expansion) over time from 1950 to 2000. In the figure, the thick black line shows the mean values derived from observations, and the gray-shaded area represents one standard deviation error estimates (Domingues et al., 2008). Results from several model calculations[1] are shown in the figure. All models include both natural variations (such as volcanic eruptions) and human-induced changes in the climate system. Stratospheric aerosol loadings from major volcanic eruptions (on an arbitrary scale) are shown at the bottom of the figure.

The observations show decadal-scale variability over the entire period and an upward trend since roughly 1970. Most of the models

[1] Models: National Center for Atmospheric Research, Boulder, CO (CCSM3); Geophysical Fluid Dynamics Laboratory, Princeton, NJ (GFDL-CM2.0); Goddard Institute for Space Studies in New York (GISS-EH, GISS-ER); Frontier Research Center for Global Change in Japan (MIROC-CGCM2.3.2 medium resolution, MIROC-CGCM2.3.2 high resolution); Meteorological Research Institute in Japan (MRI-CGCM2.3.2).

(CCSM3, GISS, MIROC3.2) capture both the trend and much of the interannual variability that is seen in the observations—though with more within- and between-model variation than is seen in the measurements. One model (the GFDL-CM2.0) does not show the same trend or interannual variability as the observations or the other models. The MRI-CGCM2.3.2 model does show an increasing trend in thermal expansion, but does not capture the same interannual variability that is seen in the observations.

While dipping perhaps a bit too deeply into details, this comparison illustrates a number of important points: (1) both observations and model calculations (with one exception) show that the oceans have been expanding due to heating over the 1950-2000 period; (2) there is clear interannual and decadal-scale variability in thermal expansion during this period; (3) the cooling effects of major volcanic eruptions can be seen in both measurements and model calculations; (4) while consistent with the observations, the differences between the various model calculations show that more work needs to be done to improve the descriptions of heat transport to and within the oceans.

Interestingly, both measurements and most of the models show decreases in thermal expansion following major volcanic eruptions—consistent with the observations of surface temperature and our understanding of how these volcanic eruptions influence the Earth's energy balance.

Glacier and Ice Sheet Melting

Freshwater is stored on the continents in the form of small glaciers and ice caps, as well as the very large ice sheets covering most of Greenland and Antarctica. While we take the major ice sheets for granted, they were not always present. The Antarctic ice sheet started to form around 35 million years before present, and the Greenland ice sheet "only" a few million years ago (Zachos et al., 2001) when atmospheric CO_2 concentrations decreased during the Late Pliocene era (Lunt et al., 2008). For the last few million years—during the period of human evolution—they have played a critical role in the Earth's climate. Currently, glaciers and ice sheets contain 29 million km^3 of ice (shown in Figure 5.4), mostly in Antarctica and Greenland.

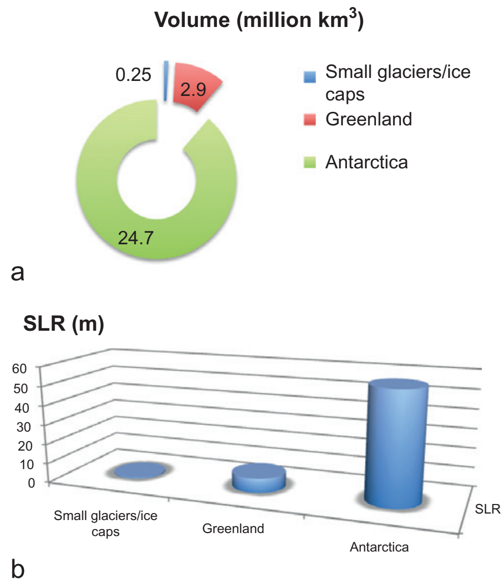

FIGURE 5.4 (a) Ice volume (10^6 km^3). (b) Sea-level rise if all ice were to melt.

Put into perspective, if all this ice were to melt, small glaciers and ice caps would cause sea level to rise by 0.6 m, the Greenland ice sheet would raise sea levels by 7.3 m, and melting all the ice on Antarctica would cause a 56.6-m increase in sea level (Steffen et al., 2010).

How rapidly the major ice sheets will respond to increases in global mean surface temperature remains unclear. Measurements of the gain or loss of ice mass in Greenland and Antarctica since the 1990s suggest that dynamical process other than simple melting has caused acceleration of the transport of water mass from the continents to the ocean. For example, meltwater can percolate down to the base of glaciers and act as a lubricant, causing the glaciers to flow more rapidly. Ice shelves (large expanses of ice partially floating on seawater but anchored to the land) act as a kind of cork, holding back the glaciers that feed into them. If they thin or break up (such as the Larsen B ice shelf in 2002—an area roughly the size of the US state of Rhode Island), then the glaciers flowing into them can flow faster, transferring ice into the oceans more rapidly. Were this trend to continue into the future, the response times of the major ice sheets would be more rapid than our previous estimates (Steffen et al., 2010).

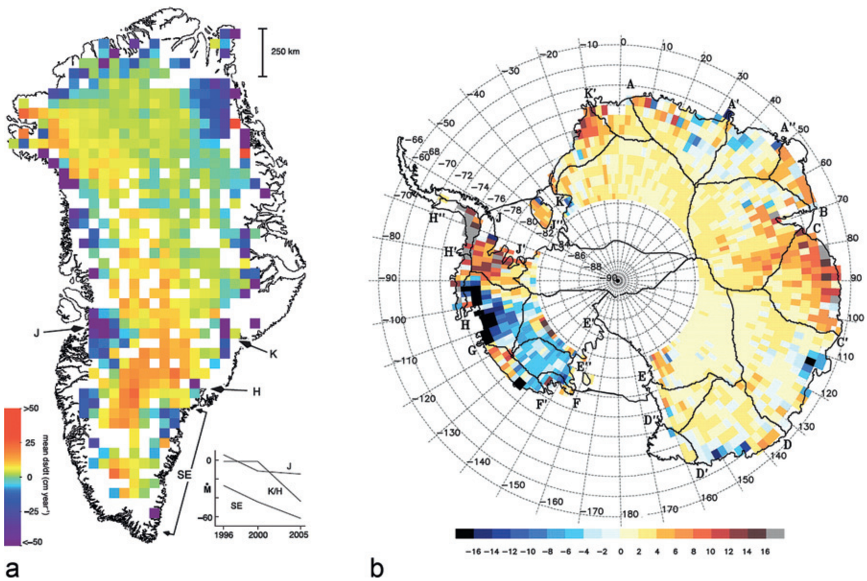

FIGURE 5.5 Change in elevation (cm year^{-1}) for (a) Greenland and (b) Antarctica. *Reprinted from Lemke et al. (2007) and Davis et al. (2005).*

Figure 5.5 shows satellite measurements of the change in elevation of the Greenland (panel a; Lemke, 2007) and the Antarctic ice sheets (panel b; Davis et al., 2005).

Both Greenland and Antarctica have areas that have gained mass and others that have lost. Greenland tends to increase in mass at the high-elevation center of the ice sheet and lose it at the edges, while Antarctica has gained mass in the eastern regions while losing it in the west. Gains in mass are caused by increases in precipitation, while losses are caused by melting or the physical flow of ice from the land into the ocean.

In terms of sea-level rise, it is the net gain or loss of mass that is important. Steffen et al. (2010) summarize the rate of mass loss for Greenland and Antarctica from a number of studies, examples of which are shown in Table 5.1.

For Greenland, the mass loss increased by a factor of 7 in the decade between the mid-1990s and the mid-2000s. For Antarctica, the ice loss nearly doubled in the same decade, almost entirely due to changes in West Antarctica and the Peninsula, with little change in East Antarctica.

TABLE 5.1 Mass Loss (Gt $Year^{-1}$) from Greenland and Antarctica for Different Time Periods

Time Period	Greenland	Time Period	East Antarctica	West Antarctica	Antarctic Peninsula
1994-1999	−27	1996-2004	+4(±61)	−106(±60)	−28(±45)
1998-2004	−80	1996		−86(±59)	
ca. 2000	−100	2006		−132(±60)	−60(±46)
ca. 2005	−200				

Melting glaciers also contribute to sea-level rise. Observations for over 300 glaciers around the world have been compiled and made available. An example of a global analysis from data in Dyurgerov and Meier (2005) is shown in Figure 5.6.

The left vertical axis in Figure 5.6 shows the yearly change in glacier volume. The right vertical axis is the cumulative contribution of glacier melting to relative sea level—effectively the sum over time of the amount of water in the oceans contributed by glacier melting, and how it influences relative sea level. There is clearly a lot of variability in glacier melt rates, and decreases in melt rate can be seen after major volcanic eruptions. Since 1960, melting glaciers have contributed more than 20 mm to sea-level rise. As can be seen in the "Summary" section, melting glaciers have been one of the largest contributors to sea-level rise.

Changes in Land Storage

The term *land storage* in this chapter refers to water stored on land in the form of snow, surface water (e.g., lakes, rivers, artificial reservoirs, marshes), or subsurface water (e.g., groundwater, liquid water trapped in soils, permafrost). Changes in land storage of water can be caused by changes in climate and by human modification of the land. Some of these human modifications are as follows:

- Damming of rivers
- Extraction of water from lakes

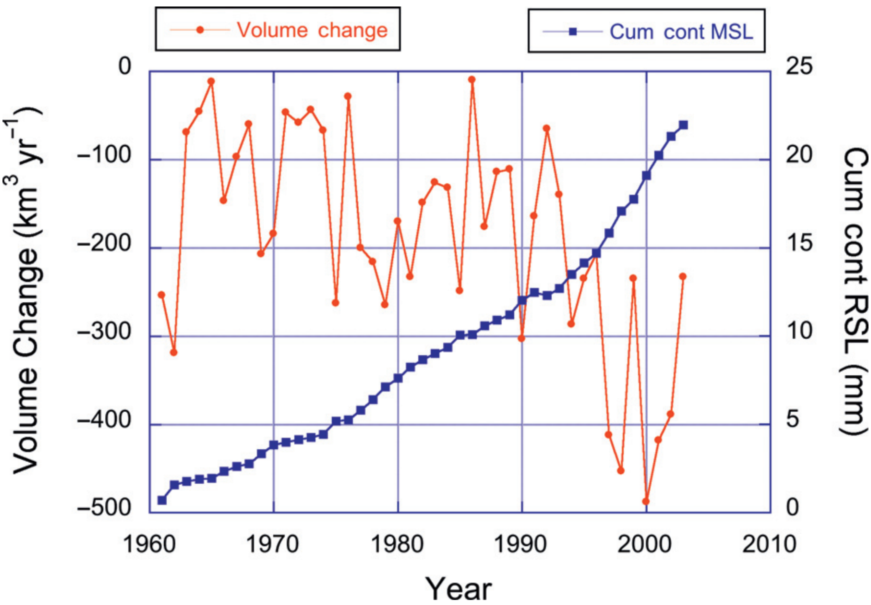

FIGURE 5.6 Time series of the change in volume (left vertical axis; km^3 year^{-1}) and the cumulative contribution to relative sea level (right vertical axis, mm) from small glaciers.

- Mining of groundwater
- Irrigation
- Wetland drainage
- Deforestation

Milly et al. (2010) provide a recent analysis of the contributions of terrestrial water storage to sea-level rise and variability. Their results are summarized in Figure 5.7.

Interestingly, the net effect of changes in land storage of water on sea-level rise is close to zero, since the major processes tend to cancel out each other (at least during the 1990s). The decrease in runoff to the oceans caused by damming rivers was balanced by the increase in flow from groundwater mining. Likewise, the decrease in flow from changes in snowpack, soil water, and shallow groundwater was offset by changes in storage in 15 of the world's largest lakes.

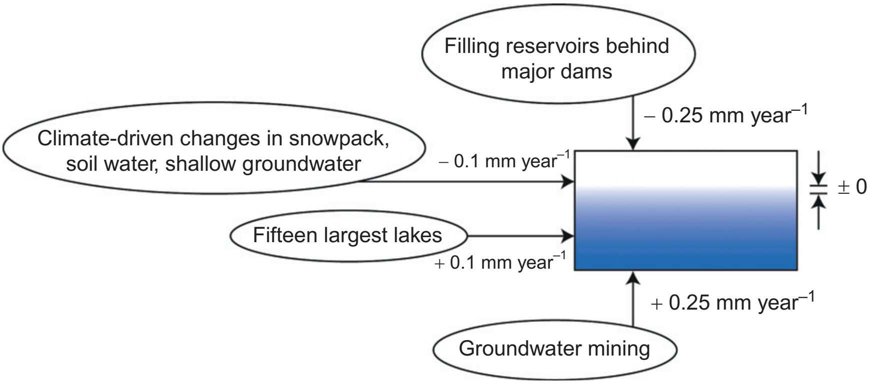

FIGURE 5.7 Estimated contributions from terrestrial water sources to sea-level change for the 1990s.

Summary

A considerable amount of research has been done over the last decades to measure and explain changes in global sea level. An overall picture was developed by Milly et al. (2010) from the IPCC 4th Assessment Report (Bindoff, 2007) and subsequent sources and is summarized in Table 5.2. Global mean sea level rose by approximately 1.8 mm year^{-1} over the last five decades, doubled to 3.1 mm year^{-1} in the 1990s, and was 2.5 mm year^{-1} in the period 2003-2007.

TABLE 5.2 Summary of the Sources of Sea-Level Rise for Three Different Time Periods

Source	**1961-2003 (mm Year^{-1})**	**1993-2003 (mm Year^{-1})**	**2003-2007 (mm Year^{-1})**
Observed change	1.8	3.1	2.5
Thermal expansion	0.4	1.6	0.35
Melting glaciers	0.5	0.8	1.1
Melting ice sheets	0.2	0.4	1
Land storage (liquid water)	–	0	–
Residual	0.7	0.3	0.1

The fractional contributions of the various sources to global sea-level rise are shown in Figure 5.8. The "residual" fraction is the difference between the observed sea-level rise rate and the sum of the four different sources. This can be interpreted as the "unexplained" amount of sea-level rise and is suspected to come primarily from melting of the large ice sheets in Greenland and Antarctica (Steffen et al., 2010). Panels (a)-(c) present data from Table 5.2 as fractions of the observed sea-level rise. Panel (d) is adapted from Domingues et al. (2008) and shows the different contributions to sea-level rise as a function of time for the period 1961-2003.

An intriguing result from these studies is the observation that the relative contributions of the various sources of sea-level rise change with time, and also that with time, the residual (unexplained) fraction has decreased—we have become better at quantifying the sources of sea-level rise. Thermal expansion of the upper 700 m of the oceans shows clear variability on 5- to 10-year timescales and can also be linked to volcanic eruptions. The contribution from liquid water from terrestrial sources (e.g., groundwater, lakes, marshes) is variable, but averages out to be roughly zero over this time interval. Glaciers and ice caps have been the dominant source of sea-level rise since about the late 1970s.

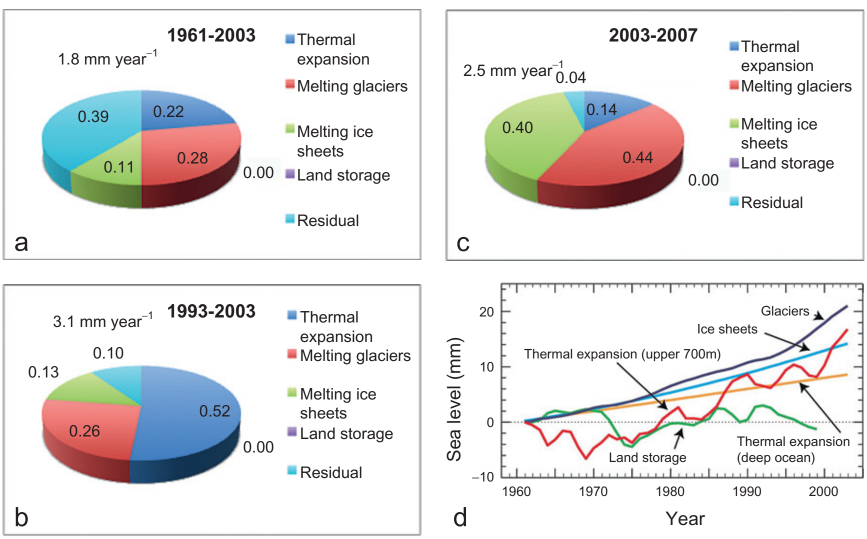

FIGURE 5.8 Sources of sea-level rise as a function of time. *Adapted from Steffen et al. (2010) and Domingues et al. (2008).*

OBSERVATIONS OF SEA-LEVEL RISE

Past Sea-Level Changes

When trying to understand how complex systems behave, it is a great advantage to have different independent sources of information on which to draw conclusions. In the following sections, two different, independent sets of observations of sea-level rise are described: direct measurements from tide gauges and remote-sensing measurements from satellites.

Direct Measurements: Tide Gauges

If observations from tide gauges around the world are put onto a consistent basis, a picture of the global mean sea-level rise can be obtained. Woodworth et al. (2009) compare five different time series of global sea-level rise derived from tide gauge measurements. Figure 5.9 shows two of these: the longer of the time series (back to 1700) comes from Jevrejeva et al. (2008), while the series from 1870 to 2007 is updated from Church and White (2006). Both investigations use the same underlying data (the Permanent Service for Mean Sea-Level compilation), but use different techniques for analysis.

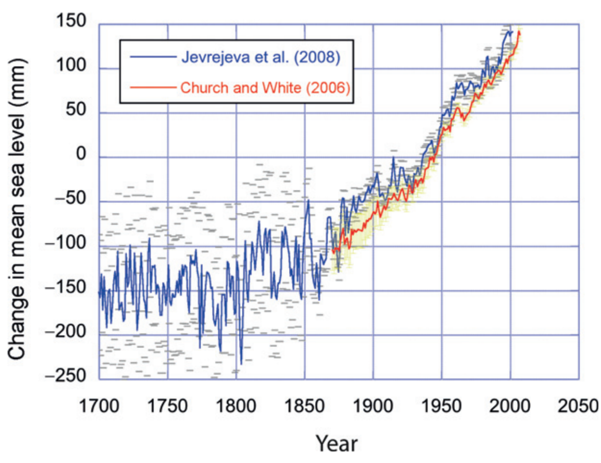

FIGURE 5.9 Changes in mean sea level derived from tide gauge data. Gray bars indicate uncertainties in the Jevrejeva et al. analysis; yellow bars for the Church and White analysis.

Both analyses show a consistent increase in sea level over the last two centuries, with an increase of about 250 mm between 1850 and 2000. For the entire twentieth century, the rate of sea-level rise was 1.7 ± 0.3 mm year^{-1} (Church and White, 2006). Sea level rose by 6 cm in the nineteenth century and by 19 cm in the twentieth century (Jevrejeva et al., 2008). The further back in time the data goes, the larger the uncertainties become. In their error analysis, Jevrejeva et al. (2008) account for both station representativity and between-region errors (Jevrejeva et al., 2006). Church and White (2006) account for serial correlation, uncertainties in corrections for glacial rebound, and uncertainties induced by the statistical method they used.

Satellite Measurements

Satellites provide another independent source of information on sea level, in addition to tide gauge measurements. However, reliable satellite measurements of global sea level did not become available until the early 1990s.

Figure 5.10 shows data from the TOPEX/Poseidon and Jason altimeters (Leuliette et al., 2004). Like the tide gauge data, the satellite observations show a clear upward trend in sea level, with year-to-year variability. The trend from the satellite observations over this period is 3.2 ± 0.8 mm year^{-1} (Leuliette and Willis, 2011).

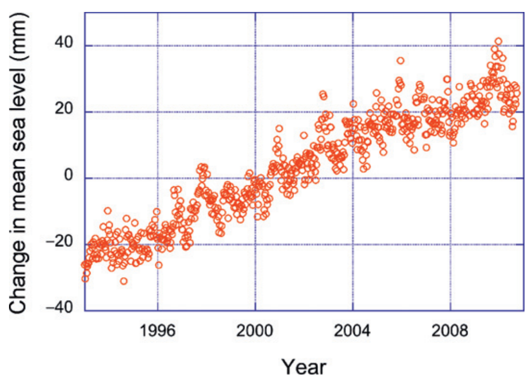

FIGURE 5.10 Changes in global mean sea level derived from satellite data available from the University of Colorado (http://sealevel.colorado.edu).

While global sea level is rising, the rate of sea-level rise depends on location. Figure 5.11 shows sea-level trends derived from a number of satellite instruments (Nicholls and Cazenave, 2010) for the period October 1992 to July 2009. There is a good deal of variability in the rate of sea-level rise in the Pacific, with maximum values in the western Pacific and minimum values in the eastern Pacific. The rate of sea-level rise at any given location will also vary with time. Despite the spatial and temporal variability, satellite measurements show a clear increase in globally averaged sea level, and together with the tide gauge measurements (corrected for GIA) tell us that sea-level rise has been accelerating.

Summary of Observations

A considerable amount of work has been done over the last decade to put observations of sea-level rise into a consistent framework. Direct measurements from tide gauges around the world have been analyzed; accounting for vertical land motion, the uneven spatial distribution of measurement sites and improvements in the statistical methods used to analyze the data have been made. New satellite instruments have provided an independent measure of sea level. A number of conclusions can be drawn from these observations:

- Independent measurements show that sea level is rising
- Sea levels have risen by about 250 mm since 1850
- Sea-level rise is accelerating

SEA LEVEL RISE IN THE FUTURE

Projections of Sea-Level Rise

Figure 5.12 shows four different projections for future sea-level rise. Panel (a) comes from the 3rd IPCC Assessment Report (AR3) (Church et al., 2001), panel (b) is from the 4th IPCC Assessment Report (AR4) (Meehl et al., 2007), panel (c) comes from Rahmstorf (2007), and panel (d) is taken from Church et al. (2008). The IPCC projections represent a consensus view at two different times (2001 and 2007) developed from a number of different

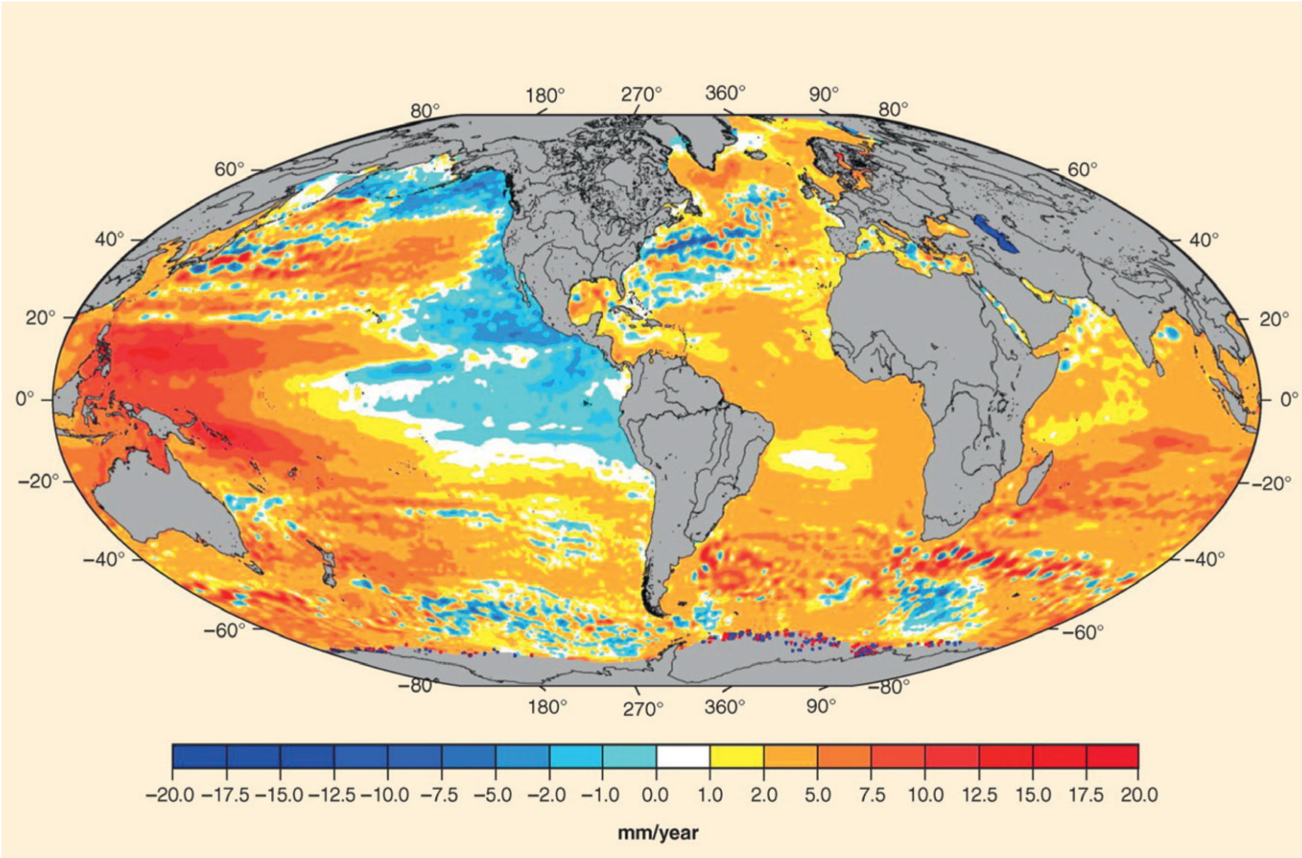

FIGURE 5.11 Rates of sea level derived from satellite measurements. *From Nicholls and Cazenave (2010), figure 2. © AAAS.*

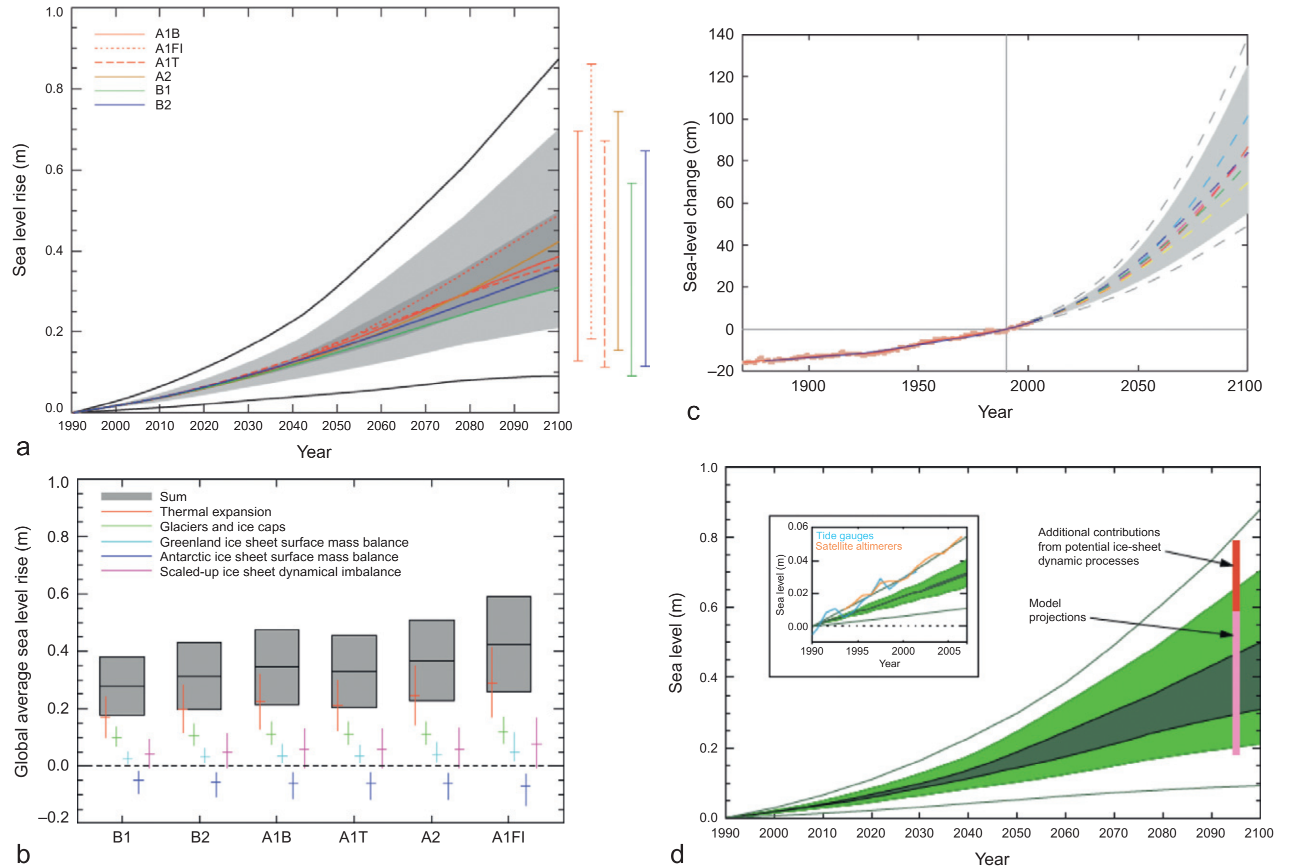

FIGURE 5.12 Four different projections of future sea-level rise: Panel (a): From Church et al. (2001), figure 11.12. © Cambridge University Press. Panel (b): From Meehl et al. (2007), figure 10.33. © Cambridge University Press. Panel (c): From Rahmstorf (2007), figure 4. © AAAS. Panel (d): From Church et al. (2008), figure 6. © Springer.

global climate models. The projections in Rahmstorf (2007) are made using a semiempirical approach using observed temperature and sea-level changes and projecting this observed relationship into the future. The Church et al. (2008) projections augment the IPCC work by adding an additional contribution from melting glaciers and ice caps in an attempt to account for observed melting that is currently not properly captured in climate models.

The intentions with presenting these figures together are to

1. show how better observations of and increased understanding about the causes of sea-level rise influence our ability to project changes into the future—learning more about how the system works allows for refinement of our predictions;
2. show that there is always a range of possibilities for future sea-level rise. This range depends on what assumptions are made about future population, demographics, technological and socioeconomic development, as well as different assumptions about how parts of the climate system work now and in the future.

Perhaps the greatest known source of uncertainty in projecting future sea-level rise is the extent to and rate at which melting glaciers, ice caps, and ice sheets will contribute in the future. The current rate of ice melt and flow of glacier ice into the ocean is not adequately captured in the climate models used in the IPCC assessments. If this current melting rate continues into the future, then the IPCC projections are likely to be underestimates. Another major uncertainty is estimating the rate at which ice flows from the continents (especially from Greenland and Antarctica) into the ocean. Like dropping an ice cube into a glass of water immediately raises the water level, transferring ice from land into the ocean will raise sea level even before the ice melts.

Three recent studies using semiempirical methods project intervals of sea-level rise by 2100 of 0.4-1 m (Horton et al., 2008), 0.9-1.3 m (Grinsted et al., 2010), and 0.6-1.6 m (Jevrejeva et al., 2010). Pfeffer et al. (2008) attempted to put an upper bound on how rapidly melting and ice flow into the ocean from Greenland could raise sea level. They concluded that sea-level rise of more than 2 m by 2100 was not tenable. A 2-m rise by 2100 was physically possible, but would require all of the variables influencing the

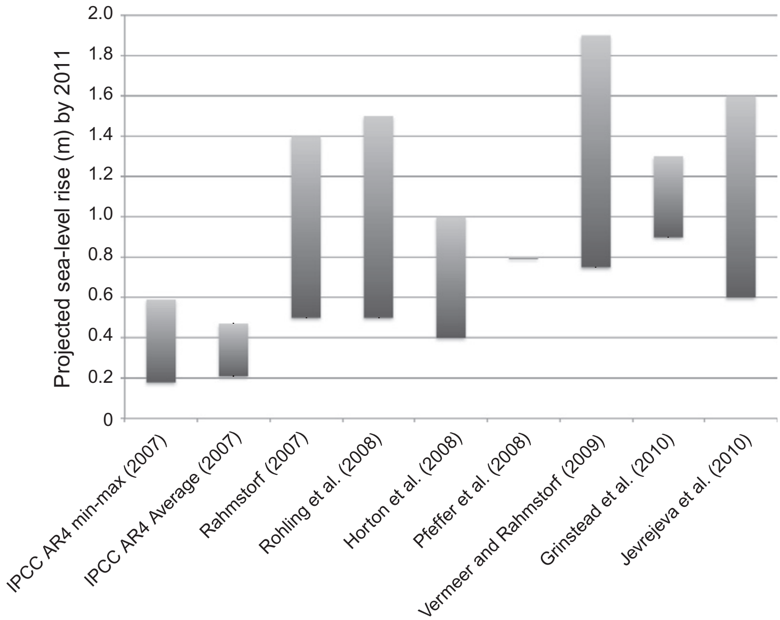

FIGURE 5.13 A summary of recent projections of sea-level rise.

melting or transport of ice into the ocean to be at their maximum values. They concluded that a more plausible value would be about 0.8 m. These results are summarized in Figure 5.13.

At this point, obtaining a very precise projection for sea level at the end of the century is beyond our abilities. The entire range of projections (from the IPCC AR3 and onwards) includes the interval from 0.2 to 2 m, with the central value for these projections increasing with time. Many of the post-IPCC AR4 projections rely on semi-empirical models, which have limitations when projecting past the interval in which data are available (Church et al., 2011; von Storch et al., 2008). Clearly, improved and more comprehensive observations of ice melt and flow are necessary, along with improvements of how these processes are described in climate models.

IMPACTS OF SEA-LEVEL RISE

Sea-level rise will impact all coastal areas, but to differing extents. It is an existential issue for some small island states, since some islands will disappear entirely with even modest increases in sea level. As of 1994, 1.88 billion people (33.5% of the world's population) lived within 100 vertical meters of sea level (Cohen and Small, 1998), and about 23% of the world's people live within 100 km of a coast (Nicholls et al., 2007). On a finer scale, Anthoff et al. (2006) estimate that about 145 million people live within 1 m of mean high water (more than 70% of whom are in Asia), and 268 and 397 million live within 5 and 10 m, respectively.

Types of Impacts

The physical impacts of sea-level rise include the following:

- The disappearance of some low-lying islands
- Submergence and increases flooding of coastal land
- Saltwater intrusion of surface and subsurface waters
- Increased erosion
- Habitat destruction in coastal areas

The effects, interacting factors, and possible adaptation approaches for these impacts have been summarized by Nicholls (2011) and are shown in Table 5.3.

The interacting factors include those related to climate change and others related more to land and resource management. In the table, the adaptation approaches are coded as protection (P), accommodation (A), and retreat (R). Examples of "hard" approaches are dikes, seawalls, and reinforced structures, while "soft" approaches include management, policy, and institutional considerations. These impacts will occur at different times, with impacts such as coastal erosion or habitat degradation often lagging inundation and flooding. These impacts will be exacerbated by the additional effects of extreme storms, discussed in Chapter 3. Rising sea levels will cause an increase in extreme water levels, which also will be increased if hurricane and severe storms become stronger.

Vulnerability to Sea-Level Rise

Nicholls and Cazenave (2010) examined the vulnerability of different regions to coastal flooding due to sea-level rise. The highest risk areas are coastal zones with high population density, low

TABLE 5.3 Impacts, Interacting Factors, and Possible Adaptation Approaches to Sea-Level Rise

Natural System Effect		Possible Interacting Factors		Possible Adaptation Approaches
		Climate	**Nonclimate**	
1. Inundation/ flooding	a. Surge (flooding from the sea)	Wave/storm climate, erosion, sediment supply	Sediment supply, flood management, erosion, land reclamation	Dikes/surge barriers/closure dams [P—hard], dune construction [P—soft], building codes/flood-proof buildings [A], land-use planning/hazard mapping/flood warnings [A/R]
	b. Backwater effect (flooding from rivers)	Runoff	Catchment management and land use	
2. Wetland loss (and change)		CO_2 fertilization, sediment supply, migration space	Sediment supply, migration space, land reclamation (i.e., direct destruction)	Nourishment/sediment management [P—soft], land-use planning [A/R], managed realignment/forbid hard defenses [R]
3. Erosion (of "soft" morphology)		Sediment supply, wave/storm climate	Sediment supply	Coast defenses/seawalls/land claim [P—hard], nourishment [P—soft], building setbacks [R]
4. Saltwater Intrusion	a. Surface waters	Runoff	Catchment management (overextraction), land use	Saltwater intrusion barriers [P], change water extraction [A/R]
	b. Groundwater	Rainfall	Land use, aquifer use (overpumping)	Freshwater injection [A], change water extraction [A/R]
5. Impeded drainage/higher water tables		Rainfall, runoff	Land use, aquifer use, catchment management	Drainage systems/polders [P—hard], change land use [A], land-use planning/hazard delineation [A/R]

From Nicholls (2011), Table 2. © The Oceanography Society.

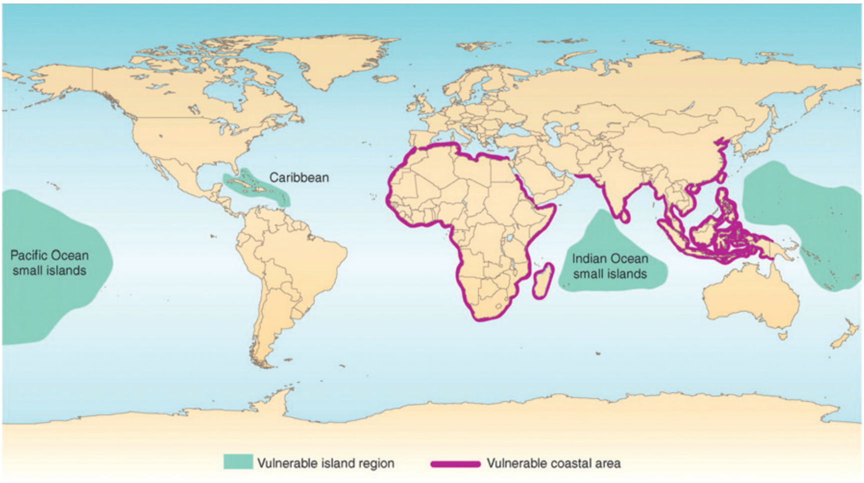

FIGURE 5.14 Regions vulnerable to flooding caused by sea-level rise. *From Nicholls and Cazenave (2010), figure 3. © AAAS.*

elevations, high rates of land subsidence, and limited adaptive capacity. Figure 5.14 is a map showing the locations of these vulnerable regions.

It is worthwhile to point out an important distinction in terms of trying to define vulnerability to sea-level rise; the impacts of sea-level rise are very asymmetrical in many important ways. For instance, there are fundamental differences in vulnerability between continental coastal locations and islands. In large, wealthy countries, coastal communities would at least in theory be able to relocate inland, given adequate preparation and support. In reality, however, relocating parts of any major coastal city would be an immense undertaking.

Such an option does not exist for some small island states, which may become uninhabitable or even entirely disappear. It is one thing to be forced to relocate within your own local region or country; it is another entirely to lose your country. In developing countries with very high populations in low-lying delta areas such as Bangladesh, sea-level rise may threaten the ability of the state to function (Byravan and Rajan, 2010).

Assessing the impacts of sea-level rise is a good example of the limitations of our current mainstream socioeconomic framework.

The monetary costs of paying to relocate a relatively small population of people from a disappearing island nation would be small compared to the costs of mitigating the cause of the relocation—increases in sea level due to global warming caused mostly by anthropogenic greenhouse gas emissions. However, the social costs of the loss of national identity and cultural history are not included in this monetary framework, but need to be accounted for.

How strongly these different impacts affect various socioeconomic sectors was examined by Nicholls (2011) and is shown in Table 5.4. Inundation and flooding affect all the socioeconomic sectors considered, while coastal erosion mainly influences infrastructure, tourism, and biodiversity, with weaker or not established impacts on other sectors.

Examples of health effects include the release of toxins from coastal landfills, increases in disease due to damaged coastal infrastructure such as sewers, or even mental health problems caused by

TABLE 5.4 The Strength of the Impact of Different Effects of Sea-Level Rise on Several Socioeconomic Sectors

Coastal Socioeconomic Sector	Sea Level Rise Natural System Effect (Table 5.1)				
	Inundation/ Flooding	**Wetland Loss**	**Erosion**	**Saltwater Intrusion**	**Impeded Drainage**
Freshwater resources	**X**	x	–	**X**	**X**
Agriculture and forestry	**X**	x	–	**X**	**X**
Fisheries and aquaculture	**X**	**X**	x	**X**	–
Health	**X**	**X**	–	**X**	x
Recreation and tourism	**X**	**X**	**X**	–	–
Biodiversity	**X**	**X**	**X**	**X**	**X**
Settlements/ infrastructure	**X**	**X**	**X**	**X**	**X**

X, strong; **x**, weak; –, negligible or not established.
From Nicholls (2011), table 2. © The Oceanography Society.

increased flooding. Aquaculture is an example of a socioeconomic sector adversely affected by several of the threats to the global oceans: sea-level rise, acidification, pollution, and hypoxia. It is very important to analyze the potential interactions between these effects and prepare strategies to deal with them (discussed in more detail in Chapter 12).

Economic Consequences of Sea-Level Rise

The economic impacts of sea-level rise will be discussed in detail in Chapter 10. The intention here is to present results from recent publications that illustrate the kinds of global-scale economic analyses that have been done and give an impression of the magnitude of the economic impacts.

People living in coastal areas close to sea level have essentially two choices about how to respond to increasing sea level: fight or flee. Fighting involves improving or building new coastal defenses—seawalls, dikes, and other built infrastructure. Fleeing involves relocating people from low-lying areas to higher ground. The choice is "simplified" for people living on some low-lying islands, since for them fighting is not an option.

Anthoff et al. (2010) examined the economic consequences of three different levels of sea-level rise: 0.5, 1, and 2 m above 2005 sea level. They use an integrated assessment model (FUND: The Climate Framework for Uncertainty, Negotiation, and Distribution), driven by four of the SRES[2] scenarios (A1, A2, B1, and B2) for socioeconomic and demographic development. They also use a control scenario in which population and GDP are kept constant at 1995 levels (C1995). In their simulations, they assume that sea level increases linearly with time until 2100.

They examine four damage components in their economic analysis: (1) the value of dryland lost; (2) the value of wetland lost; (3) the cost of protection (e.g., dikes) against rising sea levels; and (4) the cost of relocating people displaced from lost dryland. In their calculations, they assume that the number of people forced to migrate is a function of the average population density in each country and the area of dryland lost in that country. The economic

[2] Special Report on Emissions Scenarios; see Chapter 1.

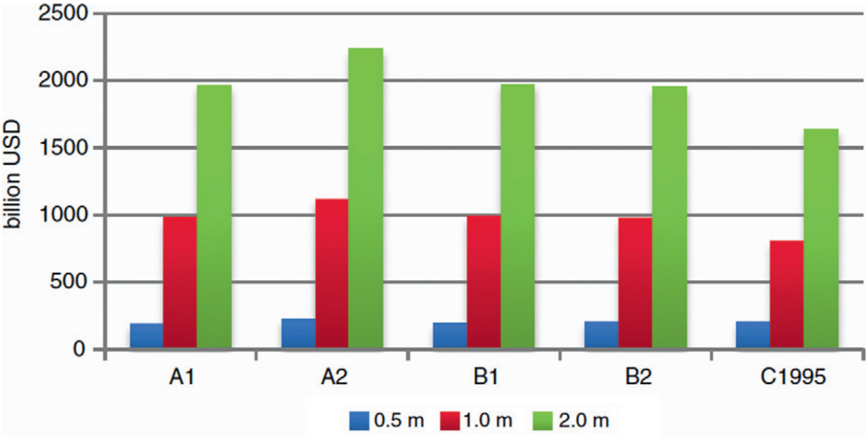

FIGURE 5.15 Total damage costs for 0.5, 1, and 2 m of sea-level rise for five different socioeconomic scenarios. *From Anthoff et al. (2010), figure 2. © Springer.*

cost of the people displaced is calculated as three times the average per capita income for the country in question. Figure 5.15 shows an example of their results.

With their assumptions, protection costs against a 0.5-m increase in sea level would be between about 170 and 200 billion USD. If sea level were to rise by 1 m, costs would become about five times as large, roughly 1 trillion USD. Costs would roughly double again to about 2 trillion USD if sea-level rise were 2 m. These costs can be compared with estimates of approximately 3 trillion USD in stimulus investments announced as a result of the economic downturn in 2008 (Robins et al., 2009a,b).

Looking "under the hood" in their calculations, protection costs are the most important component of total costs, independent of which socioeconomic scenario is chosen. Other costs vary more widely between scenarios. Furthermore, costs vary greatly between regions, with South Asia, South America, East Asia, North America, Europe, and Central America being the regions dominating total costs. As in most cost-benefit analyses for long-term issues, the results are sensitive to what discount rate is assumed. The central assumption for the pure time rate of preference in the Anthoff et al, (2010) calculations is 1%. They performed a sensitivity analysis assuming values of 0.1% and 3%, which showed that the results could be changed by roughly a factor of 2 up or down, depending on the discount rate assumed.

They conclude that the benefits of protection increase substantially with time. Compared to a scenario with no protection, substantial costs in terms of population displacement and land loss can be avoided through protection measures.

A weakness in cost-benefit analyses is that they assume perfect knowledge and a proactive approach to protection, while experience would tell us that protection is more often done in reaction to a disaster the near avoidance of a disaster. Recognizing this historical limitation is critical from the point of view of low-lying island states, since the protection option may well disappear along with the islands.

Summary and Take-Home Messages

- Globally averaged sea level has risen by about 25 cm since the 1800s
- Global sea-level rise is accelerating
- Sea-level rise is caused by melting glaciers and ice caps, loss of ice from major ice sheets on Greenland and Antarctica, thermal expansion of the oceans, and changes in terrestrial storage
- Projections of the amount of sea-level rise by the end of the twenty-first century vary from a minimum of roughly 0.2 m to a maximum of about 2 m
- The impacts of sea-level rise include the disappearance of some low-lying islands, submergence and increases flooding of coastal land, saltwater intrusion of surface and subsurface waters, increased erosion, and habitat destruction in coastal areas
- On a global scale, the costs of coastal protection and relocation of people from land areas lost to sea-level rise range from about 200 billion USD for an increase of sea level of 0.5 m and about 2 trillion USD for an increase of 2 m.
- Adaptation strategies for sea-level rise will need to be developed for local and regional conditions; how these are influenced by changes in global sea level must be taken into account.

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