Proceedings of the 2010 Land Policy Conference

# CLIMATE CHANGE AND LAND POLICIES

Edited by Gregory K. Ingram and Yu-Hung Hong

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LINCOLN INSTITUTE OF LAND POLICY
CAMBRIDGE, MASSACHUSETTS

*Library of Congress Cataloging-in-Publication Data*

Climate change and land policies /
edited by Gregory K. Ingram and Yu-Hung Hong.
p. cm.
Conference proceedings.
ISBN 978-1-55844-217-7
1. Land use, Urban—Congresses. 2. Climatic changes—Government
policy—Congresses. 3. Climatic changes—Environmental
aspects—Congresses. I. Ingram, Gregory K. II. Hong, Yu-Hung.
HD1391.C64 2011
333.73'13—dc22 2011003415

*Designed by Vern Associates*

Composed in Sabon by Achorn International in Bolton, Massachusetts.
Printed and bound by Puritan Press Inc., in Hollis, New Hampshire.
♻ The paper is Rolland Enviro100, an acid-free, 100 percent PCW recycled sheet.

MANUFACTURED IN THE UNITED STATES OF AMERICA

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# *Sea-Level Rise and Coastal Zone Management*

Robert J. Nicholls

Sea-level rise has been seen as a major threat to low-lying coastal areas around the globe since the issue of human-induced global warming emerged in the 1980s (Barth and Titus 1984; Milliman, Broadus, and Gable 1989; Warrick, Barrow, and Wigley 1993). An extensive and growing literature demonstrates that the potential impacts of sea-level rise are large (Dasgupta et al. 2009; Mimura et al. 2007; Nicholls et al. 2007). Further, coasts are already exposed to multiple hazards, including storms and storm-induced flooding (Kron 2008). More than 200 million people are vulnerable to flooding during extreme sea-level events, with as many as 20 million people living below normal high-tide levels (Nicholls 2010). This threatened population will grow substantially in the coming decades due to increasing population, especially if the strong tendency for coastward migration continues. These areas already depend on flood risk management strategies of some type, such as natural and/or artificial flood defenses and drainage systems. Hurricane Katrina's impacts on New Orleans in 2005 reminded us of what can happen in low-lying areas if those defenses fail. Rising sea levels and more intense storms will only exacerbate those risks.

Despite these threats, the actual consequences of sea-level rise remain uncertain and contested. This controversy reflects more than just uncertainty about the magnitude of sea-level rise and climate change; it also reflects uncertainty about the implementation of adaptation policies and their potential success or failure (Nicholls and Tol 2006).

This chapter focuses on understanding the threat of sea-level rise and its implications, including the two types of responses that can be implemented:

- Mitigation—reducing greenhouse gas emissions and increasing carbon sinks, thus minimizing climate change, including sea-level rise, via climate policy.
- Adaptation—reducing the impacts of sea-level rise via behavioral changes, from individual actions to collective coastal management policies, including upgraded defense systems, warning systems, and land management approaches.

Given the uncertainties about sea-level rise, both optimistic and pessimistic perspectives on the implications are considered here (Anthoff, Nicholls, and Tol 2010; Nicholls and Tol 2006).

## *Global-Mean and Relative Sea-Level Rise*

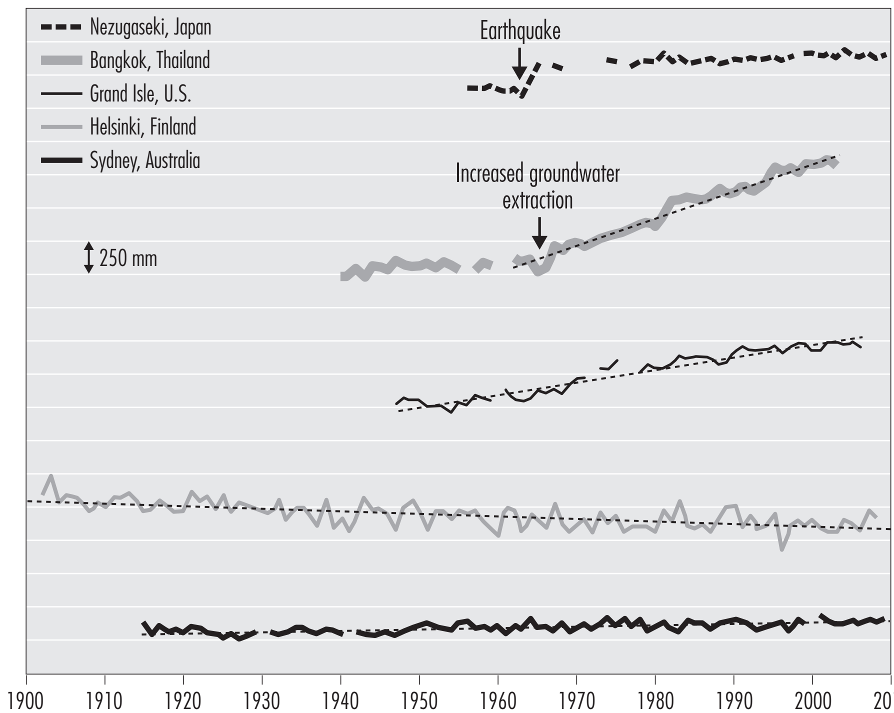
Human-induced climate change is expected to cause profound coastal effects, including rising sea levels; rising sea-surface temperatures; and changing storm, wave, and runoff characteristics (Nicholls et al. 2007; Nicholls, Wong, et al. 2008). Here we focus on climate-induced sea-level rise, which is mainly produced by (1) the thermal expansion of seawater as it warms; and (2) the melting of land-based ice, including (a) small glaciers; (b) the Greenland ice sheet; and (c) the West Antarctic ice sheet (Meehl et al. 2007). Although higher sea levels will have a direct impact only in coastal zones, these are the most densely populated and economically active land areas on earth (McGranahan, Balk, and Anderson 2007; Sachs, Mellinger, and Gallup 2001), and they also support important and productive ecosystems that are sensitive to sea-level rise (Crossland et al. 2005; Kremer et al. 2004).

A rising global-mean sea level of 1.7 mm/yr was observed throughout the twentieth century, but this rise appears to have accelerated to more than 3 mm/yr, with the main sources of the acceleration being the thermal expansion of seawater and the melting of small glaciers, although the Greenland ice sheet has become a more important source in the past few decades (Meehl et al. 2007; Nicholls and Cazenave 2010). This rise is likely to continue to accelerate through the twenty-first century. For instance, the Intergovernmental Panel on Climate Change (IPCC) has forecast a total sea-level rise in the range of 18–59 cm (7–23 in.) between 1990 and 2100 (Meehl et al. 2007). However, as noted most explicitly in the IPCC synthesis report (IPCC 2007), the quantitative scenarios do not provide an upper bound on global sea-level rise due to uncertainty concerning the large ice sheets. A global rise exceeding 1 m (3.28 ft.) is plausible but unlikely (Nicholls and Cazenave 2010; Nicholls et al. 2011). In the United Kingdom, a new scenario predicting a rise of up to 2 m (6.6 ft.) by 2100 has been developed by Lowe et al. (2009) for impact and adaptation assessment purposes. Although this high-end scenario is of low probability, its large potential impacts make it highly significant in terms of climate risks and policy. There is also increasing concern about higher extreme sea levels due to more intense storms, especially tropical storms (Meehl et al. 2007). This would exacerbate the impacts of global sea-level rise.

When analyzing sea-level rise impacts and responses, it is fundamental that impacts are a product of relative (or local) sea-level rise rather than global-mean sea-level rise. Relative sea-level rise (RSLR) takes into account the sum of global, regional, and local components. The underlying drivers of these components are (1) climate change, as already discussed, and changing ocean dynamics; and (2) nonclimate uplift/subsidence processes, such as tectonic movements, glacial isostatic adjustment, and natural and anthropogenic-induced subsidence (Church et al. 2010; Emery and Aubrey 1991). Hence, RSLR is only partly a result of climate change and varies from place to place, as illustrated by figure 3.1.

Many of the world's coastlines are experiencing a slow RSLR (see Sydney in figure 3.1), but abrupt changes due to earthquakes can occur at tectonically

**Figure 3.1**
**Selected Relative Sea-Level Records Since 1900**




Note: Helsinki shows a falling trend (–2.0 mm/yr [0.08 in./yr]); Sydney shows a gradual rise (0.9 mm/yr [0.04 in./yr]); Grand Isle is on a subsiding delta (9.3 mm/yr [0.37 in./yr]); Bangkok includes the effects of human-induced subsidence (20.7 mm/yr [0.83 in./yr] during 1962–2003); and Nezugaseki shows an abrupt rise of about 20 cm (7.87 in.) due to an earthquake in 1964.
Source: Permanent Service for Mean Sea Level, National Oceanography Centre, Liverpool, U.K.

active sites (see Nezugaseki in figure 3.1). In some high-latitude locations, such as the northern Baltic Sea and Hudson Bay, that were sites of large (kilometer-thick) glaciers during the last glacial maximum (18,000 years ago), relative sea level is actually falling due to ongoing glacial isostatic adjustment (rebound) (see Helsinki in figure 3.1). In contrast, RSLR is occurring more rapidly than global-mean trends indicate on subsiding coasts, especially deltas (see Grand Isle, in the Mississippi Delta, in figure 3.1) (Ericson et al. 2006; Syvitski et al. 2009; Woodroffe et al. 2006). Figure 3.2 shows the relative vulnerability of delta regions.

Most dramatically, human-induced subsidence of susceptible areas due to drainage and withdrawal of groundwater can produce dramatic RSLR. Subsidence in coastal cities built on deltaic land has been dramatic (IGES 2007; Milliman and Haq 1996). Over the twentieth century, for example, *parts* of Tokyo and Osaka subsided up to 5 m (16.4 ft.) and 3 m (9.8 ft.), respectively; a large part of Shanghai subsided up to 3 m (9.8 ft.); and Bangkok subsided up to 2 m (6.6 ft.).[1] This human-induced subsidence can be mitigated by stopping shallow subsurface fluid withdrawals, but the natural (background) subsidence will continue. Tokyo, Osaka, Shanghai, and Bangkok have all employed such mitigation policies, as well as adding flood defenses and updated drainage systems to avoid submergence and frequent flooding.[2] In contrast, Jakarta and metropolitan Manila are subsiding cities where little systematic action to manage and reduce subsidence has taken place (Rodolfo and Siringan 2006; Ward et al. 2010). Without a broader effort to share experience, the problems of enhanced subsidence are likely to be widely repeated throughout this century in susceptible expanding cities, especially those in Asia (Nicholls, Hanson, et al. 2008). More widely, most populated deltaic areas are threatened by enhanced subsidence to varying degrees (Ericson et al. 2006; Syvitski et al. 2009).

Taking an optimistic view, sea level will continue to rise during the twenty-first century, but not by very much—less than 50 cm (19.5 in.). Taking a pessimistic view, sea-level rise may be much larger—greater than 1 m (3.28 ft.)—and will be exacerbated by other climate and nonclimate stresses, such as subsidence in deltas.

Researchers are fairly certain that global sea-level rise will continue beyond the twenty-first century, irrespective of future greenhouse gas emissions (Nicholls and Lowe 2006). This is because it takes centuries to millennia for the full ocean depth to adjust to surface warming, resulting in ongoing thermal expansion. This inevitable rise is often referred to as the "commitment to sea-level rise." If global

1. The maximum subsidence is reported. Data on average subsidence are not available.

2. In Bangkok, subsidence declined in the city center from 1981 to 2002 due to changes in groundwater withdrawals, but it continued to accelerate, though to a lesser degree, in the surrounding area (Phien-Wej, Giao, and Nutalaya 2006). Hence, while presented as a success story in managing subsidence, the problem of subsidence in Bangkok has evolved rather than being completely solved.

**Figure 3.2**
Relative Vulnerability of Deltas to Present Rates of Relative Sea-Level Rise, to 2050 (units: displaced people)


Source: Nicholls et al. (2007), using data from Ericson et al. (2006).

warming exceeds key and still somewhat uncertain thresholds for the irreversible breakdown of the Greenland or West Antarctic ice sheets, the committed rise could be 13–15 m (42.6–49.2 ft.), albeit over long timescales (centuries or longer).

## *Sea-Level Rise and Resulting Impacts*

The five main effects of RSLR are summarized in table 3.1. Along with rising sea levels come changes in all the processes that operate in coastal zones. The immediate effects are inundation, also called submergence, and increased flooding of coastal land, as well as saltwater intrusion into surface waters. Longer-term effects occur as the coast adjusts to the new environmental conditions, including wetland loss and change in response to higher water tables and increasing salinity, erosion of beaches and soft cliffs, and saltwater intrusion into groundwater. Over time, these longer-term changes interact with the immediate effects of sea-level rise and generally exacerbate them. For instance, coastal erosion tends to degrade or remove natural protective features (e.g., salt marshes, mangroves, and sand dunes), which increases the impact of extreme water levels and hence the likelihood of coastal flooding. Inundation, wetland loss, and erosion have received significantly more research attention than saltwater intrusion and higher water tables.

Rising global-mean sea levels also result in an increase in extreme water levels. Likewise, changes in storm characteristics caused by global warming could influence extreme water levels. For example, the widely debated increase in the intensity of tropical cyclones would generally raise extreme water levels in areas such as the East and Gulf coasts of the United States (Meehl et al. 2007). Extratropical storms also may intensify in some regions. Extreme sea-level rise is an important topic that requires more research.

Changes in natural systems resulting from sea-level rise can have many socioeconomic impacts on a range of sectors, as shown in table 3.2. These impacts are overwhelmingly negative. For instance, flooding can damage coastal infrastructure (e.g., ports, industry, and the built environment) and agricultural areas, and in the worst case can lead to significant mortality, as seen in Hurricane Katrina in the United States (2005), Cyclone Nargis in Myanmar (2008), and Storm Xynthia in France (2010). Erosion can lead to loss of the built environment and related infrastructure and have adverse consequences for tourism and recreation. In addition to these direct impacts, there are also potential indirect impacts, such as adverse effects on human health. For example, toxins may be released from eroded landfills and waste sites, which are commonly located in low-lying coastal areas, especially around major cities (Flynn et al. 1984), and mental health problems may increase after an extreme environmental event such as a flood (Few et al. 2004). Although these indirect impacts have received little research attention, they can have large economic consequences in terms of both the damages caused and the investment needed to fund adaptation projects to prevent them.

**Table 3.1**
The Five Main Natural-System Effects of Relative Sea-Level Rise and Possible Adaptation Approaches

| **Natural-System Effect** | | **Possible Interacting Factors** | | **Possible Adaptation Approaches** |
|---|---|---|---|---|
| | | **Climate** | **Nonclimate** | |
| 1. Inundation (flood and storm damage) | a. Surge (flooding from the sea) | Wave/storm climate<br>Erosion<br>Sediment supply | Sediment supply<br>Flood management<br>Erosion<br>Land reclamation | Dikes/surge barriers [P]<br>Building codes/flood-resilient buildings [A]<br>Land use planning/hazard delineation [A/R] |
| | b. Backwater effect (flooding from rivers) | Runoff | Catchment management<br>Land use | |
| 2. Wetland loss (and change) | | $CO_2$ fertilization<br>Sediment supply<br>Migration space | Sediment supply<br>Migration space<br>Land reclamation (direct destruction) | Land use planning [A/R]<br>Managed realignment/forbid hard defenses [R]<br>Sand nourishment/sediment management [P] |
| 3. Coastal erosion | | Sediment supply<br>Wave/storm climate | Sediment supply | Coast defenses [P]<br>Sand nourishment [P]<br>Building setbacks [R] |
| 4. Saltwater intrusion | a. Surface water | Runoff | Catchment management (overextraction)<br>Land use | Saltwater intrusion barriers [P]<br>Change water abstraction [A/R] |
| | b. Groundwater | Rainfall | Land use<br>Aquifer use (overpumping) | Freshwater injection [P]<br>Change water abstraction [A/R] |
| 5. Higher water table/impeded drainage | | Rainfall<br>Runoff | Land use<br>Aquifer use<br>Catchment management | Upgraded drainage systems [P]<br>Polders [P]<br>Change land use [A]<br>Land use planning/hazard delineation [A/R] |

P = protection; A = accommodation; R = retreat.
Notes: Some interacting factors (e.g., sediment supply) appear twice, as they can be influenced by both climate and nonclimate factors.
Source: Adapted from Nicholls (2010).

**Table 3.2**
Sea-Level Rise Impacts on Socioeconomic Sectors in Coastal Zones

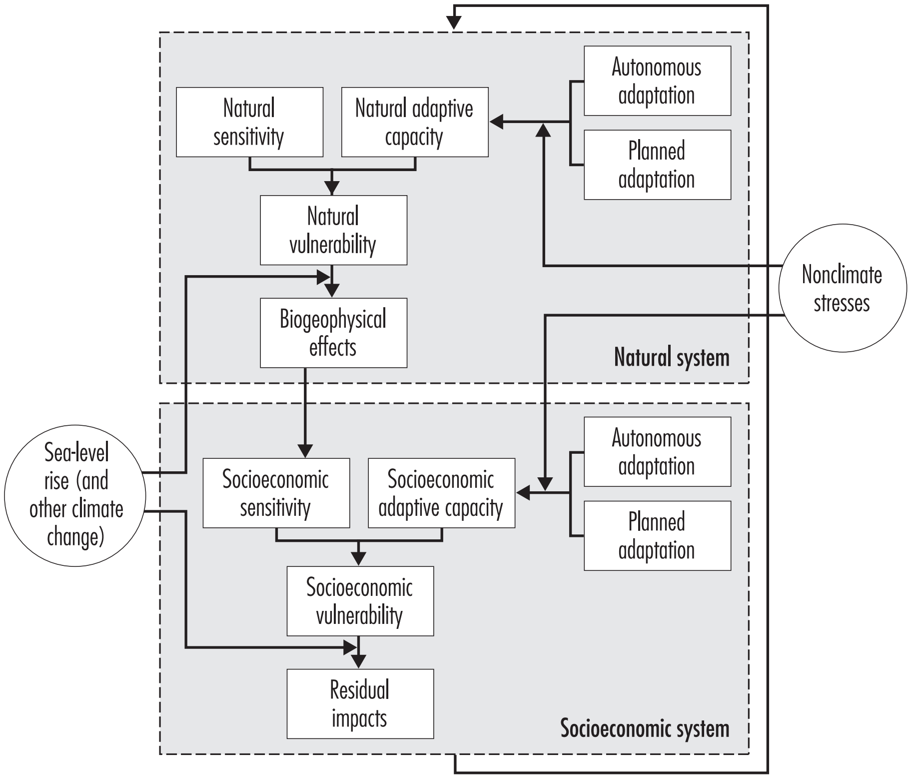
| Coastal Socioeconomic Sector | Sea-Level Rise Natural-System Effect[a] | | | | |
|---|---|---|---|---|---|
| | Inundation (flood and storm damage) | Wetland Loss | Erosion | Saltwater Intrusion | Rising Water Table/ Impeded Drainage |
| Freshwater resources | X | x | — | X | X |
| Agriculture and forestry | 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 |

[a]See table 3.1.
X = strong; x = weak; — = negligible or not established.
Note: These impacts are overwhelmingly negative.
Source: Adapted from Nicholls et al. (2007).

Clearly, coastal zones are changing significantly due to both climate and nonclimate drivers (Crossland et al. 2005; Nicholls et al. 2008; Valiela 2006), as shown in table 3.1. Potential interactions between these two types of drivers need to be considered when assessing sea-level rise impacts and responses. For instance, a coast receiving a significant sediment supply may not erode given sea-level rise, but one that is losing sediment will erode even with stable sea levels (Stive, Cowell, and Nicholls 2009). These kinds of problems require an integrated assessment approach to analyze the full range of interacting drivers and to provide feedback concerning policy interventions (adaptation). Figure 3.3 presents a systems model of the impacts of sea-level rise on coastal zones. This model characterizes the coast as comprising various interacting natural and socioeconomic systems, which have the potential to constrain one another's evolution. Sea-level rise is only one aspect of climate change that could interact with nonclimate stresses to produce coastal impacts.

The socioeconomic system influences the natural system through unintended and deliberate changes, including adaptation. *Autonomous adaptation* represents spontaneous adaptive responses to sea-level rise (e.g., increased vertical accretion of coastal wetlands within the natural system or market price adjustments within the socioeconomic system). *Planned adaptation* can reduce vulnerability via a range of anticipatory or reactive measures. Adaptation normally reduces the magnitude of impacts, hence impact assessments that do not take autonomous and planned adaptation into account will generally predict larger

**Figure 3.3**
A Conceptual Framework for Coastal Impact and Vulnerability Assessment of Sea-Level Rise



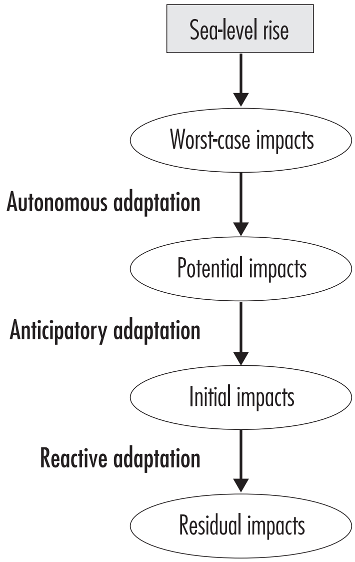

Source: Adapted from Klein and Nicholls (1999).

impacts—called worst-case or potential impacts—rather than initial or residual impacts (see figure 3.4).

## *Recent Impacts of Sea-Level Rise*

During the twentieth century, global-mean sea level rose about 17 cm (6.6 in.). This rise may seem small, but it had many significant effects, particularly in terms of reducing the return period of extreme water levels (Menéndez and Woodworth 2010; Zhang, Douglas, and Leatherman 2000) and promoting the erosive tendency of coasts, as widely observed (Bird 1985, 2000). However, quantitatively linking sea-level rise to impacts is quite difficult, as coastal zones have been subjected to multiple drivers of change over the past century (Nicholls, Woodroffe, and Burkett 2009).

**Figure 3.4**
Different Stages of Adaptation and Their Influence on Impacts




Good data on rising sea levels are available for only a few locations, and flood defenses have in some cases been upgraded substantially, especially in those (wealthy) places where sea level has been measured. Most of the upgrades reflect expanding populations and wealth in these coastal floodplains and changing attitudes toward risk; RSLR may not even have been considered in their design (Tol, Klein, and Nicholls 2008).

In general, erosion can be promoted by processes other than sea-level rise (see table 3.1), and human reduction in sediment supply to the coast due to coastal defenses and river dams must contribute to the observed changes and probably dominates in many locations, as noted by Bird (1985) and Syvitski et al. (2009). A decline in intertidal habitats, such as salt marshes, mudflats, and mangroves, is often linked to sea-level rise, but these systems are also subject to other drivers of change, including direct destruction (Coleman, Huh, and Braud 2008; Hoozemans, Marchand, and Pennekamp 1993). Therefore, while global sea-level rise was a pervasive process in the twentieth century, other processes obscure its link to impacts, except in some special cases.

There have certainly been impacts from subsidence resulting from RSLR, such as in the iconic World Heritage site: Venice (Fletcher and Spencer 2005). In the Mississippi Delta, where RSLR is 5–10 mm (0.2–0.4 in.) per year, between 1978 and 2000, 1,565 km$^2$ (610 sq. mi.) of intertidal coastal marshes and adjacent land were converted to open water due to a range of changes including a combination of RSLR, sediment starvation, and increases in salinity and water levels resulting from human development (Barras et al. 2003). By 2050 about 1,300 $km^2$ (507 sq. mi.) of additional coastal land loss is projected if current global, regional, and local processes continue at the same rate. There are significant actual and potential impacts of RSLR in deltas (see figure 3.2) and in and around subsiding coastal cities (see figure 3.3), including increased waterlogging, flooding, and submergence, and the resulting need for management responses (Nicholls 1995; Rodolfo and Siringan 2006).

In terms of lessons for adaptation, nearly all the major developed areas that have been impacted by RSLR have been defended and continue to grow economically and in population, even in cases where the change in RSLR was several meters over several decades. New Orleans may be an exception (Grossi and Muir-Wood 2006). Its population peaked in 1965, immediately before Hurricane Betsy flooded part of the city. By 2005, before Hurricane Katrina hit, its population was about 500,000, but it has yet to return to that level, even though about US$15 billion has been invested to significantly upgrade the city's defenses. The future of New Orleans will be instructive: can it prosper behind the new defenses, or will it continue the decline that started in 1965?

In other, less developed areas, coastal retreat has been allowed to occur. Around Galveston Bay in Texas, for example, subsidence of up to 3 m (9.8 ft.) took place during the twentieth century, and the San Jacinto Battleground State Historic Site, where Texas won its independence from Mexico in 1836, is now partially submerged. Similarly, the site of Jamestown, Virginia, has experienced slow subsidence, albeit over four centuries and with no human-induced component to it.

Observations during the twentieth and early twenty-first centuries reinforce the importance of understanding the impacts of sea-level rise in the context of multiple drivers of change. This will continue to be true under more rapid rises in sea levels. Human-induced subsidence is of particular interest, but this remains relatively unstudied in a systematic sense. Observations also emphasize the ability to protect against RSLR, especially in the most densely populated areas, such as Asian megacities and locations around the southern North Sea, including London, The Netherlands, and Hamburg, Germany. Optimists might be encouraged by the fact that it is more difficult to detect the signature of global-mean sea-level rise on impacts observed in these areas, but pessimists will point out the scale of current coastal problems, which any acceleration in sea-level rise will only exacerbate.

## *Future Impacts of Sea-Level Rise*

The future impacts of sea-level rise will depend on a range of factors, including (1) the magnitude of sea-level rise; (2) the level and manner of coastal development; and (3) the success (or failure) of adaptation. Assessments of the future impacts of sea-level rise have taken place on a range of scales from local to global. They all suggest potentially large impacts consistent with those listed in table 3.1, especially increases in inundation. Based on a synthesis of results from analyses such as Dasgupta et al. (2009); Nicholls (2004); and Nicholls, Hoozemans, and Marchand (1999), East, Southeast, and South Asia and Africa appear to be most threatened by sea-level rise (see figure 3.5). Vietnam and Bangladesh may be especially threatened due to their large populations living in low-lying deltaic plains. In Africa, Egypt and Mozambique are two potential hot spots for impacts resulting from sea-level rise. Hot spots also exist in South America, in Guyana, Suriname, and French Guiana. There will be significant residual risks in other coastal areas of the world as well, such as around the southern North Sea, and major flood disasters are possible in many of these regions. Small islands in the Pacific Ocean, Indian Ocean, and Caribbean Sea stand out as being especially vulnerable to sea-level rise impacts (Mimura et al. 2007). The populations of low-lying island nations such as the Maldives and Tuvalu face the real prospect of increased flooding, submergence, and forced abandonment.

## REGIONAL AND GLOBAL ASSESSMENTS

***Coastal Flooding*** In 1990 it was estimated that about 200 million people, or about 4 percent of the world's population, lived in hazard zones (below the 1-in-1,000-year floodplain) (Nicholls, Hoozemans, and Marchand 1999). Based on estimates of defense standards, on average 10 million people per year experienced coastal flooding (see table 3.3). These numbers will change over the next century due to the competing influences of RSLR, changes in coastal population, and improving defense standards as people become wealthier (Nicholls, Hoozemans, and Marchand 1999). In table 3.3, it is assumed that extreme water levels rise with RSLR (assuming constant storm characteristics). The analysis here is designed to explore the impacts of global-mean sea-level rise if it is largely ignored.

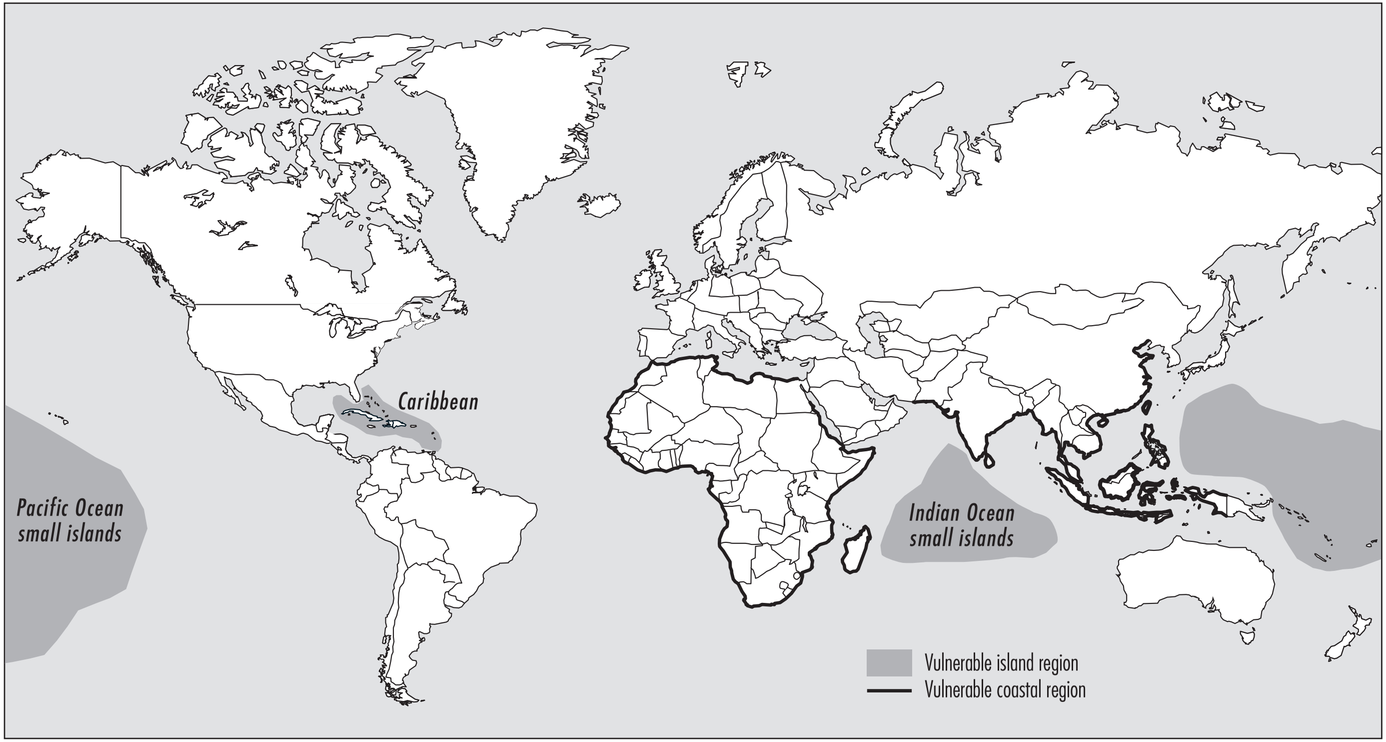
Two parameters are computed:

- People in the hazard zone (PHZ)—the expected average number of people living below the 1-in-1,000-year floodplain (the exposed population).
- People at risk (PAR)—the expected average number of people who will experience flooding each year (a measure of risk that takes into account flood protection).

Table 3.3 illustrates the flood impacts of global-mean sea-level rise up to 80 cm (31.2 in.) by the 2080s based on a business-as-usual socioeconomic scenario—that is, no adaptive measures employed. Hence, it captures a wide range of uncertainty in the sea-level rise scenarios. The following insights are apparent:

- Without sea-level rise, PAR will increase significantly between 1990 and the 2050s due to increasing coastal populations (i.e., exposure), then diminish as increasing protection standards (due to rising gross domestic (product per capita) become the most important factor controlling flood risk.

**Figure 3.5**
Regions Vulnerable to Coastal Flooding




Source: Nicholls and Cazenave (2010).

**Table 3.3**
Coastal Flooding of People Under a Range of Sea-Level Rise Scenarios (in millions)

| | Sea-Level Rise | People in the Hazard Zone (PHZ) | People at Risk (PAR) |
|---|---|---|---|
| 1990 | N/A | 197 | 10 |
| 2020s | None | 399 | 22 |
| | Low (4 cm [1.6 in.]) | 403 | 23 |
| | Mid-level (11 cm [4.3 in.]) | 411 | 24 |
| | High (22 cm [8.6 in.]) | 423 | 30 |
| 2050s | None | 511 | 27 |
| | Low (10 cm [3.9 in.]) | 525 | 28 |
| | Mid-level (27 cm [10.5 in.]) | 550 | 64 |
| | High (49 cm [19.1 in.]) | 581 | 176 |
| 2080s | None | 575 | 13 |
| | Low (19 cm [7.4 in.]) | 605 | 17 |
| | Mid-level (45 cm [17.6 in.]) | 647 | 133 |
| | High (80 cm [31.2 in.]) | 702 | 353 |

Note: The population scenario assumes that population change within the coastal floodplain is twice national trends, reflecting a coastward population migration.
Source: Adapted from Nicholls (2002).

- PHZ will increase substantially through the 2080s, driven almost entirely by socioeconomic factors.
- Significant impacts of sea-level rise will not emerge until the 2050s or later, making this a slow-onset hazard.
- The uncertainty of impacts is large, with a relatively minor increase in impacts (i.e., PAR) predicted under the low-rise scenario in the 2080s, a 10-fold increase under the mid-level scenario, and a 27-fold increase under the high-rise scenario.

All regions will see an increase in the incidence of flooding compared to the baseline, especially under the high-rise scenarios. The most vulnerable regions in relative terms will be the small islands of the Caribbean Sea, Indian Ocean, and Pacific Ocean (see figure 3.5). However, absolute increases in the incidence of flooding will be largest in the southern Mediterranean, West Africa, East Africa, South Asia, and Southeast Asia (see figure 3.5). These five regions account for about 90 percent of the estimated risk in all the scenarios for the 2080s. This analysis reflects the large populations of low-lying deltas in these parts of Asia (as well as in East Asia) and projections of rapid population growth along Africa's coasts. Although developed countries will have relatively low impacts, sea-level rise will still produce a significant increase in the number of people threatened by flooding.

Sea-level rise, therefore, could have a profound impact on the incidence of flooding—the higher the total rise, the greater the flood risk, all other factors being equal. An increase in storminess would further exacerbate coastal flooding. However, if adaptive measures such as upgraded defenses were employed, the expected number of people flooded per year could actually decline (Nicholls 2010; Nicholls et al. 2011). Hence, the success or failure of adaptation is fundamental and must be taken into account when determining impacts, as discussed later in this chapter.

***Environmental Refugees*** Sea-level rise is often associated with a large potential for environmental refugees forcibly displaced from their homes by flooding, erosion, and submergence (Myers 2002). Nicholls et al. (2011) estimated that over the next century, 72 million people could be forced to move due to a 0.5 m (1.6 ft.) sea-level rise and that 187 million people might be displaced given a 2 m (6.6 ft.) rise, assuming that no protective actions were taken. That is roughly 0.9–2.4 percent of the global population. Using the socioeconomic assumptions in table 3.2, the numbers could be even higher. However, a no-adaptation future seems unlikely, and if the world can successfully adapt to these challenges, the problem would be reduced. Adaptation could include defenses to protect urban areas from floods, as well as land use planning for new developments to avoid risky areas. Most of the threatened people are concentrated in East, Southeast, and South Asia. Given a 0.5–2 m (1.6–6.6 ft.) rise in sea levels, 53–125 million people are estimated to be displaced in these three regions alone. If we assume protection with dikes and sand nourishment, however, the estimate of the number of displaced people falls dramatically to less than 1 million.

***Coastal Wetlands*** Wetland losses are driven more by the *rate* of sea-level rise than by the total rise, as they have the capacity to respond to inundation (Cahoon et al. 2006). Given a 1 m (3.28 ft.) rise by 2100, half the global wetlands could be lost (Hoozemans, Marchand, and Pennekamp 1993; McFadden, Spencer, and Nicholls 2007; Nicholls, Hoozemans, and Marchand 1999), but even smaller rises could lead to substantial losses. Losses will be most severe on the Atlantic coasts of North and Central America; in the Caribbean, Mediterranean, and Baltic seas; and on all small islands. In most developing countries, coastal wetlands are already declining significantly due to direct and indirect human destruction (e.g., Nicholls 2004), and hence sea-level rise is an additional driver of losses that worsens the already poor prognosis for these coastal wetlands. In many developed countries, human losses are less of an issue because of regulation and protection/compensation mechanisms, and hence accelerated rise could pose a major threat to these wetland systems (Gardiner et al. 2007; Lee 2001).

## *Responding to Sea-Level Rise*

The two possible responses to sea-level rise are mitigation and adaptation. They operate on two very different scales, with mitigation being by necessity a global activity and adaptation being local, regional, or national. Given the high impact potential already discussed and the commitment to sea-level rise independent of future greenhouse gas emissions, each coastal area needs to identify the most appropriate mixture of mitigation and adaptation (Nicholls et al. 2007).

Mitigation has the important effect of stabilizing the rate of sea-level rise, rather than stabilizing sea level itself (Nicholls and Lowe 2006). But because sea-level rise will continue and remain a challenge for many generations to come, adaptation is necessary for long-term human use of coastal zones (Nicholls et al. 2007). The fundamental goal of mitigation is to reduce greenhouse gas emissions and thus prevent the breakdown of the two major ice sheets. This will in turn constrain the rate of sea-level rise so that adaptation can be employed at a reasonable economic and social cost.

Adaptation to sea-level rise involves responding to both mean and extreme rise. Given the large and rapidly growing concentration of people and activity in coastal zones, autonomous (or spontaneous) adaptation alone will not be able to cope with rising sea levels. Further, adaptation in the coastal context is widely seen as a public responsibility (Klein et al. 2000). Therefore, all levels of government have key roles to play in developing and facilitating appropriate adaptive measures (Tribbia and Moser 2008).

There are three generic approaches to planned adaptation (Bijlsma et al. 1996; IPCC CZMS 1990; Klein et al. 2001; Linham and Nicholls, 2010):

- Planned retreat—all natural-system effects are allowed to occur, and human impacts are minimized by pulling back from the coast via strategies such as land use planning and development control.
- Accommodation—all natural-system effects are allowed to occur, and human impacts are minimized by adjusting human use of the coast via flood resilience, warning systems, insurance, and the like.
- Protection—natural-system effects are controlled by soft engineering (sand-nourished beaches and dunes) or hard engineering (seawalls), reducing human impacts in coastal areas.

Examples of each approach are given in table 3.1.

In some classifications of adaptive responses, the concept of attack has been suggested as a strategy against sea-level rise, which in effect translates into building seaward (RIBA and ICE 2010). This is consistent with land claim (Linham and Nicholls 2010), which has a long history in many coastal areas (e.g., Seasholes 2003) and is an ongoing strategy in many coastal countries—such as Singapore, Hong Kong, and Dubai—to expand land area as opposed to adapting to rising sea levels.

Throughout human history, improving technology has increased the range of adaptation options in the face of coastal hazards, and there has been a slow move away from retreat and accommodation to hard engineering and active seaward advance via land claim (e.g., for The Netherlands, see van Koningsveld et al. 2008). Sea-level rise is one reason that reliance on hard engineering is being called into question, and identifying the appropriate mixture of protection, accommodation, and retreat is now considered to be more appropriate. In practice, many responses may be hybrid, combining elements of more than one approach. Note that adaptation in one sector may exacerbate impacts elsewhere. A good example of this is the “coastal squeeze” that occurs when coastal ecosystems are caught between rising sea levels and hard defenses. Coastal management plans need to consider the balance between protecting socioeconomic activity and human safety on the one hand and protecting the habitats and ecological functioning of coastal zones on the other (Nicholls and Klein 2005).

Adapting to rising sea levels requires consideration of all its sources, including local contributions as appropriate. Implementation of flood protection should not lead to complacency, and a level of residual risk always remains for all protected areas. In addition, flood risk grows in proportion to socioeconomic growth in coastal areas if defenses are not upgraded (Evans et al. 2004; Ten Brinke, Bonnink, and Ligtvoet 2008). This was a significant problem in the last century and is likely to continue to be so in this one.

The most appropriate timing for an adaptive response needs to be considered in terms of anticipatory versus reactive adaptation (or in practical terms, what actions should we do today versus what actions should we postpone until tomorrow; see figure 3.4). In coastal areas, there is significant potential for anticipatory adaptation, as many decisions have long-term implications (Fankhauser, Smith, and Tol 1999; Hallegatte 2009). Examples of anticipatory adaptation include upgraded flood defenses and wastewater discharge systems, higher design heights for land reclamations and new bridges, and building setbacks to prevent development in areas threatened by erosion and flooding.

Sea-level rise will often exacerbate existing pressures and problems, so it is important to consider adaptation in the context of existing problems (Nicholls and Klein 2005). In some cases, focusing on sea-level rise and climate change may help identify “win-win” situations in which anticipatory measures to address sea-level rise offer immediate benefits in reducing the impacts of short-term climate variability as well as long-term climate change (Dawson et al. 2009; Hallegatte 2009; Turner, Doktor, and Adger 1995).

Although there is limited experience in adapting to climate change, there is considerable experience in adapting to climate variability, and we can draw on this experience to inform decision making regarding global warming. Importantly, adaptation to address coastal impacts is a process, consisting of a series of stages which are all required: (1) information and awareness building; (2) planning and design; (3) implementation; and (4) monitoring and evaluation operating within multiple policy cycles (Hay 2009; Klein et al. 2000). The last stage, monitoring and evaluation, though critical, is too easily ignored. However, this is essential to a "learning by doing approach," which is appropriate given the uncertainty associated with sea-level rise and coastal management in general.

In many countries, there is limited capacity to address today's coastal problems, let alone tomorrow's. Therefore, a process for developing the capacity to pursue coastal management is essential, as has already been widely recommended (Adger et al. 2007; Nicholls and Klein 2005; USAID 2009).

Benefit-cost models that compare protection versus retreat generally suggest that it is worth investing in widespread protection, as populated coastal areas have high economic value (Anthoff, Nicholls, and Tol 2010; Fankhauser 1995; Nicholls and Tol 2006; Sugiyama, Nicholls, and Vafeidis 2008; Tol 2007). With or without protection, small island and deltaic areas stand out as relatively more vulnerable in most analyses, as do poor countries, mirroring the earlier impact assessments (Anthoff, Nicholls, and Tol 2010; Sugiyama, Nicholls, and Vafeidis 2008). Even though protection is optimal in a benefit-cost sense, protection costs could overwhelm the capacity of local economies, especially when they are small, such as on islands (Fankhauser and Tol 2005; Nicholls and Tol 2006).

Global estimates normally focus on the incremental costs of upgrading defense infrastructure, as this is consistent with the relevant international treaties. Incremental costs assume that there are already some defenses in place, which is often not the case. IPCC CZMS (1990) estimated the total costs of defending against a 1 m (3.28 ft.) sea-level rise at US$500 billion. Hoozemans, Marchand, and Pennekamp (1993) doubled that estimate to US$1,000 billion. Using an economic model that balanced dryland and wetland loss, as well as forced migration and incremental defense costs, Tol (2002a, 2002b) estimated that annual protection costs for 1 m (3.28 ft.) of global sea-level rise were only US$13 billion per year, much lower than widely assumed. More recently, the World Bank (2010) estimated coastal adaptation costs for the developing world at US$26–89 billion a year by the 2040s, depending on the magnitude of sea-level rise. A major issue that has not been quantified is the cost of the adaptation deficit, which comes into play when all defenses must be built from scratch (Burton 2004; Parry et al. 2009). This deficit raises the costs of protection by a substantial but unknown amount, and it has the potential to radically change the adaptation choices decision makers might make. Maintenance costs also need to be considered, as they could equal or exceed incremental upgrade costs (Nicholls et al. 2011). This topic requires much more research attention.

## *Conclusions*

The impacts of sea-level rise cut across many disciplines, and major gaps in understanding these impacts remain. Pessimists tend to focus on high sea-level rises and extreme environmental events. They view the world's ability to adapt as being rather limited, resulting in alarming impacts, such as widespread human displacement from coastal areas. Optimists tend to focus on lower sea-level rises, perceive a greater ability for the world to adapt, and stress a high benefit-cost ratio in developed coastal areas, leading to widespread protective actions.

Optimists have empirical evidence to support their view that sea-level rise does not present a big problem in terms of the subsiding megacities that are also thriving economically. Importantly, this evidence suggests that improved protection is more likely to occur than is widely assumed. Hence, a widespread retreat from the shore is not inevitable, and coastal societies will have more capacity to protect than is often assumed.

Pessimists also have evidence to support their views. First, published protection costs are incremental costs, assuming the existence of well-adapted infrastructure. This is not the case in much of the world, resulting in an adaptation deficit that needs to be assessed in the context of sea-level rise. Second, the socioeconomic scenarios that researchers use influence their findings, and most of the scenarios to date have been optimistic about future economic growth and the more equitable distribution of wealth. Lower growth and greater concentration of wealth may mean lower damages in monetary terms, but they also mean less ability to protect. Third, the benefit-cost approach implies a proactive attitude toward protection, while historical experience shows that most protection has been a reaction to an actual or near disaster. Therefore, high rates of sea-level rise (and more storms) may lead to more frequent coastal disasters and higher damages, even if the ultimate response is better protection. Fourth, disasters (or adaptation failures) such as Hurricane Katrina could trigger coastal abandonment, which could have a profound influence on society's future choices concerning coastal protection. A cycle of economic decline is not inconceivable, especially in the context of a more globalized world, highly mobile capital, and weaker collective action. If the issue of sea-level rise is widely known, disinvestment from coastal areas may be triggered even without disasters actually occurring. For example, the economies of small islands may be highly vulnerable if investors become cautious (Barnett and Adger 2003). Lastly, retreat and accommodation have long lead times: benefits are greatest if planning and implementation occur sooner rather than later. Hence, adaptation may not be as successful as some scenarios assume, especially if higher sea-level rises occur.

Sea-level rise is clearly a threat that demands a response. Ongoing adaptation will be essential throughout the twenty-first century and beyond. At the same time, climate mitigation can reduce the commitment to sea-level rise, particularly regarding the potential Greenland and West Antarctic contributions. Scientists need to better understand these threats, including the implications of using different combinations of adaptation and mitigation, and to engage with the coastal and climate policy process so that their voices can be heard. Importantly, it has been recognized that a combination of mitigation and adaptation is the most appropriate course of action, as these two policies are more effective when combined than when followed independently, and together they address both immediate and longer-term concerns (Nicholls et al. 2007).

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