Chapter 9

# Adapting to Sea Level Rise

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**ABSTRACT**
Coasts contain a large and growing population and economy including world cities such as London, New York, Tokyo, Shanghai, Mumbai, Lagos, and Rio de Janeiro, as well as important habitats and their ecosystem services. Global sea levels are rising due to climate change and this will accelerate through this century: a rise of more than 1 m is possible. In some locations these changes may be exacerbated by (1) increases in storminess due to climate change, although this is less certain, and (2) human-induced subsidence due to ground fluid withdrawal from and drainage of susceptible soils, especially in deltas and alluvial plains. Sea-level rise has a range of potential impacts including higher extreme sea levels (and flooding), coastal erosion, and salinization of surface and ground waters. This threatens the loss of large areas of land and associated assets and economic activity, the displacement of millions of people, and significant coastal habitat degradation. However, adaptation can greatly reduce these impacts and promote prosperous and desirable coasts. Adaptation measures can be characterized as (1) protect, (2) accommodate, or (3) retreat approaches. The provision of information measures such as warnings is improving significantly, while novel methods such as ecosystem-based approaches are attracting interest. Adaptation to sea-level rise should be viewed as a process that requires an integrated coastal management philosophy to be consistent with wider coastal activities and other stresses. Hence, in addition to technical skills, adaptation requires an appropriate institutional capacity. The success or failure of measures of adaptation, especially protection, is contested and this influences our view of sea-level rise as a problem. Adaptation can be best analyzed in the context of understanding the coastal system that includes the effects of all drivers, including sea-level rise, their interactions, and feedbacks: these types of analyses are only just beginning. Some proactive adaptation plans are already being formulated, such as around London and in the Netherlands. Coastal cities will be a major focus for adaptation efforts due to their concentrations of people and assets. However, there are important challenges for adaptation in developing countries, most especially in deltaic areas and small islands.

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## 9.1 INTRODUCTION

Sea-level rise has been recognized as a global major threat to low-lying coastal areas since the 1980s (e.g., Barth and Titus, 1984; Milliman et al., 1989; Tsyban et al., 1990). There is a growing literature demonstrating that the potential impacts of sea-level rise are large. To respond to this challenge interest in adaptation is increasing, even though it is recognized as a difficult and challenging problem (Moser et al., 2012; Wong et al., 2014). Although sea-level rise only directly impacts coastal areas, these are the most densely populated and economically active land areas on Earth. More than 600 million people live below 10 m elevation in the Low Elevation Coastal Zone (McGranahan et al., 2007), and the population is growing rapidly in coastal urban areas (CIESIN, 2013). Coastal areas also support important and productive ecosystems that are sensitive to sea-level rise (Crossland et al., 2005). Coasts are already "risky places" exposed to multiple meteorological and geophysical hazards, including storms and storm-induced flooding (Kron, 2013). Threatened low-lying areas already depend on various flood risk adaptation strategies, be it natural and/or artificial flood defences and drainage or construction methods. Recent flood events such as New Orleans and environs on the US Gulf Coast (Hurricane Katrina, 2005), Irrawaddy delta, Myanmar (Cyclone Nagris, 2008), New York and environs (Cyclone Sandy, 2012), or the Philippines (Typhoon Haiyan, 2013) demonstrate what can happen in low-lying areas during extreme flood events. Rising mean sea level and more intense storms are expected to exacerbate these risks significantly (Wong et al., 2014).

The main focus of this chapter is adaptation, although some brief remarks on the possible role of climate mitigation and other source control responses are included for completeness. To distinguish these responses, mitigation and adaptation are defined as follows:

- Mitigation (or source control of sea level)—reducing the magnitude of human-induced climate change and sea-level rise at the global scale, or reducing the magnitude of human-induced subsidence at the local level; and
- Adaptation (to sea level)—reducing the impacts of sea-level rise via behavioral changes. This includes a range of changes from individual actions to collective coastal management policy, such as upgraded defence systems, warning systems, and land management approaches.

Coastal adaptation to sea-level rise has been considered for the last 25 years (Barth and Titus, 1984; IPCC CZMS, 1990), building on the extensive experience in adapting to climate variability and other stresses. Despite this, the uncertainties about the success or failure of adaptation remain large, contributing significant uncertainty to the overall consequences of sea-level rise for society (Nicholls et al., 2014a).

The chapter is structured as follows. First the coast is considered as a system comprising natural and socioeconomic components, to provide an appropriate framework to analyze coasts, sea-level rise, and adaptation. Second, climate change and sea-level rise are considered in more detail, including the important distinction between global-mean and relative sea-level rise (RSLR). Then the impacts of sea-level rise are briefly considered from a physical and a socioeconomic perspective, including drawing on experience from subsiding cities. This is followed by a brief review of mitigation approaches for sea-level rise and a more detailed consideration of adaptation. This demonstrates the complexity of adaptation and the multiple factors that need to be considered. This is followed by a discussion/conclusion, including research needs.

## 9.2 COASTAL SYSTEMS

Sea-level rise and the need to adapt to it does not happen in isolation: coasts are changing significantly due to more local factors such as urbanization and changing water/sediment inputs due to river regulation and watershed land use and land cover change (Crossland et al., 2005; Valiela, 2006; Syvitski et al., 2009). These types of problems require a systems approach to analyze the full range of interacting drivers, including feedbacks such as adaptation. Figure 9.1 presents a simplified systems model of the impacts of sea-level rise on the coastal zone (Klein and Nicholls, 1999; Nicholls and Klein, 2005). This model highlights the varying implicit and explicit assumptions and simplifications that are necessary within all the available assessments of coastal impacts in general, including their limitations. It characterizes the overall coastal system as interacting natural and socioeconomic systems, which have the potential to constrain each other's evolution. Both systems can be characterized by their exposure, sensitivity and adaptive capacity to change, both from sea-level rise, related climate change, and nonclimate stresses. Collectively, sensitivity and adaptive capacity, combined with exposure, determine the vulnerability to sea-level rise and other changes.

A range of drivers may influence the boundary conditions (Figure 9.1). Sea-level rise is only one aspect of climate change for coastal areas, and all climate change drivers interact with other nonclimate stresses, often exacerbating impacts (see Table 9.1). Lastly, the socio-economic system is not passive as it influences the natural system through deliberate changes such as construction of sea dykes, destruction of wetlands, and building of port and harbor works, as well as unintended changes such as reductions of sediment and water fluxes due to the building of dams. Hence, the socioeconomic system is shaping the future of the coastal system as much, if not more than, the natural system and issues such as sea-level rise are shaping the socioeconomic system. This raises the prospect of the coast as a coevolving system where the natural system shapes the socioeconomic system and vice

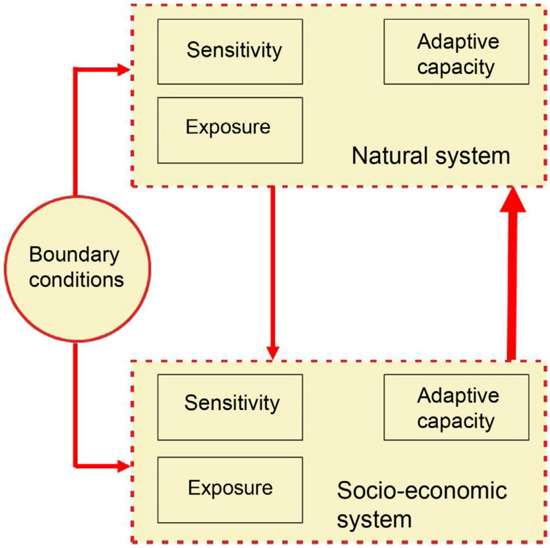


**FIGURE 9.1** The coastal system comprises interacting natural and socioeconomic sub-systems which in turn are influenced by changing boundary conditions, such as sea-level rise, climate change, and large-scale nonclimatic stresses.

versa, with adaptation playing an important role in this aspect. It raises a new way of thinking about the future of coasts, which requires further investigation (Lazarus et al., 2014).

## 9.3 GLOBAL-MEAN AND RSLR

Human-induced climate change is expected to cause a profound series of changes including rising sea level, rising sea-surface temperatures, and changing storm, wave, and run-off characteristics (Wong et al., 2014). Here we will focus on climate-induced sea-level rise, which is mainly produced by (1) thermal expansion of seawater as it warms and (2) the melting of land-based ice, comprising components from (a) small glaciers, (b) the Greenland ice sheet, and (c) the West Antarctic ice sheet (Church et al., 2010; Gornitz, 2013; Pugh and Woodworth, 2014). A global rise in sea level of 17 cm was observed through the twentieth century (i.e., 1.7 mm/year). This observed rise is almost certain to continue and will very likely accelerate through the twenty-first century with a rise of 1 m or more being plausible if the large ice sheets make a large positive contribution (Church et al., 2013). From an impact and adaptation perspective, coastal policymakers are especially concerned about the high end of possible changes (Nicholls et al., 2014b). While the probability of high-end rise is unknown, the large potential impacts make them highly significant in terms of climate risks and policy. There is also concern about

**TABLE 9.1 The Main Natural System Effects of Relative Sea-Level Rise and Examples of Adaptation Options. Potential Interacting Factors Which Could Offset or Exacerbate These Impacts Are Also Shown. Some Interacting Factors (e.g., Sediment Supply) Appear Twice as They Can Be Influenced both by Climate and Nonclimate Factors. Adaptation Options are Coded: P—Protection (Hard or Soft); A—Accommodation; R—Retreat**

| Natural System Effect | | Possible Interacting Factors | | Possible Adaptation Options |
|---|---|---|---|---|
| | | Climate | Nonclimate | |
| 1. Inundation/flooding | a. Surge (flooding from the sea) | Wave/storm climate, erosion, sediment supply | Sediment supply, flood management, erosion, land reclaim | Dikes/surge barriers/closure dams [P—hard], nourishment, including dune construction [P—soft], ecosystem-based barriers (e.g., mangrove afforestation) [P—soft], building codes/flood-proof buildings [A], land use planning/hazard mapping [A/R], planned migration [R]. |
| | b. Backwater effect (flooding from rivers) | Run-off | Catchment management and land use | |
| 2. Wetland loss (and change) | | $CO_2$ fertilization, sediment supply, migration space | Sediment supply, migration space, land reclaim (i.e., direct destruction) | Gabions/breakwaters [P—hard], nourishment/sediment management [P—soft], land use planning [A/R], managed realignment/forbid hard defences [R]. |
| 3. Erosion (of "soft" morphology) | | Sediment supply, wave/storm climate | Sediment supply | Coastal defences/seawalls/land claim [P—hard], ecosystem-based barriers (e.g., mangroves) [P—soft], nourishment [P—soft], building setbacks/rolling easements [R]. |

*Continued*

**TABLE 9.1** **The Main Natural System Effects of Relative Sea-Level Rise and Examples of Adaptation Options. Potential Interacting Factors Which Could Offset or Exacerbate These Impacts Are Also Shown. Some Interacting Factors (e.g., Sediment Supply) Appear Twice as They Can Be Influenced both by Climate and Nonclimate Factors. Adaptation Options are Coded: P—Protection (Hard or Soft); A—Accommodation; R—Retreat—cont'd**

| Natural System Effect | | Possible Interacting Factors: Climate | Possible Interacting Factors: Nonclimate | Possible Adaptation Options |
|---|---|---|---|---|
| 4. Saltwater intrusion | a. Surface waters | Run-off | Catchment management (over-extraction), land use | Saltwater intrusion barriers [P], desalination [A], move water abstraction upstream [R]. |
| | b. Ground-water | Rainfall | Land use, aquifer utilization | Insert impermeable barriers [P], freshwater injection [P], change water abstraction [A/R]. |
| 5. Impeded drainage/higher water tables | | Rainfall, run-off | Land use, aquifer utilization, catchment management | Drainage systems/polders [P—hard], change land use/crop type [A], land use planning/hazard delineation [A/R]. |

Adapted from Nicholls (2010), see also Linham and Nicholls (2010).

higher extreme sea levels due to more intense storms superimposed on mean rise in sea level, but this is much less certain (Church et al., 2013).

When analyzing sea-level rise impacts and responses, it is fundamental that impacts are a product of *relative* (or local) sea-level rise (RSLR) rather than global changes alone (Nicholls et al., 2014b). Relative sea-level change considers the sum of global, regional, and local components of sea-level change: the underlying drivers of these components are (1) climate change, as already discussed, and changing ocean dynamics and (2) nonclimate land level change (i.e., uplift/subsidence) processes such as tectonics, glacial isostatic adjustment (GIA), and natural and anthropogenic-induced subsidence. For large ice sheet changes, gravitational effects due to mass redistribution of melting ice also need to be considered. Hence, RSLR is only partly a response to climate change and varies from place to place (Figure 9.2). Where coasts are subsiding, such as Grand Isle in the Mississippi Delta, Louisiana, RSLR exceeds the global rise. Most populated deltaic areas and alluvial plains are threatened by enhanced subsidence (Ericson et al., 2006; Syvitski et al., 2009; Chaussard et al., 2013). Most dramatically, subsidence can be enhanced by human activity on susceptible soils due to drainage and withdrawal of groundwater as shown in Bangkok (Figures 9.2 and 9.3). Dramatic RSLR has occurred in many coastal cities built on deltas and alluvial plains due to this cause. Over the twentieth century, the parts of Tokyo and Osaka built on deltaic areas subsided up to 4 m and 3 m, respectively, a large part of Shanghai subsided up to 3 m, and the center of Bangkok subsided up to 2 m. Human-induced subsidence can be mitigated by stopping shallow sub-surface fluid withdrawals and managing water levels, but natural "background" rates of

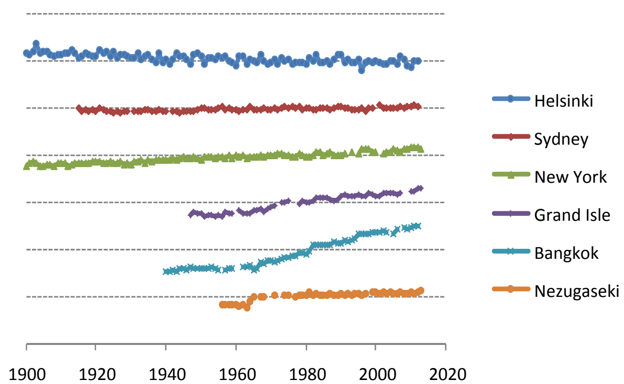


**FIGURE 9.2** Selected relative sea-level observations since 1900, illustrating different trends (offset for display purposes). Helsinki shows a falling trend (−2.0 mm/year) as the land is rising, Sydney shows a gradual rise (0.9 mm/year), New York is subsiding slowly (3.1 mm/year), Grand Isle is on a subsiding delta (9.1 mm/year), Bangkok (Station: Fort Phrachula Chomklao) is also on a delta and includes the additional effects of human-induced subsidence (18.9 mm/year from 1962 to 2012), and Nezugaseki shows an abrupt 150–2000 mm rise due to an earthquake. *Data from Holgate et al. (2013); PSMSL, 2014.*

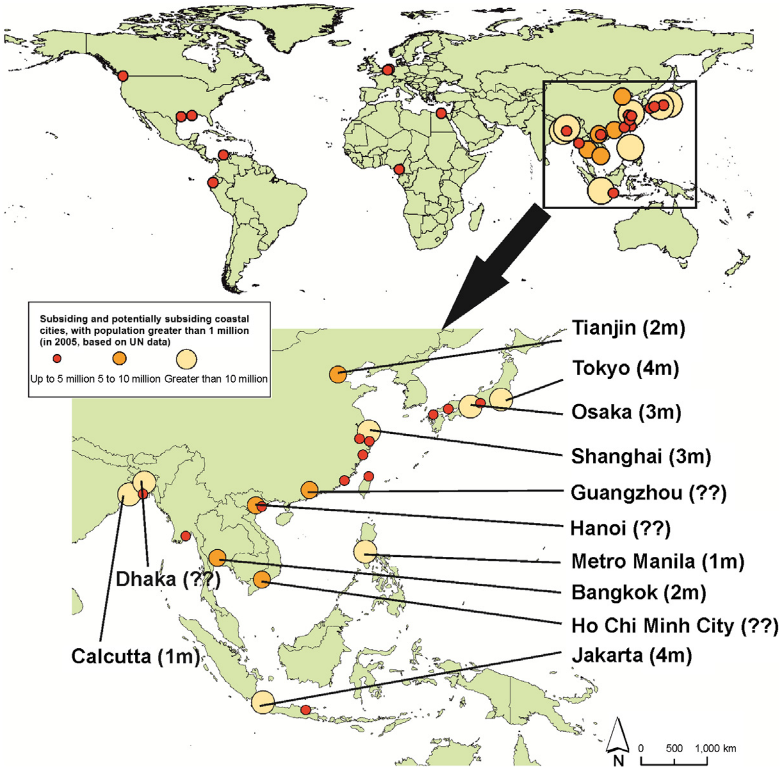


**FIGURE 9.3** Subsiding and potentially subsiding coastal cities *(adapted and updated from Nicholls (2010), Hallegatte et al. (2013), with additional data from Kaneko and Toyota (2011), Dang et al. (2014))*. The maximum observed subsidence (in meters) is shown for cities with populations exceeding 5 million people, where known. Maximum subsidence is reported as data on average subsidence is not available.

subsidence that are typical of deltas (1−5 mm/year and maybe more) will continue and RSLR will still exceed global trends in these areas. The four cities mentioned above have all implemented mitigation policies to varying degrees of success, combined with the provision of improved flood defence and pumped drainage systems to avoid submergence and/or frequent flooding. (In Bangkok, subsidence has been greatly reduced in the center of the city, but at the site of the measurements shown in Figure 9.2, which is 20 km to the south, no reduction is evident.) In contrast, other cities such as Jakarta and Metro Manila continue to subside substantially, with maximum subsidence of 4 and 1 m over the last few decades, respectively (Kaneko and Toyota, 2011). Flooding and waterlogging are common and growing problems. There is little systematic policy response to date despite these direct impacts, or the experience described in other cities. This suggests that the problems of enhanced subsidence are likely to be widely repeated in susceptible coastal cities through the twenty-first century. It is important to emphasize that only some cities are prone to this problem: of the 136 coastal cities with a population above 1 million considered by Hallegatte et al. (2013), only 32 have an appropriate geological setting to experience enhanced subsidence as these are cities wholly or partly built in deltaic or alluvial settings (Figure 9.3). Note the concentration of large cities in south, South-East or East Asia.

Greater appreciation of the importance of subsidence is urgently needed to promote responses, including planning and adaptation for RSLR. In much of the developed world quality data is limited. However, new measurement systems permit analysis and quantification, including satellite measurements (Chatterjee et al., 2006) and differential Global Positioning System (DGPS) (Teatini et al., 2005). Beyond this, the political will to tackle these issues is also necessary as discussed by Rodolfo and Siringan (2006) for Manila, the Philippines.

## 9.4 SEA-LEVEL RISE AND RESULTING IMPACTS

Relative sea-level rise causes more effects than simple submergence (the "bath-tub" effect); the five main effects are summarized in Table 9.1. Flooding/submergence, ecosystem change, and erosion have received significantly more attention than salinization and rising water tables. Along with rising sea levels, there are changes to all processes that operate around the coast. The immediate effect is submergence and increased flooding of coastal lands, as well as saltwater intrusion into surface waters. Longer term effects also occur as the coast adjusts to the new environmental conditions, including wetland loss and change, erosion of beaches and soft cliffs, and saltwater intrusion into groundwater. These lagged changes interact with the immediate effects of sea-level rise and generally exacerbate them. For instance, erosion of saltmarshes, mangroves, sand dunes, and coral reefs degrades or removes natural protection and increases the likelihood of coastal flooding.

A rise in mean sea level also raises extreme water levels. Changes in storm characteristics could also influence extreme water levels. For example, an increase in the intensity of tropical cyclones will generally raise extreme water levels in the areas affected (Church et al., 2013). Extratropical storms may also intensify in some regions, although this effect is uncertain. An improved understanding of these changes is an important research topic to support impact and adaptation assessments.

Changes in natural systems resulting from sea-level rise have many important direct socio-economic impacts on a range of sectors, with these impacts being overwhelmingly negative (Table 9.2). For instance, flooding can damage coastal infrastructure, ports and industry, the built environment, and agricultural areas. In the worst case, flooding leads to significant mortality, as recently demonstrated by Hurricane Katrina (USA) in 2005, Cyclone Nargis (Myanamar) in 2008, Storm Xynthia (France) in 2010, and Cyclone Sandy

**TABLE 9.2 Summary of Sea-Level Rise Impacts on Socioeconomic Sectors in Coastal Zones (© *Reprinted with permission from* Nicholls, 2010). These Impacts Are Overwhelmingly Negative**

| | Sea-Level Rise Natural System Effect (Table 9.1) | | | | |
|---|---|---|---|---|---|
| **Coastal Socioeconomic Sector** | **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.

(USA) in 2012. Erosion can lead to the loss of beachfront/cliff-top buildings and other infrastructure, and have adverse consequences for sectors such as tourism and recreation. In addition to these direct impacts, there are potential indirect impacts such as mental health problems triggered by floods, or economic effects that cascade through the whole economy. These indirect impacts are poorly understood, but will have economic consequences in terms of the damages caused (and/or the diversion of investment to fund the adaptation to avoid them). Thus, sea-level rise has the potential to trigger a cascade of direct and indirect human impacts.

Importantly, sea-level rise does not occur in isolation and coasts are changing significantly due to nonclimate-induced drivers (Crossland et al., 2005; Valiela, 2006; Wong et al., 2014). Potential interactions of such changes with sea-level rise are indicated in Table 9.1 (column entitled "Potential Interacting Factors") and need to be considered when assessing sea-level rise impacts and adaptation responses. For instance, a coast with a positive sediment budget may not erode given sea-level rise and vice versa. Hence, coastal change ideally requires an integrated assessment approach to analyze the full range of interacting drivers, including the feedback of policy interventions (i.e., adaptation).

## 9.5 RECENT IMPACTS OF SEA-LEVEL RISE

Over the twentieth century, global sea level rose about 17 cm (or 1.7 mm/year). While this change may seem small, it has had many significant effects, such as reducing the return periods of extreme water levels (Zhang et al., 2000; Menéndez and Woodworth, 2010) and promoting an erosive tendency for coasts (Bird, 1985, 2000). However, linking sea-level rise quantitatively to impacts is difficult as the coastal zone has been subjected to multiple drivers of change over the twentieth century (Nicholls et al., 2009; Wong et al., 2014). Good data on rising sea levels has only been measured in a few locations, and growing coastal populations and infrastructure have increased the exposure available to damage. In addition, adaptation has occurred and, for example, flood defences have often been upgraded substantially, especially in those (wealthy) places where there are long-term sea-level measurements (e.g., Ruocco et al., 2011). Most of these defence upgrades coincide with the expanding populations and wealth in the coastal flood plain and changing attitudes to risk. Hence, RSLR may not have been considered in the design. Equally, impacts can be promoted by processes other than sea-level rise (Table 9.1). For example, widespread human reduction in sediment supply to the coast must contribute to the observed erosional changes around the world and this probably dominates erosion in many locations (Bird, 1985; Syvitski et al., 2009). Hence, while global sea-level rise is a pervasive process, other processes obscure its link to impacts, except in some special cases; most coastal change in the twentieth century was a response to multiple drivers of change.

There have certainly been impacts from RSLR resulting from subsidence (Nicholls, 2010). Notable sites include the iconic city of Venice, which will shortly be protected by the MOSES storm surge barriers (see Horn, in this volume), and the Mississippi delta where thousands of square kilometers of intertidal coastal marshes and adjacent lands were converted to open water in the last 50 years. There are also significant impacts of RSLR in and around subsiding coastal cities (e.g., Figure 9.3), in terms of increased waterlogging, flooding and submergence, and the resulting need for adaptation/management responses.

These empirical observations also provide lessons for adaptation. Subsiding areas with a low population density were often abandoned, such as around Galveston Bay, Texas, and south of Bangkok, Thailand. However, most of the major developed areas that were impacted by RSLR have been defended and continue to experience population and economic growth (Nicholls, 2010). This includes areas where the change in RSLR was rapid—several meters over several decades. However, there are exceptions such as New Orleans (Grossi and Muir-Wood, 2006); its population peaked in 1965 at more than 625,000 immediately before Hurricane Betsy flooded part of the city. Before Hurricane Katrina in 2005, its population was about 500,000. Subsequently, the population has yet to recover to pre-Katrina levels, even though US$15 billion has been invested to significantly upgrade defences (completed 2011). The future of New Orleans will be instructive: Does it prosper or continue to decline behind the new defences and what are the reasons?

Observations since 1900 reinforce the importance of understanding the impacts of sea-level rise in the context of multiple drivers of change; this will remain true under more rapid rises in sea level. RSLR due to human-induced subsidence is of particular interest, but this remains relatively unstudied using a systems approach. Observations also emphasize the ability to protect against RSLR, especially for the most densely populated areas, such as the subsiding Asian megacities or urban areas around the southern North Sea.

## 9.6 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 coastal physiography, (3) the level and manner of coastal development, and (4) 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 large potential impacts consistent with Table 9.1, especially increases in inundation, flooding, and storm damage (e.g. Nicholls et al., 2008). Recent studies of flood risk (i.e., expected annual damages) under sea-level rise all emphasize that impacts could be catastrophic when assuming no adaptation (Hallegatte et al., 2013; Hinkel et al., 2014). However, if defences are upgraded and other adaptation takes place, problems are more limited and possibly almost totally avoided. This stresses the importance of understanding adaptation.

In absolute numbers, East, South-East and East Asia, and Africa appear to be most threatened by sea-level rise (Figure 9.4). Vietnam and Bangladesh appear especially threatened due to large absolute and relative populations in low-lying deltaic plains. There are also large absolute threatened populations in India and China. In Africa, Egypt (the Nile Delta) and Mozambique are two potential hotspots for impacts due to sea-level rise. Hotspots also exist outside these regions, such as Guyana, Suriname, and French Guiana in South America. There will be significant residual risk in other coastal areas of the world, such as around the southern North Sea, and major flood disasters are possible in many coastal regions. Small island regions in the Pacific, Indian Ocean, and Caribbean stand out as being especially vulnerable to sea-level rise impacts (Nurse et al., 2014). The populations of low-lying island nations, such as the Maldives, Kiribati, or Tuvalu, face the real prospect of increased flooding, submergence, salinization, and forced abandonment.

## 9.7 MITIGATION OF SEA-LEVEL RISE

Climate mitigation can slow the global rise in sea level and reduce its impacts. Given the strong inertia of sea-level rise, mitigation stabilizes the *rate* of sea-level rise (rather than stabilizing sea level itself) (Wong et al., 2014). Hence, even with mitigation, sea-level rise will continue and remain a challenge for generations to come (Church et al., 2013). This has been termed

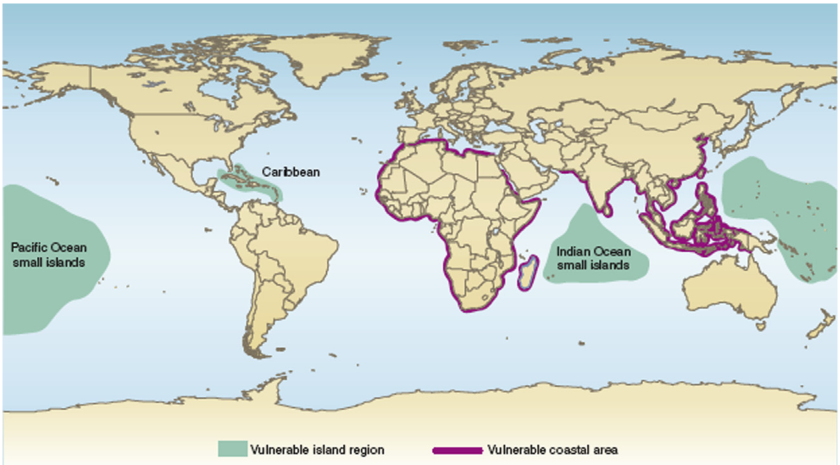


**FIGURE 9.4** Regions most vulnerable to coastal flooding and sea-level rise. At highest risk are coastal zones with dense populations, low elevations, appreciable rates of subsidence, and/or inadequate adaptive capacity. *From Nicholls and Cazenave (2010).*

the "commitment to sea-level rise," which leads to a "commitment to adapt to sea-level rise" with fundamental implications for long-term human use of the coastal zone (Nicholls et al., 2007). Hence, adaptation and mitigation are complimentary policy responses for climate change in coastal areas. The fundamental goal of mitigation in the context of coastal areas is to reduce the risk of passing irreversible thresholds concerning the breakdown of the two major ice sheets of Greenland and Antarctica, thus constraining the commitment to sea-level rise to a rate and ultimate rise which can be adapted to at a reasonable economic and social cost. This requires consideration of sea-level rise beyond 2100, which is increasingly being investigated (Church et al., 2013). However, appropriate mixtures of mitigation and adaptation remains to be assessed.

More locally, mitigation of human-induced subsidence also needs to be considered in susceptible areas, as already discussed. This translates into measures to control/reduce groundwater extraction and manage water levels, which have been successfully implemented in a number of cities to date, such as Shanghai, Osaka, and Tokyo (Kaneko and Toyota, 2011). This expertise needs to be transferred more widely to actively subsiding areas such as Jakarta, or sites where these issues are likely to emerge. However, while subsidence can be largely reduced as with climate-induced sea-level rise, it cannot be entirely avoided, and some adaptation to subsidence will be required.

## 9.8 ADAPTATION TO SEA-LEVEL RISE

Adaptation to sea-level rise involves responding to both mean and extreme rise. It is a complex process with multiple dimensions that different authors characterize differently. The overall field of climate adaptation is also evolving rapidly (e.g., Klein et al., 2014), and this is influencing coastal adaptation, even though coastal adaptation is one of the more mature sectors. It is important to distinguish autonomous (or spontaneous) adaptation versus planned adaptation. One can also distinguish proactive versus reactive planned adaptation. Given the large and rapidly growing concentration of people and activity in the coastal zone, autonomous adaptation processes alone will not be able to cope with sea-level rise. Further, adaptation in the coastal context is widely seen as a public rather than a private responsibility (Klein et al., 2000). Therefore, all levels of government have a key role in developing and facilitating appropriate adaptation measures (Tribbia and Moser, 2008).

It is worth noting that society has tended to react to coastal events and disasters rather than anticipate them. In adapting to sea-level rise we are trying to promote proactive adaptation, where appropriate. There is significant scope for anticipatory adaptation on coasts as many adaptation decisions have long-term (10–100 years) implications (e.g., Hallegatte, 2009). Examples of anticipatory adaptation in coastal zones include upgraded flood defences and drainage systems, higher elevation designs for new coastal infrastructure such as fill levels for land claim and coastal bridges, building standards/regulations to promote flood proofing and resilience, and building setbacks to prevent development in areas threatened by erosion and flooding.

The following section considers adaptation strategies and options, adaptation frameworks, adaptation selection, and adaptation experience.

### 9.8.1 Adaptation Strategies and Options

Adaptation can be classified in a variety of ways: one of the most widely followed approaches is the Intergovernmental Panel on Climate Change (IPCC) typology of planned adaptation strategies (IPCC CZMS, 1990; Bijlsma et al., 1996; Linham and Nicholls, 2010) (Figure 9.5):

- (*Planned*) *Retreat*—all natural system effects are allowed to occur and human impacts are minimized by pulling back from the coast via land use planning, development controls, planned migration, etc. (e.g., Figure 9.6);
- *Accommodation*—all natural system effects are allowed to occur and human impacts are minimized by adjusting human use of the coastal zone via changing land use/crop types, flood resilience measures, warning systems, insurance, etc. (e.g., Figure 9.7);
- *Protection*—natural system effects are controlled by soft or hard barriers (e.g., nourished beaches and dunes, or seawalls), reducing human impacts in the zone that would be impacted without protection (e.g., Figure 9.8).

Individually, there are a huge number of potential adaptation options. Examples linked to each natural system impact are provided in Table 9.1. The concept of "attack" has been suggested as a strategy against sea-level rise (e.g., RIBA and ICE, 2010). This is consistent with land claim and

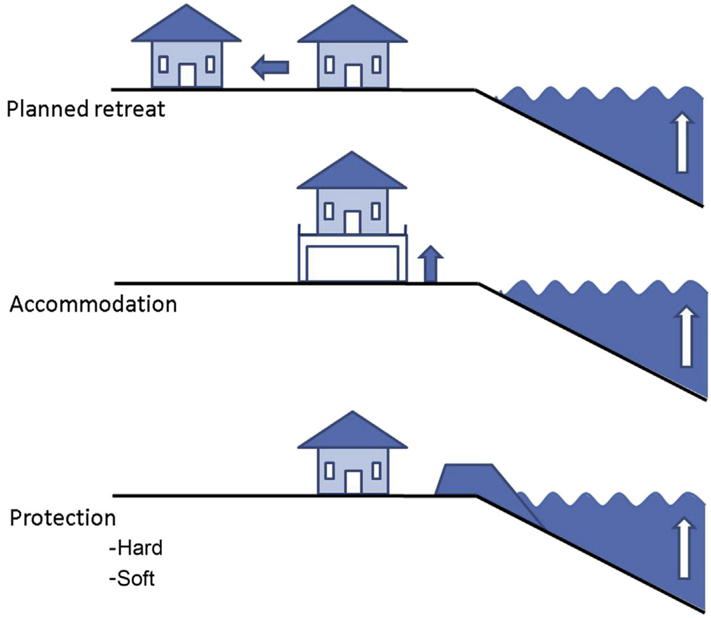


FIGURE 9.5 Generic adaptation approaches for sea-level rise. *Reprinted with permission from Nicholls (2010).*

protection (Linham and Nicholls, 2010). This has a long history in Northwest Europe and East Asia and has been practised in most coastal cities due to space constraints (e.g., Seasholes, 2003). Land claim is an active strategy in many coastal countries such as Singapore, Hong Kong, Dubai, and the Maldives to expand land area for coastal activities: sea-level rise is increasingly being considered in planning of land claim.

Information measures such as disaster preparedness, hazard mapping, and flood warning/evacuation are also increasingly important, and in many ways are cross-cutting and complementary of the three approaches above. There is also increasing interest in ecosystem-based approaches, which have the advantage of being self-sustaining and providing multiple benefits (Borsje et al., 2011; Temmerman et al., 2013). However, the uncertainties about their future state and function are much higher than engineered defences. This emphasizes that many real-world adaptation responses will be hybrid and combine options, possibly from more than one approach. For example, flood protection could use ecosystem buffers in front of artificial defences, reducing the required defence size. In addition, we need to consider the residual risk that remains for all protected areas: this suggests that adaptation needs to be combined with flood forecast and warning systems. Adaptation for one sector may however exacerbate impacts elsewhere: a good example is coastal squeeze of intertidal and shallow coastal habitats where onshore

**FIGURE 9.6** An example of a retreat option: managed realignment at Medmerry, West Sussex, UK. The defence line (a shingle barrier beach) was breached allowing the low-lying flood plain behind to be inundated creating new intertidal habitats. To landward, a new (longer) defence line was constructed. *(© Environment Agency)*

**FIGURE 9.7** An example of accommodation in a coastal flood plain in the UK. The central property is built at grade while the two adjoining properties have been raised to enhance flood resilience—the design elevation considers extreme water levels plus an allowance for sea-level rise. © *Robert Nicholls*

FIGURE 9.8 An example of a protection option: The Thames (storm surge) Barrier, Greenwich, London. © *Environment Agency*

migration of habitats due to rising sea levels is prevented by hard protection (Jones et al., 2011). In contrast, retreat and accommodation options allow habitat migration. Coastal management needs to consider the balance between protecting socioeconomic activity/human safety and the habitats and ecological functioning of the coastal zone under rising sea levels (Nicholls and Klein, 2005). While the twentieth century saw large losses of coastal habitats due to direct and indirect destruction, most coastal countries now aspire to protect these areas and their ecosystem services: sea-level rise significantly threatens such initiatives.

### 9.8.2 Adaptation Processes and Frameworks

While adaptation to sea-level rise is relatively new, there is considerable experience of adapting to climate and sea-level variability and other coastal problems. This experience informs decision making under a changing climate. Importantly, adaptation to coastal problems is a multi-stage *process*, including stages such as (1) information and awareness building, (2) planning and design, (3) evaluation, and (4) monitoring and evaluation operating within multiple policy cycles (e.g., Klein et al., 2000; Hay, 2009). The constraints on approaches to adaptation due to broader policy and development goals should also be carefully considered. Once implemented, monitoring and evaluation of adaptation measures is critical and yet easily ignored. This is essential given the large uncertainties associated with sea-level rise and other future conditions, adaptation performance, and coastal management in general.

A range of adaptation frameworks are apparent in the literature, with a diverse range of experience. For example, Integrated Coastal Zone

Management (ICZM) was strongly advocated as the response to sea-level rise in the early 1990s (e.g., IPCC CZMS, 1990; Bijlsma et al., 1996), recognizing that sea-level rise and climate change occur in a multistressed situation. However, it remains unproven as an effective response approach (Wong et al., 2014). Adaptive management where interventions are treated as experiments is also advocated, but again remains largely unproven. The risks of experimenting are raised as concerns. Community-based adaptation (CBA) is widely advocated as a bottom-up development focused approach (e.g., Huq and Reid, 2004; Rawlani and Sovacool, 2011). These provide important benefits for the participants, but in a coastal context there is concern that while they might adapt to small extremes, are the expectations of events such as the 1 in 100 year event appropriate? In the worse case, could CBA promote people to live in hazardous locations? This could be avoided by CBA being placed in a broader framework, including warning systems. Merging climate adaptation with Disaster Risk Reduction (Smith, 2013), which can be seen in part as adapting to climate variability, is also receiving increasing interest (Figure 9.9).

Shoreline management planning (SMP) has emerged in England and Wales over the last two decades as a response to coastal erosion and flood risk management (Nicholls et al., 2013). It provides a framework for thinking about the future of the entire coast over long timescales based on geomorphic principles, including the non-local effects of management. Four generic responses are considered without considering the technical detail: (1) advance the existing defence line; (2) hold the existing defence line; (3) managed realignment; and (4) no active intervention. Options 1 and 2 can be considered as generic protection, while options 3 and 4 can be considered retreat.

**FIGURE 9.9** An example of disaster risk reduction: A cyclone shelter in Bangladesh. © *International Federation of Red Cross and Red Crescent Societies. Reprinted with permission from IFRC.*

Note that accommodation is also being implemented in the UK for flood management purposes, as demonstrated by Figure 9.7, but this is implemented at the property level, and hence at a much smaller scale. Supporting the SMP process are national monitoring systems. This high-level approach could be applied widely around the world's coast, including all risks including sea-level rise.

In parallel with this, there has also been recognition that while we need to adapt to sea-level rise, there is great uncertainty about timing and an opportunity to learn. Hence, while we can see different qualitative directions of travel (or possible adaptation pathways), we are not sure how fast we need to travel along the pathway as the magnitude of future sea-level rise is uncertain. Hence, we can define adaptation pathways and even select one and take actions that preserve the option without spending large sums that are needed to realize it, until required (Figure 9.10). Adaptation pathways, combined with monitoring and learning, are an attractive approach for coastal adaptation, especially in cities where large changes will be needed. This approach has been adopted in the Thames Estuary 2100 Project in London (Ranger et al., 2013; Tarrant and Sayers, 2013).

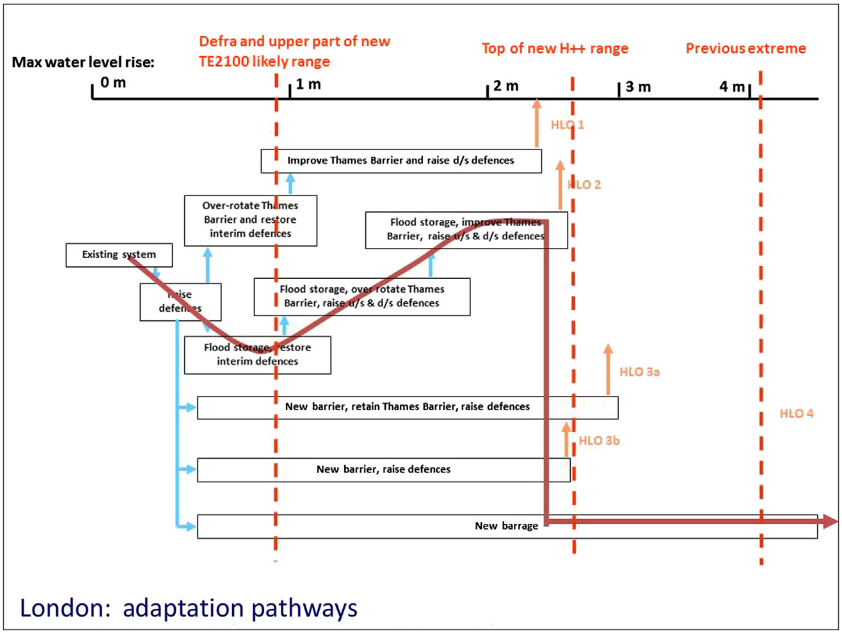


**FIGURE 9.10** An example of adaptation pathways for protecting London from coastal flooding: a number of options are shown where effective versus maximum water-level rise, and one possible adaptation pathway through these choices. The number of choices decline with increasing water level and ultimately there is only one option: a new (downstream barrage). *Ranger et al., 2013*.

### 9.8.3 Choosing between Adaptation Measures/Options

Retreat is often argued as the best response to sea-level rise (e.g., Pilkey and Young, 2009). However, benefit–cost models that compare protection with retreat generally suggest that it is worth investing in widespread protection as populated coastal areas have high economic value (e.g., Fankhauser, 1995; Anthoff et al., 2010; Nicholls et al., 2014a). This does not mean that we *should* protect. Rather the main insight is that these results suggest that significant resources should be available for adapting to sea-level rise, and further that protection can be expected to be a significant part of the portfolio of responses. With or without protection, small island and deltaic areas stand out as relatively more vulnerable in most of these analyses and the impacts fall disproportionately on poorer countries. Even though optimal in a benefit–cost sense, protection costs may overwhelm the capacity of local economies to fund, especially when they are small such as islands (Fankhauser and Tol, 2005; Nicholls and Tol, 2006). While adaptation is essentially a local activity, these funding challenges should be an issue of international concern due to the shared responsibility for climate-induced sea-level rise.

The coastal "adaptation deficit" is an important consideration. This is the cost of adapting coasts to today's climate, before considering adapting to sea-level rise and other climate changes (Burton, 2004; Parry et al., 2009). For example, Hallegatte et al. (2013) identified that US coastal cities have much higher expected damage costs than European coastal cities under current conditions. Equally, less developed and rapidly growing regions such as Africa and Asia are likely have a significant adaptation deficit (e.g., Hinkel et al., 2011), but this requires much more systematic evaluation.

Global cost estimates normally focus on the incremental costs of upgrading defence infrastructure, assuming no adaptation deficit, as this is consistent with the United Nations Framework Convention on Climate Change. Various cost estimates have been produced (Nicholls et al., 2014a), and they are generally smaller than expected, reflecting the high benefit–cost estimates already mentioned. For example, recent global protection costs for flooding were estimated to rise to US$20 and $70 billion/year over the twenty-first century (Hinkel et al., 2014). For 136 coastal cities, Hallegatte et al. (2013) argued that adaptation to sea-level rise would cost about US$50 billion/year. Considering beach erosion, global adaptation costs for sea-level rise only via nourishment estimated costs in 2100 of US$1.5–5 billion/year (Hinkel et al., 2013). These incremental costs seem affordable, but as the cost of the adaptation deficit is not addressed there are uncertainties. At the least, it raises the costs of adaptation in general and protection in particular by a substantial and unknown amount, and it may have the potential to radically change the adaptation pathway we select. Hence the choice between retreat, accommodate, and protect options continues to have significant uncertainties which require further investigation.

It should be noted that in many countries there is limited capacity to address today's coastal problems, let alone consider tomorrow's problems, including sea-level rise. Therefore, promoting coastal adaptation should include developing coastal management capacity and institutions, as already widely recommended (USAID, 2009; Moser et al., 2012).

### 9.8.4 Adaptation Experience

Through human history, developing technology has increased the range of adaptation options in the face of coastal hazards, and there has been a move from retreat and accommodation to hard protection and active seaward advance via land claim as exemplified by the Netherlands (Van Koningsveld et al., 2008). Rising sea level is one factor calling widespread reliance on protection into question, and the appropriate mixture of protection, accommodation, and retreat, and the whole philosophy of coastal adaptation is being seriously debated as already discussed (Wong et al., 2014).

While there is growing awareness of the need to adapt to sea-level rise, only a few countries or locations are comprehensively preparing for this challenge. Examples include London (Tarrant and Sayers, 2013) and the Netherlands (Kabat et al., 2009; Stive et al., 2011). Both these studies considered a wide range of sea-level rise scenarios, including scenarios of up to 5 m and 4 m, respectively, implicitly thinking beyond 2100. Importantly, they considered adaptation as a process and focused on adaptation pathways as a function of sea-level rise rather than time. This analysis demonstrates that there are options available for large rises in sea level, and in these cases protection upgrade seems feasible for the long-term. This is an effective way to deal with the uncertainty of future sea-level rise (Ranger et al., 2013; Haasnoot et al., 2013). It is worth noting that these activities were more about process and capacity than actual responses at the present time. For instance, the Netherlands has a Delta Commissioner to manage the Delta Plan and develop strategic policy processes and model tools to support this process.

In other locations such as New York City, adaptation is also being carefully considered (Rosenzweig and Solecki, 2010), but the timing of implementation is less clear. In this case, the major event of Cyclone Sandy has accelerated consideration of action, but the outcome is uncertain. In Singapore, new land claim will be raised by approximately a meter to allow for sea-level rise. In general coastal cities are expected to be a major focus for these efforts given the concentration of people and assets, and their ability to fund large investments (Hallegatte et al., 2013; Aerts et al., 2014).

## 9.9 DISCUSSION/CONCLUSIONS

The chapter illustrates that responding to sea-level rise is a multidimensional problem that crosses many disciplines and embraces natural, social, and engineering sciences, as well as engaging stakeholders, policy, and governance. Sea-level rise has important implications for the world's coast, but the actual outcome will depend on our responses, both in terms of mitigation and adaptation and their success or failure. For adaptation in general, and protection in particular, the likely success or failure is an important uncertainty that deserves more attention, as there are widely divergent views, and this strongly influences how the issue of sea-level rise is considered (e.g., Nicholls and Tol, 2006; Anthoff et al., 2010; Nicholls et al., 2014a). Pessimist and optimist camps exist who have quite different interpretations of the future, especially concerning adaptation. "Pessimists" tend to focus on high rises in sea level, extreme events like Hurricanes Katrina and Sandy and Typhoon Haiyan, and view our ability to adapt to sea-level rise as rather limited, resulting in widespread human migration away from coastal areas, reversing current trends. In contrast, "optimists" tend to focus on uncertainty and lower rises in sea level and stress a high technical ability to protect and the high benefit–cost ratios in developed areas leading to widespread protection. Hence to optimists a major consequence of sea-level rise is the diversion of investment to coastal adaptation in general, and protection in particular.

Optimists have empirical evidence to support their views that we can adapt to sea-level rise in terms of subsiding megacities that are also thriving. Importantly, these analyses suggest that improved protection under rising sea levels is more likely and rational than is widely assumed. The common assumption of a widespread, if not universal, retreat from the shore in the coming decades is not inevitable, and coastal societies will have more choice in their response to rising sea level. However, the pessimists also have evidence to support their view. First, the published protection costs are incremental costs of adapting to sea-level rise, assuming the existence of well-adapted protection infrastructure. The adaptation deficit needs to be considered in the context of adaptation and sea-level rise. Second, assumptions of substantial future population and especially economic growth in coastal areas reinforce the conclusion that protection is worthwhile, lower growth and greater inequalities of wealth may mean less damage in monetary terms, but it will also reduce our adaptive capacity. Third, taking a benefit–cost approach implies a proactive attitude to protection, while historical experience shows most protection has been a reaction to actual or near disaster. Therefore, more frequent coastal disasters and damage are likely in the near- to medium-term, even if the ultimate reactive response is upgraded protection (Hallegatte et al., 2013). Fourth, such disasters could trigger a cycle of decline and abandonment of coastal areas with a profound influence on society's choices concerning coastal protection (cf. Barnett and Adger, 2003). Lastly, maximizing the benefits of retreat and accommodation responses require that implementation occurs soon, which may not happen. Hence, adaptation may not be as successful as some assume, especially for larger rises in sea level. Hence there is much work remaining to understand these diverse issues and shape our coastal future!

Sea-level rise is clearly a threat that demands a response. Climate mitigation can reduce the commitment to sea-level rise, most particularly the potential Greenland and West Antarctic contributions. Local mitigation of human-induced subsidence also needs to be considered where appropriate as it will minimize RSLR in susceptible areas. However, a commitment to sea-level rise remains due to climate effects, supplemented by subsidence in many locations: this requires an adaptation response. There is a need to better understand these threats, including the implications of different mixtures of mitigation and adaptation, and different portfolios of adaptation and adaptation pathways. As the coast is a coupled system, it will be important to examine different scenarios of sea-level rise and climate change, socioeconomic changes, and how adaptation may coevolve with the wider coastal system. Better understanding the long-term effects of adaptation will require such a perspective. There is also a need to engage with and inform the coastal and climate policy process. Research is required at all scales from local to global, but much will be learnt about adaptation in practice (Wong et al., 2014). This will promote more appropriate adaptation options, as well as provide the opportunity to learn from experience.

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## REFERENCES

Aerts, J.C.J.H., Botzen, W.J.W., Emanuel, K., Lin, N., de Moel, H., Michel-Kerjan, E.O., 2014. Evaluating flood resilience strategies for coastal megacities. Science 344, 473–475.

Anthoff, D., Nicholls, R.J., Tol, R.S.J., 2010. The economic impact of substantial sea-level rise. Mitigation Adapt. Strateg. Global Change 15, 321–335.

Barnett, J., Adger, W.N., 2003. Climate dangers and atoll countries. Clim. Change 61, 321–337.

Barth, M.C., Titus, J.G. (Eds.), 1984. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. Van Nostrand Reinhold, New York, USA.

Bijlsma, L., Ehler, C.N., Klein, R.J.T., Kulshrestha, S.M., McLean, R.F., Mimura, N., Nicholls, R.J., Nurse, L.A., Pérez Nieto, H., Stakhiv, E.Z., Turner, R.K., Warrick, R.A., 1996. Coastal zones and small islands. In: Watson, R.T., Zinyowera, M.C., Moss, R.H. (Eds.), Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 289–324.

Bird, E.C.F., 1985. Coastline Changes: A Global Review. Wiley and Sons, New York, USA, 219.

Bird, E.C.F., 2000. Coastal Geomorphology: An Introduction. Wiley and Sons, Chichester, UK.

Borsje, B.W., van Wesenbeeck, B.K., Dekker, F., Paalvast, P., Bouma, T.J., van Katwijk, M.M., de Vries, M.B., 2011. How ecological engineering can serve in coastal protection. Ecol. Eng. 37, 113−122.

Brad Murray, A., Gopalakrishnan, S., McNamara, D.E., Smith, M.D., 2013. Progress in coupling models of human and coastal landscape change. Comput. Geosci. 53, 30−38.

Burton, I., 2004. Climate change and the adaptation deficit. In: French, A., et al. (Eds.), Climate Change: Building the Adaptive Capacity, Meteorological Service of Canada. Environment Canada, pp. 25−33.

Chatterjee, R.S., Fruneau, B., Rudant, J.P., Roy, P.S., Frison, P., Lakhera, R.C., Dadhwal, V.K., Saha, R., 2006. Subsidence of Kolkata (Calcutta) city, India during the 1990s as observed from space by differential Synthetic Aperture Radar Interferometry (D-InSAR) technique. Remote Sens. Environ. 102, 176−185.

Chaussard, E., Amelung, F., Abidin, H., Hong, S.-H., 2013. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. Remote Sens. Environ. 128, 150−161.

Church, J.A., Woodworth, P.L., Aarup, T., Wilson, W.S. (Eds.), 2010. Understanding Sea-level Rise and Variability. Wiley-Blackwell, Hoboken, NJ, USA, 428 pp.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A.R., Steven Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., Unnikrishnan, A.S., 2013. Sea level change. In: Climate Change 2013: The Physical Science Basis IPCC Working Group I, Fifth Assessment Report. Intergovernmental Panel on Climate Change.

Center for International Earth Science Information Network - CIESIN - Columbia University, 2013. Low Elevation Coastal Zone (LECZ) Urban-rural Population and Land Area Estimates, Version 2. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY. http://sedac.ciesin.columbia.edu/data/set/lecz-urban-rural-population-land-area-estimates-v2 (accessed 21.04.14.).

Crossland, C.J., Kremer, H.H., Lindeboom, H.J., Marshall Crossland, J.I., Le Tissier, M.D.A. (Eds.), 2005. Coastal Fluxes in the Anthropocene. Springer, Berlin, Germany.

Dang, V.K., Doubre, C., Weber, C., Gourmelen, N., Masson, F., 2014. Recent land subsidence caused by rapid urban development in the Hanoi region (Vietnam) using ALOS InSAR data. Nat. Hazards Earth Syst. Sci. 14, 657−674.

Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006. Effective sea-level rise and deltas: causes of change and human dimension implications. Global Planet. Change 50, 63−82.

Fankhauser, S., 1995. Protection versus retreat: estimating the costs of sea-level rise. Environ. Plann. A 27, 299−319.

Fankhauser, S., Tol, R.S.J., 2005. On climate change and economic growth. Res. Energy Econ. 27, 1−17.

Gornitz, V., 2013. Rising Seas: Past, Present and Future. Columbia University Press, New York, USA, 344 pp.

Grossi, P., Muir-Wood, R., 2006. Flood Risk in New Orleans: Implications for Future Management and Insurability. Risk Management Solutions (RMS), London, UK.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Global Environ. Change 23, 485−498.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Global Environ. Change 19, 240−247.

Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nat. Clim. Change 3, 802–806. http://dx.doi.org/10.1038/nclimate1979.

Hay, J.E., 2009. Institutional and Policy Analysis of Disaster Risk Reduction and Climate Change Adaptation in Pacific Island Countries. United Nations International System for Disaster Reduction (UNISDR) and the United Nations Development Programme (UNDP), Suva, Fiji.

Hinkel, J., Brown, S., Exner, L., Nicholls, R.J., Vafeidis, A.T., Kebede, A.S., 2011. Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. Regi. Environ. Change. http://dx.doi.org/10.1007/s10113-011-0249-2.

Hinkel, J., Nicholls, R.J., Tol, R.S.J., Wang, Z.B., Hamilton, J.B., Boot, G., Vafeidis, A.T., McFadden, Loraine, Ganopolski, A., Klein, R.J.T., 2013. A global analysis of erosion of sandy beaches and sea-level rise: an application of DIVA. Global Planet. Change 111, 150–158. http://dx.doi.org/10.1016/j.gloplacha.2013.09.002.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. of Sci.. http://dx.doi.org/10.1073/pnas.1222469111.

Holgate, S.J., Matthews, A., Woodworth, P.L., Rickards, L.J., Tamisiea, M.E., Bradshaw, E., Foden, P.R., Gordon, K.M., Jevrejeva, S., Pugh, J., 2013. New data systems and products at the Permanent Service for Mean Sea Level. J. Coastal Res. 29, 493–504. http://dx.doi.org/10.2112/JCOASTRES-D-12-00175.1.

Huq, S., Reid, H., 2004. Mainstreaming adaptation in development. IDS Bull. 35, 15–21. http://dx.doi.org/10.1111/j.1759-5436.2004.tb00129.x.

IPCC CZMS, 1990. Strategies for Adaption to Sea Level Rise. Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the Intergovernmental Panel on Climate Change. Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands.

Jones, L., Angus, S., Cooper, A., Doody, P., Everard, M., Garbutt, A., Gilchrist, P., Hansom, J., Nicholls, R.J., Pye, K., Ravenscroft, N., Rees, S., Rhind, P., Whitehouse, A., 2011. Coastal margins. In: UK National Ecosystem Assessment Technical Report. United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, UK.

Kabat, P., Fresco, L.O., Stive, M.J.F., Veerman, C.P., van Alphen, J., Parmet, B., Hazeleger, W., Katsman, C.A., 2009. Dutch coasts in transition. Nat. Geosci. 2, 450–452.

Kaneko, S., Toyota, T., 2011. Long-term urbanization and land subsidence in asian megacities: an indicators system approach. In: Taniguchi, M. (Ed.), Groundwater and Subsurface Environments: Human Impacts in Asian Coastal Cities, pp. 249–270. http://dx.doi.org/10.1007/978-4-431-53904-9_13.

Klein, R.J.T., Nicholls, R.J., 1999. Assessment of coastal vulnerability to climate change. Ambio 28, 182–187.

Klein, R.J.T., Aston, J., Buckley, E.N., Capobianco, M., Mizutani, N., Nicholls, R.J., Nunn, P.D., Ragoonaden, S., 2000. Coastal adaptation. In: Metz, B., Davidson, O.R., Martens, J.W., Van Rooijen, S.N.M., Van Wie McGrory, L.L. (Eds.), IPCC Special Report on Methodological and Technological Issues in Technology Transfer. Cambridge University Press, Cambridge, UK.

Klein, R.J.T., Midgley, G.F., Preston, B.L., Alam, M., Berkhout, F.G.H., Dow, K., Shaw, M.R., 2014. Adaptation Opportunities, constraints, and limits. In: Climate Change 2014: Impacts Adaptation and Vulnerability IPCC Working Group II, Fifth Assessment Report. Intergovernmental panel on Climate Change.

Kron, W., 2013. Coasts: the high-risk areas of the world. Nat. Hazards 66, 1363–1382.
Linham, M.M., Nicholls, R.J., 2010. Technologies for Climate Change Adaptation: Coastal Erosion and Flooding. TNA Guidebook Series. UNEP Risø Centre on Energy, Climate and Sustainable Development, Roskilde, Denmark, 150pp.
McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urban. 19, 17–37.
Menéndez, M., Woodworth, P.L., 2010. Changes in extreme high water levels based on a quasi-global tide-gauge dataset. J. Geophys. Res. 115, C10011.
Milliman, J.D., Broadus, J.M., Gable, F., 1989. Environmental and economic implications of rising sea level and subsiding deltas: the Nile and Bengal examples. Ambio 18, 340–345.
Moser, S.C., Williams, S.J., Boesch, D.F., 2012. Wicked challenges at Land's end: managing coastal vulnerability under climate change. Annu. Rev. Environ. Resour. 37, 51–78.
Nicholls, R.J., 2010. Impacts of and responses to sea-level rise. In: Church, J.A., Woodworth, P.L., Aarup, T., Wilson, S. (Eds.), Understanding Sea-level Rise and Variability. Wiley-Blackwell, pp. 17–51.
Nicholls, R.J., Cazenave, A., 2010. Sea level rise and its impact on coastal zones. Science 328, 1517–1520.
Nicholls, R.J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Chateau, J., Muir-Wood, R., 2008. Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes—Exposure Estimates. Environmental Working Paper No. 1. Paris Organisation for Economic Co-operation and Development (OECD).
Nicholls, R.J., Klein, R.J.T., 2005. Climate change and coastal management on Europe's coast. In: Vermaat, J.E., Ledoux, L., Turner, K., Salomons, W., Bouwer, L. (Eds.), Managing European Coasts: Past, Present and Future. Springer, London, UK (Environmental Science Monograph Series).
Nicholls, R.J., Tol, R.S.J., 2006. Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 364, 1073–1095.
Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., Van Der Linden, P., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK.
Nicholls, R.J., Woodroffe, C.D., Burkett, V.R., 2009. Coastal degradation as an Indicator of global change. In: Letcher, T.M. (Ed.), Climate Change: Observed Impacts on Planet Earth. Elsevier, Oxford, pp. 409–424.
Nicholls, R.J., Townend, I.H., Bradbury, A., Ramsbottom, D., Day, S., 2013. Planning for long-term coastal change: experiences from England and Wales. Ocean Eng. 71, 3–16. http://dx.doi.org/10.1016/j.oceaneng.2013.01.025.
Nicholls, R.J., Stive, M.J.F., Tol, R.S.J., 2014a. Coping with coastal change. In: Masselink, G., Gehrels, R. (Eds.), Coastal Environments and Global Change. Wiley, Chichester, UK.
Nicholls, R.J., Hanson, S.E., Lowe, J.A., Warrick, R.A., Lu, X., Long, A.J., 2014b. Sea-level scenarios for evaluating coastal impacts. Wiley Interdiscip. Rev.: Clim. Change 5 (1), 129–150.
Nurse, L., McLean, R., Agard, J., Briguglio, L.P., Duvat, V., Pelesikoti, N., Tompkins, E., Webb, A., 2014. Small islands. In: Climate Change 2014: Impacts, Adaptation and Vulnerability IPCC Working Group II, Fifth Assessment Report. Intergovernmental Panel on Climate Change.

Parry, M.L., Arnell, N.W., Berry, P.M., Dodman, D., Fankhauser, S., Hope, C., Kovats, S., Nicholls, R.J., Satterthwaite, D., Tiffin, R., Wheeler, T., 2009. Assessing the costs of adaptation to climate change: a review of the UNFCCC and other recent estimates. International Institute for Environment and Development and Grantham Institute for Climate Change, London, 111pp. Permanent Service for Mean Sea Level (PSMSL), 2014, "Tide Gauge Data", Retrieved 30 Jun 2014 from. http://www.psmsl.org/data/obtaining/.

Pilkey, O.H., Young, R., 2009. The Rising Sea. Island Press/Shearwater Books, Washington, D.C., 203pp.

PSMSL, 2014. Data from the Permanent Service for Mean Sea Level (PSMSL). http://www.psmsl.org/ (accessed 08.05.14.).

Pugh, D., Woodworth, P., 2014. Sea-level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-level Change. Cambridge University Press, Cambridge, 395pp.

Ranger, N., Reeder, T., Lowe, J.A., 2013. Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. Eur. J. Decis. Processes 1, 233–262.

Rawlani, A.K., Sovacool, B.J., 2011. Building responsiveness to climate change through community based adaptation in Bangladesh. Mitigation Adapt. Strateg. Global Change 16, 845–863.

RIBA and ICE, 2010. Facing up to Rising Sea Levels. Retreat? Defend? Attack? RIBA (Royal Institute of British Architects) and ICE (Institution of Civil Engineers), London. http://www.buildingfutures.org.uk/assets/downloads/Facing_Up_To_Rising_Sea_Levels.pdf.

Rodolfo, K.S., Siringan, F.P., 2006. Global sea-level rise is recognised, but flooding from anthropogenic land subsidence is ignored around northern Manila Bay. Philipp. Disaster Manage. 30, 118–139.

Rosenzweig, C., Solecki, W. (Eds.), 2010. Climate Change Adaptation in New York City: Building a Risk Management Response, vol. 1196. Annals of the New York Academy of Sciences, pp. 1–354.

Ruocco, A.C., Nicholls, R.J., Haigh, I.D., Wadey, M.P., 2011. Reconstructing coastal flood occurrence combining sea level and media sources: a case study of the Solent, UK since 1935. Nat. Hazards 59 (3), 1773–1796. http://dx.doi.org/10.1007/s11069-011-9868-7.

Seasholes, N.C., 2003. Gaining Ground: A History of Landmaking in Boston. MIT Press, Cambridge, MA, USA.

Smith, K., 2013. Environmental Hazards: Assessing Risk and Reducing Disaster. Routledge, London, UK.

Stive, M.J.C., Fresco, L.O., Kabat, P., Parmet, B.W.A.H., Veerman, C.P., 2011. How the Dutch plan to stay dry over the next century. Proc. Inst. Civ. Eng. 164, 114–121.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas. Nat. Geosci. 2, 681–689.

Tarrant, O., Sayers, P.B., 2013. Managing flood risk in the Thames Estuary – the development of a long-term robust and flexible strategy. In: Sayers, P.B. (Ed.), Flood Risk: Planning, Design and Management of Flood Defence Infrastructure. ICE Publishing, London, UK, pp. 303–326.

Teatini, P., Tosi, L., Strozzi, T., Carbognin, L., Wegmüller, U., Rizzetto, F., 2005. Mapping regional land displacements in the Venice coastland by an integrated monitoring system. Remote Sens. Environ. 98 (4), 403–413.

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504, 79–83.

Tribbia, J., Moser, S.C., 2008. More than information: what coastal managers need to plan for climate change. Environ. Sci. Policy 11, 315–328.

Tsyban, A., Everett, J., Titus, J., 1990. World oceans and coastal zones. In: McG. Tegart, W.J., Sheldon, G.W., Griffiths, D.C. (Eds.), Climate Change: The IPCC Impacts Assessment. Australian Government Publishing Service, Canberra, pp. 6-1–6-28.

USAID, 2009. Adapting to Coastal Climate Change: A Guidebook for Development Planners. USAID, Rhode Island. Available from. www.crc.uri.edu/download/CoastalAdaptationGuide.pdf (accessed 07.10.10.).

Valiela, I., 2006. Global Coastal Change. Blackwell, Malden, MA, USA.

Van Koningsveld, M., Mulder, J.P.M., Stive, M.J.F., Van Der Valk, L., Van Der Weck, A.W., 2008. Living with sea-level rise and climate change: a case study of the Netherlands. J. Coastal Res. 24, 367–379.

Wong, P.P., Losada, I.J., Gattuso, J., Hinkel, J., Khattabi, A., McInnes, K., Saito, Y., Sallenger, A., 2014. Coastal systems and low-lying areas. In: Climate Change 2014: Impacts, Adaptation and Vulnerability IPCC Working Group II, Fifth Assessment Report Intergovernmental Panel on Climate Change.

Zhang, K.Q., Douglas, B.C., Leatherman, S.P., 2000. Twentieth-century storm activity along the US east coast. J. Clim. 13, 1748–1761.