Chapter 2

Adapting to Sea-Level Rise

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Chapter Outline

2.1 INTRODUCTION

Sea-level rise (SLR) has been recognized as a 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 an ever growing literature demonstrating the large potential impacts of SLR. Hence, interest in coastal adaptation is also increasing (Linham and Nicholls, 2010; Moser et al., 2012; Wong et al., 2014). Although SLR 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; Neumann et al., 2015), and coastal urban areas are expanding rapidly (Hanson et al., 2011). These people and assets are exposed to multiple meteorological and geophysical hazards, including storms and storm-induced flooding (Kron, 2013). Many low-lying coastal areas already depend on various flood risk adaptation strategies, be it natural and/or artificial flood defences and drainage or flood resilient construction methods. Recent major events such as Hurricane Katrina, 2005 (New Orleans and environs, USA), Cyclone Nagris, 2008 (Irrawaddy delta, Myanmar), Superstorm Sandy, 2012 (New York and environs), Typhoon Haiyan, 2013 (the Philippines), or the 2017 Atlantic hurricane season in the Caribbean and US Gulf Coasts demonstrate the present vulnerability of low-lying coastal areas to floods during storms. SLR and potentially more intense storms have the potential to exacerbate these risks significantly unless we adapt (Wong et al., 2014). As well as the human environment, coastal areas also support important and productive ecosystems that are sensitive to SLR (Crossland et al., 2005).

This chapter focuses on adaptation to SLR. This can be defined as reducing the impacts of SLR via behavioral changes. This includes a range of actions from individuals/households to collective coastal management policy, such as upgraded defence systems, warning systems and land management approaches. SLR is a pervasive long-term problem that will continue for centuries. Hence, the chapter focuses on collective actions as only at this level of response can the long-term challenge of SLR be met. Coastal adaptation to SLR has been considered for the last 20−30 years (Barth and Titus, 1984; Dronkers et al., 1990; Bijlsma et al., 1996), building on the large experience of coastal adaptation to extremes and other stresses such as coastal subsidence. Despite this experience, uncertainties about the success or failure of adaptation to SLR remains large, contributing significant uncertainty to the overall consequences of SLR for society (Nicholls et al., 2014a; Nicholls, 2014). Hence, the chapter reviews and evaluates current efforts in coastal adaptation to SLR.

The chapter is structured as follows. First the coast as a system is elaborated. This provides an appropriate framework to analyze coasts, SLR and adaptation. Second, climate change and SLR are considered in more detail, including

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the important distinction between global-mean and relative SLR. Then the impacts of SLR are briefly considered from both a biophysical and a socioeconomic perspective, including drawing on experience from subsiding coasts. This is followed by a more detailed consideration of adaptation. This demonstrates the complexity of adaptation and the multiple factors that need to be considered. A discussion/conclusion ends the chapter, including consideration of success and failure and how can best practice be defined.

2.2 COASTAL SYSTEMS

Global SLR and the need to adapt does not happen in isolation: coasts are changing significantly due to numerous other factors such as urbanization and changing water/sediment inputs due to river regulation and watershed land use and coastal land cover change (Crossland et al., 2005; Valiela, 2006; Bianchi, 2016). Table 2.1 summarizes the key trends of which SLR is one important and pervasive factor. This requires a systems approach to analyze the full range of interacting drivers, including feedbacks of which adaptation is an example. Fig. 2.1 presents a simplified systems model of the impacts of SLR and other drivers on the coastal zone. Such a conceptual model highlights the varying implicit and explicit assumptions, simplifications, and limitations of any assessment of coastal impacts. The overall coastal system is characterized as interacting natural and socioeconomic systems. Both systems can be characterized by key system properties such as their exposure, sensitivity and adaptive capacity, both due to SLR, related climate change, and other nonclimate stresses (see Klein and Nicholls, 1999). These conceptual models have been considered and developed by the Intergovernmental Panel on Climate Change (IPCC) assessments.

TABLE 2.1 Key Coastal Trends at the Global Scale

- Population
  - Growing coastal population (double global trends)
  - Urbanizing coastal zone (new residents are urban)
  - Increasing tourism, recreation and retirement
- Subsiding, densely-populated deltas, especially in urban areas
- Globalization of trade and international shipping routes
- Increasingly costly coastal disasters
- Climate change and sea-level rise
- A reactive approach to adaptation
- Degrading coastal habitats and declining ecosystem services

Source: From Dawson, R.J., Nicholls, R.J., Day, S.A., 2015. The challenge for coastal management during the third millenium. In R.J. Nicholls, R.J. Dawson, S.A. Day (Eds.), Broad Scale Coastal Simulation: New Techniques to Understand and Manage Shorelines in the Third Millennium. Springer, Dordrecht, NL, pp. 1–78 (Dawson et al., 2015).

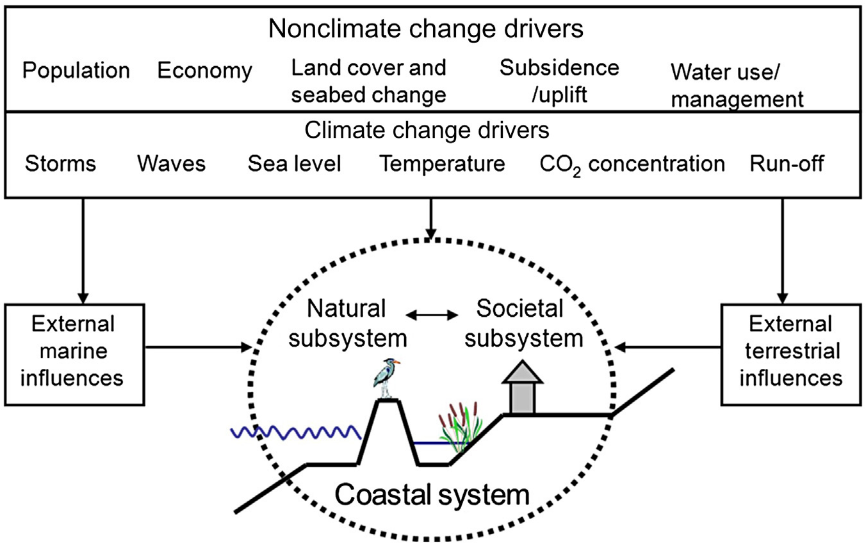

FIGURE 2.1 The Coastal System comprises interacting natural and human subsystems, and external terrestrial and marine influences. A range of nonclimate and climate drivers can act directly or indirectly on the Coastal System, including sea-level rise. *Adapted by Nicholls (2014) from Figure 6.1 in IPCC 4th Assessment Report (2007). 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 GlobalChange. Wiley, Chichester.*

A range of drivers may influence the coastal zone, either directly or via terrestrial or oceanic influences (Fig. 2.1). SLR is one aspect of climate change and these drivers interact with nonclimate stresses, often exacerbating impacts (see Table 2.2). The socioeconomic system is not passive and influences the natural system by 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

TABLE 2.2 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: At, Attack; Ph and Ps, Hard or Soft Protection, respectively; Ac, 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 claim [At] Dikes/surge barriers/closure dams [Ph], Nourishment, including dune construction [Ps], Ecosystem-based barriers (e.g., mangrove buffers) [Ps], Building codes/flood-proof buildings [Ac], Land use planning/hazard mapping [Ac/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 claim (i.e., direct destruction).	Gabions/breakwaters [Ph], Nourishment/sediment management [Ps], Wetland planting [Ps], Land use planning [Ac/R], Managed realignment/ forbid hard defences [R].
3. Erosion (of "soft" morphology)		Sediment supply, Wave/storm climate.	Sediment supply.	Land claim [At] Coastal defences/seawalls [Ph], Ecosystem-based barriers (e.g., mangroves) [Ps], Nourishment [Ps], Building setbacks/rolling easements [R].
4. Saltwater Intrusion	a. Surface Waters	Run-off.	Catchment management (water extraction/ diversion), Land use.	Saltwater intrusion barriers [P], Desalination [Ac], Move water abstraction upstream [R].
	b. Groundwater	Rainfall.	Land use, Aquifer utilization.	Impermeable groundwater barriers [P] Freshwater injection [P], Desalination [Ac], Change water abstraction [Ac/R].
5. Impeded drainage/ rising water tables		Rainfall, Run-off.	Land use, Aquifer utilization, Catchment management.	Drainage systems/polders [Ph], Change land use/crop type [Ac], Land use planning/hazard delineation [Ac/R].

Source: Adapted from 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, 2010, pp. 17—51; Nicholls, R.J., 2014. Adapting to sea level rise. In J.T. Ellis, D.J. Sherman (Eds.), Coastal and Marine Hazards, Risks and Disasters. London, GB: Elsevier, pp. 243—270.

constrains the natural system, and vice versa. This raises the prospect of the coast as a coevolving system where the natural system shapes the socioeconomic system and vice versa, with adaptation being an important feedback. It raises a new way of thinking about the future of coasts, which is shedding new insights on coastal evolution and the role of adaptation (Lazarus et al., 2016; Welch et al., 2017).

2.3 GLOBAL-MEAN AND RELATIVE SEA-LEVEL CHANGE

Climate-induced SLR is mainly due to (1) thermal expansion of seawater as it warms, and (2) the melting/destabilization 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, 2013). The global SLR trend was 1.1 ± 0.3 mm/year from 1900 to 1990 and 3.1 ± 1.4 mm/year from 1993 to 2012 showing a significant recent acceleration (Dangendorf et al., 2017). There is a large uncertainty about future SLR, and hence adaptation needs which hinders action. Over the 21st century a rise of 1 m or more is plausible if the major ice sheets make a large positive contribution to sea level with larger changes beyond 2100 (Church et al., 2013). Future SLR depends in part on future greenhouse gas emissions. Even if we achieve the Paris Agreement targets (United Nations, 2015), there will still be a significant rise due to the strong inertia of SLR. For unmitigated emissions versus 2.0°C temperature stabilization, Nicholls et al. (2017) made a median estimate of global SLR of 0.72 and 0.49 m by 2100, and 3.65 and 1.17 m by 2300 (relative to 1985–2005 mean), respectively. Hence, while aggressive climate mitigation significantly reduces the rise, a growing need for adaptation remains. As such SLR adaptation seems essential under all plausible futures, but the quantitative need is uncertain (cf. Nicholls et al., 2007; Wong et al., 2014).

When analyzing SLR impacts and adaptation responses, it is fundamental that impacts are a product of *relative* (or local) 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, and natural and human-induced subsidence. Gravitational effects due to mass redistribution of melting ice also need to be considered. Hence, relative sea-level change is only partly a response to climate change and varies in space (Fig. 2.2). Many populated deltaic areas and alluvial plains are experiencing enhanced subsidence (Ericson et al., 2006; Syvitski et al., 2009; Chaussard et al., 2013) and RSLR exceeds the global rise, as at Grand Isle in the Mississippi delta (Fig. 2.2). Most dramatically, subsidence can be enhanced by drainage and withdrawal of groundwater in susceptible soils. Multimeter RSLR has been observed in a number of coastal cities built on deltas and alluvial plains over the last 100 years due to this cause, such as Tokyo, Osaka, Shanghai, and Bangkok (Figs. 2.2 and 2.3). Human-induced subsidence can be mitigated by stopping shallow subsurface fluid withdrawals and managing water levels, but natural "background" rates of subsidence 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 successively implemented subsidence mitigation policies (Kaneko and Toyota, 2011), combined with the provision of improved flood defence and pumped drainage systems to avoid submergence and/or frequent flooding. However, other cities such as Jakarta and Metro Manila are still subsiding, suggesting that the

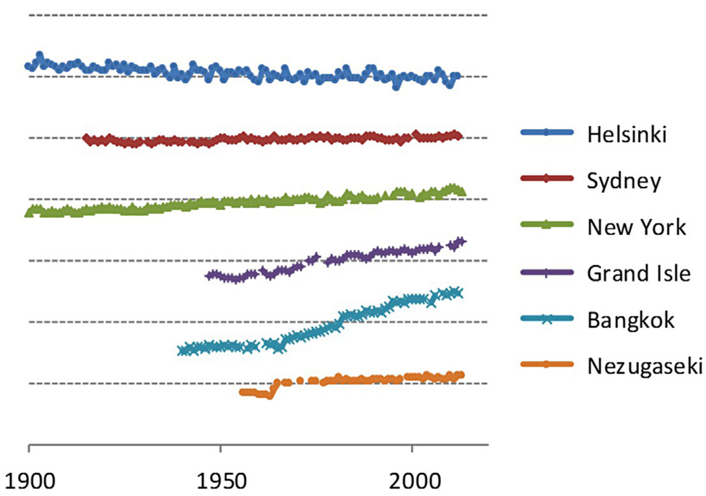

FIGURE 2.2 Selected relative sea-level observations since 1900, illustrating different trends (offset for display purposes with meter divisions). Helsinki shows a falling trend (−2.0 mm/year) as the land is rising, Sydney shows a gradual rise (0.9 mm/year), New York is subsiding slowly (3.1 mm/year), 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 0.15–0.20 mm rise due to an earthquake. *Data from Holgate, S.J., Matthews, A., Woodworth, P.L., Rickards, L.J., Tamisiea, M.E., Bradshaw, E., et al., 2013. New data systems and products at the permanent service for mean sea level. J. Coastal Res. 29, 493–504. doi:10.2112/JCOASTRES-D-12-00175.1 (Holgate et al., 2013); Permanent Service for Mean Sea Level (PSMSL), 2014. Tide Gauge Data. Retrieved 30 Jun 2014 from http://www.psmsl.org/data/obtaining/ (PSMSL, 2014).*

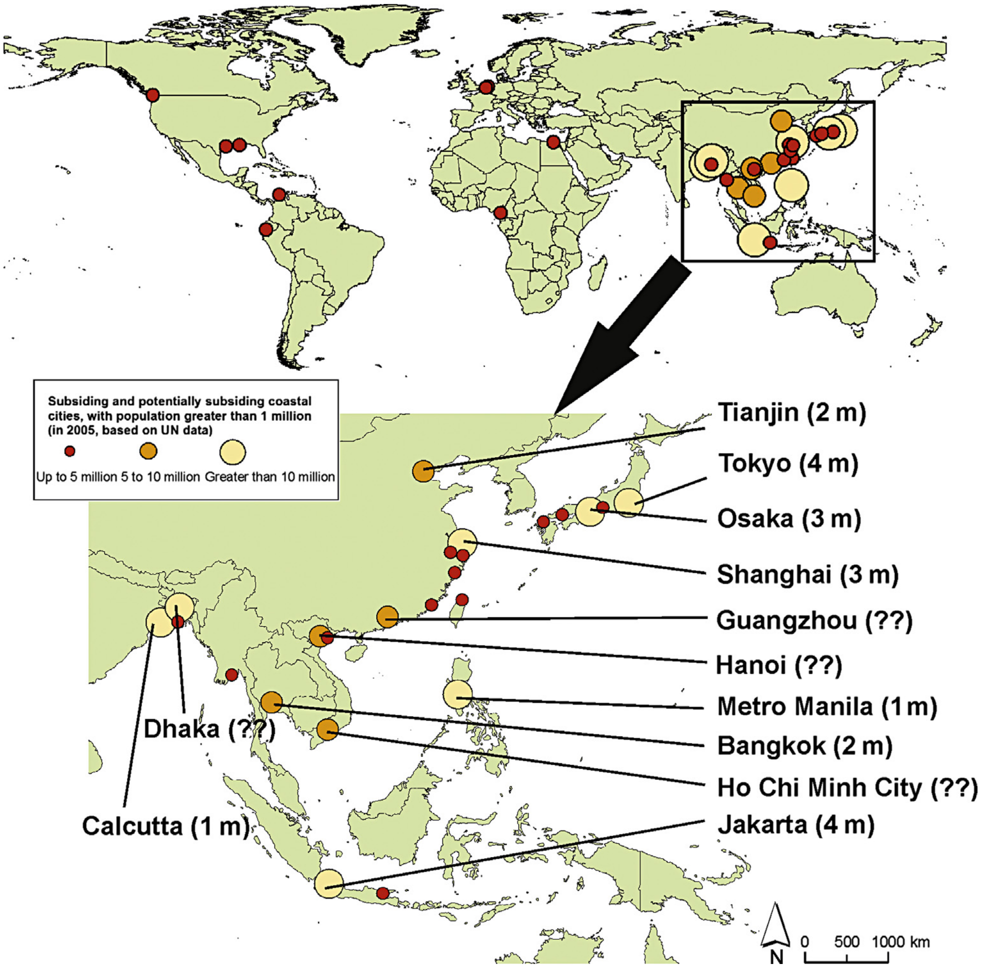

FIGURE 2.3 Subsiding and potentially subsiding coastal cities due to human influence. The maximum observed subsidence (in meters) is shown for cities with populations exceeding 5 million people, where known. The maximum subsidence is reported as data on average subsidence is not available. *Reproduced from Nicholls, R.J., 2014. Adapting to sea level rise. In J.T. Ellis, D.J. Sherman (Eds.), Coastal and Marine Hazards, Risks and Disasters. London, GB: Elsevier, pp. 243–270.*

problem of enhanced subsidence are likely to be widely repeated in other susceptible coastal cities through the 21st century. It is important to emphasize that only some cities are susceptible to this problem: of the 136 large coastal cities considered by Hallegatte et al. (2013), 32 (or 24%) have an appropriate geological setting to experience enhanced subsidence (Fig. 2.3). Note the concentration of large cities in south, south-east, or east Asia, giving this issue a strong regional dimension.

More appreciation of the importance of subsidence is urgently needed to promote appropriate responses and evidence-based adaptation needs to distinguish climate-induced and subsidence-induced RSLR as a first step to finding solutions. New measurement systems will permit analysis and quantification of subsidence (Chatterjee et al., 2006; Teatini et al., 2005), supporting such analysis.

2.4 IMPACTS OF SEA-LEVEL RISE

RSLR causes more effects than simple submergence (the "bath-tub" effect); the five main effects are summarized in Table 2.2. Flooding/submergence, ecosystem change, and erosion have received significantly more assessment 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 land, as well as saltwater intrusion into surface waters. Longer term effects also occur as the coast adjusts to the new environmental conditions, including ecosystem change and loss, erosion of beaches and soft cliffs, and saltwater intrusion into groundwater. These lagged changes interact with the immediate effects of SLR and generally exacerbate them. For instance, erosion of saltmarshes, mangroves, sand dunes, and coral reefs degrade or remove natural protection from waves and storms and increase the likelihood of coastal flooding.

TABLE 2.3 Summary of Sea-Level Rise Impacts on Socioeconomic Sectors in Coastal Zones. These Impacts Are Overwhelmingly Negative

Coastal Socioeconomic Sector	Sea-Level Rise Natural System Effect (Table 2.2)				
	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.
Source: Reproduced from 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, 2010, pp. 17–51.

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 (e.g., Wahl et al., 2017).

Changes in natural systems resulting from SLR have many important direct socioeconomic impacts on a range of sectors, with these impacts being overwhelmingly negative (Table 2.3). For instance, flooding can damage coastal infrastructure, ports and industry, the built environment, and agricultural areas. In the worst case, coastal flooding can lead to significant mortality. There were 1200–1800 deaths due to Hurricane Katrina (USA) in 2005, about 138,000 deaths due Cyclone Nargis (Myanmar) in 2008, and at least 6000 deaths due to Typhoon Haiyan (the Philippines) in 2013. 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 (Nicholls and Kebede, 2012; Hallegatte, 2012). These indirect impacts are less understood and appreciated, but can be significant. Thus, SLR has the potential to trigger a cascade of direct and indirect human impacts.

Potential interactions of nonclimate drivers with SLR need to considered. They are indicated in Table 2.2 (column entitled “Potential Interacting Factors”). For instance, a coast with a positive sediment budget may not erode given SLR 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).

2.5 RECENT IMPACTS OF SEA-LEVEL RISE

Since 1900, global sea level rose in round terms 10–20 cm following the analysis of Dangendorf et al. (2017). While this change may seem small, it has had many significant coastal effects, such as reducing the return periods of extreme sea levels (Zhang et al., 2000; Menendez and Woodworth, 2010), development of “blue sky” chronic flooding where floods become a regular rather than a rare occurrence (Sweet et al., 2014), and promoting an erosive tendency for coasts (Bird, 1985, 2000). However, linking SLR quantitatively to impacts is difficult due to the multiple drivers of change already discussed (see Nicholls et al., 2015a). Good data on rising sea levels has only been measured in a few locations, and growing coastal populations and infrastructure have significantly increased the exposure available to damage. At the same time, natural defences have been widely degraded by urban expansion and erosion trends. In addition, adaptation has occurred and, e.g., artificial flood defences have often been upgraded substantially, reducing the incidence of floods despite higher sea levels (e.g., Ruocco et al., 2011). Most of these defence upgrades coincide with expanding populations and wealth in the coastal flood plain and growing risk aversion. Hence, RSLR may not have been explicitly considered in design. Equally, impacts can be promoted by processes other than SLR (Table 2.2), including subsidence. As another 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 SLR is a pervasive process, other processes obscure its link to impacts, except in some special cases; most coastal change in the 20th century was a response to multiple drivers of change.

There have certainly been impacts from RSLR resulting from subsidence (Nicholls, 2010). Notable sites include increased floods in the iconic city of Venice, which will shortly be protected by the MOSES storm surge barriers 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 associated with subsiding coastal cities (e.g., Fig. 2.3), 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 where population declines seem linked to defence failure (Grossi and Muir Wood, 2006). The city population peaked in 1965 at more than 625,000 immediately before the Hurricane Betsy floods, and was 500,000 before Katrina in 2005. Subsequently, the population has yet to recover to pre-Katrina levels, although US$15 billion has been invested to significantly upgrade defences (completed 2011). The future of New Orleans in terms of flood occurrence, socioeconomic changes and adaptation will be instructive to monitor.

Observations since 1900 reinforce the importance of understanding the impacts of SLR in the context of multiple drivers of change; this will remain the case under more rapid rises in sea level. RSLR due to human-induced subsidence is of particular interest, but this remains relatively unstudied. 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.

2.6 FUTURE IMPACTS OF SEA-LEVEL RISE

The future impacts of SLR will depend on a range of factors, including: (1) the magnitude of SLR; (2) the coastal physiographic setting; (3) the nature of coastal development; and (4) the success (or failure) of adaptation. Assessments of the future impacts of SLR have taken place on a range of scales from local to global. They all demonstrate large potential impacts consistent with Table 2.2, especially increases in inundation, flooding, and storm damage. Recent studies of flood risk (i.e., expected annual damages) under SLR all emphasize catastrophic impacts assuming no adaptation (e.g., Hallegatte et al., 2013; Hinkel et al., 2014). However, if defences are upgraded and other adaptation takes place, flood impacts are more limited and possibly almost totally avoided. This raises the question of the long-term implications of such an adaptation pathway.

In absolute numbers East, South-East, and East Asia and Africa appear to be most threatened by SLR (Fig. 2.4). 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 SLR. Impact 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 SLR impacts (Nurse et al., 2014). The populations of low-lying island nations, founded on atolls, such as the Maldives, Kiribati, or Tuvalu face the real prospect of increased flooding, submergence, salinization, and even forced abandonment due to SLR.

2.7 ADAPTATION TO SEA-LEVEL RISE

Adaptation to SLR involves responding to both mean and extreme rise. It is a complex process with multiple dimensions which are characterized differently across the literature. The overall field of climate adaptation is 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 in climate adaptation. It is useful to recognize different dimensions of adaptation, such as (1) autonomous (or spontaneous) adaptation versus planned adaptation, (2) proactive versus reactive

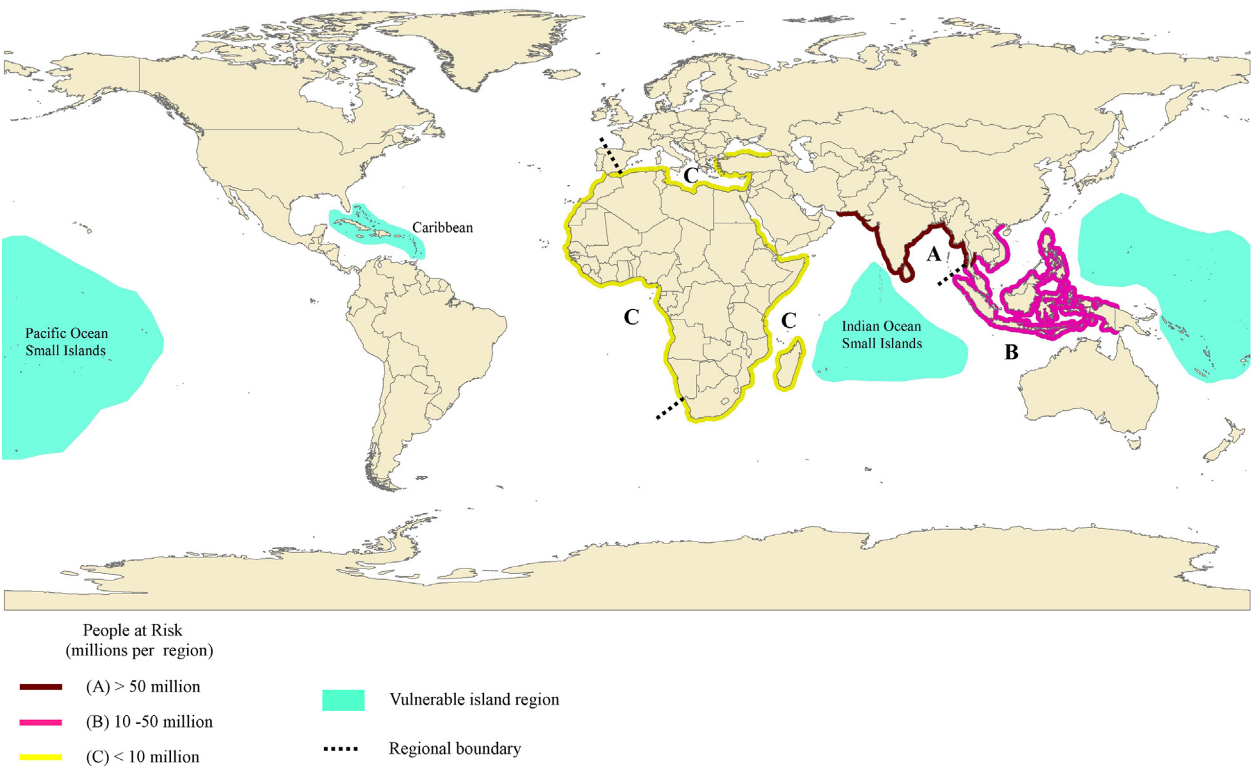

FIGURE 2.4 Regions most vulnerable to coastal flooding and sea-level rise. At highest risk are coastal zones with dense populations, low elevations, appreciable rates of subsidence, and/or inadequate adaptive capacity. *From Nicholls, R.J., Cazenave, A., 2010. Sea level rise and its impact on coastal zones. Science, 328, 1517–1520 (Nicholls and Cazenave, 2010).*

planned adaptation, and (3) individual/household versus collective 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 SLR. Further, adaptation in the coastal context is widely seen as a public rather than a private responsibility, meaning that government is expected to develop and facilitate adaptation (Klein et al., 2000; Tribba and Moser, 2008).

Historically, society has tended to react to coastal trends and disasters rather than anticipate them. For SLR there are significant benefits in promoting proactive planning of adaptation, as the demand for adaptation can be expected to grow. Further, many adaptation decisions have long-term (10–100 years) implications (e.g., Hallegatte, 2009). Examples of proactive adaptation in coastal zones include upgraded flood defences and drainage systems, higher elevation designs for new coastal infrastructure such as coastal bridges, building standards/regulations to promote flood proofing and resilience, and building setbacks to prevent development in areas threatened by erosion and flooding.

This section considers adaptation strategies and options which are the building blocks of adaptation. It then considers adaptation processes and frameworks and how adaptation strategies and options are put together in space and time. The selection of adaptation strategies and options is considered, followed by experience of adaptation.

2.7.1 Adaptation Strategies and Options

Coastal adaptation can be classified in various ways: one of the most widely followed approaches is the IPCC typology of retreat, accommodation, and protection (Dronkers et al., 1990; Bijlsma et al., 1996). The concept of “attack” has been suggested as an additional adaptation strategy against SLR (e.g., RIBA and ICE, 2010). These can be linked together as shown in Fig. 2.5 and defined below:

- *(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., Fig. 2.6);

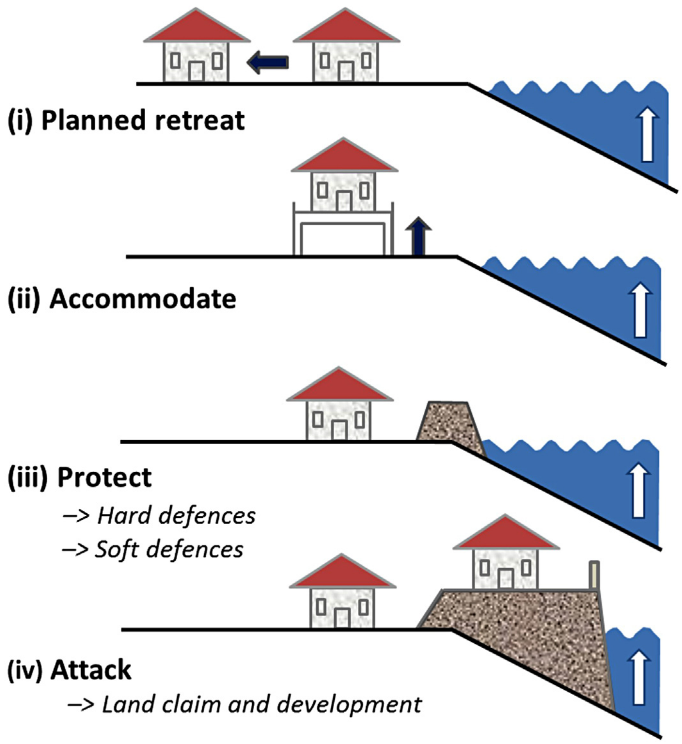

FIGURE 2.5 Generic adaptation approaches for sea-level rise, modified to include attack (via land claim and coastal development). *Modified from Dronkers, J., Gilbert, J.T.E., Butler, L.W., Carey, J.J., Campbell, J., James, E., et al., 1990. Strategies for adaption to sea level rise. Report of the Coastal Zone Management Subgroup, Response Strategies Working Group of the Intergovernmental Panel on Climate Change. The Hague, The Netherlands, Ministry of Transport, Public Works and Water Management.*

FIGURE 2.6 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. (A) Aerial view from the east and (B) the breach from the west (photograph). (A) UK Environment Agency Copyright, reprinted with permission (B) Photograph by Hachem Kassem.

FIGURE 2.7 An example of accommodation in a coastal flood plain in the United Kingdom. The older property on the left is built at grade, while the adjoining property has been raised to enhance flood resilience—the design elevation considers present extreme water levels plus an allowance for future sea-level rise.

FIGURE 2.8 An example of a protection option: a new sea dike which has been raised as part of the phase 1 upgrade to the coastal flood defences in North Portsea Island, Portsmouth. The design height includes an allowance for sea-level rise.

- *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, applying flood resilience measures, etc. (e.g., Fig. 2.7);
- *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., Fig. 2.8);
- *Attack*—build seaward and upwards, such as claiming new land to promote economic development.

Individually, there are a large set of potential adaptation options. Examples of adaptation options linked to each natural system impact of SLR are provided in Table 2.2.

Attack is consistent with land claim and advancing seawards (Linham and Nicholls, 2010). Land claim has a long history in coastal areas, including around most large coastal cities due to space constraints and high land values (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. In the context of Attack, SLR must be considered as shown in Fig. 2.5. As an extreme option, floating islands have been suggested as a response to SLR, although this remains untested in practise (Marris, 2017). Attack will be costly and it is most likely where it promotes increased economic activity, which can finance this investment.

Information measures such as disaster preparedness, hazard mapping, and flood warning/evacuation are growing in importance, and are cross-cutting and complementary of the approaches above. There is also growing interest in nature-based approaches, which have the advantage of being self-sustaining and providing multiple benefits (Borsje et al., 2011; Temmerman et al., 2013; Pontee et al., 2016). However, the uncertainties about their future state and function is much higher than engineered defences hindering application. In the future there is likely to be widespread potential for hybrid approaches which combine nature-based and more traditional engineering options. For example, flood protection could combine ecosystem buffers in front of artificial defences, reducing the required defence size (or further reduce risk). Building elevation via controlled sedimentation is another innovation option for coastal areas with large sediment supplies, especially deltas (Darby et al., 2018).

Where protection is used, we need to evaluate the residual risk that inevitably remains (but is often neglected). This suggests that protection must be combined with forecast/warning systems. Adaptation for one sector may also exacerbate impacts elsewhere: a good example is coastal squeeze of intertidal and shallow coastal habitats where onshore migration of habitats due to rising sea levels is prevented by attack and 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. While the 20th 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: SLR threatens such initiatives and requires additional action to achieve these desired goals.

2.7.2 Adaptation Processes and Frameworks

As well as the adaptation measures, the adaptation process needs to be considered in terms of when adaptation will be implemented, how options might be combined and the long-term trajectory of adaptation. As already noted, SLR is expected to continue (at a slower rate) even with aggressive climate mitigation and hence adaptation needs are growing into the future under all plausible climate scenarios.

While adaptation to SLR is relatively new, there is considerable experience of adapting to climate and sea-level extremes and other coastal problems. This experience can inform decision making under a changing climate. Importantly, adaptation to coastal problems is a multistage *process*, which can be characterized 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). There are also constraints on the approach to adaptation due to broader policy and development goals. Once implemented, monitoring and evaluation of adaptation measures is a critical step and yet easily ignored. This is essential given the large uncertainties associated with SLR and other future conditions, adaptation performance and coastal management in general. Monitoring and evaluation allows learning and improved future adaptation and this needs to be built into coastal management and adaptation.

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 SLR in the early 1990s (e.g., Dronkers et al., 1990; Bijlsma et al., 1996), recognizing that SLR and climate change occur in a multistressed situation. However, it remains unproven as an effective response approach (Wong et al., 2014). Adaptive management is also advocated and has important merits in dealing with the uncertainties of SLR. 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 address community concerns, but there is concern that the focus may not be strategic. For example, will the 1 in 100 or 1 in 1000 event be considered, when they are beyond what most if not all the community have experienced? In the worse case, could CBA promote people to stay in increasingly hazardous locations—this suggests CBA should be practised within a broader science-based framework, including consideration of extremes and warning systems. Linking climate adaptation with Disaster Risk Reduction (Smith, 2013), which can be seen in part as adapting to climate variability, is also receiving increasing interest.

Shoreline management planning (SMP) has emerged in England and Wales over the last two decades as a government-led response to coastal erosion and flood risk management (Nicholls et al., 2013). It provides a framework in applying future coastal interventions and management over long timescales, including the nonlocal effects of management. The English/Welsh coast has been divided into 22 SMPs and further about 2000 management units and three time epochs are considered. Four generic responses are considered for each management unit and epoch 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 (or even attack for option 1), while options 3 and 4 can be considered retreat. Note that accommodation is also being implemented in the United Kingdom for flood management purposes, as demonstrated by Fig. 2.7, but this is implemented at the property level, and hence at a submanagement unit scale. Supporting the SMP process are national monitoring systems. This high level approach could be applied widely around the world's coast, including consideration of SLR.

In parallel with this, there has also been recognition that while we need to adapt to SLR, 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 each pathway as the magnitude of future SLR is uncertain. Hence, we can define adaptation pathways and take actions that preserve these options without spending the large sums that are needed to realize them, until required. Adaptation pathways, combined with monitoring and learning, are an appropriate approach for SLR, especially in cities where significant adaptation will be needed. This approach has been adopted in the Thames Estuary 2100 Project addressing future flood protection for London (Ranger et al., 2013; Tarrant and Sayers, 2013; Chapter 6: Flood Risk Management in the United Kingdom, Putting Climate Change Adaptation Into Practice in the Thames Estuary).

2.7.3 Choosing Between Adaptation Measures/Options

Retreat is often argued as the best response to SLR (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 are available for adapting to SLR, 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 more vulnerable in 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 them, 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 are an issue of international concern due to the shared responsibility for climate-induced SLR.

The existing state of coastal adaptation and any associated "adaptation deficit" is an important concern—the adaptation deficit is the cost of adapting to today's situation, before we consider adapting to future SLR and other change (Burton, 2004; Parry et al., 2009). There is a lot of evidence to support an adaptation deficit on coasts, but it has not been systematically quantified. For example, Hallegatte et al. (2013) showed that US coastal cities have much higher expected damage costs than European coastal cities today reflecting much lower protection standards. Equally, less developed and rapidly growing regions are likely to have a significant and growing adaptation deficit due to explosive coastal development in increasingly hazardous areas (e.g., Hinkel et al., 2011; Mycoo and Chadwick, 2012).

Global cost estimates of coastal adaptation 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. There are several cost estimates for protection (Nicholls et al., 2014a). These are lower than conventional instinct suggests, 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 21st century (Hinkel et al., 2014). For 136 coastal cities, Hallegatte et al. (2013) argued that adaptation to SLR would be about US$50 billion/year globally to 2050. Considering beach erosion, global adaptation costs for SLR only via nourishment estimated costs in 2100 of US $1.5−5 billion/year (Hinkel et al., 2013). These costs all seem affordable, but as the cost of the adaptation deficit is not addressed they must be considered as minima. Further, a protection pathway raises questions of where it takes the coastal system in the long term: key concerns with protection are lock-in and residual risk.

The adaptation deficit reflects that many countries have a limited capacity to address today's coastal problems, let alone consider tomorrow's problems, including SLR. Therefore, promoting coastal adaptation should include developing coastal management capacity and institutions, as already widely recommended (USAID, 2009; Moser et al., 2012) and integrating it with wider coastal development.

2.7.4 Adaptation Experience

Existing adaptation experience mainly reflects adaptation to extreme events or land subsidence, which is good analogue for climate-induced SLR. 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 attack and 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 under debate, as already discussed (Wong et al., 2014).

While there is growing awareness of the need to adapt to SLR, only a few countries or locations are preparing for this challenge that recognizes the huge uncertainty around the magnitude and timing of SLR, and the inevitability of some ongoing SLR even under aggressive climate mitigation policies. Examples include London (Lavery and Donovan, 2005; Tarrant and Sayers, 2013; Chapter 6: Flood Risk Management in the United Kingdom, Putting Climate Change Adaptation Into Practice in the Thames Estuary) and the Netherlands (Kabat et al., 2009; Stive et al., 2011). Both these sites considered a wide range of SLR scenarios, including scenarios of up to 5 and 4 m, respectively, addressing post-2100 challenges. Importantly they considered adaptation as a process and London in particular focused on adaptation pathways as a function of SLR rather than time. Both analyses demonstrate that there are feasible protection options available for large rises in sea level, and progressive upgrade is feasible over a 100/200 year time frame. This is an effective way to deal with the uncertainty of future SLR and implies an adaptive approach where higher protection is provided when needed, avoiding over or under adapting (Ranger et al., 2013; Haasnoot et al., 2013; Chapter 6: Flood Risk Management in the United Kingdom, Putting Climate Change Adaptation Into Practice in the Thames Estuary). It is worth noting that these activities to date were more about enhancing planning, process, and capacity than actual responses. For instance, the Netherlands has created the new governance institution of the Delta Commission to manage the national Delta Plan and develop strategic policy processes and model tools to support this process to facilitate more strategic planning and investment (Van Alphen, 2015). The Delta Commission enjoys widespread cross-party political support and hence funds are guaranteed beyond a political cycle allowing a longer term perspective. This approach is being exported to other deltas such as Bangladesh.

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 Superstorm Sandy has accelerated action and a number of projects are planned. But a strategic response as in London or the Netherlands is not yet apparent. In Singapore new land claim will be raised by approximately a meter to allow for SLR. 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). If all coastal cities followed an assessment process similar to Thames Estuary 2100 in London, it would give them a better basis for understanding potential impacts and provide a basis for more systematic planning of adaptation (Nicholls et al., 2015b). Similar arguments could be made in vulnerable deltas and islands, and ultimately all populated coasts might make such an assessment.

2.8 DISCUSSION/CONCLUSIONS

The chapter illustrates that adapting to SLR and enhancing resilience is a multidimensional problem that crosses many disciplines and embraces natural, social, and engineering sciences, as well as engaging stakeholders, policy, and governance. Importantly, significant SLR seems inevitable under all plausible scenarios and hence adaptation is essential: the uncertainty is the magnitude and timing. The actual outcome will also depend on our responses, both in terms of climate mitigation and adaptation and their success or failure. For adaptation in general, and protection in particular, there are widely divergent views on the likely success or failure, and this strongly influences how the issue of SLR is considered in public policy. Much current thinking can be characterized into pessimist and optimist camps (Nicholls and Tol, 2006; Anthoff et al., 2010; Nicholls et al., 2014a). "Pessimists" tend to focus on high rises in sea level, extreme events with large impacts like Katrina, and view our ability to adapt to SLR as limited, resulting in widespread human migration away from coastal areas. In contrast, "optimists" tend to focus on lower rises in sea level and stress the growing technical ability to forecast, warn, and protect and the high benefit−cost ratios in developed areas leading to widespread protection. Hence to optimists a major consequence of SLR is the diversion of investment to coastal adaptation in general, and protection in particular. More work is required to reconcile these opposing perspectives, which will influence the relative role of attack, protect, accommodate, and retreat in our adaptation responses.

SLR is clearly a threat that demands a response, with adaptation being an essential activity. There is a need to better understand these threats, including the implications of different mixtures of climate mitigation and adaptation, and different portfolios of adaptation and adaptation pathways (Nicholls et al., 2007; Wong et al., 2014). To provide the basic data, coastal monitoring and coastal climate services are increasingly required (Nicholls et al., 2013; Le Cozannet et al., 2017). As the coast is a coupled system, it will be important to examine different scenarios of SLR and climate change, socioeconomic changes, and how adaptation coevolves with the wider coastal system. There is also a need to engage with and inform the coastal and climate policy process.

Assessing the success or failure of adaptation to SLR will be challenging given the long timescale of the issue. We can assess the success or failure of adaptation to present hazards such as flooding and erosion. Equally, we can learn from experience adapting to human-induced subsidence. Research aspects and operational aspects of adaptation need to be separated, as both are required in terms of developing general guidance and more detailed analysis and assessment of specific sites. Adaptation inventories provide one foundational step to both types of analysis (e.g., Tompkins et al., 2017). Similarly assessing best practise will be challenging. Research is required at all scales from local to global, but much will be learnt about adaptation in practise (Wong et al., 2014). This will promote more appropriate adaptation options and the opportunity to learn from experience.

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