Chapter 5
Sea-Level Rise Impacts and Responses: A Global Perspective

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Abstract Coastal hazards have long been present and are evolving due to a variety of different drivers: the long-term threat of climate change, including sea-level rise, adds a new dimension to these problems which is explored here. Globally, sea levels could rise in excess of 1 m this century, but the local rate of relative sea-level rise could be much greater than this because of subsidence or other factors which lower the land surface. This is important as the population of these subsiding areas is significant. Relative sea-level rise will result in inundation, flooding, erosion, wetland loss, saltwater intrusion and impeded drainage. This chapter has investigated the impacts of sea-level rise at a global scale on: (1) Sandy environments; (2) Wetlands and low-lying coasts; (3) Built environments; and (4) Energy and transport systems. Results indicate that without appropriate adaptation, environments could be

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significantly impacted, and those remote or financially less well off could become increasingly vulnerable. Further research and action is required into integrated impact assessments (including non-climatic drivers of change) to help those at risk and develop appropriate adaptation polices over short, medium and long timescales.

5.1 Introduction

A range of natural hazards occur on the coast, including storms with high wind speeds, extreme waves and tsunamis, all of which can cause flooding and erosion (Kron 2009). These geophysical events only become a risk when people use or resides in the path of the hazard. According to Munich Re's (2012) risk research which records global natural catastrophes based on insurance claims, in 2011 there were 820 loss events with 74% of these resulting from meteorological or hydrological events. Seventy percent of losses and 85% of fatalities were in Asia. The total overall losses from meteorological and hydrological events was US$144 billion. Seven percent of loss events were a direct consequence of extreme waves from tropical storms, surges or tsunamis (Kron, personal communication from Munich Re 2012 data). However, there are many more coastal events due to landslides, freshwater flooding and other climatological extremes, prompting insurance claims. This emphasises that the coast is a potentially vulnerable place to live. Despite these risks, people are attracted to the coast and it plays an important role in the lives of hundreds of millions of people. Even if a population does not directly live in the coastal zone, they can benefit from it due to the many advantageous natural, cultural and built environments it provides.

Coasts are some of the most densely populated areas in the world, on average containing two or three times greater population density than the same area further inland (McGranahan et al. 2007; Small and Nicholls 2003). More than 205 million people are already vulnerable to coastal flooding through extreme water levels (Mimura 2001; Vafeidis et al. 2011), and this will increase substantially just due to population growth and coastward migration (Nicholls 2004). It is anticipated that virtually all this growth will happen in urban areas (Kamal-Chaoui and Roberts 2009), placing more people and infrastructure (e.g. energy supplies, nodes of transport and industry) in potentially hazardous locations. Coastal ecosystems such as wetlands, estuaries and deltas provide many goods and ecosystem services, such as flood control and natural protection in the event of storms, shoreline stabilisation, habitats for wildlife, pollution filtering, sediment and nutrient retention and cycling, farming, fishing, aquaculture and other wildlife resources, recreation provision and cultural heritage (Barbier 2012; Costanza et al. 1997, 2008; Luisetti et al. 2011). Consequently many countries' economies are focused on the coast, which can be responsible for a larger than average share of its gross national product (Das Gupta and Babel 2005).

However, these coastal environments are under threat from many drivers, such as sea-level rise, natural and human induced subsidence, changes to wind and

storminess, salinisation, rising river levels in their coastal parts (the backwater effect), rising water tables, reduced sediment supply, eutrophication, intertidal destruction and land claim, farming, urbanisation and tourism (Valiela 2006). In flooding, there can be changes to sources, pathways and receptors (Evans et al. 2004), such as follows:

- Sources: e.g. climate variability, eustatic sea level changes, subsidence;
- Pathways: e.g. degradation of natural defences, hard and soft defences, channelling of flood water, decreased surface water drainage due to urbanisation and land claim, changes to water flow due to farming practices through land conversion or changes to crop type;
- Receptors: e.g. the location of people, population density, infrastructure.

Some of these threats are predictable, and therefore adverse impacts can be considered and planned for. An adaptive response can keep risks at an acceptable level. However if there is insufficient time to respond, or threats are unpredictable, risk levels increase, potentially leading to increased flooding and erosion. During the twentieth century, changes in receptors were the major driver that increased flood risk, and will probably remain significant for decades to come. However, changes in the sources, particularly with anticipated climate change, are of increasing importance.

This chapter focuses on the impacts of sea-level rise, with an emphasis on those localities which are vulnerable on a global scale. First, the magnitudes of past and future sea-level rise will be reviewed. Second, impacts on natural and human environments will be described, with a focus on:

1. Sandy environments;
2. Wetlands and low-lying coasts;
3. Built environments;
4. Transport and energy systems.

Finally possible adaptive responses and vulnerability will be explored for places and continents in response to these impacts.

5.2   How Much Will Sea Levels Rise?

Understanding sea-level rise is challenging due to the number of complex and interacting factors which influence the rate of rise and variability over a variety of time and geographic scales. To appreciate how rising sea levels will affect the coastal zone, it is important to consider relative sea-level change – the combination of eustatic sea level change and local vertical movements of the land as this is what produces impacts and requires a response. Where relative sea-level rise increases mean sea levels, lower surge elevations compared with present day levels will produce a sea level rise high enough to cause flooding or erosion (Haigh et al. 2011).

In the twentieth and twenty-first centuries, relative mean sea-level rise comprises:

(a) Eustatic rise of global mean sea levels resulting from a change in ocean volume: thermal expansion, melting ice sheets or changes to fluvial inputs for semi-enclosed seas, such as the Baltic Sea or Black Sea;
(b) Vertical land movement, e.g. due to natural tectonic activity and isostatic uplift, artificial water abstraction and drainage of susceptible soils, sediment compaction and subsidence.
(c) Decadal to seasonal fluctuations, e.g. large scale oceanic processes such as El Niño that can last one year or more, and also short lived storms that can result in extreme waves conditions;

The two main ways humans are believed to have influenced sea-level rise is via temperature-rise induced eustatic changes including: (i) the accelerated melting of land based ice, including the large ice sheets of Greenland and Antarctica, and smaller ice caps and glaciers and (ii) thermal expansion, which increases oceanic volume (Church et al. 2010). It is anticipated that these two ways will be the dominant cause of global relative sea-level rise over the twenty-first century and beyond (Meehl et al. 2007).

There is also concern that human activities are exacerbating existing trends. For example, in highly populated naturally subsiding deltas, over extraction of ground water and drainage can lead to accelerated subsidence. Ericson et al. (2006) investigated 40 deltas (many located in Asia) and their rate of relative sea-level rise, including subsidence from ground water and hydrocarbon extraction. Relative sea-level rise ranged from 0.5 to 12.5 mm/year. Some of the highest rates of subsidence (due to man's actions) occur on deltas which can be a home to cities. Observed subsidence values for cities include Bangkok (2 m from the 1950s), Shanghai (3 m from 1921) and Tokyo (5 m from the 1930s) (see Nicholls 1995). In some parts of these cities, the annual rate of local subsidence is fast, and so agriculture/aquaculture land and infrastructure is inundated (e.g. telegraph polls have been inundated due to relative sea-level rise in the Gulf of Thailand). Where local subsidence occurs in densely populated areas, vulnerability can increase, as investigated in Sect. 5.3. To assess future rise, past changes must be analysed and understood.

5.2.1   Past Changes

Past sea levels over many thousands or millions of years can be interpreted through, for instance, marsh sediment records (e.g. Leorri et al. 2010) or corals (e.g. Chappell and Polach 1991). Over the past 100 years or so, sea level has been recorded through tide gauges. Many of these records are part of the 1,300 tide gauge dataset at the Permanent Service for Mean Sea Level (Woodworth and Player 2003; Woodworth et al. 2011). One of their oldest records (Amsterdam, the Netherlands)
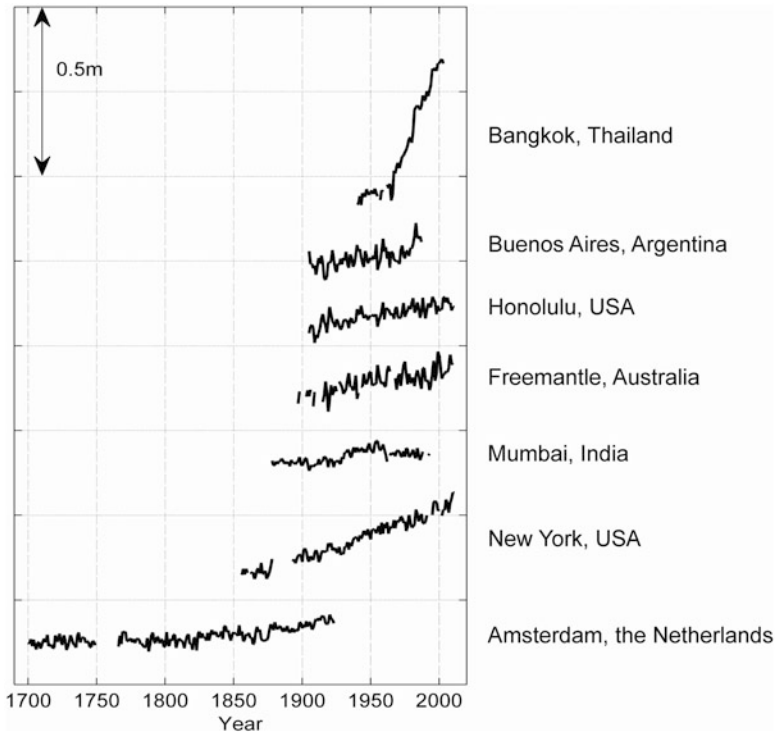
Fig. 5.1 Tide gauge measurements showing relative sea-level rise at selected sites around the world. The sharp rise in Bangkok after 1960 is due to subsidence induced by increased water abstraction. Records are offset for display purposes (Data extracted from Permanent Service for Mean Sea Level (2012))

dates back to 1700. Relative sea-level rise for Amsterdam and six other long term records are shown in Fig 5.1. Each record shows relative sea-level rise, with linear trends of 0.5, 2.8, 0.8, 1.5, 1.4 and 1.6 mm/year for Amsterdam, New York, Mumbai, Freemantle, Honolulu and Buenos Aires respectively. In Bangkok, from around 1960 there was a sharp increase in the rate of relative sea-level rise to around 17 mm/year for the next 50 years. The cause of this is subsidence due to water abstraction, which started in the 1950s at 10,000 m^3/day. Over the following decades, this rapidly increased to over 1 million m^3/day. Although there have been periods of reduced abstraction and restriction of the building of new wells, in 2003 over 1.7 million m^3/day was abstracted from shallow sand aquifers. Controls have meant that subsidence rates in the city centre have declined, but it is still widespread in the suburbs, where rates of up to 35 mm/year have been recorded (Das Gupta and Babel 2005; Nicholls 2010). With restrictions to abstraction, the rate of subsidence in the last 20 years has been reduced (Nicholls 2010).

Church and White (2011) reconstructed global sea levels using long-term tide gauge records and estimated the linear trend of global average sea-level rise

from 1900 to 2009 was 1.7 ± 0.2 mm/year. They also report that there has been considerable variation in rates during the twentieth century. Whilst some of this rise is due to natural variation, part (~75%) is believed to be caused by anthropogenic climate change (Jevrejeva et al. 2009), and it is envisaged that this trend will continue. Satellite altimetry data has supplemented the tide gauge record and provides a quasi-global observational dataset. From 1993 to 2009, satellite measurements indicate a rise of 3.2 ± 0.4 mm/year, whilst the sparse and unequally distributed tide gauge dataset indicate a rise of 2.8 ± 0.8 mm/year for this period. The short timescale of these measurements does not indicate with confidence a long-term significant increase in trend, but illustrates the complex nature of measuring and projecting future sea-level rise.

5.2.2   Future Changes

In 2007, the Intergovernmental Panel on Climate Change (IPCC) produced its Fourth Assessment Report (AR4), and stated that global sea levels could rise 0.18–0.59 m by 2090 to 2099, with respect to 1980 to 1999 (Meehl et al. 2007). The projections varied depending on future emissions, socio-economic scenarios and uncertainties in ice melt processes. In the models run for the IPCC AR4 report, around two thirds of sea-level rise was attributable to thermal expansion. Warming of the oceans takes centuries to reach equilibrium – even if greenhouse gas emissions (and any changes in global mean temperature) stabilise or are reduced today. Thus there is a time lag between an observed temperature rise and oceanic response. This process is known as 'the commitment to sea-level rise'. Given that the global mean surface air temperature has risen $0.76\,^{\circ}$C from 1850–1899 to 2001–2005 (Solomon et al. 2007), sea-level rise due to thermal expansion is expected to continue through the twenty-first century and beyond.

The remaining third of sea-level rise in the IPCC AR4 projections was attributable to the melting of land-based ice (Meehl et al. (2007) reports that due to a projected increase in precipitation, Antarctica is expected to give a negative contribution to sea-level rise. However, ice melt from Greenland and other land based ice is projected to give a larger positive contribution). However, immediately prior to the publication of the IPCC AR4 report, new rapid changes were observed on the Greenland and Antarctic ice sheets. Subsequently, an additional range of ice melt was added to the IPCC projections (to 0.76 m) in case increased ice sheet discharge was maintained (Solomon et al. 2007). Since then, concerns regarding the rate of ice melt from large ice sheets, glaciers and ice caps have continued (e.g. Rignot et al. 2011; Van de Wal et al. 2008). With improving, but still limited knowledge about ice sheet dynamics, particularly over long time scales, their dynamic behaviour and the rate of ice melt remains subject to debate and challenges scientific knowledge and understanding (Church et al. 2011). Even as new science and understanding emerges, there remains large uncertainties into the historic mass
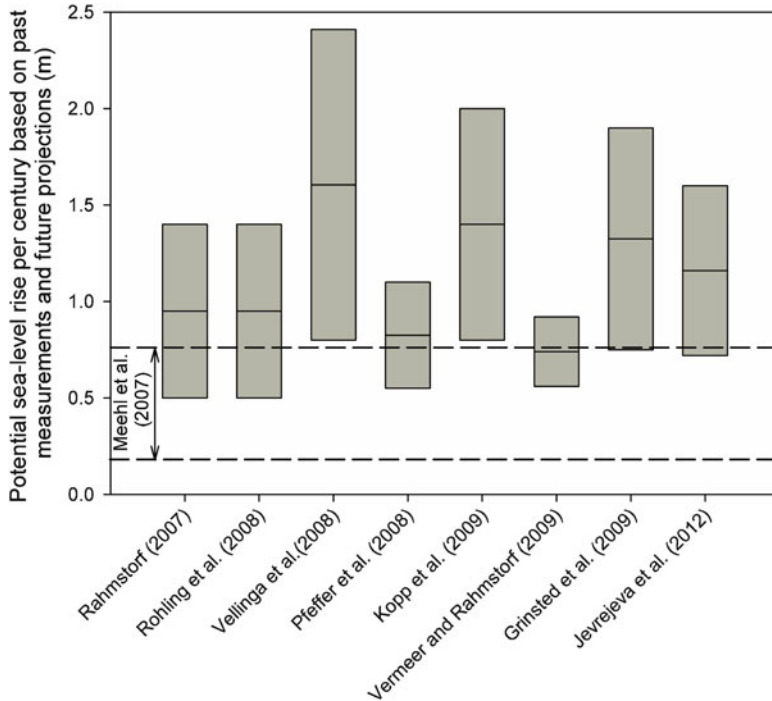
Fig. 5.2 Potential magnitude of global mean sea-level rise per century from post AR4 research (with a range of 0.5–2.4 m) based on past measurements and future projections (Adapted from Nicholls et al. 2011). The AR4 range (Meehl et al. 2007) is shown by the *dashed horizontal lines*

balance of glaciers and ice caps due to the sample size (e.g. Bamber 2012; Jacob et al. 2012). Projecting future changes brings further uncertainties.

Since the AR4 report, further research indicated large uncertainties in the magnitudes of ice melt, and thus sea-level rise. Part of this uncertainty is due to the different ways of measuring sea level response (e.g. semi-empirical methods, paleo-climate analogues and physical constraint analyses). From paleo-studies, scientists have investigated how much sea levels have risen in previous centuries. However it is uncertain that these rates of rise could happen again, but they are not considered impossible (Nicholls et al. 2011). A summary of potential sea-level rise at a century scale based on post-AR4 research is shown in Fig. 5.2, with a range of 0.5–2.4 m of rise per century. It should be noted that high-end projections (greater than 1 m per century), whilst scientifically plausible, are considered unlikely. However, it is prudent to consider the implications of rises greater than 1 m in order to evaluate possible responses and policy options to aid decision making.

The projections in Fig. 5.2 report global mean values, but regional variations will inevitably occur following historical observations. This is seen in evidence through tide gauge records, and more recently satellite altimetry. For instance, in some regions sea levels are rising three times faster than others (Cazenave and Llovel

2010). This is expected to continue and alter as the climate changes. Additionally, some places (e.g. northern Scandinavia) may experience a fall in relative sea levels due to isostatic rebound – where the land uplifts at a greater rate than sea-level rise.

5.3 Impacts

Where climatic and non-climatic factors interact producing a rise in sea levels, it increases the probability of an extreme event, and thus the adverse impacts which can affect natural and human environments. This includes inundation, flooding and storm damage by surges and also by raising rivers in their coastal parts (the backwater effect), saltwater intrusion into surface and ground water, rising water tables, erosion of dunes, beaches and cliffs and wetland loss and change (Nicholls 2010). During extreme events, flooding and erosion are the immediate effects, but over long time scales (many decades) slower subtle changes (e.g. salinisation) can create increased pressures on coastal environments. This can also impact coastal ecosystems and other aspects of the coast such as freshwater resources, agriculture, fisheries, recreation and tourism, biodiversity and infrastructure. Here, the effects on (1) Sandy environments; (2) Wetlands and low-lying areas; (3) Built environments; and (4) Transport and energy systems are investigated, illustrating a contrasting set of natural and human environments.

5.3.1 Sandy Environments

Coastal landscapes and ecosystems will experience the impacts of sea-level rise. Beaches, and the dunes behind them, being composed of unconsolidated sand, will be especially prone to erosion. Beaches can undergo erosion (and subsequent recovery) as a result of a series of factors, including an interruption to longshore drift, or a reduction in sediment supply following damming of a river. Therefore, attributing particular erosional events directly to sea-level rise is difficult. Over a period of time during which the average level of the sea has risen, most sandy shorelines will recede landwards, unless they receive substantial volumes of additional sand. It can be inferred that the coastline has migrated landwards across the inner continental shelves during the rapid sea-level rise that accompanied the melting of the polar ice-caps after the end of the last Ice Age 18,000 years to 6,000 years ago (Roy et al. 1994). However, it remains difficult to use either geological facies models or historical observations to foreshadow the rates at which shorelines will recede in the future.

One of the simplest approaches that has been widely used to project future shoreline position is based on the principle of conservation of mass and assumes that a similar cross-shore profile will be maintained as the shoreline migrates landwards. This method was introduced by Per Bruun (Bruun 1962), and has become

known as the 'Bruun Rule.' It assumes that sand is eroded from the beach as the sea rises and is redistributed across the adjacent shallow-water seafloor as far seaward as waves influence sediment movement (called closure depth). Bruun (1962) inferred that rates of retreat are a function of foreshore gradient, which is typically of the order of 0.01–0.02, producing retreat at 50–100 times the rate of sea-level rise (that is, if the sea level rose by 1 m, the shoreline would be anticipated to retreat between 50 and 100 m).

There has been considerable criticism of this simple 'equilibrium morphology' approach because it only considers one process operating at the shore. Hence, it cannot take into account many factors that can be very significant at particular coastal locations, such as geological constraints or variable rates of longshore sediment transport (Cooper and Pilkey 2004; Ranasinghe et al. 2012). Consequently a more complete model encompassing the entire sediment budget is required (Cowell et al. 2003a, b). Some of the most dynamic sandy coasts are associated with low-lying barrier islands, such as those along the eastern coast of the USA or the northern coast of the Netherlands. Many of these undergo a process of rollover, with sand washed from seaward spilling onto marshy areas behind, in contrast to the seaward movement described above (FitzGerald et al. 2008). Nevertheless, for large area studies, the application of these simple principles is meaningful to attain order-of-magnitude estimates, and in fact, underlies most engineering studies that attempt to forecast where the shoreline will be at successive times in the future. This becomes particularly important along highly developed coasts, where substantial infrastructure or coastal protection occurs behind the active beach (such as promenades, boardwalks, ports, residential and tourist facilities, seawalls and other hard structures). Many beaches will erode, but it will be important to incorporate better estimates of the volumes of sand mobilised during storms of different magnitudes in the context of the entire coastal sediment budget. It is desirable to produce probabilistic estimates that enable coastal managers and policy-makers to consider a wider range of sensitivities and uncertainties in model estimates (Ranasinghe et al. 2012).

The small sandy islands (called cays) that have accumulated on top of coral reefs, and around the rim of atolls, appear particularly threatened by sea-level rise. They are vulnerable to shoreline erosion, inundation of low-lying areas, and saline intrusion into the freshwater lens on which island communities often depend (Woodroffe 2008). Although the carbonate sediments from which these islands are built are still being produced through breakdown of marine organisms, such as corals and shells, human activities have often exacerbated the threats. The Asian region contains some of the most diverse coral reefs and mangrove forests anywhere on earth. These coastal ecosystems provide both direct (timber, shellfish) and indirect (fish nursery) services to many people. The reefs are subject to many stresses, both through pollution and over-exploitation, but also as a consequence of climate change (Hughes et al. 2003).

5.3.2   Wetlands and Low-Lying Coasts

Although it is often perceived that sea-level rise will have particularly far-reaching effects on sandy coasts, the immediate response of unconsolidated sand to wave action means that beaches can undergo rapid adjustments which can, in some cases, increase their resilience. The response of coastal wetlands is slower, and sea-level rise impacts and responses are less obvious but more pervasive (Day 2008). Wetlands flourish on muddy shorelines and support a diversity of organisms. Salt marshes extend across upper intertidal mudflats from polar through to tropical regions, whereas mangrove forests dominate sheltered intertidal coastlines in the tropics. There are often other associated wetland habitats, such as seagrass ecosystems on subtidal flats and freshwater wetlands that occur landward of salt marshes or mangroves.

Intertidal wetland environments have coped with changes of sea level in the past (Woodroffe 1990). The stratigraphy beneath many coastal plains contains sedimentary records of past ecological changes. For example, several metres of muddy sediments, intercalated with peats, underlie coastal plains of northwest Europe and the east coast of North America, exceeding in thickness the intertidal and shallow-marine zones in which the equivalent habitats are presently found. This indicates that they accumulated over a period of gradual sea-level rise (Allen 2000).

As sea level rises, tidal incursion into coastal wetlands is increased and the rate of surface accretion is likely to also increase across the entire wetland surface. The response of the wetland is therefore to continue to accrete vertically provided there is sediment available. Tidal waters will reach further inland, beyond the coastal wetlands, extending into freshwater or upland systems. All too often, further landward incursion of wetland communities will not be possible because their hinterland is occupied by human settlements or defence infrastructure (e.g. sea walls), with the consequence that the intertidal wetlands will contract, a process termed coastal squeeze (Doody 2004).

Many intertidal wetlands have been considerably modified by human activity. Low-lying plains have proved attractive locations for a range of intensive agricultural, industrial and residential developments. They have been subject to both deliberate and unintentional dumping of wastes and land claim. Mangrove shorelines around much of the tropics have been converted into shrimp farms or salt ponds, causing such disruption to the substrate and its chemistry that mangroves can rarely re-colonise. Often these perils can be a greater threat than climate induced sea-level rise, and they have been pervasive over the last few decades (e.g. Coleman et al. 2008; Ericson et al. 2006).

As sea level rises in the future, coastal wetland communities appear increasingly threatened. Scientists now realise that these ecosystems provide a series of goods and services (Costanza et al. 1997), particularly in densely populated parts of the developing world where there is a heavy reliance on seafood produced as part of food chains that rely on mangrove wetlands for their sustainability. Re-establishing such intertidal wetlands is seen as a priority in many parts of the world; for example,
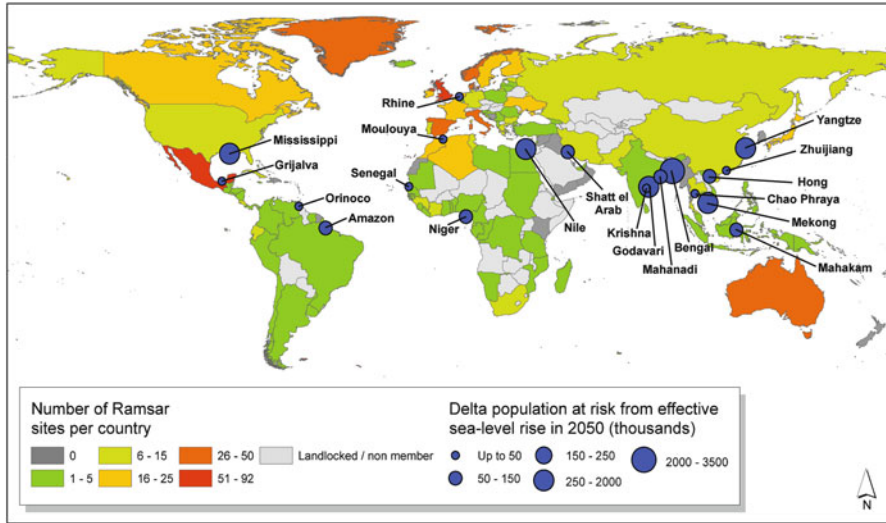
Fig. 5.3 Number of coastal and marine Ramsar sites per country (Ramsar Wetlands International 2007), and the delta population at risk due to effective sea-level rise in 2050 for the top 20 major deltas listed in Ericson et al. (2006). Note that Angola, Eritrea, Guyana, Saudi Araba and Somalia are not part of the Ramsar Convention so do not contain Ramsar sites

a program of managed realignment has been instigated in parts of Europe, where embankments that were built to claim salt-marsh habitat from the intertidal zone are being deliberately breached to promote further marsh establishment as an adaptive measure to sea-level rise and mitigation of coastal habitat destruction (French 2006; Rowlands et al. in review). In tropical regions, buffers of mangroves have been replanted, particularly in parts of south-east Asia, and mangroves are increasingly seen as a valuable form of shoreline protection contributing to better coastal management procedures (Alongi 2002).

Figure 5.3 illustrates coastal and marine Ramsar sites – important designated sites which are subject to international protection and co-operation in their use and resources (Ramsar Wetlands International 2007). The figure illustrates that many of these wetlands are in developed countries where anthropogenic pressures infringe upon the natural environment. Since its initialisation in 1971, numerous developing countries have joined the Ramsar Convention, and many large protected wetlands can be found in these countries. This is encouraging as it demonstrates that people and governments recognise and appreciate the international importance of wetlands and this may influence their future management (Nicholls et al. 2008a).

Not only are coastal wetlands threatened, but the extensive plains that have developed through several millennia of sedimentation, particularly in estuaries or on deltas, are also vulnerable. Deltas are dynamic landforms that have formed extensive low-lying areas as a result of large sediment loads that are carried to the sea by some of the world's biggest rivers. Reduction of sediment delivery as a result of the construction of dams upstream presents a more imminent threat than

sea-level rise for many deltas. Such deltas are already subject to subsidence and sediment compaction, and this has often been exacerbated through human activities such as hydrocarbon and groundwater extraction (Syvitski et al. 2009; Ericson et al. 2006) (also see Sect. 5.2). The rate of relative sea-level rise is accentuated in such situations. Much of New Orleans lies below the level of the Mississippi River and of the highest ocean water level in the Gulf of Mexico. Devastation by Hurricane Katrina in 2005 has forcefully demonstrated the dangers such cities will increasingly face in the future. The defences have since been substantially upgraded at the cost of US$15 billion and the management has moved to a more proactive and risk-based perspective. Time will tell how efficient these defences are and how they perform as New Orleans has a long history of flooding and a similar set of meteorological conditions could occur again (Hanson and Nicholls 2012).

Globally about ten million people on average were estimated to be subject to coastal flooding per year in 1990, based on modelling by Nicholls (2004). The vast majority were in south, south-east and east Asia – often in low-lying delta regions. The proportion of people at risk from these regions is also likely to continue to increase as a result of sea-level rise and also population growth. In addition to Ramsar sites, Fig. 5.3 illustrates the population at risk in 2050 due to sea-level rise based on the analysis of Ericson et al. (2006). For the 20 deltas illustrated it indicates that in excess of two million people could be at risk from flooding in the 2050s, just based on extrapolating present trends. Most of these people are in Asian delta plains that are already subject to extensive flooding and which serve as the 'rice-bowl' of Asia. Bangladesh lies almost entirely on alluvial and deltaic plains deposited where the Ganges and Brahmaputra Rivers converge. The low-lying plains, extending into west Bengal in India, supported a population of about 130 million in 1990 and that is likely to rise to more than 166 million by 2015 (Woodroffe et al. 2006). This area includes the Sundarbans, the largest area of mangroves under conservation in the world, covering approximately one million hectares. Erosion predominates along the Bay of Bengal coastline and these wetlands have decreased in area at an average of about 4 km^2/year over the past several decades (Rahman et al. 2011). More than 11 million people live on the delta plains in each of the Irrawaddy, Chao Phraya, Mekong, Red, Pearl, Changjiang (Yangtse) and Huanghe (Yellow) river deltas (Woodroffe et al. 2006). Each of these experiences shoreline erosion along much of its margin, as well as differential subsidence; as a consequence millions of people are already at risk today and sea-level rise will further exacerbate these problems.

5.3.3 Built Environments

Many of the fastest growing megacities (population greater than eight million) are on or adjacent to deltas (Woodroffe et al. 2006). These and other coastal urban centres are growing faster than the hinterland, driven by rapid economic growth and coastward migration (Alig et al. 2004; Balk et al. 2009; McGranahan et al. 2007;
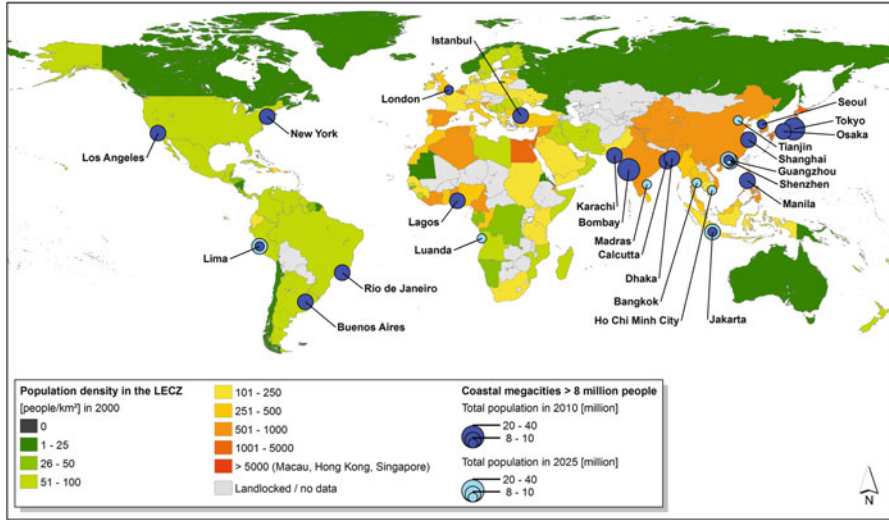
Fig. 5.4 Population density in the LECZ (Vafeidis et al. 2011) and the location of coastal megacities (United Nations 2010)

Smith 2011). These trends, which have strong impacts on the environmental system (Sekovski et al. 2011), are expected to continue and possibly intensify in the future.

When assessing impacts and vulnerabilities of population and assets in coastal built environments, the low-elevation coastal zone (LECZ)[1] is commonly used as a spatial reference (Balk et al. 2009; Lichter et al. 2011; McGranahan et al. 2007). The LECZ occupies approximately 2% of the global land area, but accommodates 10.2% of the global population (year 2000 population estimates) (McGranahan et al. 2007). These types of estimates are commonly employed as a measure of exposure of coastal population to sea-level rise and associated impacts, in particular flooding and submergence. Although they are subject to various limitations (see Lichter et al. 2011) they provide a good first-order indication of the distribution of population and assets in the coastal zone.

Figure 5.4 illustrates the population density in the LECZ (Vafeidis et al. 2011) and the location of coastal megacities with a population greater than eight million. Estimates of current and future populations are from UN population data (United Nations 2010). The highest population densities occur along western Europe and Africa, countries bordering the Mediterranean Sea and south, south-east and east Asia, and particularly in small nation states and islands. These nations are often highly dependent on the coast. In 2010, 20 out of 31 megacities were within the LECZ, with 12 in Asia. The number of megacities in the LECZ is expected to

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[1] Defined as the contiguous area below 10 m of elevation that is hydrologically connected to the sea.

Table 5.1 Total area, population and people living in the low-elevation coastal zone (LECZ) in 2000 and projected by 2060, per continent

Continent	Total area and population in 2000		Area and population in LECZ 2000		Total population and population in LECZ in 2060[a]	
	Area (km^2) (000)	Population (000)	Area (km^2) (000)	Population (000)	Total population (000)	Population LECZ (000)
Africa	29,620	811,101	194	54,167	2,955,291	245,245
America:						
Central	2,451	135,555	119	6,768	268,745	8,917
South	17,631	347,433	263	21,909	596,774	37,705
Caribbean	233	38,441	42	3,536	57,523	5,640
America:						
North	18,944	313,289	508	24,617	466,270	45,536
Asia	30,695	3,697,108	860	460,840	6,170,286	983,293
Oceania	8,455	31,130	143	3,333	62,130	6,086
Europe	22,548	726,777	471	50,018	702,346	55,741
World	130,578	6,100,834	2,599	625,188	11,279,364	1,388,162

[a]Scenario assumptions: Population growth towards the highest end of forecasts (rich economies: medium population growth at 50th percentile, coastal growth 1.7 times the inland growth; developing world: high population growth at 90th percentile, coastal growth 1.7 time the inland growth for rural areas and 1.8 times the inland growth for urban areas. See Vafeidis et al. (2011) for details)

increase to 25 by 2025 as shown in Fig. 5.4. More Asian cities emerge, plus one African city – Luanda, Angola.

Vafeidis et al. (2011) indicated that exposure of population in the coastal zone may rise substantially in the future (Table 5.1). According to their study the LECZ population is expected to grow from 625 million (in 2000) to 950 million in 2030, and 1,400 million in 2060 (12% of the global population) for a range of socio-economic scenarios. This is driven by rapid population growth in developing countries and coastward migration. Population growth and urbanisation are expected to be highest in Africa (especially the Sub-Saharan region) for all scenarios, and increase the population exposed to sea-level rise (Hinkel et al. 2012a). By 2060, coastal urban[2] areas could shelter two thirds of Africa's coastal population under highest-end growth assumptions. At the same time, Asia's coastal population, will be growing at only half to two-thirds of the rate of Africa. Nevertheless, the LECZ population in Asia is expected to increase from 460 million (74% of the global population within the LECZ in 2000) to 980 million people (71% of the global population within the LECZ in 2060). North America will experience the highest urbanisation of the coastal zone in the LECZ with an increase of the urban population from 61% in 2000 to up to 78% by 2060 under highest-end growth assumptions. Other countries (e.g. Australia) may have a higher

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[2] Defined as places dominated by built environments – see Vafeidis et al. (2011).

percentage of coastal population, but these may not be classed as residents of 'urban' areas, as population is dispersed in less built up zones.

It must be noted however that coastal urbanisation trends can vary significantly between countries and regions. For example, national policies and tight global economic links support the strong coastal urban growth that is observed in China (McGranahan et al. 2007; Pannell 2002, 2003). The opposite, however is true in Bangladesh, where predomiantly the rural population in the LECZ is growing faster than the country's urban average (McGranahan et al. 2007). Thus urban areas and megacities in the LECZ will continue to grow and be at threat from rising sea levels throughout the twenty-first century.

5.3.4 Transport and Energy Systems

Transport and energy networks have important infrastructure located in the coastal zone which, if adversely affected by sea-level rise, could have ramifications over a wide area and indirectly impact much of the world's population. Key within these networks are sea ports and airports, which are often located in low-lying or reclaimed coastal areas, and large-scale energy generation plants which require coastal locations for either transport and/or water supply for cooling. Relocating such infrastructure would be costly, so there is a need for on-going awareness and planning to upgrade facilities appropriately in response to sea-level rise.

Using global data sets, the number of airports, ports, oil refineries and nuclear power plants within 10 km of the coast were estimated to assess the proportion of these key assets located in coastal areas, and their importance within energy and transport networks. A horizontal distance of 10 km around the coastline was chosen to define the coastal zone rather than an elevation limit above mean sea level (e.g. LECZ) due to data quality, as otherwise important areas of the datasets were omitted. Maps showing the number of assets for each country are shown in Fig. 5.5.

Air transport is an important part of the world's transport network with a total of 2.5 billion passengers and approximately 50 million tonnes of freight flown worldwide annually (Oxford Economics 2009). Globally just over 2,000 (approximately 30%) airports are located within 10 km of coast (Fig. 5.5a), of which nearly 200 airports are located on small remote islands in the Atlantic, Indian and Pacific Oceans (data from OpenFlights 2012). For these islands, airports located adjacent to the coast may be susceptible to the effects of sea-level rise (either erosion or flooding) but, due to their land limitations and remoteness, adaptation may be challenging. Therefore small islands are expected to be vulnerable to environmental change and experience some of the worst effects from rising sea levels and other climate change effects (Mimura et al. 2007). Elsewhere, the size of the airport is also important to consider. Large airports on low-lying land may be affordably protected, whereas smaller airports may not. However, these smaller airports (e.g. a landing field) may be easier to move further
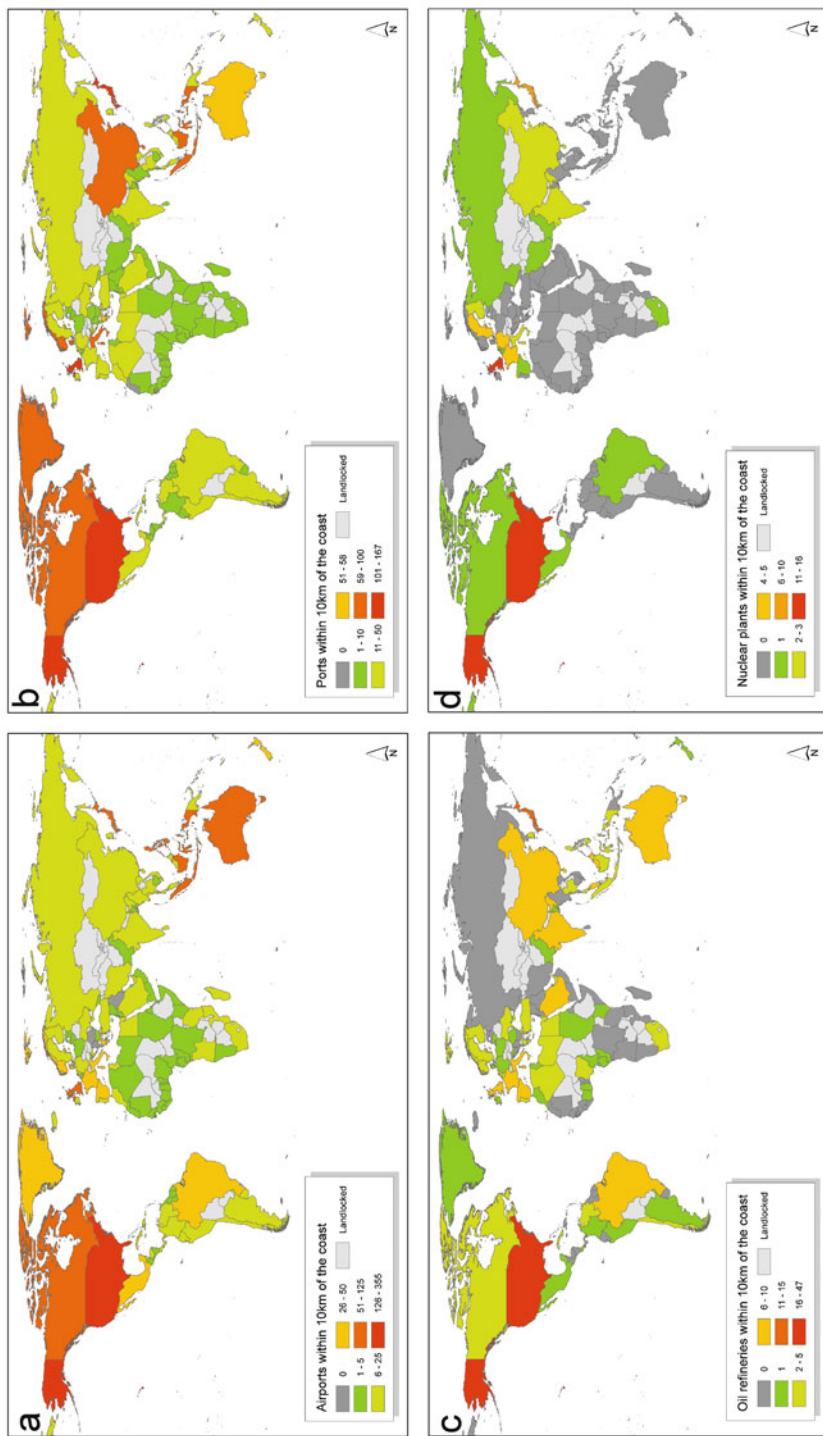
Fig. 5.5 Transport and energy infrastructure within 10 km of the coast. (**a**) Airports (OpenFlights 2012); (**b**) Sea ports (Lloyd's List 2009); (**c**) Oil refineries (GeoCommons 2012); (**d**) Nuclear power plants (GCMD 2010)

inland or even operate under low-tide conditions. This already happens at Barra airport, north-west Scotland where the runway is a beach.

The majority of the world's ports are located on the coast (the remainder being located on major rivers) and are therefore directly affected by changing sea levels. Nicholls et al. (2008b) found that from 136 global port cities (greater than one million people) in 2005, US$3,000 billion assets and 40 million people were at risk from a 1:100 year flood event, and this would increase significantly in the future. Thus protecting and upgrading infrastructure is important to maintain smooth transport links (Hanson and Nicholls 2012; Nicholls and Kebede 2010). Of the over 2,700 ports recorded in Lloyd's List (2009), 2213 are located within 10 km of the coast (Fig. 5.5b). Countries with a large number of coastal ports include the UK, the USA, China, Canada, Japan and Indonesia, the most interconnected in terms of trade routes being China and Germany (UNCTAD 2011). Despite the recent economic downturn, seaborne trade remains vital for the global economy with developing countries accounting for 61% of all cargo loaded and 55% of unloaded cargo, reflecting their growing importance in driving the global economy (UNCTAD 2010, 2011). Forty four of the ports recorded in Lloyd' List (2009) are associated with remote islands, although other important anchorages probably exist. Maintaining boat access to these small ports or harbours or beaches is potentially vital for small islands. These ports are important transport hubs, helping to provide livelihoods by supporting fishery and aquaculture industries and provide trade. If agricultural land is threatened or is subject to salinisation, small islands may become reliant on trade routes for food supplies. Adapting to sea-level rise (including infrastructure) may be costly for small islands particularly due to their large reliance on the coast, but arguably it is vital if they are to survive.

Figure 5.5c illustrates the distribution of the global oil refineries within 10 km of the coast. In 2008 global crude oil imports/exports amounted to 1,970 million tonnes (BP 2009). Globally, about 257 oil refineries (approximately half of the global total) have been identified as being within 10 km of the coast (data extracted from GeoCommons 2012). North-west Europe, the Middle East and the Gulf of Mexico contain a high density of oil refineries. Oil refinery infrastructure is not expected to increase on the coast, and more likely will decline as oil production decreases due to dwindling resources (Nicholls and Kebede 2010). Until recently, defence construction did not take account of long-term trends of extreme events. Therefore older structures are more likely to be at risk from future flooding than more recent constructions (Rayer and MacKenzie 2010). However, if design lifetimes are extended, or infrastructure is used for other purposes (e.g. carbon capture and storage), the exposure to extreme events should be reconsidered.

In 2010, 14% of global electricity generation came from nuclear power (World Nuclear Association 2012a). Nuclear power stations require water as a coolant and are often located on the coast. About 75 (approximately 30%) of the world's nuclear power stations (data extracted from GCMD 2010) are within 10 km of the coast (Fig. 5.5d), with many concentrated around Europe, the USA and east Asia (Nicholls and Kebede 2010). Around two thirds of reactors that are under construction, planned, or proposed are in Asia (many in coastal China – World Nuclear Association

2012b). Due to high safety standards and emergency procedures, risk from extreme water levels from an individual storm may be low, but over time this will increase. To avoid contamination of radioactive waste, sites require high levels of protection (Wilby et al. 2011) over long time scales (greater than 100 years). With high safety standards, defences and their planning require regular review and monitoring, with anticipation of future conditions which could induce flooding or erosion – including sea-level rise, changes to storminess and sediment movement (where it acts as a protective barrier).

Planning to maintain the operability of the coastal infrastructure discussed here will be an important issue over the coming century, requiring the long-term consideration of energy and transport needs, together with existing and new adaptation techniques. Where this cannot be done, alternative methods of transportation or supply nodes need to be considered in advance, and changes phased in to ensure a smooth transition and minimal environmental impact between these nodes. For ports and airports it is also important to remember that, while they are often located in areas of high population and economic activity, they additionally have an important role in allowing and maintaining contacts with isolated locations, such as small islands (e.g. Wright and Hogan 2008). If ports and airports on small islands are threatened, it could locally have knock-on effects due to the connectivity and dependence on these vital transport routes.

5.4   Response to Impacts

With knowledge of potential sea-level rise impacts, climate mitigation and adaptation are two distinct methods to reduce risk. It is important to identify the cause of relative sea-level rise, so to determine which method is appropriate to reduce vulnerability.

Mitigation involves technological change and substitution to reduce inputs and emissions per unit of output. When specifically referenced to climate, this means implementing policies to reduce emissions (and subsequent temperature rise) and enhance sinks for greenhouse gases (IPCC 2007). For non-climatic factors, this involves changing practices to reduce adverse effects, or compensating for them accordingly. Adaptation takes place through actions to reduce vulnerability or improve resilience in response to observed or expected events. This includes planned or unplanned, reactive or anticipatory, private or public, successful or unsuccessful responses (IPCC 2007).

Climate mitigation relies on governments and policy implementations to reduce emissions. Mitigation will not stop sea-level rise, but will reduce the rate of rise. Given the commitment to sea-level rise, the benefits of climate mitigation may take a long time to be felt, but it has multiple advantages to many ecosystems and human environments. These benefits can extend to people and environments who sometimes do not feel that it is appropriate to adapt to rising sea levels or do not have the means to do so. Mitigation of non-climatic factors (e.g. mitigation of subsidence by reducing water abstraction) is more immediate and has long lasting benefits.
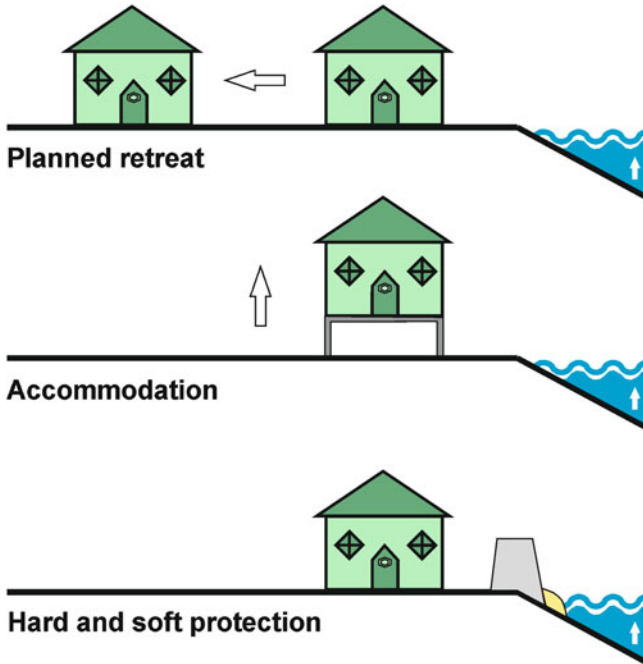
Fig. 5.6 Adaptation response from rising sea levels (After IPCC 1990)

Adaptation is undertaken at local to national levels to reduce vulnerability and/or enhance resilience, including practices, processes and perceptions of risk (Adger et al. 2007). It benefits those in the immediate coastal zone, as well as those further afield who rely on coastal goods and services. Given the commitment to sea-level rise, risk levels can be continually assessed so that adaptation can be strategically planned for, and if necessary, altered as environmental conditions change. Adaptation is frequently seen as the more immediate way to reduce or manage a hazard (Nicholls et al. 2007). However, adaptation can be costly and some schemes require ongoing maintenance and monitoring to ensure that they remain effective. Adaptation schemes may also have unanticipated or adverse effects, or even exacerbate existing problems (e.g. hard defences can lead to increased erosion down-coast, Brown et al. 2011).

For sea-level rise, planned adaptation can be categorised, following IPCC (1990) as shown in Fig. 5.6:

(a) Planned retreat: where a system moves or migrates landward away from the sea;
(b) Accommodation of relative sea-level rise: where environments, including the people who reside there, remain in situ and adjust to the changing environment (either spontaneously, anticipatory or planned) through changes in their behaviour or living conditions;

(c) Protection: by hard (e.g. sea walls, dikes) and soft defences (beach nourishment, planting of vegetation).

Many responses may involve a combination of these measures (Nicholls et al. 2007).

Erosion and flooding may result in landward migration of wetlands, unless it is prevented from doing do so by hard adaptation structures creating coastal squeeze. This could potentially reduce biodiversity and environmental quality. Ecosystems may be able to accommodate sea-level rise, and where crops are grown, if more salt tolerant species are introduced, it may result in a larger or more reliant yield (Foresight 2011). Protection of the natural environment may mean investing in the ecosystem, such as planting mangroves which helps trap sediment and protect the hinterland (see Sect. 5.3). Whilst mangroves take a long time to grow and act as protection, they have dual benefits with their ecosystem goods and services, such as filtering nutrients, reducing pollution and providing a habitat for wildlife (World Bank 2011).

Urban environments and their associated infrastructure require protection from sea-level rise in order to 'hold the line'. This can mean building or extending defences or other adaptive methods, perhaps to a higher standard or supplementing hard defence practices with soft methods. Within Europe, large protection schemes such as the Netherland's Delta Plan or London's Thames Estuary 2100 help to strategically plan for erosion and flood risk across urban areas and the hinterland (Delta Commissie 2008; Environment Agency 2010). There are also innovative ways to accommodate sea-level rise such as raised walkways, floating buildings and multi-functional defences (Stanlenberg 2012). In developing countries, adaptation can mean micro-insurance, changing agriculture patterns, building embankments, raising vital infrastructure (Linham and Nicholls 2010). Cities can try to 'advance the line' by building seaward (i.e. land claim), which has happened in many locations in north-west Europe and east Asia. 'Managed realignment' is possible, but not widely considered in urban areas due to high value of land and logistic complications. However if carefully managed this has the potential to provide additional space for flood water (Sherwin and Nicholls 2007).

Transportation and infrastructure require long term planning, and without adaptation could be subject to significant impacts that extend beyond the coastal zone. This could include relocation, redesign, deployment of temporary barriers, contingency planning for extremes and improved early warning systems for high water levels (Hanson and Nicholls 2012). In a global survey of port administrators, Becker et al. (2011) found that many were 'uninformed' about climate change, including the magnitude of sea-level rise. Given rapid port expansion, greater communication and awareness is required to maintain protection levels. Many coastal oil refineries are located near to ports, so may adapt in a similar way. For nuclear power plants, planned retreat is potentially challenging due to the long-term hazardous nature of the materials involved. Hence regular monitoring and where necessary upgrading of protection is required.

Finally, where coastal environments come under increasing pressure from rising sea levels and other environmental change but are unable to sufficiently adapt, environmental conditions could degrade. For those people who directly rely on or live off the land (often the poorer population), it may be increasingly difficult to reside there. For instance, rising sea levels can result in land salinisation, decreasing agricultural production, resulting in land abandonment, or force people to look for alternative employment. This could result in migration, including forced migration (Black et al. 2011). Whilst many migrants move within their own country, some may wish or need to travel over international borders. This may be particularly important for small islands. International co-operation is required to plan ahead accordingly to assist such migrants.

5.5 Assessing Vulnerability

Section 5.3 illustrated potential localities where impacts due to sea-level rise could occur and highlighted areas that are potentially threatened. However, despite similar geographical conditions, not all of these areas are necessarily highly vulnerable to rising sea levels. Here, vulnerability is defined following the IPCC guidelines as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes" (IPCC 2007). Vulnerability integrates knowledge on exposure, potential impacts (as discussed in Sect. 5.3) as well as on the adaptation capacity to these impacts (as discussed in Sect. 5.4) and other influencing factors. Using this information, together with research on coastal ecosystem and human systems (e.g. Nicholls et al. 1999), Table 5.2 summarises the potential impacts, adaptation history and potential, and estimates vulnerability at the continent scale.

There is no standard way of assessing vulnerability (Hinkel 2009) and hence approaches differ (Wolf et al. in review). One method is to assess adaptation implicitly and separately from impacts by means of evaluating the adaptive capacity of human systems to respond using socio-economic indicators. The disadvantage of this approach is that the capacity assessed is not specific to the impact considered and it is difficult to combine information on capacity and impacts (Hinkel 2009). Another approach is to assess adaptation explicitly and jointly by means of running impact models that include models of adaptation. The advantage of this approach is that it yields temporally explicit results on cost and benefits of adaptation. The disadvantage of this approach is that usually only a narrow range of adaptation options, in particular defence options, can be considered as only these can be modelled. An example of this approach is the Dynamic Interactive Vulnerability Assessment (DIVA) model which, using projected rates of sea-level rise together with socio-economic projections, calculates potential impacts of sea-level rise (e.g. land loss, people flooded) on a global scale (Vafeidis et al. 2008). Assessments of vulnerability also need to integrate across the wide range of uncertainty about scenarios, impacts and adaptation. For coastal impacts, this means that assessments of vulnerability need to consider the range of plausible socio-economic development in the coastal zone, as well as the range of local sea-level changes expected (Nicholls et al. 2008a).

Table 5.2 Coastal impacts adaptation and vulnerability of relative sea-level rise per continent based on data presented in this report and other research

Continent	Major potential impacts	Adaptation history and potential	Vulnerability
Africa	Deltas/cities/wetlands	Low – little experience, limited resources	High
America: Central, South and Caribbean islands	Deltas/wetlands/cities (hotspots). For small islands, airports/ports	Medium	Medium (small islands have a high risk)
America: North	Wetlands/urban areas/ nuclear/ports/oil	High – mainly land use planning, building regulations (retreat and accommodation), limited protection	Medium, but wetlands highly threatened
Asia	Numerous large densely populated deltas/ wetlands/megacities/ corals	Low to high – depending on wealth (which is increasing), population density and management of coastal resources. Long tradition of defence, especially in east Asia	High, especially in deltaic areas
Oceania	Beaches/corals/oil/ airports/ports	Land use planning, regulations, retreat and accommodation options	Low, but coral reefs highly threatened
Europe	Wetlands/beaches/ nuclear/oil	High, mostly protection especially in north-west Europe	Low, but wetlands highly threatened
Small oceanic islands	Natural environment/ ports/airports/ groundwater	Low – potentially limited resources/capacity	High

5.5.1   A Continental-Level Review

Each continent is considered in turn, together with small islands nations.

Urbanised areas in Africa could experience some of the highest growth rates in coming decades, so there is a need to protect potentially densely populated, only poor urban populations such as the urban strip from Lagos to Abidjan in West Africa. The competing factors of urbanisation and sea-level rise makes the environment and the people who reside there vulnerable. Coastal cities are expected to expand – probably at a greater rate than interior cities. By 2025 expansion is expected to create a new megacity (Luanda, Angola), bringing the African total to two (with Lagos, Nigeria, see Fig. 5.4). Lessons need to be learnt from other

urbanised environments in that the ecosystems and resources required to support them are sustainable and do not adversely affect environmental quality (Black et al. 2011). When environmental quality is compromised, vulnerability increases. Deltas are hotspots of potential impacts, especially the Nile delta which stands out in global terms (Ericson et al. 2006). Other parts of the African coast are less developed, and with a lack of protection structures, the coast has a greater freedom to respond to environmental change. However, if sea levels rise at rates faster than ecosystem response, this could lead to environmental degradation. Some people may depend on the natural environments for their livelihood, so require support to be able to adapt as the environment slowly changes. For instance, sea-level rise could lead to greater salinisation affecting coastal agriculture and therefore food supply (Foresight 2011). Some natural defences are being degraded and there is little experience of human adaptation in Africa. Thus coastal changes could have wide implications for vulnerability. National and local investment in adaptation and maintaining environmental quality is required (Hinkel et al. 2012a).

Central and South America are less coast focused than other continents with many capital cities often being inland (except for the Caribbean). Hence they have mixed impacts and vulnerabilities: Hard, rocky coasts on the western coast, but also cities and deltas on the eastern coast. The Caribbean islands are also vulnerable: Sea-level rise is expected to add significant pressure due to its high exposure of area and population (Anthoff et al. 2006) and its reliance on its coastal resources, habitats and wetlands (Schnack 1993; FAO 2006). Sea-level rise increases risk of disruption to transportation systems, such as ports or airports. Major hotspots include the Guyana, Suriname and the French Guiana coast where the population is concentrated in a narrow coastal lowland. Other areas of South America that are expected to be most affected by sea-level rise and other climate impacts are the low-lying Pampas region including Buenos Aires metropolitan area and cities on the coast of Brazil such as Rio de Janeiro. In Venezuela there are a number of urban centres and the majority of industry is concentrated along the coastal zone, including Lake Maracaibo which is subsiding due to oil extraction. Assessments of exposed land area and population show that this varies considerably between countries. Experience of adaptation is focused on the areas with impacts and required development.

Much of the North American coast is developed and the coast is a major focus for development, with states such as Florida being some of the most populous in the region. The main approach to manage current coastal hazards is land use planning, flood resilience, warning systems and evacuation, and flood insurance allowing rebuilding and repair. Local protection is apparent in a few regions, such as in Louisiana and New Orleans (where subsidence is significant – see Sect. 5.3). Compared to Europe and Japan, higher levels of risk appear to be accepted in North American coastal cities (Nicholls et al. 2008b). East coast barrier beaches are under threat from human influence and rising relative sea levels, and large areas of

wetlands are at risk. Since colonisation in the 1700s, only 47% of wetlands remain in the USA. Wetlands have been lost due to reclamation, with California losing up to 90% of its original wetlands. Recognising the importance of wetlands and the designated laws to protect it, wetland loss has slowed since the 1970s (Watzin and Gosselink 1992).

The south, south-east and east Asian coasts contain a large part of the world's coastal population, often situated in many of the large deltas and recent alluvial plains. In contrast, Russia and the Middle East have a lower coastal population. The continued growth of coastal cities, including megacities, means that their impacts to sea-level rise should be considered. A major threat (which can be greater than climate-induced sea-level rise) in many cities is local subsidence, especially for those located in deltas, where groundwater pumping enhances subsidence (World Bank 2010). Monitoring and mitigating by reducing water extraction helps reduce the problem (see Sect. 5.2). In east Asia in particular, there is a long history of defence, as exemplified by 12,000 km of dike in China (Li et al. 2004), and defence construction and upgrade seems likely in the future. Around poorer parts of Asia, wetlands are under threat (e.g. conversion to farming which is a major issue due to the large and growing population), but these ecosystems offer vital services, soft protection and livelihoods, and so need to be preserved.

Ranging from coral reef and mangrove-fringed shorelines in the tropics to extensive cliffs along the Great Australian Bight, and comprising more than 10,000 beaches, the Oceania coast is very diverse (Short and Woodroffe 2009). Eighty percent of the population lives near the coast. With a growing population and increasing coastward migration, there is pressure for more coastal urban development. However there is increasing awareness and planning, including building setbacks (where development is prohibited within a strip adjacent to the coast) to reduce vulnerability. Parts of the Australian coast have a high tidal range, and so the effects of sea-level rise and changes to salinity can in places extend 100 km inland. Large areas of wetlands, such as mangroves and associated wildlife and adjacent freshwater ecosystems are vulnerable to the effects of sea-level rise. Rising temperatures and reduced river flow could also exacerbate problems. Coral reefs are already showing some of the most dramatic effects of climate change in response to thermal stress and elevated sea surface temperatures. Signs of adverse conditions have already been seen on the Great Barrier Reef. Monitoring programmes need to be enhanced, with all forms of climate change integrated to better assess vulnerability (Harvey and Woodroffe 2008).

In Europe, developed urbanised coastlines are highly threatened by sea-level rise, but where it is economically possible to adapt, this is already being undertaken and planned, thus reducing vulnerability. Dike systems are especially extensive around the southern North Sea in Germany, the Netherlands, Belgium and England. Broadly, Europeans are considering growing vulnerability and are proactive in reducing risk. This includes research and development (e.g. The EU Framework programmes), directives (e.g. the EU Flood Directive), and national planning (e.g. the Delta Commissie in the Netherlands). The natural environment will become increasingly under pressure as sea levels rise, and where natural and built environs coincide,

coastal squeeze could result causing environmental degradation, challenging the EU Habitats Directive. The port and energy sector also needs to plan for sea-level rise, such as raising port infrastructure or regularly assessing or increasing protection around vulnerable areas. Due to awareness of climate change and financial means, vulnerability is low. European Union directives and other international regulations focuses attention on the natural environment.

Small islands, such as the Maldives or Tuvalu, are especially vulnerable places to rising sea levels. The sand cays on the perimeter of coral atolls are some of the most low-lying locations in which people live, few rising more than 3 m above sea level (Woodroffe 2008). They potentially have low adaptive capacity, even if there is large investment in adaptation on an island. Transport by aeroplane or ship may be threatened if there are insufficient resources to protect or raise port infrastructure or if land becomes flooded or eroded. Their natural environment is also threatened (e.g. beaches, salinity) and this could affect the economy (e.g. tourism) or freshwater supplies. This could have further impacts on income, fishing industry and agriculture, threatening livelihoods. With limited resources and capacity to change, small islands, particularly remote islands are some of the most vulnerable places to be affected by sea-level rise (Hinkel et al. 2012b). Small 'high' islands are also at risk due to their remoteness, strong coastal focus in urban areas and associated infrastructure and low adaptive capacity. Subsequently adaptation (e.g. port upgrade) would need to be widespread. Finally some small island states, as well as other coastal states (e.g. Bahamas), may further encounter losses or face disputes over their maritime territory if coastlines retreat and islands become submerged (Houghton et al. 2010).

5.5.2 Engendering Vulnerability: Awareness, Response and Integration

From a global perspective it is clear that there are cross cutting issues and challenges to face, and areas where knowledge of vulnerability needs to be improved. This study has illustrated the diversity of problems that occur on each continent. Whilst lessons can be learnt from one country to another, some issues and risks are specific to a global region and need attention in this context.

Environmental change makes people vulnerable and we need to understand, learn, live and ultimately adapt to new conditions. Subtle environmental change (that people may not even be aware of) can potentially result in a slow increase in vulnerability. People assume that the status quo provides sufficient protection and they can ignorant in assessing risks. Large increases in vulnerability can result from rapid changes. People are often more responsive to these large changes of risk because they are more apparent. Mitigation can reduce ongoing risk and vulnerability. In terms of vulnerability over time, the end destination of slow subtle change versus a sudden change may be the same, but the risks en route may not. Subsequently expected human

behaviour due to potential adaptation or mitigation differs as does the decision making processes to reduce risk (or an individuals or organisations perception of that risk). Hence risk and impacts must be periodically reviewed, and adaptation and mitigation options assessed.

Here, only the effects of sea-level rise have been assessed, but this will be accompanied by other climate and marine effects (e.g. storminess, salinity and sea surface temperature) and non-climate-induced environmental problems, compounding the threat of adverse change. As such, there is a need for integrated approaches to assess the complex interdependencies and tradeoffs between management and the natural environment. Knock on effects need to be investigated and their relationship to impacts and vulnerability, such as changes to biodiversity or influences on agriculture or freshwater supplies. Finally, coastal vulnerability driven by non-climatic factors, such as socio-economic development, coastal management, water abstraction or agriculture practices can be profound and yet are often overlooked in impact studies (Nicholls et al. 2008a).

5.6 Conclusion

Relative sea-level rise due to global climate-induced changes, and more local non-climatic changes such as land subsidence, particularly in densely populated areas potentially have serious impacts in the coastal zone affecting the natural environment and human activities. As relative sea levels rise, lower surge elevations are required to bring about a high water level or extreme event. Global mean sea levels may rise more than 1 m during the twenty-first century with the key uncertainties being the contribution of ice melt from Greenland and Antarctica. Due to regional and local factors, local sea-level rise will be variable around this mean with subsidence in some densely populated areas potentially greatly exacerbating the global trends (as observed during the twentieth century). Other places may experience a fall in relative sea levels as land levels rise at a greater rate than sea levels. This chapter has illustrated that there is a large reliance on coastal zone ecosystems and services, including beaches, wetlands, and much of the infrastructure in urban areas, transport and energy systems. These systems are highly interlinked and any adverse consequences of extreme water levels could have major impacts to those on the coast, and those inland who rely on coastal services.

Coastal wetlands are highly vulnerable to sea-level rise, whilst sandy environments are likely to erode as they are more mobile and have greater potential to cope with sea level rise. These environments offer multiple services, such as for habitat creation and also help to protect the coast. What is important is how fast sea levels will rise and how this effects changes to sediment availability. Sediment availability (e.g. in delta regions) is affected by fluvial water availability and erosional processes – both of which could be affected by other climatic and non-climatic drivers. There is a need for further integration between climate and other

environmental drivers of change, in terms of their impacts, potential to adapt, and therefore vulnerability.

Significant growth in the built environment and the transport and energy network is occurring, some of which is planned, others unplanned. Unplanned urban sprawl, growing populations, water abstraction and conversion of wetlands puts increasing pressures on the built environment and its environs making them more vulnerable to rising sea levels and extreme events. Improved regulation, information and monitoring is required to help authorities and stakeholders better understand the risks, and where possible avoid or adapt to them. Examples of proactive planning such as the Delta Commission (Delta Commissie 2008) and the Thames Estuary 2100 (Environment Agency 2010) approaches should be developed into more generic approaches for widespread application.

At the continental scale considered in the paper, there are different impacts and vulnerabilities, and therefore varying needs and challenges to adapt to sea-level rise. Small islands are vulnerable due to their remoteness (particularly those at low elevation), Africa and other parts of the developing world are vulnerable due to a lack of financial capacity to adapt, and south, south-east and east Asia due to high population densities in subsiding deltas. The coastal environment should be carefully monitored and managed: By maintaining or improving the natural environmental quality, benefits can extend to other environs (including human activities), reducing potential problems and economic costs. Climate mitigation aims to reduce the rate of sea-level rise, but this does not stop it instantaneously rising. The benefits of this may take decades to centuries to be apparent, so adaptation is also required. Given that the magnitude of future sea-level rise is uncertain, adaptation measures need to be flexibly planned and integrated taking consideration of other aspects of climate change and relevant non-climatic drivers. By identifying and improving our understanding of local and global drivers of change, different integrated approaches to manage and adapt to hazards in the most effective way possible to reduce risk can be undertaken.

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