BACKGROUND: A true-color Moderate Resolution Imaging Spectroradiometer (MODIS) image from October 5, 2002, shows water-logged lowlands in India and Bangladesh. *Photo credit: Jacques Descloitres, MODIS Land Rapid Response Team, NASA/GSFC; from http://visibleearth.nasa.gov/view_rec.php?id=3895*

Planning for the Impacts of Sea Level Rise

BY ROBERT J. NICHOLLS

ABSTRACT. Coastal areas constitute important habitats, and they contain a large and growing population, much of it located in economic centers such as London, New York, Tokyo, Shanghai, Mumbai, and Lagos. The range of coastal hazards includes climate-induced sea level rise, a long-term threat that demands broad response. Global sea levels rose 17 cm through the twentieth century, and are likely to rise more rapidly through the twenty-first century when a rise of more than 1 m is possible. In some locations, these changes may be exacerbated by (1) increases in storminess due to climate change, although this scenario is less certain, and (2) widespread human-induced subsidence due to ground fluid withdrawal from, and drainage of, susceptible soils, especially in deltas. Relative sea level rise has a range of potential impacts, including higher extreme sea levels (and flooding), coastal erosion, salinization of surface and ground waters, and degradation of coastal habitats such as wetlands. Without adaptation, large land areas and millions of people could be displaced by sea level rise. Appropriate responses include climate mitigation (a global response) and/or adaptation (a local response). A combination of these strategies appears to be the most appropriate approach to sea level rise regardless of the uncertainty. Adaptation responses can be characterized as (1) protect, (2) accommodate, or (3) retreat. While these adaptation responses could reduce impacts significantly, they will need to be consistent with responses to all coastal hazards, as well as with wider societal and development objectives; hence, an integrated coastal management philosophy is required. In some developed countries, including England and the Netherlands, proactive adaptation plans are already being formulated. Coastal cities worldwide will be a major focus for adaptation efforts because of their concentrations of people and assets. Developing countries will pose adaptation challenges, especially in deltaic areas and small islands, which are the most vulnerable settings.

INTRODUCTION

Sea level rise has been seen as a major threat to low-lying coastal areas worldwide since the issue of human-induced global warming emerged in the 1980s (e.g., Barth and Titus, 1984; Milliman et al., 1989; Warrick et al., 1993). An extensive and growing literature demonstrates the large potential impacts of sea level rise (e.g., Nicholls et al., 2007a; Dasgupta et al., 2009). The concentration of population and assets, including many major cities, along the coasts already make them "risky places," exposed to multiple meteorological and geophysical hazards, such as storms and storm-induced flooding (Kron, 2008). Globally, it is currently estimated that as many as 20 million people live below normal high tide levels, while over 200 million people are vulnerable to flooding during temporary extreme sea level events produced by storms (Nicholls, 2010). This threatened population is growing significantly (McGranahan et al., 2007), and it will almost certainly increase in the coming decades, especially if the strong tendency for coastward migration continues. These threatened low-lying areas already depend on flood risk management strategies of some type, for example, natural and/or artificial flood defenses and drainage or construction methods. Hurricane Katrina's impacts on New Orleans in 2005 remind us of what can happen in low-lying areas if those defenses fail (see cover photo of this issue). Rising mean sea level and more intense storms will exacerbate these risks. Despite these threats, the actual consequences of sea level rise remain uncertain and contested. These drawbacks reflect the uncertainty in the magnitude of sea level rise and climate change, and also the uncertainties about whether the implementation of adaptation would succeed or fail (Nicholls and Tol, 2006; Anthoff et al., 2010).

This paper focuses on how to best plan for the threat of sea level rise and its implications. Two major responses are possible:

- Mitigation. Reduce greenhouse gas emissions and increase sinks, minimizing climate change, including sea level rise, via climate policy.
- Adaptation. Reduce the impacts of sea level rise via behavioral changes, beginning with individual actions and ranging to collective coastal management policy, such as upgraded defenses and warning systems and land management approaches.

The main focus of this article is adaptation, although some brief remarks on mitigation are included as both strategies need to be combined to develop the most effective response to sea level rise (Nicholls et al., 2007a). This article first considers climate change and sea level rise, including the important distinction between global mean and relative sea level rise. Then, it briefly considers the impacts of sea level rise from physical and socioeconomic perspectives, including drawing on experience from subsiding cities. These sections are followed by a discussion of the potential responses to the challenges of sea level rise, with an emphasis on adaptation, including its implications for coastal zone management.

GLOBAL MEAN AND RELATIVE SEA LEVEL RISE

Human-induced climate change is expected to cause a profound series of changes, including rising sea level, increasing sea surface temperatures, and changing storm, wave, and runoff characteristics (Nicholls et al., 2007a, 2008a). Here, I focus on climate-induced sea level rise, which is mainly produced by: (1) thermal expansion of seawater as it warms, and (2) the melting of land-based ice, comprising components from (a) small glaciers, (b) the Greenland Ice Sheet, and (c) the West Antarctic Ice Sheet[1] (Meehl et al., 2007). Although higher sea level only directly impacts coastal areas, they are the most densely populated and economically active land areas on Earth (Sachs et al., 2001; McGranahan et al., 2007), and they also support important and productive ecosystems that are sensitive to sea level rise (Kremer et al., 2004; Crossland et al., 2005). A global sea level rise of 17 cm was observed through the twentieth century, faster than that of the nineteenth century (Church and White, 2011). This observed rise is almost certain to continue and very likely to accelerate through the twenty-first century. From 1990 to the last decade of the twenty-first century, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) has forecast a total rise in the range of 18–59 cm (Meehl et al., 2007). However, as noted most explicitly in the IPCC Synthesis Report (IPCC, 2007), the quantitative AR4 scenarios do *not* provide an upper bound on sea level rise during the twenty-first century due to uncertainties concerning the large ice sheets. For this reason, IPCC estimates have been debated extensively in the literature since 2007, and many higher estimates of future rise have been published based on different types of evidence (see Nicholls et al., 2011). It is concluded that a global rise of sea level exceeding 1 m is a plausible scenario for the twenty-first century if the Greenland and/or Antarctic ice sheets are significant sources of sea level rise. In the UK, Lowe et al. (2009) developed a new high-end scenario of up to 2-m rise by 2100, termed the H++ scenario, specifically for project appraisal purposes, including planning London's flood defenses. The probability of high-end scenarios is unknown, but even if they are relatively unlikely, their large potential impacts make them highly significant in terms of climate risks and policy. There is also increasing concern about higher extreme sea levels due to more intense storms superimposed on these mean rises, especially for areas affected by

[1] The larger East Antarctic Ice Sheet is not expected to contribute to sea level rise during the twenty-first century.

tropical storms (Meehl et al., 2007). These possible storms would exacerbate the impacts of global mean sea level rise, particularly the risk of more damaging floods and storms.

In analyzing sea level rise impacts and responses, it is fundamentally understood that impacts are a product of *relative* (or local) sea level rise rather than global changes alone. Relative sea level change takes into account the sum of global, regional, and local components of sea level change. The underlying drivers of these components are: (1) climate change and changing ocean dynamics, and (2) nonclimate uplift/subsidence processes such as tectonics, glacial isostatic adjustment (GIA), and natural and anthropogenic-induced subsidence (e.g., Emery and Aubrey, 1991; Peltier, 2000; Church et al., 2010). Hence, relative sea level rise is only partly a response to climate change and varies from place to place, as illustrated by the measurements depicted in Figure 1. Despite a global rise, relative sea level is presently falling due to ongoing GIA-induced rebound in some high-latitude locations that were sites of large (kilometer-thick) glaciers during the Last Glacial Maximum (18,000 years ago), such as the northern Baltic and Hudson Bay (see Helsinki, Figure 1). However, most of the world's coasts are experiencing a relative sea level rise

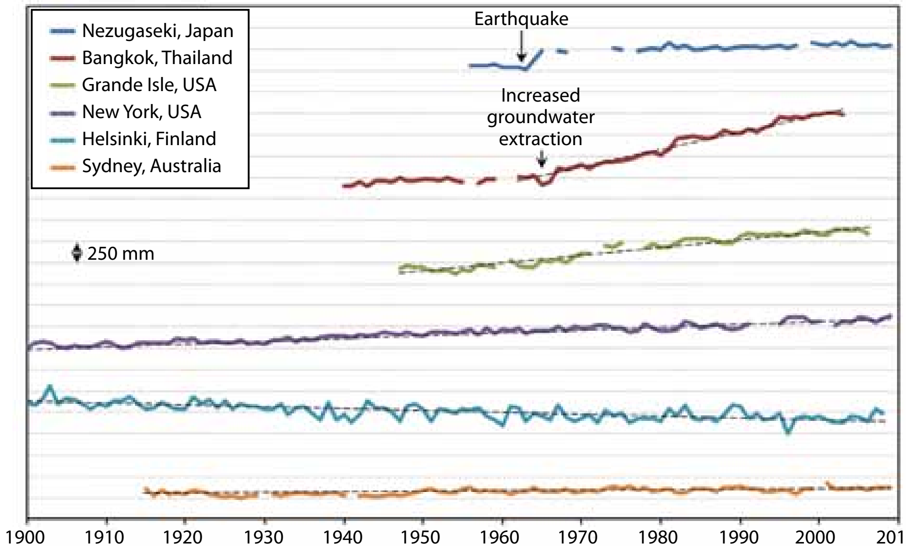

Figure 1. Selected relative sea level observations since 1900, illustrating different trends (offset for display purposes). Helsinki shows a falling trend (-2.0 mm yr^{-1}), Sydney shows a gradual rise (0.9 mm yr^{-1}), New York is subsiding slowly (3.0 mm yr^{-1}), Grand Isle is on a subsiding delta (9.3 mm yr^{-1}), Bangkok includes the effects of human-induced subsidence (20.7 mm yr^{-1} from 1962 to 2003), and Nezugaseki shows an abrupt rise due to the 1964 Niigata earthquake. *Source: http://www.pol.ac.uk/psmsl*

(RSLR), but this rise varies in rate from relatively stable coasts (e.g., Sydney; Figure 1) to naturally subsiding coasts, such as New York City (Figure 1), which is experiencing GIA-induced subsidence, and especially deltas (see Grand Isle in the Mississippi delta, Figure 1). In these cases, RSLR exceeds global rise. Most dramatically, subsidence can be enhanced by human activity in susceptible areas due to drainage and withdrawal of groundwater as in many coastal cities built on deltas (Milliman and Haq, 1996; IGES, 2007) and illustrated in Figure 1 for Bangkok. Over the twentieth century, the parts of Tokyo and Osaka built on deltaic areas subsided up to 5 m and 3 m, respectively, a large part of Shanghai subsided up to 3 m, and Bangkok subsided up to 2 m (Figure 2)[2]. This human-induced subsidence can be mitigated by stopping shallow, subsurface fluid withdrawals and managing water levels, but natural "background" rates of subsidence will continue, and RSLR will still exceed global trends in these areas. A combination of policies to mitigate subsidence has been instituted in the four delta cities mentioned above, combined with improved flood defenses and pumped drainage systems designed to avoid submergence and/or frequent flooding.[3,4]

In contrast, Jakarta and Metro Manila are subsiding significantly, with maximum subsidence of 4 m and 1 m to date, respectively (e.g., Rodolfo and Siringan, 2006; Ward et al., 2011), but little systematic policy response is in place in either city, and future flooding

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[2] Maximum subsidence is reported because data on average subsidence are not available.
[3] In Bangkok, while subsidence declined in the city's center from 1981 to 2002, it accelerated to a lesser degree over a wider surrounding area (Phien-Wej et al., 2006). Thus, the problem is evolving, but not yet solved—this situation is probably more widespread than appreciated.
[4] Note also that avoiding or at least minimizing subsidence is one key goal of water management in the coastal lowlands of the Netherlands.

problems are anticipated. Without a broader effort to share experiences, the problems of enhanced subsidence are likely to be widely repeated in susceptible expanding cities over the twenty-first century. There are many candidates in deltaic settings, especially in South, Southeast, or East Asia (see Chatterjee et al., 2006; Nicholls et al., 2008b). More widely, most populated deltaic areas are threatened by enhanced subsidence to varying degrees (Ericson et al., 2006; Syvitski et al., 2009). Lastly, note that abrupt changes in relative sea level can occur at tectonically active sites due to earthquakes (see Nezugaseki in Figure 1), and significant coastal subsidence of up to 1 m was observed after the 2011 Tōhoku earthquake (and tsunami) in Japan.

When compared to other climate factors, it is fairly certain that global sea level rise will continue beyond the twenty-first century, irrespective of future greenhouse emissions (Nicholls and Lowe, 2004, 2006). It takes centuries to millennia for the full ocean depth to adjust to surface warming, resulting in ongoing thermal expansion. This inevitable rise has been termed the "commitment to sea level rise." If global warming continues to occur and passes key but uncertain thresholds for the irreversible breakdown of the Greenland or West Antarctic Ice Sheets, the committed rise could be 13 to 15 m, albeit over long time scales (centuries or longer). The implications of this commitment are considered later.

SEA LEVEL RISE AND RESULTING IMPACTS

Table 1 summarizes the five main effects of sea level rise. Flooding/submergence, ecosystem change, and erosion have received significantly more attention than salinization and rising water tables. When sea level rises, all the processes that operate around the coast change. The immediate effect is submergence (the "bathtub" effect) and increased flooding of coastal land, as well as saltwater intrusion into surface waters. Longer-term effects that occur as the coast adjusts to new environmental conditions include wetland loss and change in response to higher water tables and increasing salinity, erosion of beaches and soft cliffs, and saltwater intrusion into groundwater. These lagged changes interact with the immediate effects of sea level rise and generally exacerbate them. For instance, erosion of sedimentary features (e.g., salt marshes, mangroves, sand dunes, and coral reefs[5]) will tend to degrade or remove natural protection and hence increase the likelihood of coastal flooding.

A rise in mean sea level raises extreme water levels. Changes in storm characteristics could also influence extreme water levels. For example, the widely debated potential for an increase in the intensity of tropical cyclones would generally raise extreme water levels

[5] Healthy coral reefs can keep pace with quite rapid sea level rise, but reefs that are unhealthy due to human stress are less resilient. Other climate change impacts, such as rising seawater temperature and falling ocean pH, are also of concern for reefs (Nicholls et al., 2007a).

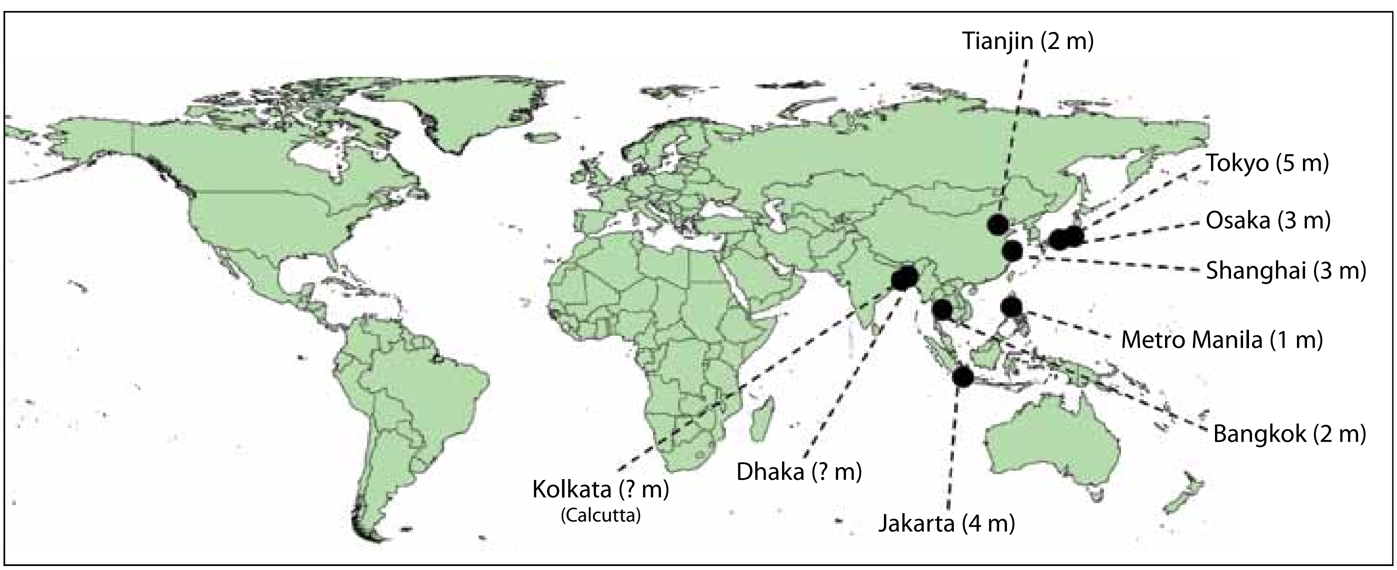

Figure 2. Subsiding coastal megacities with the maximum observed subsidence (in meters). Dhaka and Kolkata are thought to be subsiding, but data are limited. *Adapted and updated from Nicholls (1995).*

in areas such as the US East and Gulf Coasts (Meehl et al., 2007). Extratropical storms may also intensify in some regions. Changes in mean sea level will also change surge propagation, which could have additional significant effects (positive or negative) on extreme sea levels. Understanding these changes is an important research topic to support impact and adaptation assessment.

Changes in natural systems resulting from sea level rise have many important, direct, overwhelmingly negative socioeconomic impacts on a range of sectors (Table 2). For instance, flooding can damage coastal infrastructure, ports and industry, the built environment, and agricultural areas, and in the worst case lead to significant mortality as shown recently in Hurricane Katrina (USA) in 2005, Cyclone Nargis (Myanamar) in 2008, and Storm Xynthia (France) in 2010. Erosion can lead to loss of beachfront/cliff-top buildings and related 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 adverse effects on human health, for example, the release of toxins from eroded land fills and waste sites (e.g., Flynn et al., 1984), or mental health problems triggered by floods (Few et al., 2004). These indirect impacts are little researched, but will have economic consequences in terms of the damages caused (and/or the diversion of investment to fund the adaptation to avoid them). Thus, sea level rise has the potential to trigger a cascade of direct and indirect human impacts.

Sea level rise does not happen in isolation, and coasts are changing significantly due to nonclimate-induced drivers (Crossland et al., 2005; Valiela, 2006; Nicholls et al., 2008b). Table 1 indicates potential interactions with sea level rise that need to be considered

Table 1. The main natural system effects of relative sea level rise and example adaptation approaches in each case. Also shown are other interacting factors that could offset or exacerbate these impacts due to other climate changes and effects of nonclimate factors. Some interacting factors (e.g., sediment supply) appear twice because they can be influenced both by climate and nonclimate factors. Adaptation approaches are coded: P = Protection (hard or soft). A = Accommodation. R = Retreat. *Adapted from Nicholls (2010); see also Linham and Nicholls (2010)*

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

when assessing sea level rise impacts and responses. For instance, a coast with a positive sediment budget may not erode given sea level rise and vice versa (Stive et al., 2009). Deltas with healthy sediment budgets are potential examples of such environments. 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; Klein and Nicholls, 1999).

RECENT IMPACTS OF SEA LEVEL RISE

Over the twentieth century, global sea level rose about 17 cm. While this change may seem small, it will have many significant effects, most particularly in terms of reducing the return periods of extreme water levels (Zhang et al., 2000; Menéndez and Woodworth, 2010) and promoting an erosive tendency for coasts, as has been widely observed (Bird, 1985, 2000). However, linking sea level rise quantitatively to impacts is quite difficult because the coastal zone was subjected to multiple drivers of change over the twentieth century (Nicholls et al., 2009). Good data on rising sea levels were only collected in a few locations, and growing coastal populations and infrastructure continued to increase exposure damage. Further, flood defenses were often upgraded substantially through the twentieth century, especially in those (wealthy) places where there were sea level measurements. Most of this defense upgrade reflects the expanding populations and wealth in the coastal flood plain and changing attitudes toward risk; relative sea level rise may not have even been considered in the design (e.g., Tol et al., 2008). Equally, erosion can be promoted by processes other than sea level rise (Table 1), and human reduction in sediment supply to the coast must contribute to the observed changes and probably dominates in many locations, as noted by Bird (1985) and Syvitski et al. (2009). Hence, while global sea level rise was a pervasive process, other processes obscure its link to impacts, except in some special cases—most coastal change in the twentieth century was a response to multiple drivers of change.

There have certainly been impacts from relative sea level rise resulting from subsidence, such as in Venice (Fletcher and Spencer, 2005). In the Mississippi delta, 1,565 km^2 of intertidal coastal marshes and adjacent lands were converted to open water between 1978 and 2000, with relative sea level rise of 5 to 10 mm yr^{-1} being an important driver of these changes (Barras et al., 2003). There are significant actual and potential impacts of relative sea level rise in deltas (Figure 3) and in and around subsiding coastal cities (e.g., Figure 2) in terms of increased waterlogging, flooding, and submergence, and the resulting need for management responses (Nicholls, 1995; Rodolfo and Siringan, 2006).

In terms of lessons for adaptation, nearly all the major developed areas that were affected by relative sea level rise had instituted some type of defense, such as levees and seawalls, and continue to

Table 2. Summary of sea level rise impacts on socioeconomic sectors in coastal zones. These impacts are overwhelmingly negative. *Adapted from Nicholls et al. (2007a)*

COASTAL SOCIOECONOMIC SECTOR	SEA LEVEL RISE NATURAL SYSTEM EFFECT (TABLE 1)				
	INUNDATION/ FLOODING	WETLAND LOSS	EROSION	SALTWATER INTRUSION	IMPEDED DRAINAGE
Freshwater Resources	**X**	x	–	**X**	**X**
Agriculture and Forestry	**X**	x	–	**X**	**X**
Fisheries and Aquaculture	**X**	**X**	x	**X**	–
Health	**X**	**X**	–	**X**	x
Recreation and Tourism	**X**	**X**	**X**	–	–
Biodiversity	**X**	**X**	**X**	**X**	**X**
Settlements/Infrastructure	**X**	**X**	**X**	**X**	**X**

X = strong; x = weak; – = negligible or not established grow economically and in population, even where the change in relative sea level rise was up to several meters over several decades. Note that New Orleans may be an exception (see Grossi and Muir-Wood, 2006). Unusually, compared to other low-lying coastal cities, its population peaked in 1965 at more than 625,000 immediately before Hurricane Betsy flooded part of the city. Before Katrina in 2005, its population was about 500,000. Subsequently, the population has yet to recover to pre-Katrina levels, although $15 billion has been invested to significantly upgrade the city's defenses (completed in 2011). Hence, the future of New Orleans will be instructive: can it prosper behind the new defenses or will it continue to decline? In less-developed areas, coastal retreat due to subsidence has been allowed, such as in Thailand south of Bangkok, in the Mississippi delta (see above), and around Galveston Bay in Texas.

Hence, observations through the twentieth century and the early twenty-first century reinforce the importance of understanding the impacts of sea level rise in the context of multiple drivers of change—this will remain true under more rapid rises in sea level. Human-induced subsidence is of particular interest, but it remains relatively unstudied in a systematic sense. Observations also emphasize the ability to protect against RSLR, especially for the most densely populated areas, such as subsiding Asian megacities or around the southern North Sea, including London, the Netherlands, and Hamburg.

FUTURE IMPACTS OF SEA LEVEL RISE

The future impacts of sea level rise will depend on a range of factors, including (1) the magnitude of sea level rise, (2) coastal physiography, (3) the level and manner of coastal development, and (4) the success (or failure) of adaptation. Assessments of future impacts of sea level rise have taken place on local to global scales. They all suggest potentially large impacts consistent with Table 1, especially increases in inundation, flooding, and storm damage. Based on synthesis of results from analyses such as Nicholls et al. (1999), Nicholls (2004), and Dasgupta et al. (2009), in absolute numbers, South, Southeast, and East Asia and Africa appear to be most threatened by sea level rise (see Figure 4). Vietnam and Bangladesh appear especially threatened due to their large populations in low-lying deltaic plains. In Africa, Egypt (the Nile Delta) and Mozambique appear to be two potential hotspots for impacts due to sea level rise. Hotspots also exist outside these regions, such as Guyana, Suriname, and French Guiana in South America. There will be significant residual risk in other coastal areas of the world, such as around the southern North Sea, and major flood disasters are possible in many coastal regions. Small island regions in the Pacific and Indian Oceans and Caribbean Sea stand out as being especially vulnerable to sea level rise impacts (Mimura et al., 2007;

Figure 3. Relative vulnerability of deltas (in terms of displaced people) to present rates of relative sea level rise to 2050, including deltaic subsidence. Extreme = > 1 million. High = 1 million–50,000. Medium = 50,000–5,000. *Reproduced from Nicholls et al. (2007a), using data from Ericson et al. (2006)*

Simpson et al., 2009). The populations of low-lying island nations such as the Maldives or Tuvalu face the real prospect of increased flooding, submergence, and forced abandonment.

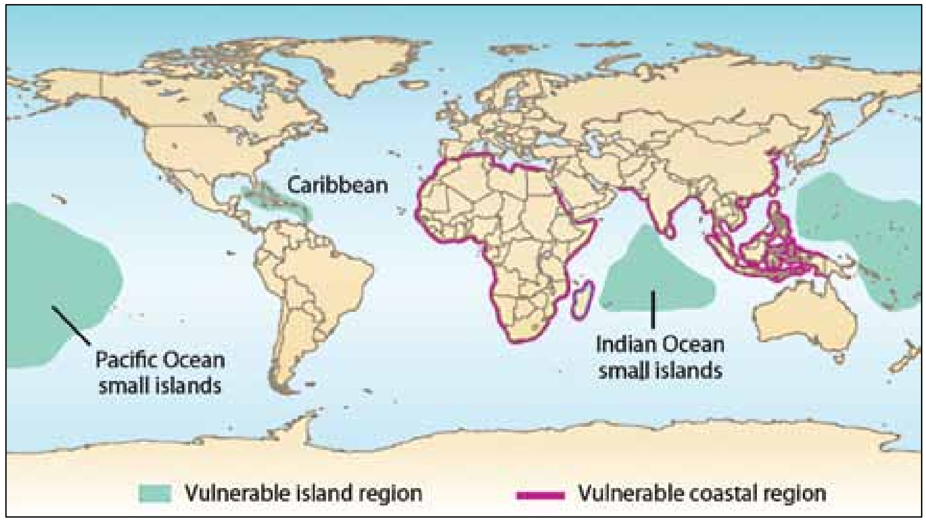

Figure 4. Several regions are vulnerable to coastal flooding caused by future relative or climate-induced sea level rise. At highest risk are coastal zones with dense populations, low elevations, appreciable rates of subsidence, and/or inadequate adaptive capacity. *From Nicholls and Cazenave (2010)*

RESPONDING TO SEA LEVEL RISE

The two potential responses to sea level rise are mitigation and adaptation. They operate at very different scales: mitigation, by necessity, is a global-scale activity linked to climate policy, while adaptation is a local-to-national activity linked to coastal management policy. Hence, our understanding and assessment of responses to sea level rise also need to operate at multiple scales.

Mitigation can slow the rise in sea level and reduce its impacts, and given its strong inertia, mitigation has an important additional effect of stabilizing the *rate* of sea level rise (rather than stabilizing sea level itself; Nicholls and Lowe, 2006). But, sea level rise will continue and will remain a challenge for generations to come. *In essence, the commitment to sea level rise leads to a commitment to adapt to sea level rise with fundamental implications for long-term human use of the coastal zone* (Nicholls et al., 2007a). Given that the rate of sea level rise controls some impacts, such as wetland loss or coral reef submergence, mitigation reduces these impacts. In the case of flooding, absolute sea level rise is of more concern, and many of its impacts may be delayed rather than avoided due to the commitment to sea level rise (this commitment gives more time to adapt, which is an important benefit that includes lowering annual adaptation [and damage] costs). Hence, adaptation and mitigation are complementary policies in coastal areas (Nicholls et al., 2007a). The fundamental goal of mitigation in the context of coastal areas is to reduce the risk of passing irreversible thresholds concerning the breakdown of the two major ice sheets, and constraining the commitment to sea level rise to a rate and ultimate rise that can be adapted to at a reasonable economic and social cost. Quantification of the most appropriate mixtures of mitigation and adaptation remains to be done.

Mitigation of human-induced subsidence needs to be considered in susceptible areas.[6] Such mitigation includes measures to control/reduce groundwater extraction and manage water levels, and these measures have been successfully implemented in a number of cities and delta areas to date. However, this strategy is not being transferred elsewhere in a proactive manner.

The remaining discussion considers adaptation options.

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

Adaptation can be classified in a variety of ways. One widely followed approach is the IPCC typology of planned adaptation strategies (IPCC CZMS, 1990; Klein et al., 2001; Figure 5):

- (Planned) Retreat. All natural system effects are allowed to occur and human impacts are minimized by pulling back from the coast via land-use planning, development controls, and other means.

[6] Natural subsidence, such as the 1.5 to 2.0 mm yr^{-1} decline in the mid-Atlantic region of the United States due to GIA, or sudden subsidence during earthquakes such as in Japan, cannot be mitigated. Adaptation is the only option.

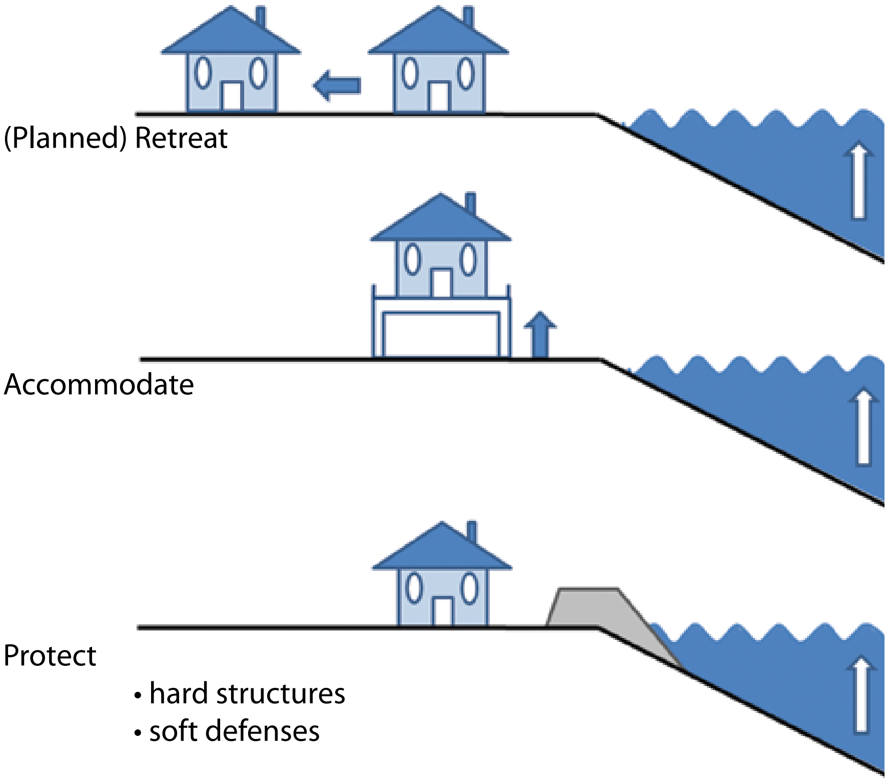

Figure 5. Generic adaptation approaches for sea level rise. *After IPCC CZMS (1990)*

- **Accommodation.** All natural-system effects are allowed to occur and human impacts are minimized by adjusting human use of the coastal zone via flood-resilience measures, such as warning systems and insurance.
- **Protection.** Natural-system effects are controlled by soft or hard engineering (e.g., nourished beaches and dunes, or seawalls), reducing human impacts in the zone that would be impacted without protection.

Table 1 gives examples of each strategy. In some classifications of adaptation responses, the concept of "attack" (or "advance the line") as opposed to "hold the line" has been suggested as a strategy against sea level rise (e.g., RIBA and ICE, 2010), which in effect translates into building seaward. This strategy corresponds to land claim (Linham and Nicholls, 2010), which has a long history in many coastal areas, such as Northwest Europe and East Asia, and has been practiced to some degree in most coastal cities due to space constraints. Land claim is an active strategy in many coastal countries such as Singapore, Hong Kong, and Dubai to expand land area as opposed to adapt to sea level rise, although sea level rise is increasingly considered in design.

Throughout human history, improving technology has increased the range of adaptation options in the face of coastal hazards, and there has been a move from retreat and accommodation to hard protection and active seaward advance via land claim as described for the Netherlands by Van Koningsveld et al. (2008). Rising sea level is one factor calling automatic reliance on protection into question, and the appropriate mixture of protection, accommodation, and retreat is now being more seriously debated. In practice, many real-world responses are hybrid, combining elements of more than one approach. For example, when offering flood protection, the residual risk that remains for all protected areas needs to be considered, suggesting flood protection needs to be combined with flood forecast and warning systems. Adaptation for one sector may exacerbate impacts elsewhere; a good example is the coastal squeeze of intertidal and shallow coastal habitats where onshore migration due to rising sea levels is prevented by fixed, hard protection (Doody, 2004).[7] Coastal management needs to consider the balance between protecting socioeconomic activity/human safety and the habitats and ecological functioning of the coastal zone under rising sea levels (Nicholls and Klein, 2005). While there were large losses of coastal habitats due to direct and indirect destruction in the twentieth century, most coastal countries now aspire to protect these areas and their ecosystem services. Sea level rise threatens such initiatives.

The most appropriate timing for an adaptation response needs to be considered in terms of anticipatory versus reactive planned adaptation (or, in practical terms, what should we do today, versus wait and see until tomorrow; see Figure 6). *Autonomous adaptation* represents the spontaneous adaptive response to sea level rise (e.g., increased vertical accretion of coastal wetlands

[7] Note that soft protection, accommodation, and retreat reduces this problem and allow coastal habitats to persist in place or migrate landward as sea levels rise.

within the natural system, or market price adjustments within the socioeconomic system). *Planned adaptation* (by the socioeconomic system) can serve to reduce vulnerability by a range of (anticipatory or reactive) measures. Adaptation normally reduces the magnitude of the impacts that would occur in their absence. Hence, impact assessments that do not take autonomous adaptation and/or (proactive or reactive) planned adaptation into account will generally estimate larger impacts (determining *worst-case* or *potential impacts* rather than *actual* or *residual impacts*) (Figure 6). The coastal zone is an area where there is significant scope for anticipatory adaptation as many decisions have long-term implications (e.g., Fankhauser et al., 1999; Hallegatte, 2009). Examples of anticipatory adaptation in coastal zones include upgraded flood defenses and drainage systems, higher-elevation designs for new land claim and coastal bridges, building standards/regulations to promote flood proofing and resilience, and building setbacks to prevent development in areas threatened by erosion and flooding.

In general, sea level rise will exacerbate existing pressures and problems; thus, there are important synergies in considering adaptation to climate change in the context of existing problems (Nicholls and Klein, 2005). In some cases, the focus of sea level rise and climate change may help identify "win-win" situations where adaptation measures for sea level rise are worthy of implementation just based on solving today's problems (Turner et al., 1995; Dawson et al., 2009; Hallegatte, 2009). Adaptation measures are more likely to be implemented if they offer immediate benefits by reducing impacts of short-term climate variability and other hazards as well as long-term climate change.

Although there is limited experience in adapting to climate change, there is considerable experience in adapting to climate variability, and we can draw on this experience to inform decision making under a changing climate. Importantly, adapting to coastal problems is a multistage *process*, including (1) information and awareness building, (2) planning and design, (3) evaluation, and (4) monitoring and evaluation operating within multiple policy cycles (e.g., Klein et al., 2000; Hay, 2009). The constraints on approaches to adaptation due to broader policy and development goals should also be carefully considered. Monitoring and evaluation is critical and yet easily ignored, and it is essential to a "learning-by-doing approach," which is appropriate to the large uncertainties associated with adaptation and sea level rise and coastal management in general. Fortunately, technological developments are greatly improving our ability to monitor, store, and distribute relevant data, but these efforts need to be fostered and disseminated more widely. In many countries, there is limited capacity to address today's coastal problems, let alone consider tomorrow's problems, including sea level rise. Therefore, promoting coastal adaptation should include developing coastal management capacity, as already widely recommended (Nicholls and Klein, 2005; Adger et al., 2007; USAID, 2009).

In terms of selecting adaptation options, there are some views that retreat is the only possible response to sea level rise (e.g., Pilkey and Young, 2009; see also Nicholls, 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; Sugiyama et al., 2008; Anthoff et al., 2010). These results suggest that significant resources should be available for adapting to sea level rise, and further that protection can be expected to be a part of the portfolio of responses. With or without protection, small island and deltaic areas stand out as relatively more vulnerable in most of these analyses, and the impacts fall disproportionately on poorer countries. Even though optimal in a cost-benefit sense, protection costs could also overwhelm the capacity of local economies, especially when they are small such as islands (Fankhauser and Tol, 2005; Nicholls and Tol, 2006). While adaptation is essentially a local

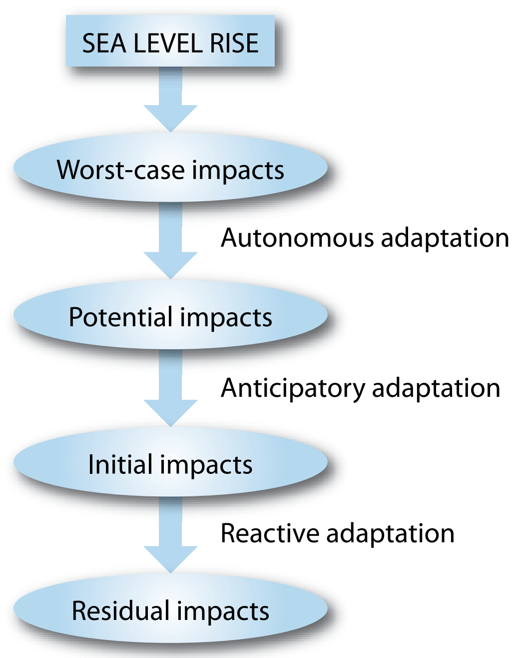

Figure 6. The different stages of adaptation and their influence on impacts.

activity, these funding challenges should be an issue of international concern.

Global cost estimates normally focus on the incremental costs of upgrading defense infrastructure, as this upgrading is consistent with the United Nations Framework Convention on Climate Change. IPCC CZMS (1990) estimated the total costs of defending against a 1-m sea level rise at $500 billion. Hoozemans et al. (1993) doubled these costs to $1,000 billion. Using an economic model that balanced dryland and wetland loss, forced migration, and incremental defense investment, Tol (2002a,b) estimated that the optimal annual protection costs for 1 m of global sea level rise were only $13 billion per year—much lower than widely assumed. More recently, the World Bank (2010) and Nicholls et al. (2010) estimated coastal adaptation costs for the developing world at only $26–89 billion a year by the 2040s, with the cost depending on the magnitude of sea level rise. Maintenance costs of defenses are also included and are found to be significant as the stock of defenses grows. A major issue that has not been quantified is the large cost of the adaptation deficit.[8] At the least, it raises the costs of adaptation in general and protection in particular by a substantial and unknown amount. It may have the potential to radically change the adaptation pathway we select.

While there is widespread awareness of the need to adapt to sea level rise, only a few countries or locations are comprehensively preparing for this challenge. Examples include London and the Netherlands (e.g., Kabat et al., 2009). Both have considered a wide range of sea level rise scenarios, including rises of up to 5 m and 4 m, respectively, implicitly thinking far into the future (beyond 2100). Importantly, they have identified adaptation pathways that are a logical sequence of protection and related measures as a function of sea level rise rather than time. This strategy confirms that there are options available for large increases in sea level. In these cases, protection seems feasible for the long term, and adaptation is explicitly being considered as an ongoing process. It is an effective way to deal with the uncertainty of future sea level rise. 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. Coastal cities are expected to be a major focus of these efforts given their concentration of people and assets, and their ability to fund large investments.

DISCUSSION/CONCLUSIONS

This paper illustrates that planning for sea level rise is a multidimensional problem that crosses many disciplines and embraces natural, social, and engineering sciences. Sea level rise has important implications for coasts worldwide, but the actual outcome will depend on our responses, both in terms of mitigation and adaptation, and their successes or failures. For adaptation in general, and protection in particular, the likelihood of success or failure is an important uncertainty that deserves more attention. There are widely divergent views on this issue, which influences how sea level rise is considered (e.g., Nicholls and Tol, 2006; Anthoff et al., 2010). "Pessimists" tend to focus on high rises in sea level and extreme events like Hurricane Katrina. They view our ability to adapt to sea level rise as being limited, resulting in alarming impacts, including widespread human displacement from coastal areas. In contrast, "optimists" tend to focus on lower rises in sea level. They stress a high technical ability to protect, and the high benefit-cost ratios in developed areas leading to widespread protection. Hence, a major consequence of sea level rise is the diversion of investment to coastal adaptation.

Optimists have empirical evidence to support their views that sea level rise is not a big problem in terms of the subsiding megacities that are also thriving. Importantly, these analyses suggest that improved protection under rising sea levels is more likely and rational than is widely assumed. Hence, the common assumption of a widespread retreat from the shore is not inevitable, and coastal societies will have more choice in their responses to rising sea level. However, the pessimists also have evidence to support their view. First, the published protection costs are incremental costs of adapting to sea level rise, assuming the existence of well-adapted protection infrastructure. This is not the case in much of the world, and the adaptation deficit needs to be assessed in the context of sea level rise. Second, assumptions of substantial future population and especially economic growth in coastal areas reinforce the conclusion that protection is worthwhile: lower growth and greater inequalities of wealth may mean less damage in monetary

[8] The "adaptation deficit" is the cost of adapting coasts to today's climate (Burton, 2004; Parry et al., 2009). Incremental cost estimates do not consider this cost, which is unquantified, but could be substantial, especially in undeveloped regions such as Africa.

terms, but they will also lower the ability to protect. Third, the benefit-cost approach implies a proactive attitude toward protection, while historical experience shows that most protection has been a reaction to actual or near disaster. Therefore, high rates of sea level rise (and more intense storms) may lead to more frequent coastal disasters and damage, even if the ultimate reactive response is upgraded protection. Fourth, disasters (or adaptation failures) could trigger decline and abandonment of coastal areas. These actions could have a profound influence on society's future choices concerning coastal protection. A cycle of economic decline is not inconceivable, especially if capital is highly mobile and collective action is weaker. Because the issue of sea level rise is so widely known, disinvestment from coastal areas may be triggered even without disasters actually occurring. For example, the economies of small islands may be highly vulnerable if investors avoid these areas due to sea level rise and climate change (Barnett and Adger, 2003). Lastly, the retreat and accommodation responses have long lead times—benefits are greatest if planning and implementation occur soon, which they may not. Hence, adaptation may not be as successful as some assume, especially for larger rises in sea level. Thus, much work remains to be done to understand these diverse issues.

Sea level rise is clearly a threat, demanding a response. The commitment to sea level rise means that an ongoing adaptation response is essential through the twenty-first century and beyond. However, mitigation can reduce the commitment to sea level rise, most particularly the potential Greenland and West Antarctic Ice Sheet contributions. Scientists need to better understand these threats, including the implications of different mixtures of mitigation and adaptation, and they need to engage with the coastal and climate policy process so that scientific perspectives are heard. While research must continue from local to global scales, much will be learned about adaptation in practice, and this engagement is critical to promote more appropriate adaptation options, as well as the opportunity to learn from the experience of these projects.

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