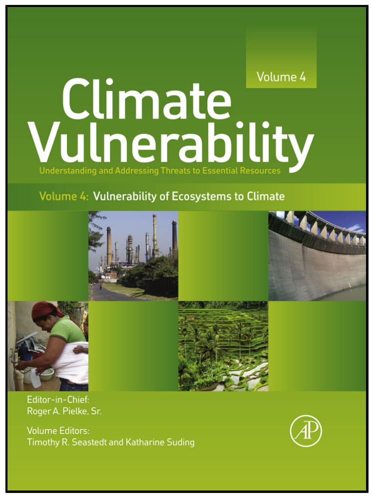

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4.14 Sea-Level Rise and Coastal Ecosystems

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Glossary

Asset Any item of value that potentially is exposed to hazards; can include buildings, other infrastructure, human beings, ecosystems, etc.
Coastal zone The potentially wide area between the dry land above the littoral and the shelf margin.
Hazard A potentially harmful event.
Local sea-level The vertical distance between the sea surface and land surface.
Global sea-level The global average of local sea-level.
Resilience The ability of a system to absorb disturbance while retaining its basic function and structure.
Risk The probability that a hazardous event will cause a certain damage to an asset.
Vulnerability Characteristic of an asset to experience damage if exposed to a hazard.

4.14.1 Introduction

Coastal ecosystems provide important environmental, social, and economic service functions. Coastal habitat and ecosystems are generally some of the richest areas for biodiversity. These systems are adapted to the various compartments that typically occur in the wide coastal zone between the hinterland and the shelf margin. Coastal wetlands include marshes, swamps, and other plant communities that are flooded part of the time, and that are hydraulically connected to the sea. Located at the interface between land and sea, tidal marshes provide unique ecosystem services for waste treatment, biological productivity, and regulation of disturbances.

Small changes in Local Sea Level (LSL) can lead to significant changes in some of these compartments posing extreme challenges to the ecosystems, particularly if these changes take place rapidly. LSL changes depend on both changes in sea surface height and land surface height. Tectonic uplift and land uplift due to postglacial rebound reduce local sea-level rise (LSLR), while local subsidence will accelerate it. In combination with changing weather extremes, changes in LSL could modify the pattern of coastal inundation with severe impacts on sensitive coastal ecosystems. The process of inundation leads to both the conversion of dry land to wetland and the conversion of wetlands to open water, thus destroying coastal habitats or forcing the ecosystems to migrate inland. However, coastal protection often inhibits migration, and a loss of valuable ecosystems would be inevitable.

Local sea-level rise would also increase the destructive force of coastal storms, leading to increased coastal erosion and an acceleration of ecosystem losses. Increased erosion would likely amplify the effects of LSLR. As a consequence, the total shoreline retreat could be much larger than suggested by present-day topography. Globally, the combined effect of LSLR and erosion could be devastating. For example, an average LSLR of 1 m along the coasts of Bangladesh would inundate 17% of the country (Titus 1990), 20% of the farmland in Egypt is below 2 m of current sea-level, and many other coastal areas would face large erosion (Figure 1). Any LSLR would also shift the tidal zone and areas inundated during storm surges further inland, with the speed of this shift depending on the local topography and the speed of the LSLR.

The vulnerability of coastal wetlands to LSLR depends on many factors, such as the coastal topography, the tidal range, and human interferences such as coastal protections and development. Depending on these factors, coastal wetlands may compensate for LSLR by vertical or horizontal migration, if the speed of change does not exceed the capability of the

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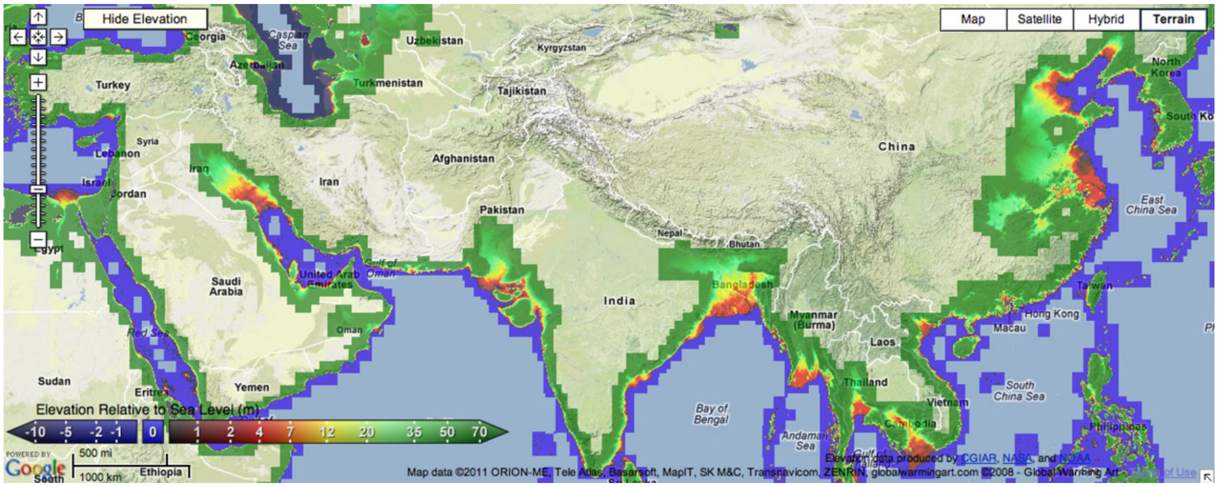

Figure 1 Coastal areas in Asia that are at risk of inundation. The color code of the map indicates elevation above current sea level. Most areas below 2 or 3 m are at risk of inundation from storm surges, and the probability of inundation and erosion during storm surges will increase dramatically if LSL rise in these location. Areas below 1 m are likely to be permanently inundated if LSL rise by 1 m at these locations. Graphics produced with the tool available at http://www.globalwarmingart.com/wiki/Special:SeaLevel.

ecosystems to migrate. In general, a rise of LSL leads to a reduction of terrestrial influence and an increase of marine influence. However, the changes depend strongly on coastal topography and do not linearly increase with the LSL change (Craft et al. 2009). In areas with large tidal ranges of 2 m or more, tidal marshes are less susceptible to LSLR than in areas with small tidal variations. If sediment supply allows tidal marshes to migrate vertically, then LSLR can be compensated to some extent. In some coastal areas, an LSLR would result in submergence and significant reductions of tidal marshes, while in other areas, salt marshes may transgress landward and in this process replace tidal freshwater and brackish marshes. A possible decline in the area of tidal marshes area and the conversion of habitats would impact the delivery of ecosystem services provided by coastal wetlands.

Coastal zones are attractive to humans for a variety of reasons. Besides a significant migration trend in human population from rural to urban areas, a migration into the coastal zone is taking place, increasing the pressure on coastal environments. During the last several decades, human interaction has reduced coastal wetlands globally by more than 30%, and more than 35% of the mangroves have been lost during the last 20 years (Gilman et al. 2006a). Any LSLR will add stress on top of this on-going human alteration of the coastal zones. In many areas, coastal protection in response to LSLR will further acerbate the stress.

Regional changes in weather patterns, melting of ice sheets, and increases in ocean heat could lead to significant global sea-level rise (GSLR), and assessments of the potential impact indicate possible extreme costs particularly for urban coasts (see Plag and Jules-Plag 2012). Very few assessments have focused on the economic impact of sea-level rise associated with ecosystem loss through inundation, erosion, and other sea-level related processes. Examples of a few exceptions are studies of potential sea-level rise impacts on the Everglades in Florida (Madden and Goodin 2007), on the vast coastal area and flood plain zone in Bangladesh (Sarwar 2005), and on mangroves (Gilman et al. 2006a,b). The development of policies for adaptation and mitigation of sea-level rise related impacts is also mainly focused on urban coastal areas. As a consequence, coastal ecosystems would likely be in a triple-loss situation: human alterations are leading to degradations and loss; sea-level rise would increase stress and require ecosystem migration; the human response to sea-level rise would increase coastal alterations and add stress.

IPCC prediction of the 21st GSLR displays a large range ranging from a few centimeters to 1 m, but many climate change assessments conclude that Global Sea Level (GSL) will only rise on the order of 0.5 m by the end of the twenty-first century (e.g., Bindoff et al. 2007), although it is often stated that larger values cannot be excluded (e.g., Church et al. 2010). However, studies of paleo-records indicate that there is no scientific basis to exclude GSL changes of 2 m or more within several decades. This renders model predictions unsuited as a basis for the planning of adaptation. Taking into account that LSLR can deviate more than ±100% from the global average, this implies that changes of several meters within a few decades are within the possible range of LSLR. Superposing this potential LSLR over the low-lying coastal areas shown in Figure 1 for Asia indicates the scale of the inundation and erosion problem. The situation in other coastal areas is similar to the one shown for Asia.

A key consequence of sea-level rise is the loss or degradation of wetlands in the coastal zone. There are, however, two compensating processes that might offset this potential threat: (1) an LSLR would inundate and flood areas that are now dry land, and thus, create new wetlands; (2) wetlands can grow vertically by accumulating sediment and organic material. The potential of these processes to slow down or prevent a major loss of wetlands as a consequence of LSLR may be limited due to two factors: (1) in many cases, land just inland of wetlands has been developed, and moving people and infrastructure to make room for the creation of new wetlands may not be acceptable socially and economically; (2) the rate of 21st LSLR could exceed the rates experienced during the last four to six thousand years, and while wetland ecosystems may have been able to keep pace with the past rise, they may not be capable of coping with a much accelerated rise.

In order to understand the potential impact of LSLR and the associated changes in the compartments of the coastal zone on ecosystems and their services, we need to characterize the different compartments, identify their services, and assess their resilience to spatio-temporal variations in these compartments. The coastal zone is an incredibly complex and diverse environment, which defies easy organization into neat compartments. Even a clear definition of the coastal zone is not available. Coastal ecosystems display a wide range of geological features, dynamic conditions, climate conditions, and species. Nevertheless, for an understanding of the vulnerability of coastal ecosystems to LSLR and inundation changes, as well as, their susceptibility to human activities to protect the coasts and reduce the impact of flooding, a classification is required. Here we will focus on those coastal and marine compartments most sensitive to changes in LSL.

For the marine environment, we follow Madden and Goodin (2007), who identify five main regions from the supratidal zone on the landward endpoint to the central ocean: the estuarine, freshwater-influenced marine, nearshore marine, neritic, and oceanic regimes (see Table 2 in Section 4.14.4). In addition, we also need to consider the land above the supratidal zone, which may be inundated, converted into wetlands, and eroded due to LSLR, depending on the current topography, the energy environment, and the geology.

In the following, we will first clarify our risk-based approach to the mitigation of impacts of LSL changes on coastal flooding and ecosystems. We will then discuss plausible changes in LSL and GSL and provide a typology of the sea-level hazards in the coastal zone including coastal protection (see Section 4.14.3). In Section 4.14.4, we will review the coastal ecosystems with emphasis on their service functions, and in Section 4.14.5 discuss the vulnerability of these systems to LSLR and coastal protection. Section 4.14.6 summarizes the sea-level related risk for coastal ecosystems, and in Section 4.14.7, we will discuss strategies and policies that might limit future loss of coastal wetlands.

4.14.2 A Risk-Based Approach to Mitigation and Adaptation

Changes in mean LSL and short-term temporal variations (such as waves, tides, storm surges) of LSL can significantly change the energy environment of a coastal area and lead to coastal erosion and inundation. Inland hazards caused by LSL rise include inundation, saltwater intrusion, increased erosion, and higher storm surges. As a result of LSL rise, the Probability Density Function (PDF) of these sea-level related hazards can change significantly. Any risk-based planning of mitigation and adaptation has to account for this.

Any decision on mitigation and adaptation needs to take into account the probability of the hazard actually occurring, and the ability of a system, be it a human socio economic system or an ecosystem, to cope with the hazard. The study of the vulnerability of human and natural systems to hazards is a relatively new interdisciplinary field, which is developing particularly with a view on climate effects, and other natural hazards. A common language has not been developed yet and experts from different field put different meanings to the terms used (e.g., Dolan and Walker 2003). In particular, approaches differ between natural and social sciences (e.g., Brooks 2003).

Here we take a risk-based approach that is commonly used for natural hazards and particularly geohazards. For a given hazard h, a given recurrence time interval T, and for a prescribed intensity I, the associated risk $r(I)$ expressed in currency is given by

$$r_h^T(I,x,t) = p_h^T(I,t)\cdot V_h^{a(x,t)}(I,t)\cdot a(x,t) \qquad [1]$$

where x is the location, t time, p the hazard giving the probability that the hazard with intensity I will occur in the considered recurrence interval, V the vulnerability of an asset a for hazard h at intensity I, and a being the asset exposed at location x. To assess the total risk R associated with a hazard, we can use

$$R_h^T(x,t) = \int_0^{I_{\max}} r_h^T(I,x,t)\mathrm{d}i. \qquad [2]$$

Equations [1] and [2] provide a basis for risk management and the prioritizing of mitigation, adaptation, and monitoring. The risk is strongly dependent on the chosen recurrence time interval. Selecting a short time interval may seriously underestimate the risk, while a very long interval may lead to unrealistically high risks.

Assets can be any system from a single building, a transportation infrastructure, a city, a socio economic system, to an ecosystem or a natural resource such as groundwater. We use the term vulnerability to indicate the damage a hazard would cause to an asset, if the asset was exposed to the hazard. This is the approach taken mostly in disaster risk research for natural hazards. Climate scientists tend to consider vulnerability in terms of the likelihood of impacts of weather and climate related events (Nicholls et al. 1999) or the damage inflicted by changes in climate statistics (outcome vulnerability (e.g., Kelly and Adger 2000; Pielke Sr. et al. 2012)), while social scientists often consider vulnerability as the set of socio economic factors determining the ability of a social system to cope with stress or change (contextual vulnerability) (Allen 2003). In our definition, vulnerability does not depend of the hazard actually occurring, but is a latent characteristic of the asset. For example, one building may be more vulnerable to fire hazards than another building, independent of the fire actually occurring.

All three factors in eqn [1] depend on time. Both natural and anthropogenic assets at a given location can change and their value can change as well. Vulnerability of the assets also can change over time. In particular, adaptation can reduce vulnerability, while pre-stress can increase it. If we denote the impact of adaptation at time t on vulnerability by $\alpha(t)$, then vulnerability is given by

$$V_h^{a(x,t)}(I,t) = V_h^{a(x,t)}(I,t)\Big|_{t=t_0} - \int_{t_0}^{t} \alpha(t)\mathrm{d}t. \qquad [3]$$

The probability p of a hazard h of intensity I occurring within time interval T also depends on time. Particularly for climate-related hazards, climate change will change p.

For most natural hazards, including most sea-level related hazards, there are limited options to impact p. However, in some cases, land use can significantly change the PDF of a hazard (e.g., for floods, droughts, landslides). Likewise, climate (in particular changes in precipitation and temperature) can modify the PDF significantly. Examples are the increasing melting of permafrost in northern Canada and Alaska, which has led to increased landslides that threaten roads and pipelines. Increased precipitation and periods of more rapid snow melt can change the PDF for floods and droughts (e.g., Solomon et al. 2007), and, importantly, changing intensity, frequency, and path of storms impact the PDFs for storm surges with potentially large spatial variability (e.g., Katsman et al. 2011; Schwerzmann and Mehlorn 2009).

The main measures for risk reductions lie in a reduction of vulnerability and, if possible, the spatial exposure of assets. For coastal ecosystems, mitigation through changes in exposure is of limited value, since coastal ecosystems are adapted to locations and often cannot be relocated. Thus, coastal protection is often the only means to reduce the impact of LSL changes on coastal ecosystems. However, coastal protections also modify many compartments of the coastal zone and thus can have a degrading impact on coastal ecosystems, or even remove the basis for existing ecosystems. It is this trade-off between protection and negative impacts that poses a great challenge to coastal zone management.

Adaptation and mitigation are insurance against the risk. While eqns [1] and [2] provide a basis for a quantitative analysis of the risk, willingness to engage in adaptation and mitigation depends on risk perception. Zahran et al. (2008) studied why cities would voluntarily commit to the Cities for Climate Protection (CCP) campaign and found that those cities that had suffered more from extreme events were more willing to commit. The challenge of LSLR is that it is a slowly developing disaster. We normally do not realize the hazard until it is too late. While there is a growing acceptance of the risk for coastal cities associated with LSLR, the risk for ecosystems, for which the societal value is not obvious, is much less accepted, and costs for adaptation and mitigation are often postponed.

Another term relevant for our discussion is resilience. Resilience can be defined as the ability of a system to absorb disturbance while retaining its basic function and structure (Walker and Salt 2006). Social and ecological resilience are related (Adger 2000). For a social system, resilience is the ability to cope with external and internal stresses as a result of social, political, and environmental change. For an ecological system, resilience is a characteristic of the ecosystems to maintain itself in the face of disturbance. Particularly, for social communities depending on ecological and environmental resources for their livelihoods, there is a clear link between social and ecological resilience. On a global scale, resilience of humanity is linked to the resilience of the global biosphere to human interference, including human climate forcing (National Research Council 2005) coupled with natural climate variations, which are often quite large (Rial et al. 2004; Meko et al. 2007). There are global boundaries the transgression of which may put the global ecosystem into a new state, which could still be acceptable for the ecosystems, but outside of the safe space for humanity (Rockström et al. 2009a,b). Decisions on mitigation of impacts on ecosystems have to account for this link between ecological and social resilience.

4.14.3 The Hazards: Sea-Level Change and Coastal Protections

We define LSL as the height h of the sea surface above the underlying surface of the solid Earth, e.g.,

$$h(\lambda,\theta,t) = \begin{cases} r_1(\lambda,\theta,t) - r_0(\lambda,\theta,t) & : \text{ in the ocean} \\ 0 & : \text{ on land,} \end{cases} \qquad [4]$$

where r_0 and r_1 are the geocentric positions of the sea floor and sea surface, respectively (Plag 2006a). λ and θ are the geographical longitude and latitude, respectively. Variations $\xi(t) = h(t) - h_0$ of LSL are the result of variations in r_0 or r_1 or both. GSL is the average taken over the surface of the oceans. Changes in GSL equal the changes in the Global Ocean Volume (GOV). We note here that in many publications, the term 'sea-level' is not explicitly defined, and often refers to sea surface height observed in a geocentric reference frame (also sometimes falsely referred to as absolute sea-level, Blewitt et al. 2010). LSL defined by eqn [4] often is referred to as relative sea-level, although the distance between sea surface and land surface is an absolute quantity independent of the reference frame.

LSL as defined above is the quantity that is directly related to the potential impact of global and regional changes in climate and sea-level in a given coastal area. At any location, LSL is the result of a number of global, regional, and local-scale Earth system processes altering sea surface height, land surface height, or both (Figure 2). These processes, which act on a wide range of time scales, from a few seconds to millions of years, include mass relocation in ice sheets, glaciers, land water storage, and oceans; deformation of the solid Earth and gravity field changes caused by the mass relocation; changes in ocean heat storage and ocean currents; changes in atmospheric circulation; tectonic processes; and local coastal subsidence caused by natural and anthropogenic processes. These processes lead to large spatial variation in LSL on all time scales, and the relation between changes in GSL and LSL at any given coastal location is rather complex. For example, melting of ice on Greenland would increase GSL, but it would lead to a fall of LSL at the coasts of Greenland and any land mass in the vicinity of Greenland, while the rise in LSL on the Southern hemisphere would be larger than the global average.

No single Earth system model is currently available that can accurately predict past, present, or future LSL changes, and it is unlikely that such a model will become available in the near future. Moreover, underlying processes (including future greenhouse gas and aerosol emissions and land use change Lovejoy and Schertzer (2012); effects on climate of anthropogenic re-engineering of the planet (Syvitski 2012); changes of ice sheets and glaciers; natural low-frequency climate variations National Research Council (2005)) likely will remain unpredictable on century time scales for a long time to come (McMichael et al. 2006; Lipscomb et al. 2009). Thus, quantitative, model-based predictions for twenty-first century LSL with sufficiently narrow uncertainties to be actionable cannot be provided today, and most likely not in the foreseeable future.

Our inability to predict future LSL trajectories within narrow uncertainty bands rules out a deterministic approach to coastal risk assessments and the planning of coastal protection as

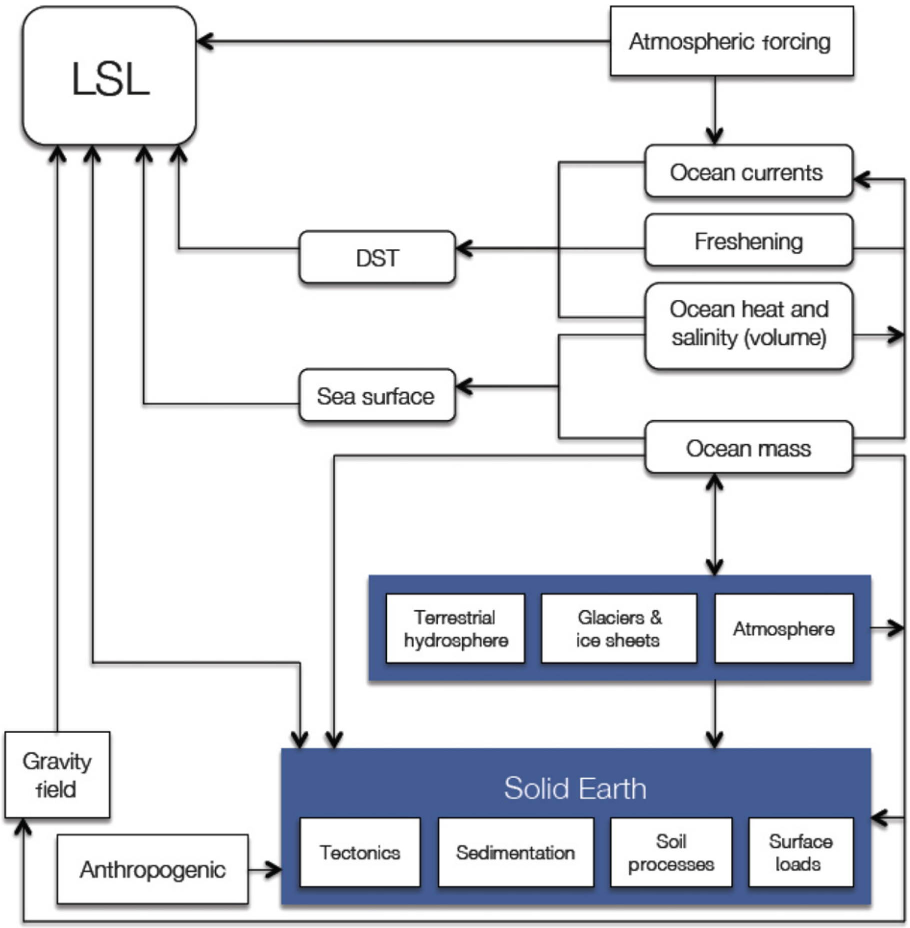

Figure 2 Processes and factors causing long-period LSL changes. Mass movements in the terrestrial hydrosphere (groundwater, rivers, lakes, and reservoirs) and land-based cryosphere (glaciers and ice sheets) and mass exchange with the ocean load and deform the solid Earth and affect the gravity field. The deformations and the associated gravitational changes result in LSL changes, depending on where mass has been relocated. Ocean mass changes as well as ocean volume changes caused by heat and salinity changes affect the sea surface position. Heat and salinity changes also affect the ocean currents and thus change the Dynamic Sea Surface Topography (DST). Freshening caused by melting sea ice contributes to both changes in GOV and DST. Atmospheric circulation forces regional wind-driven currents affecting the DST. DST and sea surface changes caused by regional and global processes change LSL in any location. The atmosphere also acts locally on the sea surface and thus changes sea level. Past changes in the ice sheets and glaciers lead to postglacial rebound, which affects sea level through vertical land motion and geoid changes. Tectonic processes in the solid Earth both result in vertical land motion, changes in the size of the ocean basins, and changes in the geoid. In areas where sedimentation takes place, the compaction of the sediments and their load on the solid Earth introduce vertical land motion. Moreover, changes in LSL feedback on the solid Earth and can cause the destruction of peat through oxidation and thus lead to subsidence. Anthropogenic vertical land motion associated with exploitation of groundwater, oil, and gas as well as changes in sedimentation can change the Earth surface position. Variations in sedimentation due to river regulation (reduction) or land use (increase) also affect LSL, particularly near river deltas. Figure modified from Plag, H.-P., 2006a: Recent relative sea-level trends: an attempt to quantify the forcing factors. *Phil. Trans. Roy. Soc. London, A*, **364,** 1841–1869 and Sahagian, D., et al., 2009: Earth observation: serving the needs of an increasingly global society. *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020,* H.-P. Plag and M. Pearlman, Eds., Springer Verlag, Berlin, 153–196.

a basis for mitigation of inundation risks. Instead, a statistical approach is needed that takes into account the PDF of decadal to century-scale LSLR. In order to avoid under or over investments, this approach requires a reliable estimate of the PDF of LSLR. In particular, the reliability of the PDF at the high end, e.g., the large rapid rises, is crucial. For sea-level hazards, a rapid large rise is the improbable, high-impact event that is difficult to plan for. It is this event that will cause huge disasters if not anticipated and planned for, and the event that will demand extreme economic efforts to prepare for, which could be wasted if the probability of the event is overestimated.

4.14.3.1 GSLR Discussion: The Deterministic Approach

Much of the discussion on ocean-warming and ice-melt induced sea-level rise has focused on projected GSLR for the twenty-first century. A related question raised in many contributions is to what extent the observed twentieth century GSLR of $\approx 0.2\ \mathrm{mm\ year^{-1}}$ already showed an accelerated rise compared to a presumably far more stable GSL during the last few millenniums (Figure 3, see also Church and White (2006)). Cronin (2011) points out that the notion of a very stable sea-level over the last two millenniums is not supported by

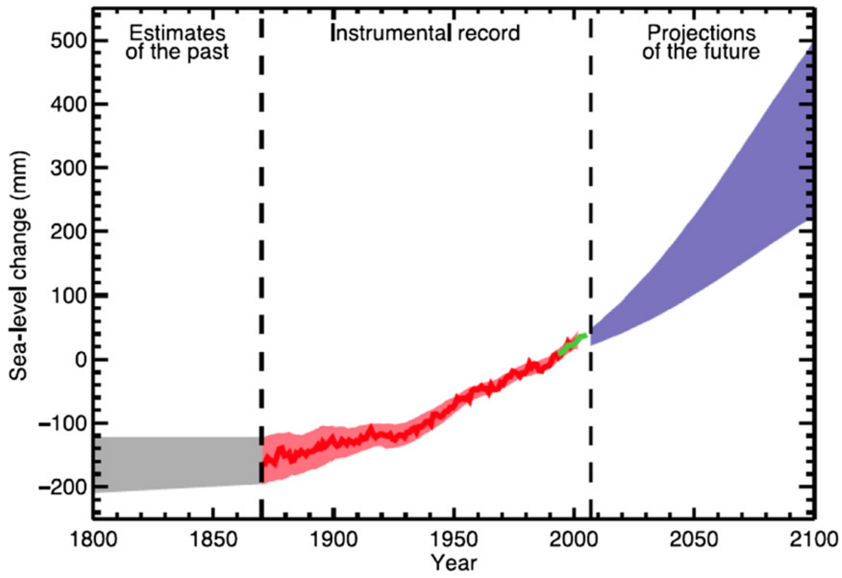

Figure 3 GSL changes between 1800 and 2100. GSLR prior to about 1850 is generally estimated to be on the order of 0 to 2 mm year^{-1}. Since 1850, the rate of GLSR has been on the order of 2 mm year^{-1} with a possibility of larger rates of about 3 mm year^{-1} at the end of the last century (e.g., Cazenave et al. 2010). IPCC projected rates of GSLR for the twenty-first century are between 3 and 5 mm year^{-1}, depending on assumptions of the emission scenario (Bindoff et al. 2007). However, as noted in the text, the models used for these projections do not accurately include all human climate forcings nor are they able to represent low-frequency climate variability and longer-term changes in climate statistics. If, for example, the large ice sheets contribute significantly, then the rates would be much higher. Consequently, the range of plausible GSL trajectories for the twenty-first century is much wider than the figure indicates. Figure from Bindoff, N. L., et al., 2007: Observations: oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

observations, particularly if regional deviations from the global mean are taken into account. However, compared to the large fluctuations of GSL and even larger fluctuations of LSL in many locations, during the last million years, GSL has to be considered exceptionally stable over the last few thousand years (Figure 4).

Figure 5 summarizes the GSLR projections for the twenty-first century given in the IPCC assessments. The models used for the predictions have been validated against the recorded data from past decades, but the model simulations underestimate the GSLR observed during the twentieth century (see Figure 5.21 in Bindoff et al. 2007). The large range of IPCC twenty-first century GSL trajectories arises from the range of the projected emission scenarios, as well as, uncertainties in the model response to these scenarios. However, since the models used for the projections do not accurately capture all human and natural climate forcings, the actual range of plausible GSL trajectories is much larger than indicated in Figure 5. It is interesting to note that in earlier studies, sea-level rise estimates for the twenty-first century were larger than those predicted by IPCC AR4 (see, e.g., Figures 1–4 in Titus 1988).

Concerning thermal expansion, model simulations of twentieth century heat uptake by the oceans do not fully match the model predictions (Cazenave et al. 2009, 2010), thus putting a question mark on the validity of the projections for this contribution. Observations of the retreat of glaciers and ice caps exclusive of Greenland and Antarctica (GIC) have been, in a number of situations, more rapid than models have simulated (e.g., Meier et al. 2007). The uncertainty in the projections of surface climate, where glaciers and ice sheets exist, adds to the uncertainty of the modeling of GIC response to temperature and environmental changes.

Most importantly, uncertainties related to the potential contribution of the Greenland Ice Sheet (GIS) and Antarctic Ice Sheet (AIS) make it very difficult to constrain the upper limit of the 21st GSLR. Particularly, the AR4 emphasizes the large uncertainty in the upper limit arising from an unknown potential contribution of the large ice sheets. This has lead to a significant debate within the scientific community about the quality of the IPCC GSLR projections for the twenty-first century. A strong focus has been on the potential contribution of the large ice sheets due to potential dynamic processes that may occur if the ice sheets warm (e.g., Pfeffer et al. 2008; Holland et al. 2008; Bamber et al. 2009; Jiang et al. 2010). Potential dynamic effects include very rapid movements of ice streams, leading to potential GSLR exceeding 10 mm year^{-1}, a contribution far larger than any of the other terms. The possibility of a collapse of parts of the ice sheets cannot be excluded (e.g., Vaughan et al. 2007), especially if there would be rapid loss of surrounding ice shelves that could increase the ice stream flows (e.g., Rignot et al. 2008a). The physics of these processes are not well understood and, hence, these processes are not accounted for in the models. However, omitting what likely will be the most important contributor to GSLR must raise a red flag: the IPCC projections of 21st GSLR and beyond may be significantly too low. It is important to emphasize, however, that since our understanding of the climate system is incomplete; other changes in global sea-level rise (including a leveling off or even a fall) are certainly possible. This could

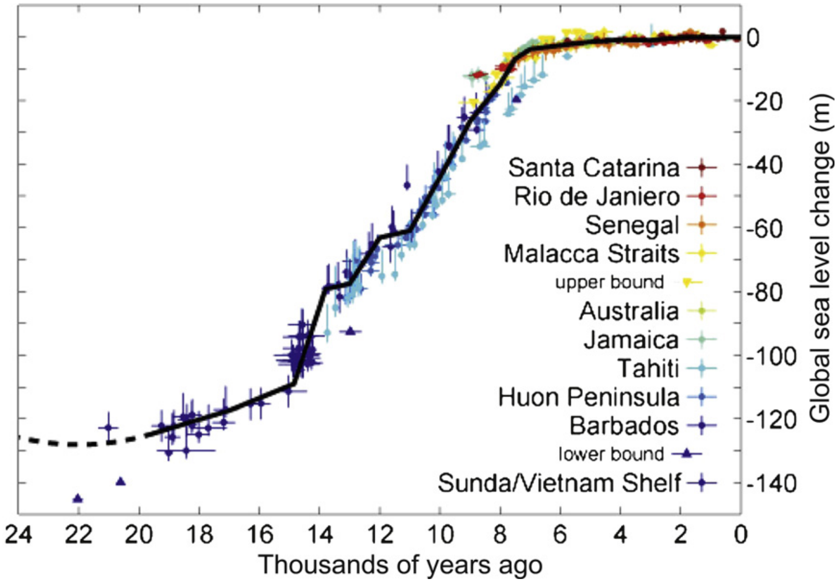

Figure 4 GSL during the last 24 000 years. Data from Fleming, K., P. Johnston, D. Zwartz, Y. Yokoyama, K. Lambeck, and J. Chappell, 1998: Refining the eustatic sea-level curve since the last glacial maximum using far- and intermediate-field sites, *Earth Planet Sci. Lett.* **163** (1–4), 327–342, http://dx.doi.org/10.1016/S0012–821X(98)00198–8; Fleming, K. M., 2000: Glacial rebound and sea-level change constraints on the Greenland ice sheet, Ph.D. thesis, Australian National University; Milne, G. A., A. J. Long, and S. E. Bassett, 2005: Modelling holocene relative sea-level observations from the Caribbean and South America. *Quat. Sci. Rev.*, **24** (10–11), 1183–1202, http://dx.doi.org/10.1016/j.quascirev.2004.10.005. Modified from the figure available at http://en.wikipedia.org/wiki/File:Post-Glacial_Sea_Level.png.

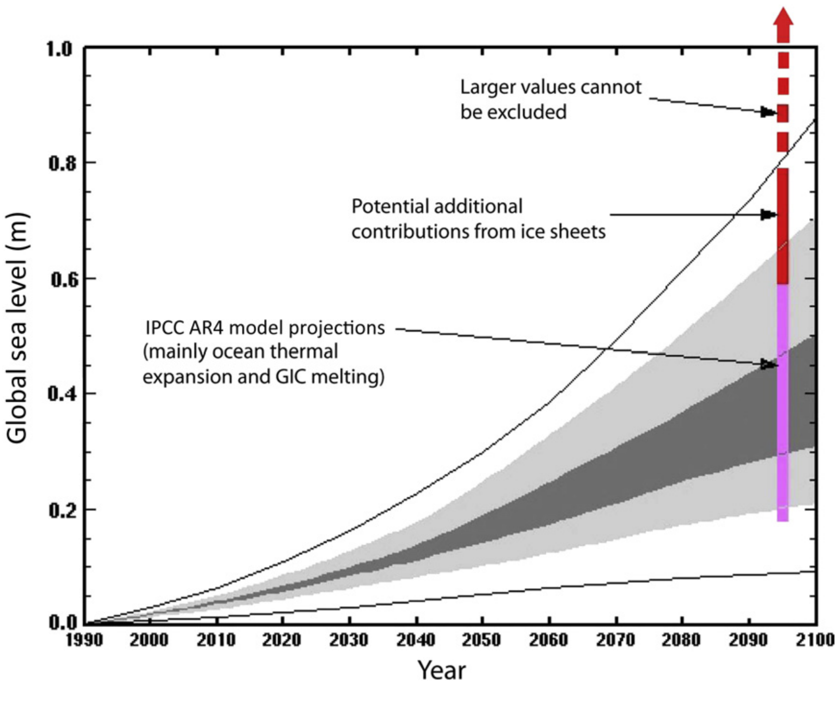

Figure 5 Summary of projected GSLR for the twenty-first century: The lines and shading indicate the IPCC 2001 projections for the period 1990–2100 (Church et al. 2001), with the central dark shading being an average of models for the range of SRES greenhouse gas emission scenarios. The light shading is the range for all models and all SRES scenarios and the outer bold lines include an allowance for land-ice uncertainty. The vertical bars at 2095 indicate the spread of the updated AR4 IPCC projections for the SRES scenarios (Meehl et al. 2007): the magenta (lighter) bar indicates the range of model projections, mainly accounting for ocean thermal expansion and melting of GIC. The red bar is a potential additional contribution from a dynamic effect of the GIS and AIS. Note that the IPCC AR4 states that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise." Modified from Church, J., et al., 2010: Sea-level rise and variability: synthesis and outlook for the future, in understanding sea-level rise and variability. *Understanding Sea-Level Rise and Variability.* J. Church, P. L. Woodworth, T. Aarup, and S. Wilson, Eds., Wiley-Blackwell, 402–419, ISBN: 978-1-443-3451-7.

occur, for example, from multiple large volcanic eruptions, which could significantly reduce ocean heat content. There is also an inadequate understanding of long-term variations in solar forcing and of low-frequency natural variations in climate system heating and cooling.

The focus on deterministic model predictions, which are the basis of most of the recent climate change assessment and impact studies (even those based on quasi-statistical approaches such as ensemble studies), however, are hampering our ability to assess the true probabilities of climate change (Dessai et al. 2009). As a consequence, the risk associated with future sea-level hazards may be underestimated, eventually misguiding adaptation. As emphasized by McMichael et al. (2006), modeling cannot be an exact science, as the models themselves are hypotheses. As just one incompletely understood issue, there is considerable uncertainty about the future trajectories for greenhouse gas emission, e.g., one of the key human climate forcings, which together with residual uncertainties about the sensitivity of the climate system to these trajectories produces a wide range of plausible trajectories for GT and regional temperatures. As the human climate forcing continues, the probability of exceeding critical thresholds and causing rapid changes in climate and environment should be expected to also increase (Harrison and Stainforth 2009).

If we cannot skillfully predict sea-level changes in the coming decades, what would be a more prudent approach? An assessment of risks from any plausible change in sea-level can provide guidance (Donner 2012). For this approach, considering the statistical characteristics of past behavior of the Earth system is a starting point. Compared to the large fluctuation in GT and GSL over the last million years and more, the Earth system has been in a mediocre state over the last few thousand years with very small changes. In 'Mediocristan,' single extremes do not matter; it is the integral over the gradual changes that count (Taleb 2010). However, human climate forcing and long-term climate variability could push the Earth system into a state where extremes are more common and much larger. In 'Extremistan,' single events are crucial. For example, a rapid melting of a large portion of the GIS or AIS would constitute such an extreme event. Similarly, a significant change of ocean circulation could catapult the Earth system into a different state with severe consequences for ecosystems and humanity.

While we are used to our socio economic system being in Extremistan, with the Great Depression, the First and Second World Wars, and the Internet being examples of extreme events that determined the future, we do not have this view on the development of the Earth system. In our planning, we basically rule out that extreme events can have a determining impact. Climate modeling is based on the assumption that the planet is in Mediocristan. The multi-decadal climate models have demonstrated no skill at predicting extreme events leading to a change in the state of the system. The models are not able to model past extreme events. For a system that has the potential to be in Extremistan, these models are almost useless as a basis to determine the PDFs of hazards. For a system in Extremistan, so-called 'Black Swan' events have a larger impact on the system's future than the gradual changes. Black Swan events are improbable, high-impact events that (1) are outside our experience; (2) have an extreme impact; (3) can be explained after the fact Taleb (2010). Considering the dependence of our civilization on the coastal zone and coastal ecosystems (Edwards 2008) and the fact that we are still migrating into the coastal zone, a sea-level Black Swan, that is a rapid rise exceeding all expectations, would be truly disastrous. Coastal ecosystems have the ability to adapt to slow changes in mean sea-level through migration, but for most systems, there will be a threshold for the speed of changes with the systems not being able to adapt to changes at a pace above the threshold.

There is a chance that the current scientific discussion of GSLR is preparing the ground for a 'Black Swan' event. Recent assessments of GSLR in the twenty-first century have been based on models calibrated to the recent past (Figure 3). These models, however, are incapable of predicting the rapid sea-level rise events that have taken place many times over the last one million years, with changes during one century exceeding present-day rates by a factor of 50 and more. The discussion of the upper limit for the twenty-first century is also based on the recent past and assumptions, excluding the rapid rises that are documented in the paleo-records. This bias to low estimates and low upper bounds creates a mindset that is no longer open for the improbable, high-impact event, e.g., the Black Swan. Another reason why the last few thousand years with relatively stable condition may not be a good basis for assessing the future, is the fact that, humanity over the last few hundred years has re-engineered the Earth system, with the most dramatic changes during the last decades, as human population continues to grow and increasingly alters the environment (Syvitski 2012, e.g.,). A more comprehensive look at the statistical properties of the Earth system in terms of century-scale GT, GSL, and LSL changes is needed.

4.14.3.2 Probability Density Function of GSLR

In order to assess the character of the sea-level rise Black Swan, we need to consider the PDFs of century-scale changes in relevant parameters and relate these to plausible changes in these parameters for the twenty-first century. There are many relevant parameters, but we will consider here only two examples, namely century-scale GSLR and Global Temperature Rise (GTR) (denoted here as $GSLR_{100}$ and GTR_{100}, respectively). Considering that over the last 50 years, the world ocean accounts for 90% of the global warming (Levitus et al. 2012), we have to acknowledge that GTR is a poor indicator of GSLR, but many discussions focus on GTR. For example, ocean heating and continental glacier changes cannot be directly related to the GTR. Ocean heating measured in Joules depends on the process in which heat is transferred to the ocean, and only weather patterns (temperature, precipitation, cloud cover) and other environmental changes in the ice-covered region matter in terms of melting and runoff into the sea.

There is very little information available to determine the location-dependent PDF of LSL rise for many locations. For GSL, information on changes over the last 400 000 to 800 000 years is available from studies of several proxies (see, e.g., Hansen et al. 2008; for an overview). In the following, we have used observed Antarctic temperature (Vimeux et al. 2002) as a proxy for GT to determine time series of GTR_{100} (Figure 6) for the last 425 000. The comparison of the observed Antarctic

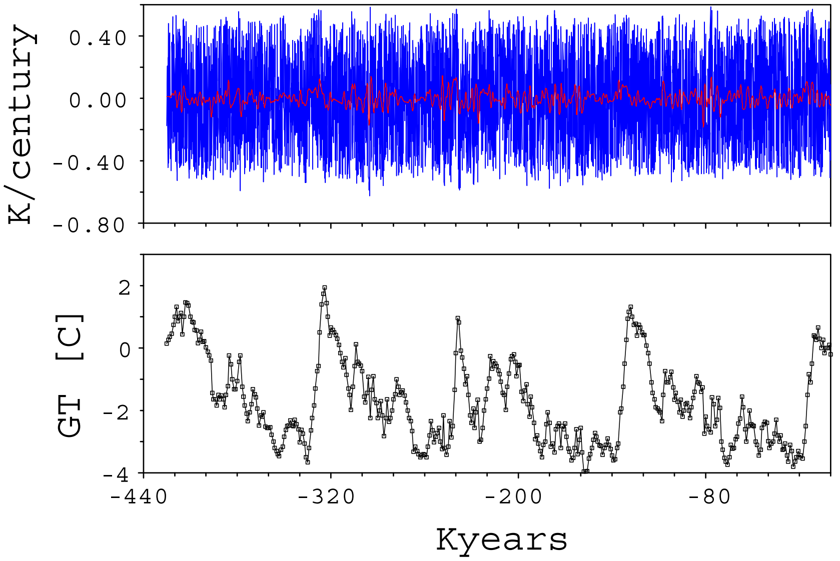

Figure 6 GT and GTR_{100} over the last 425 000 years. Lower diagram: observations of Antarctic temperature changes (Vimeux et al. 2002), which compare well to the GTR modeled by Hansen et al. (2008). Upper diagram: GTR_{100}; the red curve is the GTR_{100} determined from a spline interpolation of the lower curve; the blue line has a random fluctuation of the GTR_{100} around the GTR_{1000} of ± 0.4 K/century. See text for details.

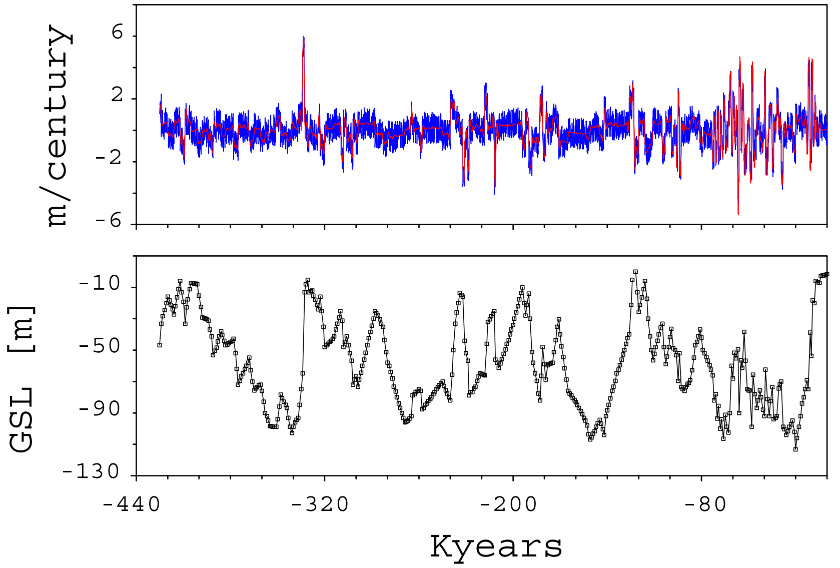

Figure 7 GSL and $GSLR_{100}$ over the last 425 000 years. Lower diagram: GSL determined from Red Sea sediments Siddall et al. (2003). Upper diagram: $GSLR_{100}$; the red curve is the $GSLR_{100}$ determined from a spline interpolation of the GSL curve; the blue line has a random fluctuation of the $GSLR_{100}$ around the $GSLR_{1000}$ of ± 1 m/century. See text for details.

temperature to model GT (Hansen et al. 2008) show that the fluctuations of the Antarctic data is larger than the modeled GT, thus leading to a slightly more variable GTR_{100}. For the GSL, we use data provided by Siddall et al. (2003) to determine a time series of $GSLR_{100}$ (Figure 7). We then use these time series of GTR_{100} and $GSLR_{100}$ to determine the PDFs of GTR_{100} and $GSLR_{100}$ (Figure 8).

For most of the period considered, the data available for GT and GSL has a temporal resolution of 1000 years or less. In the first step, we use a spline interpolation of the data to determine the century changes. However, the spline interpolation very likely is too smooth, thus resulting in a PDF far too narrow. Particularly the temperature data lead to a very narrow PDF confined to the interval between ± 0.25 K per century. In order to get a better assessment of the century-scale rates, we have to make assumptions with respect to the deviation of these rates from the millennium averages. For GT, we assume that GTR_{100} fluctuates randomly around the millennium average with ± 0.4 K. The random fluctuation drastically changes the PDF, and it appears that the assumed amplitude of 0.4 K per century is at the upper limit of what is consistent with the available data.

For sea-level, the values for $GSLR_{100}$ determined from a spline interpolation of millennium rates cover the interval between −5 m per century and +7 m per century, with larger positive rates (rise) being more likely than larger negative rates. For GSLR, we also test the effect of adding a random fluctuation of $GSLR_{100}$ around $GSLR_{1000}$ and assume a fluctuation of ±1 m. For GSL, adding a random fluctuation with this amplitude does not significantly change the PDF.

Comparing the twentieth century change in global temperature of (0.74 ± 0.18) K (Meehl et al. 2007) to the PDF for GTR_{100}, it is clear that this rise falls outside the PDF for the last 425 000 years. More drastically, the IPCC AR4 predictions for several emission scenarios are far outside the range of GTR_{100} documented in the paleo-data. There are two alternative interpretations: (1) the predictions are inaccurate, and by far, overestimate of the GTR_{100} for the twenty-first century possible in the Earth system or (2) the predictions are realistic, in which case the Earth history of the last 450 000 years provides no useful analog for the impact of the predicted GTR_{100} for the twenty-first century. In particular, if alternative (2) were correct, many ecosystems would not be able to cope with the unparalleled speed of GTR_{100}. For coastal ecosystems, any such rapid change would lead to double stress from changes in the region's weather patterns and from rising sea-levels.

Do we have indications which of the two alternatives are more likely? The fact that many of the characteristic parameters of the Earth system (including atmospheric constituents such as CO_2N_2O, and CH_4, damming of rivers, water use, nitrogen deposition, ozone deletion, urban population, ocean ecosystems, coastal zone structures, ocean zone biogeochemistry, loss of tropical rain forests and woodlands, and global diversity; see e.g., Steffen et al. (2004) and Figure 1 in Syvitski (2012)) have already attained values outside their range of variability during the last one million years or more seems to support alternative 2. It is interesting to note that, for example, the CO_2 concentration of 385 ppm observed in 2008 exceeds the previously occurring maximum of 300 ppm observed during the last 800 000 years by 65% of the total Glacial-Interglacial Range (GIR) of 130 ppm during this time (Karl et al. 2009). The speed of change in many Earth system parameters is also unparalleled. For example, while during the last million years, maximum changes in CO_2 on the order of 100 ppm took place over thousands of years, humanity accomplished this in less than three centuries. Under these unparalleled conditions, the response of the climate system to the combined changes in the Earth system may also exceed all rapid responses documented in the paleo-records. However, this does not exclude alternative 1.

The twentieth century $GSLR_{100}$ of (0.2 ± 0.1) m per century falls well into the PDF for $GSLR_{100}$ (Figure 8). Similarly, the IPCC AR4 prediction for twenty-first century thermal expansion and for combined GSLR due to thermal expansion, ice sheet, glaciers, and land water storage contributions are within the more or less central domain of the PDF. However, considering that the predicted GTR_{100} is far outside any past experience, there are unresolved questions as to their value to assess the risks associated with GSLR and LSLR in the coming decades.

Is there a relation between GTR_{100} and $GSLR_{100}$? Using the data determined from the spline-interpolated curves, we find no correlation between GTR_{100} and $GSLR_{100}$. One reason for this lack of correlation could be large errors in the timing of the rapid changes in GT and GSL. The proxies used to determine these curves have significant uncertainties in time. Another reason could be the complex nature of the Earth climate systems, where GSL changes do not lead to correlated GSL changes. If, for example, an increase in GSL leads to changes in ocean circulation with impacts on the latitudinal temperature and precipitation distribution, then an increase in GT could lead to increasing ice sheets and a fall in GSL. The high correlation between IPCC AR4 predicted 21st GTR and GSLR is an indication of the models not reflecting the complexity of the climate system.

How much does the location-dependent $LSLR_{100}$ deviate from $GSLR_{100}$? The answer to this question helps to assess the probability of large rises along parts of the coasts. In the following, we will first review the science basics of LSL changes and analyze the relevant processes. This will provide the basis to assess both the range of plausible changes and the spatial variability.

4.14.3.3 The Cumulative LSL Equation

As mentioned above, Earth system models available today are not capable of modeling all LSL forcing processes and predicting LSL changes. However, the scientific understanding of the link between individual global, regional, and local processes and LSL changes is well developed. Therefore, a local approach can be used to describe the relation between forcing processes and LSL. For our purpose, it is helpful to separate the equation describing LSL as a function of the various forcing processes into a high-frequency and a low-frequency part (Plag 2006a). For the assessment of impacts, the combined effects of the high-frequency and low-frequency part of the LSL equation are important.

LSL variations ξ can be written as:

$$\begin{aligned}\xi(\vec{x},t) &= W(\vec{x},t)+T(\vec{x},t)+A(\vec{x},t)+S(\vec{x},t)\\ &\quad +C(\vec{x},t)+F(\vec{x},t)+I(\vec{x},t)+G(\vec{x},t)\\ &\quad +L(\vec{x},t)+P(\vec{x})(t)+V(\vec{x},t),\end{aligned} \quad [5]$$

where t is time, t_0 an arbitrary time origin, and ξ is given relative to an arbitrary zero level (modified from Plag (2006a)). Here we include the processes W: waves, T: tides, A: LSL changes caused by atmospheric forcing, S: steric changes, C: ocean circulation, F: freshening due to melting of sea and land ice, I: mass changes in the large ice sheets, G: mass changes in the continental glaciers and ice caps, L: land water storage changes, P: postglacial rebound, V: vertical land motion other than postglacial rebound or land motion caused by other surface loading. Some of these processes lead to predominately short-period variations (e.g., waves), while others are pre-dominantly long-period to secular in nature (e.g., postglacial rebound caused by the melting of the ice sheets of the last ice ages). Most terms have both short and long-period variations, although with different significance (Table 1).

Equation [5] illustrates the complex nature of LSL variations as the result of processes in the global water and energy cycles merged with geodynamic processes and, recently, anthropogenic activities. The processes separate into two large groups, namely those that are mainly volume changes of the ocean

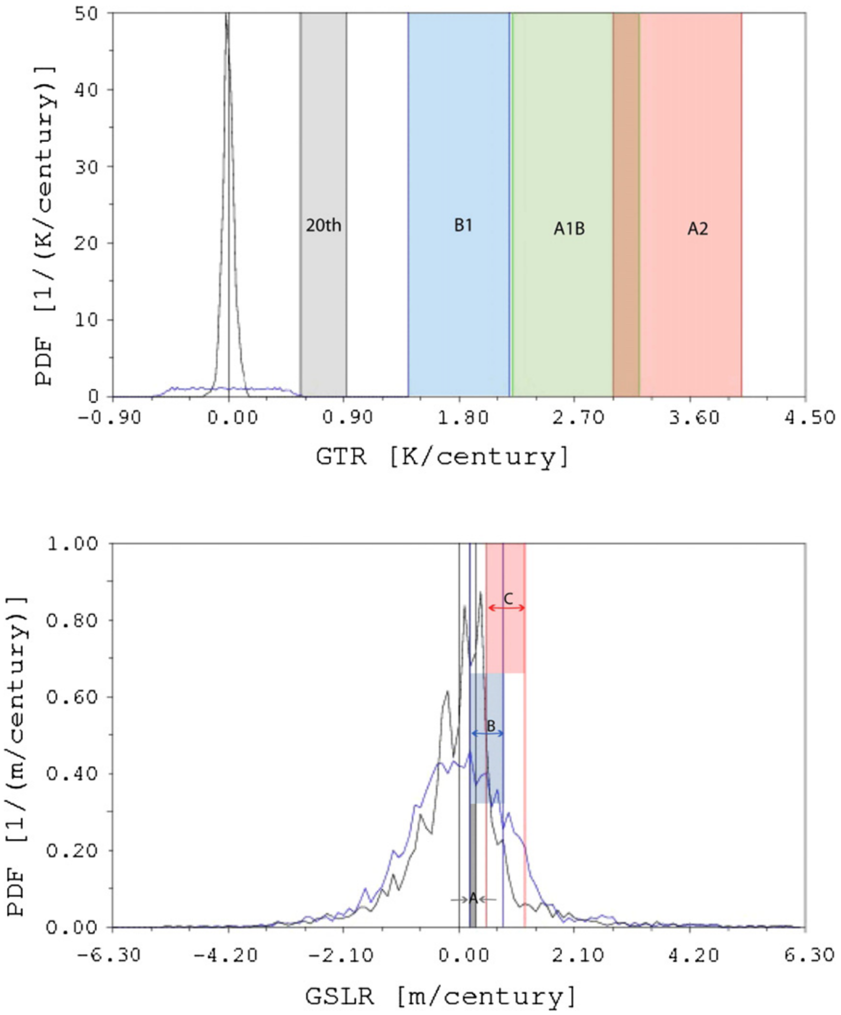

Figure 8 Probability density function of $GSLR_{100}$ and GTR_{100}. In each diagram, the black curve is the PDF based on the spline-interpolated millennium averages; and the blue curve the PDF determined from the rates including the random variation of the century rates around the millennium averages. The vertical lines indicate current rates and twenty-first century predictions. Left: PDF for GTR_{100}; A2, A1B, and B1 are the SRES emission scenarios used in IPCC AR4 (Meehl et al. 2007). Right: PDF for $GSLR_{100}$. A: twentieth century observed GSLR (Bindoff et al. 2007); B: predicted twenty-first century GSLR due to thermal expansion (Meehl et al. 2007); C: plausible twenty-first century GSLR including contributions from ice sheets, glaciers, and land water storage.

water (and thus affect GOV, but not GOM) and those that are associated with significant mass redistribution in the global water cycle (and thus may also affect). Before we address our ability to predict LSL variations on century time scales, we first provide the theoretical background for LSL changes caused by mass redistribution and describe the current knowledge in terms of current contributions and predictions for each of the processes included in eqn [5].

4.14.3.4 Mass-Induced LSL Variations

Processes involving redistribution of mass in the water cycle are all associated with viscoelastic–gravitational effects on LSL, leading to very distinct spatial and temporal patterns of LSL variations caused by these processes. In order to emphasize the importance of the fundamental relationship between any mass transport in the global water cycle and the LSL, we consider the case where the GIS mass increases and the AIS melts with the two changes being exactly in balance. This mass movement will not change the GOM or induce any GSL change, but LSL will fall significantly over large regions of the southern oceans and increase over large parts of the northern hemisphere. Thus, LSL changes caused by mass redistribution in the global water cycle depend crucially on where the mass redistribution takes place (as reconfirmed by Mitrovica et al. 2009).

The governing equation that links mass redistribution to LSL variations ξ (first introduced by Farrell and Clark 1976) can be written as:

$$\xi(\vartheta,\lambda,t) = c(t) + \int_{-\infty}^{t}\int_{0}^{\pi}\int_{0}^{2\pi} G(\vartheta,\lambda,\vartheta',\lambda',t-t') \qquad [6]$$

$$\frac{\mathrm{d}}{\mathrm{d}t'}\{O(\vartheta',\lambda',t')\rho_{\mathrm{W}}\xi(\vartheta',\lambda,t') + [1-O(\vartheta',\lambda',t')]\rho_{\mathrm{L}}\eta(\vartheta',\lambda,t')\}\sin\vartheta'\mathrm{d}\lambda'\mathrm{d}\vartheta'\mathrm{d}t',$$

Table 1 Processes contributing to LSL variations. Upper part: processes with significant short-period variations. Lower part: processes with negligible short-period variations

S.	*Process*	*Short-term*	*Long-term*	*Comment*
W	Waves	From seconds to more than 30 min (tsunamis)	Changes in wave energy due to climate	Relevant for coastal erosion
T	Tides	Monthly, fortnightly, diurnal, semi-diurnal, and shorter periods	Semi-annual, annual, and nodal tides	Changes due to climate are very small
A	Atmosphere	From seconds to months	Intraseasonal to secular; with multi-decadal variation in mean air pressure distribution and wind field changes impacting sea level	Can create multi-decadal trends on the order of several millimeters per year

S.	*Process*	*Long-term*	*Comment*
S	Steric	Most changes are on seasonal time scales, with multi-decadal to secular trends	Can contribute on the order of 50 cm per century
C	Circulation	Some interannual to multi-decadal variations; long-term changes in ocean circulation, including a significant slowing or an interruption of the thermohaline circulation	Long-term changes could have significant impacts on the DST and a feedback on regional climate
F	Freshening	Contributes to the seasonal cycle in sea level	A significant long-term reduction of sea ice would impact ocean salinity and GOV
I	Ice sheets	Contribute to the seasonal changes in Global Ocean Mass (GOM) as well as interannual to multi-decadal variations	The ice sheets are the main source for potentially large and rapid GSLR, with large spatial variations in LSLR (fall in the near-field and rise in the far-field).
G	Glaciers/ice caps	Contribute to seasonal changes in GOM; are a main contribution to present-day GSLR	Could contribute to increased GSLR; the spatial pattern in LSLR is complex due to the spatial distribution
L	Land water storage	Contributes to seasonal, interannual, and multi-decadal changes in GOM	Land use changes such as deforestation, irrigation, water reservoirs contribute to long-term changes in GOM; permafrost melting also may have an effect
P	Postglacial rebound	Produces significant secular land uplift in and around formerly glaciated areas and small subsidence in some far-field regions	
V	Vertical land motion	Earthquakes can lead to significant (order 1 m or more) sudden vertical displacement; tectonic processes and natural and anthropogenic subsidence can cause transient and secular vertical displacements of 250 mm $year^{-1}$ and more	

Table 2 Regimes of the coastal zone

Regime	*Description*
Dry land	Land above the high water mark, which is rarely inundated by storm surges.
Littoral zone	The littoral zone extends from the high water mark to shoreline areas that are permanently submerged.
Estuarine	Estuarine regimes are enclosed or semi-enclosed coastal water bodies that are influenced by freshwater input that reduces salinity to below 3.0% during at least two months of the year. These waters are intimately linked with their watersheds, receiving nutrients, materials, and freshwater during a significant part of the year.
Freshwater influenced	Freshwater-influenced regimes are coastal waters that have no distinctly enclosing morphology, yet receive a significant amount of freshwater input from land during at least parts of the year. In such cases, an unenclosed marine water column may be influenced by freshwater in the form of an active river plume, an overlying freshwater lens or a groundwater seep discharge. They often may have surface characteristics of estuaries, but deeper waters may be completely marine.
Nearshore marine	Nearshore marine regimes are those coastal waters that are truly marine in character (>3.0% throughout the year) and not influenced by significant freshwater. The nearshore marine regime extends from the land margin to the 30 m depth contour.
Neritic	The neritic regime is the region of marine waters (>3.0% throughout the year) between the 30 m depth contour and the continental shelf break, which occurs at approximately at 200 m water depth.
Oceanic	The oceanic regime represents the marine realm beyond the continental shelf break, generally occurring at 150–300 m of water depth at the seaward edge of the continental shelf. These waters can range to several thousands of meters depth. The marine waters of the oceanic regime are sufficiently distant from land that they receive little or no influence of freshwater, nutrient and sediment inputs, except around large islands.

Modified from Madden, C. J., and K. L. Goodin, 2007: *Ecological Classification of Florida Bay Using the Coastal Marine Ecological Classification Standard (CMECS)*, Tech. Rep., NatureServe, Arlington, Virginia, to suit the purpose of the LSLR discussion.

where ϑ, λ, and t are co-latitude, longitude, and time, respectively, ρ_W and ρ_L are the densities of the ocean water and the load on land (water or ice), respectively, G is the Green's function for LSL defined below, O the ocean function, defined to be one over ocean and zero over land, and η the accumulated ice load change due to mass added or removed from land. $c(t)$ is determined such that mass is conserved. ξ as defined by eqn [6] is a continuation of LSL onto the continents, and the true LSL has to be defined as $\hat{\xi} := O\xi$. The function ξ has the important advantage over $\hat{\xi}$ of being continuous at the coastlines. The mass-LSL eqn [6] assumes instantaneous distribution of the water in the global ocean and thus is only valid for sufficiently long time scales. Hydrodynamic studies showed that the equation is appropriate at annual to longer time scales (see Plag 2006b; and the reference therein). Over the last two decades, eqn [6] has been augmented by several groups (e.g., Milne et al. 1999), with the most comprehensive version (Mitrovica and Milne 2003; Kendall et al. 2005) accounting for melt-water inundation of deglaciated areas and rotational effects of LSL changes (pole tide) in a self-consistent manner. There are many technical details related to the use of eqn [6], including the Earth model, the ice history, and numerical procedures which are discussed e.g., in Plag et al. (1998); Mitrovica et al. (2010).

The mass-LSL eqn [6] has been applied extensively to studies of LSL changes caused by the ice ages and the subsequent Postglacial Rebound (PGR) (see Mitrovica et al. 2006; and the references therein). In the PGR studies, main focus has been on the viscous part and the determination of the radial viscosity profile of the Earth mantle (e.g., Peltier 1974; Farrell and Clark 1976; Nakada and Lambeck 1987; Mitrovica et al. 1994a,b; Vermeersen et al. 1996). There are still considerable inter-model differences in predictions of present-day PGR signals in LSL, surface displacements, geoid, and rotation (e.g., Chambers et al. 2009), which originate mainly in differences in ice history and the treatment of rotational effects. Using eqn [6] to describe the relation between present-day mass changes and LSL so far has been restricted to a few examples (e.g., Plag and Jüttner 2001; Mitrovica et al. 2001; Plag 2006a; Mitrovica et al. 2009; Bamber et al. 2009). It has to be noted that in many scientific communities outside the solid Earth sciences, the very large spatial variations of LSL compared to the global average are not well known and often ignored in GSLR impact studies.

Major mass redistribution in the global water cycle can result from significant mass loss from ice sheets, ice caps, and glaciers. Net ice-mass depletion of land-based ice will add to the net water mass in the ocean, unless it is intercepted by surface water or terrestrial storage reservoirs. The mass loss is accomplished by direct climate forcing (through changes in precipitation, melt rate, etc) and by dynamic changes (e.g., subglacial sliding, iceberg calving) that can be indirectly and non-linearly influenced by climate. Dynamic changes can act to accelerate mass loss from glaciers and ice sheets, but generally not to retard it. If these mass changes are known sufficiently, for example, from model predictions, then the resulting LSL variations can be calculated using eqn [6]. However, there are differences in the LSL admittance functions (e.g., the global pattern of LSL change caused by a 1 m unit ice change over an ice sheet or glacier normalized by the globally averaged LSL change) computed by different groups for the GIS and AIS. For example, the global admittance functions for the AIS and GIS computed by Plag and Jüttner (2001) exhibit larger spatial variability than those computed by Mitrovica et al. (2001, 2009) and Vermeersen et al. (2008, personnel communication). Due to a lack of abundant modern observations close to sufficiently large and rapidly changing ice masses, a comparison of near-field concurrent LSL changes to predictions has not been possible so far. Thus, the solutions of the elastic part of eqn [6] have not been validated against observations. Results of a recent study of near-field vertical uplift induced by present-day ice load changes in Svalbard (Kierulf et al. 2009) indicate near-field values for the LSL admittance function in the range of -50 to -70, which would require a much larger spatial variability of the LSL admittance function than predicted by Mitrovica et al. (2001, 2009), but somewhat smaller than what Plag and Jüttner (2001) predict. The origin of the inter-model discrepancies can be in the Earth model itself; the computation of the Load Love Numbers (LLNs) and the parameterization of the Earth model for this computation; the convolution of the Green's function with the load anomalies; and the solution of the mass-LSL equation. The availability of increasingly dense GPS networks in the vicinity of rapidly changing ice loads provides a unique opportunity to identify the origin of the inter-model differences and to resolve them.

Best estimates for the total present-day volume of land-based ice are: for the East Antarctic Ice Sheet (EAIS), ca. 70 m Sea-Level Equivalent (SLE); for the West Antarctic Ice Sheet (WAIS), ca. 3.3 m SLE (Bamber et al. 2009); for the GIS, ca. 7.2 m SLE (Bamber et al. 2001); and for the aggregate of all other glaciers and ice caps world-wide, ca. 0.6 m SLE (Radic and Hock 2010). Current and next-century contributions from the EAIS are believed to be comparatively small, while the WAIS and GIS are large present-day sea-level contributors, at ca. 0.5 and 0.74 mm $year^{-1}$ SLE, respectively (Rignot et al. 2008a,b); The total aggregated contribution of GIC to SLE volume is small, but the GIC are presently a very large source of sea-level rise, at ca. 1.1 mm $year^{-1}$ (Meier et al. 2007), although Jacob et al. (2012) reach a much reduced estimate of 0.41 ± 0.08 mm $year^{-1}$. The large loss rate from GIC is diminishing the source volume at a rate of close to 0.2%, so reservoir depletion will eventually reduce the GIC flux, but not significantly in the near term (next century). Jacob et al. (2012) estimate the current total contribution of GIC and the two large ice sheets to be 1.48 ± 0.26 mm $year^{-1}$.

Prediction of GSL from land-ice sources depends critically upon numerical simulations and requires knowledge of atmospheric and oceanic forcing, as well as, geometric landscape boundary conditions. While significant progress has been made in ice sheet numerical modeling capacity, robust operational models do not yet exist for prediction. Chief among obstacles to be overcome are a lack of knowledge of the processes of subglacial sliding (boundary slip) and iceberg calving. Comprehensive global predictive modeling is also hindered by a lack of basic information for ca. 40% of the GIC area, including glacier and ice cap volume, basal topography, and location of marine-based outlets (Pfeffer et al. 2008).

4.14.3.5 Impacts of Sea-Level Rise

Coastal zones are complex and dynamic environments with many interactions between physical processes, such as waves and tidal currents, imposed on underlying geology, the availability of sediments, and changes in sea-level. The spatial variations in these factors lead to a wide variety in the characteristic coastal landforms, including beaches, cliffs, and barrier islands. The general response of coastal landforms that can occur in response to LSLR are widely understood (e.g., FitzGerald et al. 2008), but determining precisely how and what changes occur in response to a specific rise in sea-level has been difficult, due to the wide range of spatial and temporal scales involved in the processes that cause the LSLR and interact at a given coastal location. Consequently, it has been difficult to determine a quantitative relationship between LSLR and shoreline change. No scientific consensus has been reached as to whether or not observed shoreline changes can be quantitatively related to LSLR (Gutierrez et al. 2009; and the references therein).

Focusing on coastal ecosystems, the impacts of LSLR (in combination with other sea-level hazards) can be broadly classified into effects of (1) wetland loss, (2) salinity increases, and (3) beach erosion (Titus 1988). LSLR is a coastal hazard with the potential to amplify the impacts of waves, storm surges, shoreline erosion, wetland loss, and saltwater intrusions. Even a small increase in LSL can change the statistics of extreme sea-level events significantly. Depending on the coastal topography, what today is a 100-year flood could easily become a 10-year flood or an even more frequent flood.

Many recent assessments of the coastal impacts of LSLR have focused on identifying land located at elevations below plausible LSL trajectories (e.g., Anthoff et al. 2006; Rowley et al. 2007; CCSP 2008). While these elevation-based analyses are an important first step in the understanding of the potential impacts of LSLR, this approach only reveals a part of the potential consequences for the coastal zone. Changes in the coastal zone are driven by interrelated, complex processes including waves, tsunamis, storms, LSLR, sediment transport, and biological processes acting on a wide range to temporal scales. As a result, the response of a coastal region to LSLR results from a combination of one or more of the processes in the following broad categories (e.g., FitzGerald et al. 2008): increased frequency of storm flooding; land loss due to permanent inundation of low-lying lands; land loss due to erosion of beaches, dunes, and cliffs; barrier island breaching, segmentation, and migration; wetland conversion to open water, migration inland, and accretion through increased flooding; expansion of estuaries; saltwater intrusion into freshwater aquifers and surface waters.

Even the lowest GSLR scenarios considered in the IPCC AR4 would have a wide range of impacts on many coastal environments and infrastructure. Effects are likely to include coastal erosion, wetland and coastal plain flooding, salinization of aquifers and soils, and a loss of habitats for fish, birds, and other wildlife and plants (Meehl et al. 2007). IPCC estimates that a continuation of the current GSLR likely would lead to a loss of as much as 33% of coastal land and wetland habitats in the next hundred years. Considering that the impacts in most areas do not scale linearly with the sea-level rise (Craft et al. 2009), any increase in the rate of GSLR could increase land and habitat losses dramatically, putting a very large number of wetland and swamp species at serious risk. In the polar regions, the retreat of coastal sea ice is already threatening species that depend on the existence of sea ice with extinction (Arctic Climate Impact Assessment (ACIA) 2004).

4.14.3.6 Coastal Protection

If coasts come under increasing threats from inundation, flooding, and increased erosion, mitigation of LSLR impacts and adaptation strategies are needed. Coastal protections, such as sea walls and dikes, have been constructed since Roman times to protect human settlements from the sea. In the twentieth century, large parts of the low-lying coasts have been protected with massive so-called 'hard' engineered defenses, particularly in Europe and North America. Disasters caused by storm surges such as the 31 January 1953 event in The Netherlands, Belgium, and the United Kingdom triggered many national programs to strengthen coastal protection. This 'hold-the-line' approach and the security provided by these protections has enabled and encouraged development of coastal regions otherwise at risk of flooding (Figure 9). Following this line, many economic assessments conclude that the only viable strategy is to improve coastal protection by improving the engineered defenses (e.g., Schwerzmann and Mehlorn 2009).

It is, however, now increasingly recognized that these hard defenses are unsustainable for several reasons (Turner et al. 2007). In the case of failure, the ensuing disaster is severe, as was illustrated by the impact of Hurricane Katrina in New Orleans. In many cases, the protections themselves have led to a reduction or loss of intertidal habitat, reducing also the natural protection these compartments often provide. Coastal habitat migration, loss and gain in response to sea-level changes have occurred throughout geological times. However, the perspective for the twenty-first century is different due to the presence of developed shorelines, which introduces a new barrier for habitat migration. Moreover, the rate of LSLR could be at the upper end of the spectrum (see Section 4.14.3.2).

We can distinguish between five generic strategies for dealing with coastal defense in areas with rising sea-level, with different impacts on ecosystems, society, and economy (Figure 10). (S1) Do nothing: inaction eventually will lead to abandonment and destruction of infrastructure built within the zone inundated by the rising sea. This will leave room for the tidal zone to migrate inland. (S2) Managed realignment: plan infrastructure in the potentially inundated areas such that it can be realigned if sea-level rise and shoreline transgression requires this. This also leaves room for the tidal zone to migrate inland. (S3) Hold-the-line: hard engineered protections (seawalls, dikes, barriers) are constructed to prevent transgression of the shoreline. Over time, this eliminates the tidal zone completely. (S4) Progression: new defenses are constructed seaward of the original shoreline, thus creating new land and protecting existing infrastructure. This approach generally leads to reorganization of ecosystems. (S5) Soft intervention: the ability of ecosystems to migrate vertically is utilized to raise parts of the tidal zone and the adjacent land vertically. Not all of these strategies are applicable to all sites.

Figure 9 Examples of coastal protection and developments. Upper picture: the Thames Barrier, London, U.K., which is protecting more than 800 000 houses in the flood plane, including crucial infrastructure such as about 50 hospitals; Middle: Imperial Beach, California, where houses at a transgressive beach in a tsunami-prone area are protected with boulders, while the beach is transgressing past the developed coastline. Bottom: The island of Malé, capital of the Maldives Islands in the Indian Ocean. The maximum elevation is 2.4 m, and population is around 100 000. This extreme example of the hold-the-line (or even progression) strategy (**Figure 10**) required a seawall around the entire island.

For example, in urban coastal areas such as London, New York City, Jakarta, Shanghai, and Malé, Maldives (Figure 9), the strategies (S1) and (S2) may not be viable alternatives for economic and social reasons. For urban areas in deltas, storm surge barriers (S3) are an option to handle extreme events. The protection of world heritages (such as the city of Venice) may also require floodgates with potentially significant impacts on the marine ecosystems. The applicability of the strategies also depends on the rate and amount of LSLR. The very rapid subsidence in parts of Jakarta eventually may only leave (S2) as an option, while a significant LSLR only will leave (S1) for the Maldives. In rural coastal areas, the negative ecological impact of (S3) or (S4) may exceed the social and economic impact of living within the future flood plain resulting from a projected LSLR. Economic and social conditions impact the choice, too. In many developing countries, (S1) and partly (S2) are the only viable options.

Considering the impact on ecosystems, strategies (S1), (S2), and (S5) are the least impacting. In general terms, the potential ecological effects of strategies (S3) and (S4) involving hard coastal protections are understood (e.g., Seitz et al. 2006). Likewise, the impact of an LSLR on ecosystems has been studied abundantly. However, few studies on the combined effect of LSLR and coastal protections have been published (Shellenbarger Jones et al. 2009). Nevertheless, it can be stated that hard engineered protection combined with sea-level rise would narrow down or eliminate most of the tidal zone and the adjacent wetlands. Similar to developed coastlines, these protections would prohibit inland migration of the sea-side coastal zone compartments in response to LSLR.

Turner et al. (2007) considered managed realignment as an alternative to maintaining 'hard' defenses for the protection of land from LSLR. In this approach, the engineered defenses are deliberately breached, thus allowing the coastline to recede to a new shoreline further inland, where a new intertidal habitat is created providing natural protection from flooding and erosion. Their cost–benefit analysis shows that managed realignment can be economically more efficient than holding-the-line, if the time period considered is sufficiently long (generally greater than 25 years). Particularly for rapid rates of LSLR, managed alignment may be the only viable options both for ecosystems and for human population.

4.14.4 The Assets: Coastal Ecosystems and Their Services

The assets of the coastal zone include geomorphological features, as well as, coastal ecosystems. Depending on the geological and environmental settings, coastal ecosystems include tidal marshes, tidal forests, aquatic vegetation beds, tidal flats, beaches, cliffs, and estuaries (Shellenbarger Jones et al. 2009). Providing habitat for many species (including many endangered and threatened species), the coastal ecosystems are among the most productive ones and they provide essential ecosystem services that no other ecosystem can provide (Daily et al. 1997; de Groot et al. 2002). These services include not only those processes supporting the ecosystem itself but also many human benefits derived from those processes. The wide range of services include nutrient cycling and uptake, natural water quality improvement, water storage and delivery, flood protection, shoreline erosion control, fish production, and the provision of recreational opportunities helping to promote human well-being.

Wetland plants hold the soil in place with their roots, absorb the energy of waves, and reduce the impact of tidal streams. They provide a buffer to major storm impacts, particularly to damaging storm surges, and thus reduce coastal erosion.

Tidal marshes and mangroves can store flood waters that runoff from upland. By retaining excess nutrients and some pollutants in surface-water runoff from higher dry land before the runoff reaches open water, they provide an important filter service, and reduce sediment that otherwise would degrade

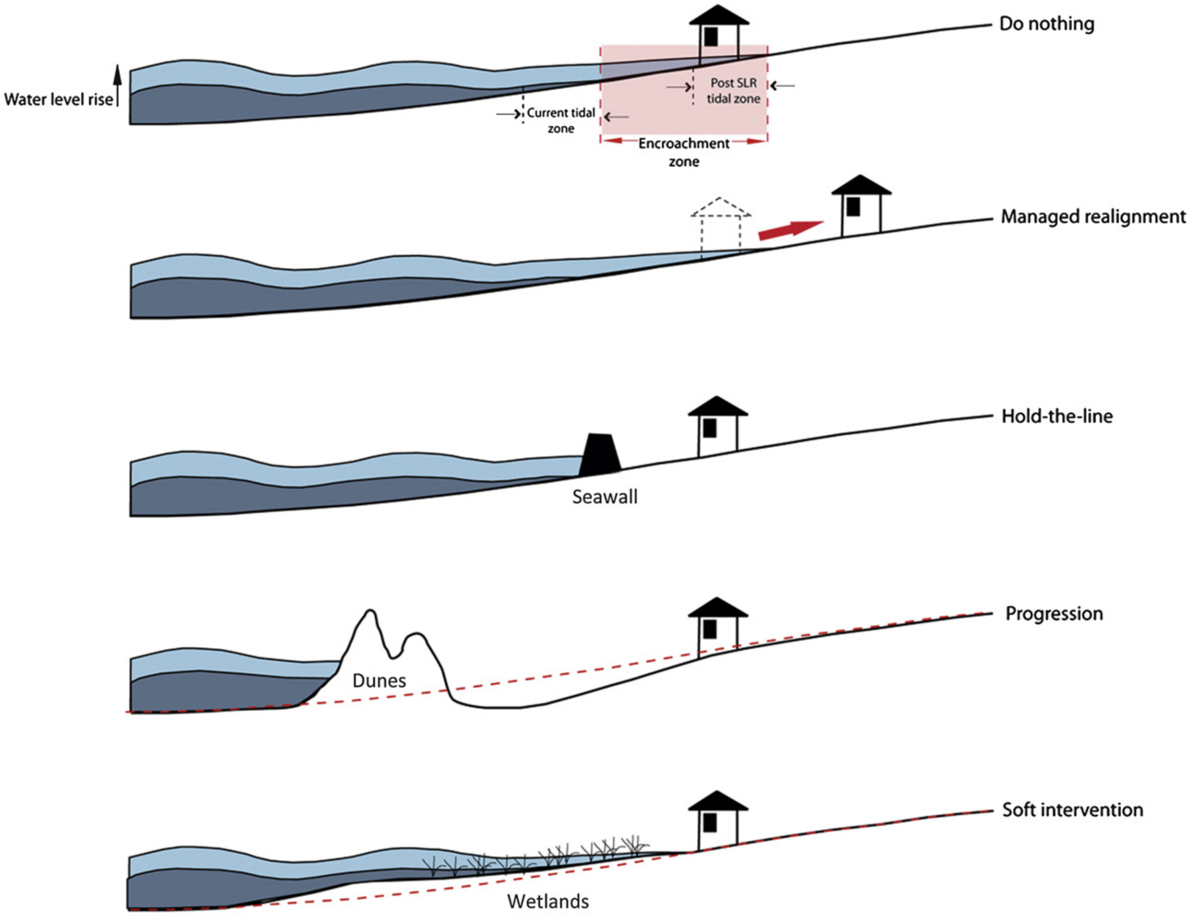

Figure 10 Five generic strategies for coastal management in areas with potentially rising sea levels.

estuarine and adjacent marine compartments and impact fish and amphibian egg development.

Estuarine, marine fish, and shellfish depend on coastal wetlands to survival. The wetlands are critical for juvenile and adult stages of many economically important marine fish and shellfish species. In fact, most commercial and game fish breed in coastal marshes and estuaries. Various birds and certain mammals, many of them with economic value, also depend crucially on coastal wetlands.

For many coastal communities, wetlands, estuaries, and the adjacent marine zone contribute to the economic livelihoods. Coastal wetlands have recreational, historical, scientific, and cultural values, and they offer significant esthetic value to humans. Estimates of the global economic value of all the services coastal wetlands provide are in excess of $1.6 Trillion per year (Costanza et al. 1997). Particularly, the recreational opportunities are economically important. There is an estimated half of international tourists travel to wetlands of all types, particularly those in the coastal zone.

The marine and coastal zone wetlands can be separated into the following:

1. Marine waters: permanent shallow waters less than 6 m deep at low tide; includes sea bays, straits;
2. Subtidal aquatic beds: sea grasses, tropical marine meadows;
3. Coral reefs;
4. Rocky marine shores: rocky offshore islands, sea cliffs;
5. Sand, shingle, or pebble beaches: sand bars, spits, sandy islets;
6. Intertidal mud, sand, or salt flats;
7. Intertidal marshes: salt marshes, salt meadows, raised salt marshes, tidal brackish, and freshwater marshes;
8. Intertidal forested wetlands: mangrove swamps, swamps, tidal freshwater swamp forests;
9. Brackish to saline lagoons and marshes with one or more relatively narrow connections with the sea;
10. Freshwater lagoons and marshes in the coastal zone;
11. Non-tidal freshwater forested wetlands.

Mangroves are an important component of the coastal wetlands. Mangrove distribution in latitude is controlled by temperature. Perennial mangroves generally cannot survive temperatures below freezing, constraining their occurrence to the tropics and subtropics with maximum development between 25 °N and 25 °S. The richest mangrove communities occur in areas where maximum water temperatures exceed 24 °C. The most recent estimates suggest that mangroves presently occupy about 146 530 km^2 of tropical and subtropical coastline (McLeod and Salm 2006). Mangroves provide the entire ecosystem services mentioned above, and they provide income from the collection of mollusks, crustaceans, and fish, and the harvest of firewood, timber, and wood chips.

Despite the recognized value of coastal ecosystems, the loss of coastal wetlands over the last few decades has been severe. The cumulative effects of natural and anthropogenic pressures have turned mangrove wetlands into one of the most threatened ecosystems worldwide. About 50% of the global area has been lost since 1900 and 35% in the past two decades, primarily due to human activities, such as conversion for aquaculture. The global average annual rate of mangrove loss is about 2.1% (Gilman et al. 2006a). Over the last few decades, coastal wetlands were reduced globally by 30%. Protecting wetlands is important for humanities safety and welfare. This was recognized in the last century, and in 1971 the Convention on Wetlands of International Importance, called the Ramsar Convention, was adopted in the Iranian city of Ramsar. The Ramsar Convention's mission is "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution toward achieving sustainable development throughout the world." The definition of wetlands in the Convention is broad, including lakes and rivers, swamps and marshes, wet grasslands and peatlands, oases, estuaries, deltas and tidal flats, near-shore marine areas, mangroves and coral reefs, and human-made sites such as fish ponds, rice paddies, reservoirs, and salt pans. The wise use of wetlands, defined as "the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development," aims at the conservation and sustainable use of wetlands and their resources, for the benefit of humankind.

Coral reefs are very valuable and diverse ecosystems providing food and habitat for many other species. In addition to their ecological services, these systems provide billions of dollars in services including tourism, fish breeding habitat, and protection of coastlines. The coral reefs face many challenges arising from anthropogenic activities such as pollution, destructive fishing, poorly regulated tourism, and ocean acidification, as well as, from changes in local and regional weather, which over the last 30 years have led to the death or severe damage of about one-third of the world's corals (Janetos et al. 2008).

The quest to understanding how shorelines form and how human activities affect these processes has led to the creation of a number of classification schemes (e.g., Anderson et al. 1976; Cowardin et al. 1979; Cowardin and Golet 1995; Kutcher et al. 2005; Madden and Goodin 2007; Lund and Wilbur 2007). Most of the authors group coastal areas into classes that have similar features, as a result of having developed in similar geological and environmental settings. Detailed inventories available for certain regions may characterize the shore zone using shoreline morphology, substrate, wave exposure, and biota and subdivide the coast into more or less homogeneous units (e.g., Berry et al. 2001), while others use less granular and more descriptive approaches (e.g., ACCC 2006).

A separation in the main regimes based on the Coastal Marine Ecological Classification Standard (CMECS) as used in Madden and Goodin (2007) is provided in Table 2. The boundaries of CMECS are explicitly defined from the supratidal zone to the central oceans. For the discussion of LSLR impacts, we also have to include the dry land above the high water mark, to which the supratidal zone and, potentially, other zones relocate in case of the rising sea-level. The CMECS considers the following six levels:

- Level 1: Regime: differentiated by a combination of salinity, geomorphology, and depth;
- Level 2: Formation: large physical structures formed by either water or solid substrate within systems; including geoforms and hydroforms such as lagoons, embayments, deltas, reefs, seamounts, islands, ocean gyres, upwellings, etc.;
- Level 3: Zone: the water column, littoral or bottom; position with reference to the water: whether it is a continuously submerged bottom or at the waterline (littoral), or entirely within the water column (pelagic);
- Level 4: Macrohabitat: mesoscale physical structures that contain multiple habitats;
- Level 5: Habitat: a specific, repeatable combination of physical and other environmental characteristics that tend to co-occur;
- Level 6: Biotope: the characteristic dominant association of attached, sessile, or sedentary biota; the smallest quantum unit of the habitat in CMECS.

4.14.5 Vulnerabilities: Impact of Sea-Level Change and Coastal Protection on Coastal Ecosystems

As mentioned in the introduction, the concept of vulnerability differs between scientific disciplines (Brooks 2003). While we use here the concept mostly applied to natural hazards and their impact on the built environment and the population in this environment, we acknowledge that the vulnerability of ecosystems is comparable to that of social system. For these systems, the concept of a threshold is important, that is, the possibility that the system collapses if a certain stress level is exceeded.

While we can provide a concise typology of the physically defined sea-level hazards (see Section 4.14.3), it is more difficult to define the relationship between a given hazard and the vulnerability and adaptive capacity of a human system or ecosystem, as these depend critically on the nature of the hazard faced. As expressed in Section 4.14.2, vulnerability of a system (human or ecosystem) is time variable and depends on the capability of the system to adapt in a timely manner to changing hazards. It also depends on the level of stress the system is already exposed to.

Most of the coastal ecosystems discussed in the previous section, such as sea grass meadows, coral reefs, rocky intertidal zones, mangroves and other wetlands, and estuarine communities, are structured around sea-level. Many of these ecosystems are already stressed by coastal development, eutrophication, and industrial pollution. These impacts reduce the resilience of the ecosystems to recover from disturbances. A rapid LSLR is a disturbance that many coastal ecosystems might face in the coming decades. There are many unanswered questions regarding the resilience of coastal ecosystems with respect to rapid LSLR.

Human activity has been the major threat to wetlands. This is also true for coastal wetlands. Conversion for aquaculture, pollution through agriculture, industrial development, and urban and suburban sprawl in the coastal zone has caused the greatest losses of coastal wetlands. In many areas, the biggest source of loss for freshwater coastal wetlands is from urban sprawl. In some areas, the primary source of saltwater wetland loss is a rise in LSL caused by land subsidence associated with mining of oil, gas, and groundwater. Coastal protection and urban development often narrow down the area in which wetlands can exist or migrate into, if changes in the shoreline due to erosion or LSLR require this.

Estuarine wetlands are dependent upon freshwater inflow from rivers. In some estuaries, freshwater inflow has been reduced through river regulations and rerouting. In many deltas, sediment influx is needed to compensate for subsidence of the delta, and river regulations often reduce the influx, leading to subsidence and the permanent drowning of wetlands. An example are the Everglades in Florida, where human interventions changed the freshwater influx (Walker and Salt 2006), and LSLR increases the salt content of existing bodies of freshwater. Local rainfall also has been reduced in this region, at least in part due to land use change in the Everglades area (Marshall et al. 2004), with a resultant reduced flux of freshwater into the coastal waters.

LSLR would add stress to the already stressed coastal wetlands. The main vulnerability of coastal ecosystems to LSLR result from changes in the physical and dynamical environment, leading to increased coastal erosion, more extensive coastal inundation, and higher storm-surge flooding; changes in the location of the different regimes through landward intrusion of sea water in estuaries and aquifers; inhibition of primary production processes through elimination of crucial ecosystems. It is important to note that most of these impacts do not scale linearly with LSLR (Craft et al. 2009).

Other climate-change related processes can increase the stress, e.g., through changes in surface-water quality and groundwater characteristics, changes in the distribution of pathogenic microorganisms, also in combination with higher sea surface and sea water temperatures, and, for the polar regions, reduction of sea-ice cover.

Coastal wetlands have two main adaptation strategies: vertical migration and horizontal migration. Vertical migration requires sufficient influx of sediments that can be captured within the ecosystem and helps to raise the base to compensate for an LSLR. Migratory organisms will most likely be able to adapt to a sufficiently slow LSLR if there is space for migration. More rapid rates of LSLR may lead to changes that may hamper the successful migration of a number of organisms. If coastal LSL continues to rise, low-lying wetlands would be permanently inundated, and ecosystems in these areas would be flooded. Formerly dry land would turn into wetland. This would impact significantly the structure and function of the coastal and inland ecosystems and impact their capabilities to perform ecosystem services.

Moreover, adaptation by an ecosystem may be inhibited by processes originating outside the ecosystem. Understanding the vulnerability requires to consider 'external' obstacles to adaptation. Coastal development creates obstacles to ecosystems as they are trying to adapt to changes in the environmental conditions. For example, along the coasts of Denmark, Germany, and The Netherlands, dikes built to protect the land against storm surges increasingly narrow the mud-flats in the Watt and hinder ecosystems to move further inland. The increase of storm surge heights of up to 1 m predicted for most of these coast by Schwerzmann and Mehlorn (2009) and others will likely lead to more flood protections. In combination with a possible LSLR, this prediction-based adaptation would lead to a significant reduction of the unique Watt ecosystems.

In many coastal areas, wetlands and mangrove forests act as buffers to storm surges and tidal waves. In Bangladesh and Thailand, these natural coastal protections are already submerged by rising sea-levels. Normally, the mangroves would re-establish themselves at the new low-tide zone, and wetlands would migrate inland. However, in large parts of these coasts, buildings and other types of development on the coast are blocking them. As a result, interaction of LSLR and coastal protection causes a reduction of the valuable ecosystems.

LSLR is one of the greatest challenges for mangrove ecosystems (McLeod and Salm 2006). If LSLR is slow enough, then mangroves can adapt if adequate expansion space exists, and if other environmental conditions are met. If LSL is rising, the seaward and landward margins of the mangrove would have to migrate landward in order to maintain the preferred environmental conditions (period, frequency, and depth of inundation and salinity). Whether or not such a migration is successful or even possible depends on the rate of LSLR, the slope of adjacent land, sediment composition of the upland habitat, and the absence of obstacles (seawalls and other shoreline protection structures) to landward migration. In some locations, the lateral extent of mangrove would narrow down or the LSLR would lead to complete removal. What rates of LSLR would exceed the capabilities of mangroves to adapt? The answer depends on the location, but several studies indicate that in some locations $LSLR_{100}$ values of 0.12 m per century would be too much (Ellison and Stoddart 1991), while in other locations mangroves have adapted to rates of 0.25 m per century. However, we have no indication that mangroves would be able to adopt to $LSLR_{100}$ values of 0.5 m per century or more.

LSLR also would add to the stress on wild fish stocks by narrowing down crucial areas for juvenile and adult stages of many economically important marine fish and shellfish species. This would add to increasing stress due to ocean acidification, which weakens the ability of shellfish, corals, and marine phytoplankton to form their skeletons, increasing nutrient loads and pollution.

Healthy coral reefs could likely keep up with a moderate LSLR, but many reefs are already severely degraded by the effects of coral bleaching, UV-B radiation, pollution, and ocean acidification. Future increases of sea surface temperature will very likely increase stress on coral reefs, reducing their ability to compensate for LSLR.

There is a high risk that the combined stress of anthropogenic activities, climate effects, and LSLR could lead to the crossing of certain thresholds and a dramatic loss of biodiversity and degradation of services from marine and coastal ecosystems. As discussed in Section 4.14.3.2, the rates of changes in critical Earth system parameters are far outside rates experienced in the past, and coastal ecosystems might not be resilient with respect to these unprecedented disturbances.

4.14.6 Risk Assessments

As stated in Section 4.14.2, we define risk as probability, times vulnerability of assets, and times value of exposed assets. For the probability of LSLR, we have established in Section 4.14.3.2 that it is possible that for many locations (see Figure 3), twenty-first century $LSLR_{100}$ could exceed 0.5 m. There is a moderate probability that many locations could experience far more extreme $LSLR_{100}$ values in excess of 1 m. If the main contribution to a rapid rise would come from increased melting of both the GIS and the AIS, then low-latitude LSLR would be largest, while LSLR in many polar regions would be negative (e.g., sea-level would fall). If only one of the two ice sheets would have a large contribution, then sea-level would fall in the near-field of this ice sheet, and rise more than average in the opposite polar region. However, mangroves and coral reefs in the tropics and sub-tropics likely would experience a rapid rise. We also concluded that the possibility of a catastrophic LSLR of more than 2 m per century cannot be excluded for many regions particularly at low latitudes.

In Section 4.14.4 The Assets: Coastal Ecosystems and Their Services, we have underlined the high ecological, social, and economic value of coastal ecosystems. Taking the economic value alone, the estimated value of the services of coastal ecosystems is on the order of $1.6 trillion per year (Costanza et al. 1997).

The vulnerability discussion in Section 4.14.5 indicated that many of the coastal ecosystems are pre-stressed, while their capacity to adapt to LSLR is limited due to human interferences. In many cases, resilience to rapid LSLR is greatly reduced.

If we conservatively assume that for 20% of the coastal ecosystems a 21st $LSLR_{100}$ of 0.5 m would cross a threshold leading to the complete loss of the ecosystem services, and if we further arbitrarily assume that such a rise has a probability of 0.8, then we are exposed to a risk of $250 000 year^{-1}. A more detailed computation of the LSLR-related risk of ecosystems could be done using eqn [1]. However, due to the quantitative uncertainties in the location-dependent PDF of LSLR, the location-dependent vulnerability of the ecosystems (which depends on many factors) and the location-dependent service values would only allow an order of magnitude estimate. What we can say is that the possible 21st LSLR will lead to a reduction of the coastal ecosystem services exceeding $250 Billion year^{-1} toward the end of the century.

4.14.7 Adaptation and Mitigation – Recommendations

During the last century, a common strategy for mitigation of sea-level hazards was (S3) (Figure 10), e.g., the 'hold-the-line' approach based on hard engineered coastal defenses. This approach likely would acerbate the impact of a rapid LSLR on ecosystems. It is therefore necessary to reconsider the mitigation-based approach and, where possible, to progress toward an adaptation-focused approach. The corresponding generic strategies are (S1), (S2), and (S5). In many locations, the 'do nothing' (S1) and 'managed realignment' (S2) strategies are those with the least costs in terms of lost ecosystem services, but highest in costs in terms of infrastructure and social impact. 'Soft intervention' (S5) could turn out to provide the most balanced approach, which is a hybrid of mitigation and adaptation.

Importantly, the planning for the adaptation strategy has to start as early as possible. By responsible land use planning, with limited development of those low-lying areas that likely will turn into future floodplains or areas that are need for migration of coastal ecosystems, we can keep strategies (S1) and (S2) viable. The underlying vision for the development of most low-lying coastal land areas should be based on the premise that eventually this land could give way to a rising sea. By carefully managing the factors that impact the ability of coastal ecosystems to migrate vertically, we can prepare for (S5).

The decision of where to apply the adaptation strategies (S1), (S2), and (S5) should be based on a detailed assessment of the coastal ecosystems, their specific service functions and value, and their resilience to rapid LSLR. These assessments should be carried out based on a widely accepted best practice. For many countries, this assessment would require capacity building in order to collect the required information and to carry out the assessments.

The uncertainty of GSLR projections and the fact that we cannot exclude a GSLR significantly larger than what current models can predict render long-term (century-scale) projections almost useless for planning. What is needed is an approach based on monitoring of the Earth system and forecasting of LSLR on decadal time scales, if such a model can even be developed (Plag et al. 2010). This would constitute an early warning system capable of detecting the onset of a rapid GSLR, e.g., by detecting an accelerated melting of one of the large ice sheets. Such a sea-level monitoring and forecasting service is comparable to a smoke-detector, which is a standard approach to identify a low-probability, high-impact event of a fire in a timely manner. Building such a service through international cooperation (comparable to the approach taken in the field of meteorology) would be of particular value for those countries where capabilities in analyzing and forecasting the relevant processes are not sufficiently developed. Capacity building for necessary in situ observations in the coastal zone should be a priority.

The value of coastal ecosystems and their conservation is often underestimated, especially in less developed countries, where high population growth and development pressure create a focus on short-term economic gains and a neglect of long-term economic necessities. A dedicated outreach is needed to better inform decision makers and the public about the value of coastal ecosystems and the extreme risk associated with the sea-level rise. There is also a need to develop new approaches to the dialog between science and society in order to allow for the development of an informed risk perception. Importantly, the currently common one-way interaction between science and practice needs to be augmented by feedback to science from the practitioners (Vogel et al. 2007).

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