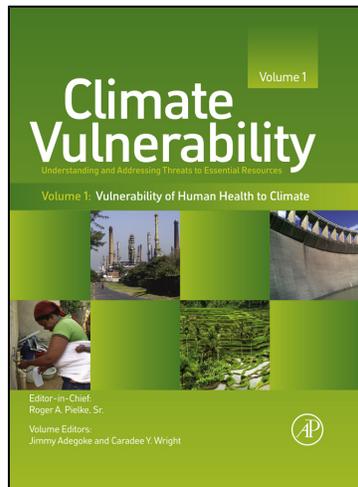


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1.03 Sea-Level Rise and Health

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Glossary

asset any item of value that potentially is exposed to hazards; can include buildings, other infrastructure, human beings, public health, 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.

1.03.1 Introduction

Considerable work has been published on the impact of climate variability and climate change on human health (e.g., Patz et al. 2005; McMichael et al. 2006; Karl et al. 2009). However, besides a few exceptions (e.g., Nicholls et al. 2007a; Craig 2010), the question of how local sea-level rise (LSLR) may impact human health surprisingly has not received the same level of attention. Mostly, focus has been on the direct impacts of sea level-related disasters, whereas the impact of a slow rise in sea level on human health has received little attention. While there are many challenges to predicting or projecting future LSLR, even a seemingly small increase in sea level can have a dramatic impact on many coastal environments (e.g., Titus 1990). There are a number of 'domino effects' potentially triggered by LSLR that can impact human health in various ways. Storm surges amplified by LSLR would lead to more severe impacts on health infrastructure. Hurricane Katrina in 2005 demonstrated the damage of flooding to health infrastructure at a time when more health infrastructure was needed. In London, 16 hospitals are in the Thames estuary at high flooding risk (Reeder 2010), and a storm surge exceeding the capacity of the Thames Barrier would put this infrastructure at risk. In many coastal areas, potentially polluting infrastructure is exposed to inundation. For examples, in the Galveston area in the United States, an LSLR of 0.69 m could inundate or impact a total of 23 waste treatment or holding facilities (Yoskowitz et al. 2009). Ten of these sites are wastewater treatment plants; five of them contain industrial and hazardous waste; and three sites (so-called superfund sites) are highly contaminated. An inundation of these sites would lead to

a high risk for the population, through reduced water and air quality, soil contamination, and pollution of coastal waters.

The impacts of LSLR and coastal protection on ecosystems (Plag and Jules-Plag 2012) also potentially could impact water and air qualities. In many regions, where coastal ecosystems are important resources for the local economy, LSLR might reduce access to these resources and thus impact the socioeconomic fabric of the local settlements.

Coastal erosion is a serious issue in many coastal areas, which has the potential to increase the local socioeconomic impacts. For example, most of the West African coasts are experiencing significant coastal erosion, and climate change and LSLR are expected to increase this trend (ACCC 2006). Coastal erosion in Lagos, the largest city in Nigeria, which on average is less than 2 m above current sea level, could rapidly move the coastline into the city. A similar situation exists for Shanghai, the largest city in China.

The possibility of a rapid LSLR in many coastal regions is increasingly recognized. It also needs to be emphasized that a rapid global sea-level rise (GSLR) is a new challenge for our civilization: never before in modern human history, with major built environments in the coastal zone, have humans been faced with a significant GSLR (Rowley et al. 2007; Orbach 2010). During the last deglaciation, rapid changes in local sea level (LSL) altered coastlines within decades. However, during that time, large-scale built environment was absent, and with much lower populations, human beings could easily adopt to shifting coastlines. Today, there is substantial built environment and crucial infrastructure in coastal zones, and urbanization of the coastal zone continues to increase. Over 600 million people live in coastal areas that are less than 10 m

above LSL, and a large fraction of these areas can be impacted even by a small LSLR through increased inundation during storm surges. Two-thirds of the world's cities with populations over five million are located in these areas. Under these conditions, rapid changes in coastlines and increased inundation risks during storm surges would be devastating both economically and environmentally.

Adaptation and mitigation is insurance against the risk of impacts of a hazard on lives and property, including impacts on human health. For informed decision, a detailed analysis of the risk needs to take place. Crucial ingredients for risk assessments are hazard analysis, an accepted basis for determining the value of the assets potentially exposed to the hazards, and a quantitative understanding of the vulnerability of the assets to the hazards. In the following, the terminology used here for the risk-based approach to potential health impacts of LSLR is first summarized (see Section 1.03.2). A more detailed description of the methodology is given in Plag and Jules-Plag (2012). Sea level-related hazards that might impact human health directly or indirectly, including their probability density functions (PDFs), are considered next (see Section 1.03.3), followed by the assets that may be exposed to these hazards and their vulnerability (see Section 1.03.4). Finally, the authors discuss adaptation and mitigation measures to reduce the risk (see Section 1.03.5) and give recommendations to decision makers (see Section 1.03.6).

1.03.2 Risk-Based Approach to the Impact of Sea-Level Rise on Human Health

In assessing the impact of coastal LSLR on human health, the authors take a risk-based approach (Plag and Jules-Plag 2012). The concept of vulnerability to natural hazards, including climate variability, climate change, and climate change impacts, is a relatively new one, and a common language still needs to be developed (e.g., Dolan and Walker 2003). Different disciplines use different approaches with different terminologies. Therefore, the authors briefly introduce their approach, which is derived from an insurance approach. Risk is defined as the product of hazard probability times vulnerability of exposed assets times the value of the assets. The mathematical details are given in Plag and Jules-Plag (2012).

The probability of the hazard states the likelihood of a hazard of intensity I occurring during a time interval T . This probability may be time dependent. For example, at a given location x the probability of a storm surge exceeding a certain height (e.g., 3 m) within, e.g., 500 years, may change because of climate change impacting the frequency and intensity of storm surges or because of changes in the mean sea level. Thus, a risk-based approach will have to use realistic estimates of future probabilities. For many natural hazards, the PDF can be determined based on past occurrences of the hazard. However, climate change can be expected to change the PDF of climate-related hazards. Under these conditions, the past may be a poor analog for the future. In order to achieve realistic risk estimates, including the uncertainties of these estimates, the potential change in the PDF of the climate-related hazards has to be kept in mind.

Assets can be anything from a building or service infrastructure, human population, and ecosystems to natural resources such as groundwater, fishing grounds, and beaches for tourist activities. Health services are also among the assets and so is the general state of public health in an area. Assigning value to the various assets in the coastal zone can be difficult. While the economic value of the built environment is relatively easy to determine, the value of human conditions and resources, human services, and ecosystem services is far more difficult to agree upon.

Assessing the vulnerability of assets also poses a wide range of challenges. For built structures, the vulnerability to natural hazards can be estimated based on knowledge of the materials' capacity to tolerate hazardous environmental conditions and the structural capacity to withstand environmental loads. Vulnerability of socioeconomic systems is far more difficult to assess, particularly if there are hidden thresholds that can lead to a collapse of the system. Likewise, determining vulnerability of ecosystems is difficult because of thresholds that are often not known. Vulnerability of health services to direct impacts of natural hazards and indirect impacts of the socioeconomic consequences of the hazards are difficult to quantify. The concept of resilience of these services to environmental, social, and economic disturbances can be an alternative to the risk-based approach.

1.03.3 Sea-Level Hazards

Coastal sea-level hazards include waves, currents, storm surges combined with tides, and slow inundation. These hazards can be exacerbated through slow changes in mean LSL. LSL is defined as the distance from the sea surface to the land surface. LSL changes whenever the sea surface height or the land surface height changes. At any coastal location, LSL is the result of many processes acting on local to global scales in space, and from instantaneous to millions of years in time. A complete overview of the processes impacting LSL is provided by Plag (2006) and Plag and Jules-Plag (2012).

In many coastal regions, the PDF of sea-level hazards can be determined based on long LSL records obtained by tide gauges (Tawn and Vassie 1989; Batstone et al. 2009), although multidecadal climate variability can lead to biased attributions (Donner 2102). Changes in the PDF of the sea-level hazards can result from two contributions: (1) the hazard (waves, currents, storm surges) itself may change in its frequency and intensity because of dynamic changes in the ocean/atmosphere system; and (2) the impact of the hazard may change because of a change in mean sea level. Figure 1 illustrates this interaction of slow, mediocre changes in mean conditions with possible changes in the extremes for the case of storm surges. With rising sea levels, storm surges will lead to increased and more frequent inundation of wetlands and lowlands, exacerbated coastal flooding, and eventually permanent submersion. LSLR will alter tidal ranges in rivers and bays, increase the heights of waves relative to land, and increase the salinity of estuaries and aquifers and impair water quality. Storm surges and waves will also erode shorelines more rapidly. LSLR will lead to changes in the locations where rivers deposit sediment and decrease the amount of light reaching the bottoms.

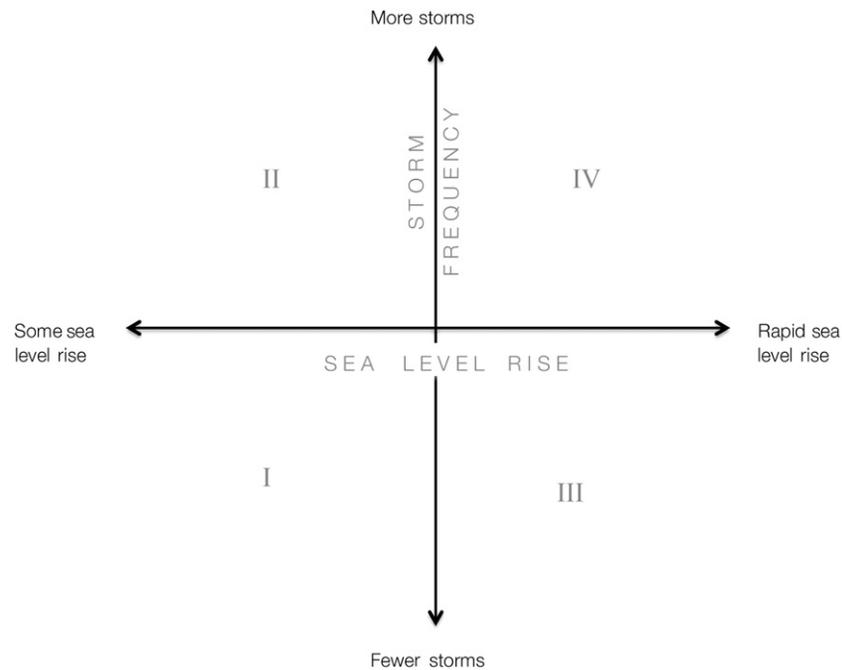


Figure 1 Impact of LSLR and storm surge frequency on hazard probability. A small LSLR and fewer storms (I) will not lead to any significant change in storm surge probability. However, even a small LSLR and more storms (II) would significantly increase the probability of a storm surge and inundation. Fewer storms combined with a rapid LSLR (III) would lead to less frequent but more intense storm surges and impact the higher end of the PDF. The most severe change in inundation risks result from more storms combined with a rapid LSLR (IV).

Considering the high sensitivity of the PDF of sea-level hazards to sea-level changes, it is mandatory to have an understanding of the PDF of LSL changes. Over the past two decades, an increasing number of GLSR and risk assessments have been carried out on national and international bases (e.g., Warrick and Oerlemans 1990; Warrick et al. 1996; Church et al. 2001; Hulme et al. 2002; Lowe and Gregory 2005; Anthoff et al. 2006; Plag et al. 2006; Tol et al. 2006; Rowley et al. 2007; Jacob 2007; CCSP 2008; Katsman et al. 2008, 2011). The large uncertainties in the plausible range of LSL trajectories and PDF resulting from these studies greatly reduce the value of these long-term assessments for risk management. A summary of these assessments shows that future LSL variations currently are not predictable on century timescales. Even with respect to the upper end of the range of plausible future LSL trajectories, large uncertainties exist, and recent scientific papers have sent an unclear and mixed message to decision makers and the public (see, e.g., the comments in the *New York Times* in 2008 and 2009 on recent papers such as Pfeffer et al. 2008; van de Wal et al. 2008; Rignot et al. 2008a; Blanchon et al. 2009; Hu et al. 2009; McPhee et al. 2009).

Following the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (AR4), most of the recent assessments do not assume a significant future contribution from the ice sheets. Recent research has shown that dynamic links between climate and cryosphere are becoming more active (e.g., surface melt influence on ice sheet flow (Zwally et al. 2002), and ice dynamic response to ocean/ice interaction (Motyka et al. 2003; Holland et al. 2008)). Moreover, observed recent changes in the large ice sheets (e.g., Rignot et al. 2008a,b; Jiang et al. 2010; Jacob et al. 2012) as well

as glaciers and ice caps (Meier et al. 2007; Pfeffer et al. 2008; Kierulf et al. 2009) indicate that an early onset of significant nonlinear responses of the cryosphere cannot be excluded, thus opening for a significant GSLR already over the next two to three decades. Current ice models cannot provide reliable long-term predictions of such a dynamic response (Lipscomb et al. 2009), and a major uncertainty for global sea-level (GSL) predictions is associated with the contribution from glaciers and ice sheets (see Plag and Jules-Plag 2012 for more details). There is also a potential for rapid GSLR not captured by any of the recent assessments, and the paleorecord may underestimate the maximum possible future rates. Over the past few centuries, humanity has reengineered the Earth in many aspects (e.g., atmospheric composition, land surface use, urbanization, water cycle, and biodiversity) and created states not encountered over the past few million years (see Section 1.03.3 Sea-Level Hazards in Plag and Jules-Plag 2012). The speed of changes in critical Earth system parameters is also unparalleled. Under these conditions, the response of the climate system may also exceed all rapid responses documented in the paleorecords. Thus, unparalleled sea-level change cannot be excluded.

The large uncertainties of any deterministic predictions and the existence of a low-probability, high-impact event (i.e., rapid LSLR) necessitate that risk-based planning considers the extreme event and aims to reduce the potential impact of such an event. The extreme sea-level event is a rapid rise combined with significant increases in storm intensity (area IV in Figure 1). Schwerzmann and Mehlorn (2009) conclude that for most of the countries around the Southern North Sea, climate change would lead to increased storms, and combined with LSLR, to increases in storm surge heights. Even a moderate LSLR

limited to 37 cm (corresponding to the IPCC A2 estimate) would lead to an increase of between 36 and 55% in peak surge height compared to present-day levels. For the affected countries, these scenarios require systematic integration of the likely impacts of climate change into risk assessment and risk management processes.

1.03.4 The Assets and Their Vulnerability

As mentioned in the introduction, an increasingly large fraction of the human population is living in the coastal zone, often in urban areas. Air and water qualities have a significant impact on public health, and environmental changes in the coastal zone that negatively impact air and water qualities can have a significant impact on public health in the coastal zone and its hinterland. In many coastal zones, the local population depends on the rich coastal resources such as fishing grounds and mangroves. Healthy socioeconomic conditions are the basis for a healthy population. As discussed by [Plag and Jules-Plag \(2012\)](#), LSLR likely will degrade ecosystem services and thus impact both socioeconomic conditions and public health.

Urban areas host most of the advanced health service infrastructure, such as hospitals and laboratories. In coastal urban areas, this infrastructure is at risk from flooding during storm surges and slow degradations due to long-term effects.

Coastal LSLR can negatively impact health in many direct and indirect ways ([Nicholls et al. 2007b](#); [Craig 2010](#)). [Table 1](#) summarizes the main groups of potential health impacts of LSLR and its associated effects. However, the vulnerability of public health also very much relates to the preparedness and socioeconomic status of communities from villages, towns, and cities to individual nations. For example, Bangladesh experiences only 1% of the world's cyclones but accounts for 50% of the deaths from cyclones worldwide ([Khan et al.](#)

2007). A large exposure to sea-level hazards combined with high socioeconomic vulnerability makes the population in the low-lying areas of Bangladesh particularly susceptible to adverse health impacts and threaten development achievements.

A main direct health impact of LSLR is associated with catastrophic flooding caused by storm surges. Coastal flooding has caused many deaths through drowning and other direct causes as well as many injuries. These floods also spread bacteria, viruses, and chemical contaminants. In the aftermath, flooding will foster the growth of fungi and contribute to the breeding of insects.

Flooding can cause environmental conditions leading to increased infectious diseases. Particularly, the spreading of vector-borne diseases, i.e., infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, and triatomine bugs, and flies, such as sandflies and blackflies, can be promoted. Both permanent and intermittent flooding will allow vector-borne disease such as cholera and malaria to extend their ranges further inland. More frequent and intense flooding will also increase the number of occurrences and duration of exposure to pathogens. Rodent-borne disease, i.e., diseases carried by rats, mice, squirrels, or other rodents, can also be promoted by flooding because of altered patterns of human–pathogen–rodent contact.

The interruption of health services, energy supplies, communication, and transportation, and the reduced availability of health service staff tends to increase the direct impacts of the flooding. In many urban areas, flooding also results in severe water and air pollution, which will increase infectious and allergic diseases. The impact of Hurricane Katrina on New Orleans in 2005 illustrated the potential direct and indirect health impacts in developed areas of future similar disasters intensified by LSLR ([Reible et al. 2006](#)). This case also illustrates the long-term health effects from soil contaminations caused by the heavily polluted floodwaters. The Cyclon Sidr

Table 1 Vulnerability to and impacts of LSLR

| <i>Hazard or impact</i> | <i>Direct health impacts</i> | <i>Health infrastructure</i> |
|---|--|--|
| Catastrophic coastal flooding | Deaths through drowning and other causes, injuries, infectious diseases (respiratory, intestinal, skin), mental health disorders | Health services interruption, availability of health staff, transportation disruption, energy and other supplies |
| Flood-induced pollution | Infectious diseases, allergies | Long-lasting degradation of health service infrastructure |
| Reduced water quality and reduced access to potable water due to salinification and/or pollution | Diarrheal diseases (giardia, cholera), hepatitis, other water borne diseases | Reduced water supply for health services |
| Impairment of food quality (through pollution of farmland and fisheries) and reduction of food supply (e.g., loss of farmland and decreasing productivity of fisheries) | Malnutrition; shellfish poisoning, marine bacteria proliferation | Food safety |
| Change in transmission intensity, distribution of vector-borne disease, abundance of vectors | Changes in malaria and other mosquito-borne infectious diseases | |
| Population displacements, degradation of livelihoods | Less well defined; can include increased social conflicts; increased crime rate; prostitution to replace lost income | General stress on health services because of rapid changes in demands |

Modified from [Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe, 2007b: Coastal systems and low-lying areas. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315–356.](#)

disaster, which hit Bangladesh in November 2007, underlines the multiple health threats resulting from the disruption of water and food supplies, dislocation of people in the areas affected by flooding and the resulting overcrowding in refugee areas, the combination of malnutrition and transmission of communicable disease, vector breeding, and poor access to health services (WHO 2007).

Indirectly, flooding can also lead to pollution of farmland and fisheries, with the consequence of degrading food quality. Polluted farm produce and fish can lead to slow degradation of human health, and increased events of shellfish poisoning can cause a higher death toll. A reduction in food supplies due to a loss of farmland through permanent inundation or erosion could increase malnutrition, particularly in regions of poverty.

The disruption of systems for sanitation, sewage disposal, and storm-water drainage would also have health implications. A reduction in water quality and in the supply of potable water due to pollution will increase the occurrence of cholera and other diarrheal diseases, as well as hepatitis and other water borne diseases. The cholera bacterium has a sea stage, during which copepods (type of zooplankton) act as host organisms (Colwell 2002). Between epidemics, the bacteria can survive with these hosts as an inactive but still infectious sporelike form. LSLR in connection with changes in sea temperature and currents could facilitate the spread of cholera (Colwell 2002), both directly and through contamination of drinking water.

Fish, shellfish, and sea mammals in the marine environment consume algae that are at the base of the marine food web. A reduction in these plankton feeders as a result of overfishing, water pollution, or disease may thus contribute to blooms of harmful algae. Plankton blooms can also harbor cholera and other bacteria, thus increasing health risk.

In combination with higher temperatures in many coastal zones, increased flooding will contribute to resurgence of mosquito-borne diseases, such as malaria, in some areas and the introduction of new mosquito-borne diseases, such as dengue fever, in others (see the reference in Craig 2010). Malaria is already found in areas where it was never found before.

The forced displacement of coastal communities through storm surges or permanent inundation, particularly in areas with limited resources, would further increase the risk of various infectious, psychological, and other diseases.

Although salt water intrusion can have a negative impact on the biodiversity and productivity of estuaries, its effects on public water supply are the most important consequences for public health. The most vulnerable coastal communities often depend on local sources of freshwater. These sources of coastal freshwater can be either surface sources, such as lakes and rivers, or groundwater aquifers accessed through wells. Both sources are vulnerable to salt water intrusion and salinification as a consequence of LSLR.

In coastal aquifers, fresh groundwater normally overlies saline water because freshwater is less dense than salt water. Although the dynamics impacting the interface between fresh and saline waters are complicated and depend on many parameters, a simple static approximation provides a rough estimate expressed by the Ghyben–Herzberg relation (see e.g., Barlow 2003): if h is the height of the groundwater table above

sea level and z the depth below sea level of the interface between fresh and saline waters, then

$$z = \frac{\rho_f \cdot h}{\rho_s - \rho_f}, \quad (1)$$

where ρ_f is the density of freshwater and ρ_s the density of the saline water.

For average freshwater and seawater densities, $z \approx 40h$. Thus, even in areas where the groundwater table is only a few meters above sea level, saline waters are confined to greater depths, and freshwater resources can be extracted for use by humans. Many coastal urban areas depend on water resources in coastal aquifers. However, if freshwater is extracted more rapidly than replenished by rain and inflow from inland aquifers, the groundwater table will fall and the interface between fresh and saline waters will rise. The impact on the interface between fresh and saline waters can be on the order of 40 times the fall in groundwater level. In many cases, water management authorities currently prevent salinification by releasing and recharging freshwater from reservoirs during droughts. Nevertheless, overextraction of groundwater is today the leading cause of salinification of coastal groundwater resources.

However, coastal groundwater resources are also impacted by salinification caused by LSLR (Figure 2). As LSL rises, low-lying coastal areas are inundated with saline waters. The height of the groundwater level relative to LSL changes over a wide zone, and this impacts the position of the interface between fresh and saline waters over a large area. This process can lead to a slow salinification of freshwater in wells further away from the inundated area. If not discovered, this slow salinification can have severe direct and indirect impacts on human health. Salinification of coastal aquifers is a long-lasting process. For example, the rapid LSLR of about 120 m at the end of the last glacial period led to salt water intrusions in many aquifers in Florida, where it continues to circulate today (Morrissey et al. 2008).

1.03.5 Risk Assessment

As summarized in Section 1.03.2 Risk-Based Approach to the Impact of Sea-Level Rise on Human Health, the LSLR-related health risk is the product of hazard probability, vulnerability of the assets in terms of health impacts, and the value of the assets exposed. In terms of hazard probability, the authors have outlined that there is a very high probability for a moderate GSLR, resulting in many coastal areas in a high probability for a twenty-first century LSLR on the order of 0.5 m or more. While it is difficult to assess the probability of an extreme LSLR of 2 m or more, such large values cannot be excluded.

Over the past few centuries, the assets exposed in the coastal zones have dramatically increased, and this tendency is likely going to continue. Coastal LSLR has the potential to impact on the order of 50% of all human assets. Vulnerability related to health is high because of several threats, including degradation of health services and infrastructure during flooding, reduced food and water security, increased exposure to disease, and increased pollution of water, air, and soils due to toxic materials and infrastructure inundated by seawater. A main vulnerability threatening public health may, however, not be in

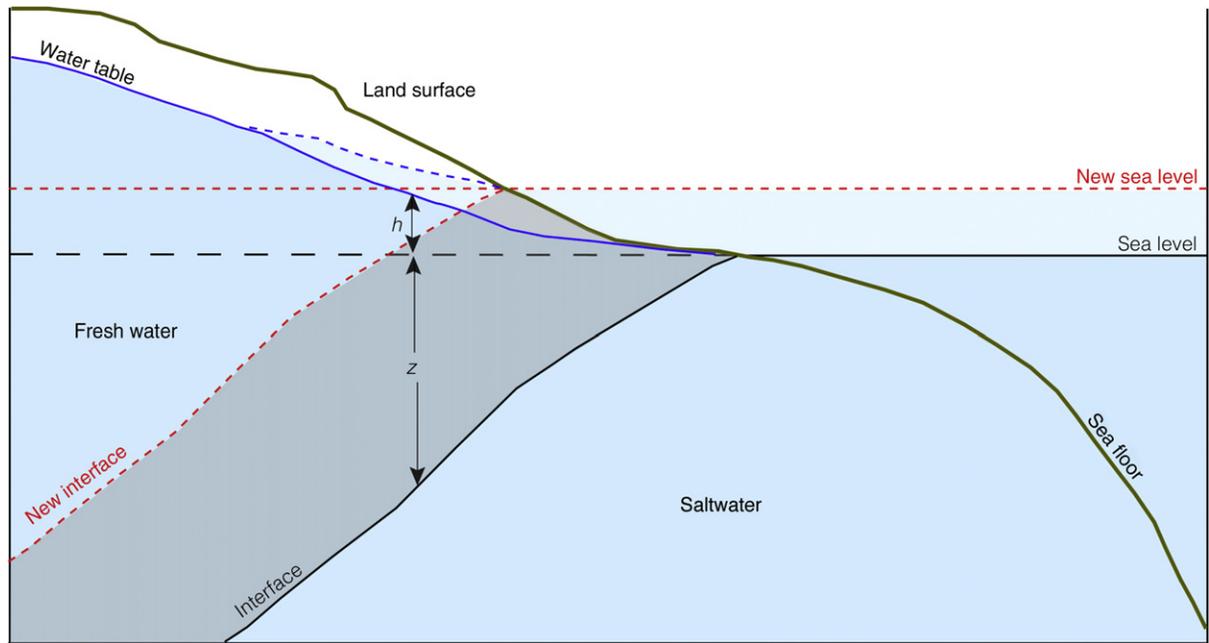


Figure 2 Impact of LSLR on groundwater resources. Depending on the coastal topography, even a small increase in sea level (broken lines) can significantly alter the interface between fresh and saline waters and lead to salinification of groundwater over a wide zone (shaded area). h is the height of the water table above sea level, and z the depth of the interface between fresh and saline waters below sea level. Modified from Barlow, P. M., 2003: *Ground Water in Fresh Water–Salt Water Environments of the Atlantic Coast, Circular 1262*. U.S. Geological Survey, Reston, Virginia.

the direct and indirect impacts listed here, but rather in the socioeconomic impacts. A significant GSLR and the increased frequency and magnitude of storm surges resulting from the associated LSLR would potentially have devastating impacts on coastal cities and settlements (e.g., Rowley et al. 2007; Edwards 2008), including a 'displacement through flooding and tropical storm activity of up to 332 million people in coastal and low-lying areas' (Watkins and HDR Team 2007). The societal and economic impacts would be felt globally. Loss estimates for single major disasters due to storm surges and hurricanes hitting urban coastal areas in the United States are in excess of \$100 billion for the immediate damages (e.g., Chapman et al. 2006; Jacob 2007; Nicholls et al. 2007a). Even the slow increases in GSL projected by the IPCC AR4 (Meehl et al. 2007) would change the risks associated with storm surges and hurricanes in many coastal areas, potentially leading to extreme disasters in coastal areas with dense urban settlements. Regionally, LSLR can exceed the global average rise by 50% and more. A rapid LSLR over a few decades, which cannot be excluded scientifically, would amplify the risks and the ensuing disasters, and it would reduce the time for adaptation.

Consequently, our civilization is challenged by a high health risk associated with LSLR. A detailed quantification of this risk would have to take into account several scenarios for LSLR. For example, if the main source of GSLR would be a rapid melting of parts of the Greenland ice sheet, then the Southern Hemisphere would experience a larger than average LSLR, with severe consequences for the coasts of Africa, South America, Australia, and Southern Asia, while many coastal areas in the Northern Hemisphere would experience lower than average LSLR, and at coastal zones closer to Greenland even an LSL fall.

If the main source would be a melting of a part of Antarctica, we would experience the reversed geographical pattern, with a significantly different regional and global risk. If both large ice sheets contribute, the higher latitudes would have lower than average rates, while the lower latitudes would experience the main impact with a larger than average LSLR.

Taking into account the high costs of adaptation and of potential disasters caused by coastal hazards, both over- and underprotection and adaptation can be very costly and can significantly impact national economies. Adaptation may require relocation of settlements (e.g., Vellinga 2007) and major infrastructure, including railroads, highways, and airports (see, e.g., CCSP 2008). Already the projected relatively moderate GSLR puts large numbers of people in vulnerable locations. Complete and partial relocation of populations living in severely affected areas such as Tuvalu, Bangladesh, and Samoa is already creating climate change refugees. Other areas where populations may need to be relocated include the Maldives, Guyana, and the Netherlands. If adaptation, including relocation of people and infrastructure, is delayed and a GSLR as projected or larger happens, large numbers of environmental refugees are likely to result, and inundated infrastructure is likely to cause considerable pollution and environmental impacts. Thus, policy and decision makers are faced with a trade-off between investing today large amounts in coastal protection and adaptation or loading the large human and economic costs of potential disasters on future generations.

Considering the extent of assets at risk in the coastal zone, any significant GSLR will challenge the global society at an unparalleled scale. Therefore, this risk, no matter how low the probability of a GSLR is, cannot be ignored. As pointed out by

Craig (2010), an adaptive management based on a public health approach may be the most suitable approach to address this risk of LSLR.

1.03.6 Conclusions

The risk of a rapid and large LSLR is real for many coastal areas, and even a slow and moderate LSLR has the potential to cause significant changes in storm surge intensity, with severe threats for human health. Reducing the risk associated with LSLR poses two challenges for policy and decision makers trying to formulate adaptation plans: (1) Even a rapid LSLR will seldom exceed a few centimeters per year and will be perceived as slow. Therefore, even in the worst case, realizing climate change-driven LSLR will take decades, and will often be obvious only during storm surges. (2) Predictions of GSLR are highly uncertain, and there is a nonzero probability that the actual GSLR will be outside the projected range of plausible trajectories.

The analysis by Lonsdale et al. (2008) for London shows that extreme scenarios could be highly challenging, even for areas with well-developed institutions. As in the case of London, experts and decision makers are often polarized between two extreme options to reduce the risk: (1) reconfiguring the urban area around the rising sea and (2) building new barriers that would allow the urban areas to continue as today. In many coastal areas, this lack of consensus has the potential for paralysis in response to the low-probability, high-impact extreme LSLR. In the case of rapid LSLR, it could lead to an unplanned response as the existing defense capabilities are overwhelmed. Hence, any extreme, low-probability, high-impact LSLR will likely challenge the existing institutions. Adaptive management is presented by Lonsdale et al. (2008) as an approach to address this challenge. Adaptive management has the ability to react to new information concerning the magnitude and speed of LSLR as that information becomes available. It also helps decision makers not to be overwhelmed by the scientific uncertainties about the trajectory of future LSLs (Craig 2010).

Adaptive management addresses core concerns, which will lead to improvements no matter how LSL is going to change, and at the same time will reduce the risk of disasters if LSL rises significantly. The core concerns for coastal areas identified in the previous sections relate to (1) the availability of potable water; (2) the potential for toxic contamination of water, air, and soil as seawater inundates coastal areas; and (3) potential changes in the exposure to diseases. The first requires drinking water supplies based on resources less prone to salinification, and to reduce other pollution threats for these resources. The second may necessitate changes in land use in the coastal zone and the removal of toxic material and infrastructure from potential inundation areas in the coastal zone. The third might lead to changes in health services and training needs. In each of these areas of core concerns, governments and planners can identify adaptation measures that can be implemented immediately, which will increase resilience and be beneficial to coastal communities independent of the actual impacts of LSLR on these communities.

In the absence of actionable century-scale GSL and LSL predictions, recently, several city managers have indicated that

'early warnings' for a rapid LSL rise with lead times of 5–15 years would provide actionable information for decision makers (e.g., T. Reeder 2009, personal communication). Such short lead times require a continuously operating LSL forecasting on decadal timescales (e.g., Plag et al. 2010). To a certain extent, such a service would be comparable to the ongoing sky watch for near-Earth objects, which aims to provide early detection of the low-probability/high-risk event of a large object approaching Earth. The development of policies and mitigation and adaptation strategies for resilient coastal areas would benefit from an LSL service that combines continuous observations of key components of the Earth system (such as the ice sheets, ice caps, and major glaciers; ocean currents; ocean temperature; land water storage; sea surface height changes; and vertical land motion) with models that assimilate these observations and forecast short-term (years) and intermediate (decades) LSL changes. Such a service is required in order to facilitate adaptive management where and when necessary. Of particular importance is the continuous monitoring of the large ice masses in order to identify any ice masses that enter a state of instability. For these masses, predictions of their disintegration trajectories will be possible. On the basis of such disintegration predictions, LSL can be forecast with the same time horizon as for the ice sheets if a validated ice–ocean–solid-Earth model is available. Likewise, ocean observations will be able to detect the onset of major changes in ocean circulation and heat content affecting GSL and LSL, and validated atmosphere–ocean models will be able to forecast further development on decadal timescales. Living on a reengineered planet with potentially unprecedented rapid changes requires a well-developed monitoring and predictive system to inform decision makers in a timely manner about any pending extreme events.

References

- ACCC, 2006: Inventory of coastal resources vulnerable to climate and shoreline change, background document, Tech. Rep., National Environment Agency and Adaptation to Climate and Coastal Changes Project, GEF/UNDP & UNESCO/IOC.
- Anthoff, D., R. J. Nicholls, R. S. J. Tol, and A. T. Vafeidis, 2006: *Global and regional exposure to large rises in sea-level: a sensitivity analysis*. Work paper 96. Tyndall Centre for Climate Change Research, Norwich, UK.
- Barlow, P. M., 2003: *Ground Water in Fresh Water–Salt Water Environments of the Atlantic Coast, Circular 1262*. U.S. Geological Survey, Reston, Virginia.
- Batstone, C., M. Lawless, K. Horburgh, D. Blackman, and J. Tawn, 2009: Calculating extreme sea level probabilities around complex coastlines: a best practice approach. National Hydrology Seminar 2009: Innovative Approaches in Hydrology – Putting Research into Practice. [Available online at <http://www.opw.ie/hydrology/data/speeches/3 - Calculating extreme sea level probabilities around complex coastlines - A best practice approach.pdf>.]
- Blanchon, P., A. Eisenhauer, J. Fietzke, and V. Liebetrau, 2009: Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. *Nature*, **458**, 881–884. [Available online at <http://dx.doi.org/10.1038/nature07933>.]
- CCSP, 2008: Impacts of climate change and variability on transportation systems and infrastructure: Gulf Coast study, phase I. *A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. M. J. Savonis, V. R. Burkett, and J. R. Potter, Eds., Department of Transportation, Washington, DC, USA, 445 pp.
- Chapman, D., and Coauthors, 2006: Workshop on inundation response: coastal managers needs for coastal and ocean observations, Workshop Report, November 15–16, 2006, Wyndham Baltimore Inner Harbor Baltimore, Maryland.
- Church, J. A., J. M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. T. Nguan, D. Qin, and P. L. Woodworth, 2001: Changes in sea level. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment*

- Report of the Intergovernmental Panel on Climate Change. J. T. Houghton et al., Eds., Cambridge University Press, Cambridge, 639–693.
- Colwell, R. R., 2002: A voyage of discovery: cholera, climate, and complexity. *Environ. Microbiol.*, **4**, 67.
- Craig, R. K., 2010: A public health perspective on sea-level rise: starting points for climate change adaptation. *Widener Law Rev.*, **15** (2), 521–540.
- Dolan, A. H., and I. J. Walker, 2003: Understanding vulnerability of coastal communities to climate change related risks. *J. Coastal Res.*, **SI 39**. Proceedings of the 8th International Coastal Symposium, Itajaí, Brazil, ISSN 0749-0208.
- Donner, S., 2012: Sea level rise and the ongoing battle of Tarawa. *EOS, Trans. Am. Geophys. Union*, **93** (17), 169–176.
- Edwards, R., 2008: Sea levels: science and society. *Prog. Phys. Geogr.*, **32**, 557–574.
- Holland, D. M., R. H. Thomas, D. De Young, M. H. Ribergaard, and B. Lyberth, 2008: Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nat. Geosci.* [Available online at <http://dx.doi.org/10.1038/ngeo316>.]
- Hu, A., G. A. Meehl, W. Han, and J. Yin, 2009: Transient response of the MOC and climate to potential melting of the Greenland ice sheet in the 21st century. *Geophys. Res. Lett.*, **36**, L10707. [Available online at <http://dx.doi.org/10.1029/2009GL037998>.]
- Hulme, M., and Coauthors, 2002: Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tech. Rep., Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK, 120 pp.
- Jacob, T., J. Wahr, W. T. Pfeffer, and S. Swenson, 2012: Recent contributions of glaciers and ice caps to sea level rise. *Nature*. [Available online at <http://dx.doi.org/10.1038/nature10847>.]
- Jacob, K. H., 2007: Climate change: challenge to urban planning, infrastructure, and sustainability – the New York example. Presentation given at the symposium Chronic Risk of Global Climate Change to Urban Coasts and Economies, Hoboken, NJ, November 15–16, 2007. [Available online at <http://www.dezinefusion.com/stevens/>.]
- Jiang, Y., T. H. Dixon, and S. Wdowinski, 2010: Accelerating uplift in the North Atlantic region as an indicator of ice loss. *Nat. Geosci.*, **3**, 404–407. [Available online at <http://dx.doi.org/10.1038/ngeo845>.]
- Karl, T. R., J. M. Melillo, and T. C. Peterson, 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press.
- Katsman, C. A., and Coauthors, 2008: High-end projection for local sea level rise along the Dutch coast in 2100 and 2200, Tech. Rep., Report for the Delta Commission of the Dutch Government.
- Katsman, C. A., and Coauthors, 2011: Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying deltas – the Netherlands as an example. *Clim. Change*. [Available online at <http://dx.doi.org/10.1007/s10584-011-0037-5>.]
- Khan, S. A., J. Wahr, L. A. Stearns, G. S. Hamilton, T. van Dam, K. M. Larson, and O. Francis, 2007: Elastic uplift in southeast Greenland due to rapid ice mass loss. *Geophys. Res. Lett.*, **34**, L21701. [Available online at <http://dx.doi.org/10.1029/2007GL031468>.]
- Kierulf, H. P., H.-P. Plag, and J. Kohler, 2009: Surface deformation induced by present-day ice melting in Svalbard. *Geophys. J. Int.*, **179**, 1–13. [Available online at <http://dx.doi.org/10.1111/j.1365-246X.2009.04322.x>.]
- Lipscomb, W., R. Bindshadler, E. Bueller, D. Holland, J. Johnson, and S. Price, 2009: A community ice sheet model for sea level prediction. *EOS Trans. Am. Geophys. Union*, **90** (3), 23 pp.
- Lonsdale, K. G., T. E. Downing, R. J. Nicholls, D. Parker, A. T. Vafeidis, R. Dawson, and J. Hall, 2008: Plausible responses to the threat of rapid sea-level rise in the Thames Estuary. *Clim. Change*, **91** (1–2), 145–169.
- Lowe, J., and J. M. Gregory, 2005: The effects of climate change on storm surges around the United Kingdom. *Phil. Trans. Royal Soc. A*, **363**, 1313–1328.
- McMichael, A. J., R. E. Woodruff, and S. Hales, 2006: Climate change and human health: present and future risks. *Lancet*, **367**, 859–869. [Available online at [http://dx.doi.org/10.1016/S0140-6736\(06\)68079-3](http://dx.doi.org/10.1016/S0140-6736(06)68079-3).]
- McPhee, M. G., A. Proshutinsky, J. H. Morison, M. Steele, and M. B. Alkire, 2009: Rapid change in freshwater content of the Arctic Ocean. *Geophys. Res. Lett.*, **36**, L10602. [Available online at <http://dx.doi.org/10.1029/2009GL037525>.]
- Meehl, G. A., and Coauthors, 2007: Global climate projections. *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 et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Meier, M. F., M. B. Dyrgerov, U. K. Rick, S. O'Neel, W. T. Pfeffer, R. S. Anderson, and A. F. Glazovsky, 2007: Glaciers dominated eustatic sea-level rise in the 21st century. *Science*, **317**, 1064–1067.
- Morrissey, S. K., J. F. Clark, M. W. Bennett, E. Richardson, and M. Stute, 2008: Effects of sea level rise on groundwater flow paths in a coastal aquifer system. *EOS Trans. Am. Geophys. Union*, **89** (23). Jt. Assem. Suppl., Abstract H41C–07.
- Motyka, R. J., L. Hunter, K. E. Echelmeyer, and C. Conner, 2003: Submarine melting at the terminus of a temperate tidewater glacier, LeConte Glacier, Alaska, USA. *Ann. Glaciol.*, **36**.
- Nicholls, R. J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Chteau, and R. Muir-Wood, 2007a: *Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes*. OECD Environment Working Papers No. 1. OECD Publishing, 63 pp.
- Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe, 2007b: Coastal systems and low-lying areas. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315–356.
- Orbach, M., 2010: Cultural and historical perspectives on sea level rise: our migrating coasts and human communities. Presentation at *Sea Level Rise 2010 Conference*, March 1–3, 2010, Corpus Christi, TX, USA. [Available online at <http://gulfealevel.org>.]
- Patz, J. A., D. Campbell-Lendrum, T. Holloway, and J. A. Foley, 2005: Impact of regional climate change on human health. *Nature*, **438**, 310–317. [Available online at <http://dx.doi.org/10.1038/nature04188>.]
- Pfeffer, W. T., J. T. Harper, and S. O'Neel, 2008: Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science*, **321** (5894), 1340–1343. [Available online at <http://dx.doi.org/10.1126/science.1159099>.]
- Plag, H.-P., 2006: Recent relative sea level trends: an attempt to quantify the forcing factors. *Phil. Trans. Roy. Soc. London, A*, **364**, 1841–1869.
- Plag, H.-P., and S. Jules-Plag, 2012: Cross-cutting threats to human health and healthcare systems: sea level rise and coastal inundation. *Health*. J. Adegoke, and C. Wright, Eds., *Climate Vulnerability*, Vol. 5, Elsevier. (in review)
- Plag, H.-P., W. Hammond, N. M. Tsimplis, and D. Pugh, 2006: Appraisal of relative sea level rise scenarios for Venice. Tech. Rep., Nevada Bureau of Mines and Geology, University of Nevada, Reno. Project Report.
- Plag, H.-P., J. Adegoke, M. Bruno, R. Christian, P. Digiaco, L. McManus, R. Nicholls, and R. van de Wal, 2010: *Observations as decision support for coastal management in response to local sea level changes*. Proceedings of Ocean Obs'09: Sustained Ocean Observations and Information for Society, Vol. 2, Venice, Italy, 21–25 September 2009. J. Hall, D. E. Harrison, and D. Stammer, Eds., ESA Publication WPP-306. [Available online at <http://dx.doi.org/10.5270/OceanObs09.cwp.69>.]
- Reeder, T., 2010: Flood risk and sea level rise in London and the UK. Presentation at *Sea Level Rise 2010 Conference*, March 1–3, 2010, Corpus Christi, TX, USA. [Available online at <http://gulfealevel.org>.]
- Reible, D. D., C. N. Haas, J. H. Pardue, and W. J. Walsh, 2006: *Toxic and contaminant concerns generated by Hurricane Katrina*. Bridge, **36** (1). [Available online at <http://www.nae.edu/Publications/Bridge/TheAftermathofKatrina/ToxicandContaminantConcernsGenerated-byHurricaneKatrina.aspx>.] Accessed 1 April 2012.
- Rignot, E., J. L. Bamber, M. R. van den Broekem, C. Davis, Y. Li, W. J. van de Berg, and E. van Meijgaard, 2008: Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nat. Geosci.*, **1**, 106–110. [Available online at <http://dx.doi.org/10.1038/ngeo102>.]
- Rignot, E., J. E. Box, E. Burgess, and E. Hanna, 2008: Mass balance of the Greenland ice sheet from 1958 to 2007. *Geophys. Res. Lett.*, **35**, L20502.
- Rowley, R. J., J. C. Kostelnick, D. Braaten, X. Li, and J. Meisel, 2007: Risk of rising sea level to population and land area. *EOS Trans. Am. Geophys. Union*, **88** (9), 105, 107.
- Schwerzmann, A., and J. Mehlorn, 2009: The effects of climate change: an increase in coastal flooding damage in Northern Europe. Tech. Rep., Swiss Reinsurance Company Ltd, Munich, Germany.
- Tawn, J. A., and J. M. Vassie, 1989: Extreme sea levels: the joint probability method revisited and revised. *Proc. Inst. Civil Eng.*, **87**, 429–442.
- Titus, J. G., 1990: Greenhouse effect, sea level rise and land use. *Land Use Policy*, **7** (2), 138–153.
- Tol, R. S. J., and Coauthors, 2006: Adaptation to five metres of sea level rise. *J. Risk Anal.*, **9**, 467–482.
- van de Wal, R. S. W., W. Boot, M. R. van den Broeke, C. J. P. P. Smeets, C. H. Reijmer, J. J. A. Donker, and J. Oerlemans, 2008: Large and rapid melt-induced velocity changes in the ablation zone of the Greenland ice sheet. *Science*, **321** (5885), 111–113. [Available online at <http://dx.doi.org/10.1126/science.1158540>.]
- Vellinga, P., 2007: Adaptation of the Dutch Delta to a changing climate. Presentation given at the symposium Chronic Risk of Global Climate Change to Urban Coasts and Economies, Hoboken, NJ, November 15–16, 2007. [Available at <http://www.dezinefusion.com/stevens/>.]
- Warrick, R., and J. Oerlemans, 1990: Sea level rise. *Climatic Change. The IPCC Scientific Assessment*. J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, Eds., Cambridge University Press, 257–282.

- Warrick, R. A., C. I. Provost, M. F. Meier, J. Oerlemans, and P. L. Woodworth, 1996: Changes in sea level. *Climate Change 1995—The Science of Climate Change*. J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds., Cambridge University Press, Cambridge, UK, 359–405.
- Watkins, K., and HDR Team, 2007: *Human Development Report 2007/2008—Fighting Climate Change: Human Solidarity in a Divided World*. Palgrave Macmillan, New York, USA. for United Nations Development Programme. [Available at <http://hdr.undp.org/en/reports/global/hdr2007-2008/>.]
- WHO, 2007: *Communicable Disease Risk Assessment and Interventions – Cyclone Sidr Disaster: Bangladesh November 2007*. Who/hse/epr/dce/2007.6. World Health Organization.
- Yoskowitz, D. W., J. Gibeaut, and A. McKenzie, 2009: *The Socio-Economic Impact of Sea Level Rise in the Galveston Bay Region. A Report for Environmental Defense Fund, Harte Research Institute for Gulf of Mexico Studies*. Texas A&M University-Corpus Christi.
- Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen, 2002: Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, **297**, 218–222.