

Sea-level rise and its possible impacts given a ‘beyond 4°C world’ in the twenty-first century

BY ROBERT J. NICHOLLS^{1,*}, NATASHA MARINOVA², JASON A. LOWE³,
SALLY BROWN¹, PIER VELLINGA², DIOGO DE GUSMÃO⁴, JOCHEN HINKEL^{5,6}
AND RICHARD S. J. TOL^{7,8,9,10}

¹*School of Civil Engineering and the Environment and the Tyndall Centre
for Climate Change Research, University of Southampton,
Southampton SO17 1BJ, UK*

²*Wageningen University and Research Alterra, Wageningen, The Netherlands*

³*Met Office Hadley Centre, Reading Unit, Reading, UK*

⁴*Met Office Hadley Centre, Exeter, UK*

⁵*Research Domain Transdisciplinary Concepts and Methods,
Potsdam Institute for Climate Impact Research (PIK),
Potsdam, Germany*

⁶*European Climate Forum, Potsdam, Germany*

⁷*Economic and Social Research Institute, Dublin, Republic of Ireland*

⁸*Research Unit Sustainability and Global Change, Hamburg University and
Centre for Marine and Atmospheric Science, Hamburg, Germany*

⁹*Institute for Environmental Studies and Department of Spatial Economics,
Vrije Universiteit, Amsterdam, The Netherlands*

¹⁰*Department of Engineering and Public Policy, Carnegie Mellon University,
Pittsburgh, USA*

The range of future climate-induced sea-level rise remains highly uncertain with continued concern that large increases in the twenty-first century cannot be ruled out. The biggest source of uncertainty is the response of the large ice sheets of Greenland and west Antarctica. Based on our analysis, a pragmatic estimate of sea-level rise by 2100, for a temperature rise of 4°C or more over the same time frame, is between 0.5 m and 2 m—the probability of rises at the high end is judged to be very low, but of unquantifiable probability. However, if realized, an indicative analysis shows that the impact potential is severe, with the real risk of the forced displacement of up to 187 million people over the century (up to 2.4% of global population). This is potentially avoidable by widespread upgrade of protection, albeit rather costly with up to 0.02 per cent of global domestic product needed, and much higher in certain nations. The likelihood of protection being successfully implemented varies between regions, and is lowest in small islands, Africa and parts of Asia, and hence these regions are the most likely to see coastal abandonment. To respond to these challenges, a multi-track approach is required, which would also be appropriate if a temperature rise of less than 4°C was

*Author for correspondence (R.J.Nicholls@soton.ac.uk).

One contribution of 13 to a Theme Issue ‘Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications’.

expected. Firstly, we should monitor sea level to detect any significant accelerations in the rate of rise in a timely manner. Secondly, we need to improve our understanding of the climate-induced processes that could contribute to rapid sea-level rise, especially the role of the two major ice sheets, to produce better models that quantify the likely future rise more precisely. Finally, responses need to be carefully considered via a combination of climate mitigation to reduce the rise and adaptation for the residual rise in sea level. In particular, long-term strategic adaptation plans for the full range of possible sea-level rise (and other change) need to be widely developed.

Keywords: sea-level rise; impacts; adaptation; protection; retreat

1. Introduction

Since the emergence of concerns about human-induced global warming in the 1980s, sea-level rise and its impacts on the coastal areas have attracted considerable concern. The large and growing concentration of people and assets in coastal areas mean that the potential impacts are high. It is estimated that at least 600 million people live within 10 m of sea level today [1], and these populations are growing more rapidly than global trends. Populated deltaic areas and many coastal cities are highly threatened by small rises in sea level [2,3]. While in global terms relatively small in number, the very existence of small-island nation states makes them vulnerable to rises in sea level of the order of 1 m [4]. Hence, the magnitude of global sea-level rise during the twenty-first century (and beyond) is of great importance.

Since the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) [5], the possible magnitude of sea-level rise has attracted renewed attention, and a number of authors have suggested that the widely reported numbers in the AR4 underestimate the range of potential sea-level rise during the twenty-first century (e.g. [6,7]). Renewed concerns about the stability of the Greenland and west Antarctic ice sheets reinforce these messages, and at the least, a low-probability, high-consequence rise of sea-level rise of more than 1 m cannot be ruled out during the twenty-first century. This has important and direct implications for coastal society, and more widespread indirect effects in terms of potential disruption and displacement of people, economic activities and economic flows. However, while the equilibrium sea-level rise may scale linearly with temperature, the relationship between temperature and sea level is likely to be nonlinear on century time scales, complicating the analysis of sea-level rise in a rapidly warming world. This is because of the different climate system response times for surface temperature and both heat input to the deep ocean and ice-sheet adjustment. These issues are noted in our analysis of sea-level rise, and our analysis examines sea-level rise and its impacts during the twenty-first century for a range of scenarios, including for a world with a no mitigation policy where the global mean near-surface temperature may reach 4°C by 2100.

Sea-level rise causes a range of impacts for coastal areas, including submergence/increased flooding, increased erosion, ecosystems changes and increased salinization. Based on the exposed population, a large rise in sea level by 2100 could have major impacts, including in the worst-case scenario, a

forced displacement¹ of a large proportion of the coastal population and economy. However, humans also adapt proactively to these changes via a range of measures, which can be characterized as protection, accommodation or (planned) retreat [2,8]. Such adaptation can greatly reduce the possible impacts. Most analyses have contrasted the simplest case of protection versus retreat (or land abandonment). While protection has significant costs, the available analyses suggest that in densely populated coastal areas, protection costs are generally much less than the avoided impacts, and protection generally makes economic sense (e.g. [9,10]). However, this does not mean that protection will take place, and a question remains about its practicality—and proactive adaptation in general, especially in the world's poorest countries, such as most small-island states or sub-Saharan Africa [11]. Looking at the literature, two distinct views concerning protection emerge [12]. The pessimists assume that protection is unaffordable and/or largely fails, and that most potential impacts are realized with sea-level rise leading to large-scale forced displacements of population on an unprecedented scale. This leads to an argument for stringent and immediate climate mitigation and preparation for environmental refugees. The optimists assume that protection will be widespread and largely succeed, and residual impacts will only be a fraction of the potential impacts. Hence, the main consequence of sea-level rise is the diversion of investment into new and upgraded coastal defences and other forms of adaptation (e.g. flood-warning systems). As we consider larger rises in sea level, hence concern that protection and proactive adaptation, in general, may fail, increases, and the potential for the pessimist's view to be realized grows.

This paper explores these issues, with a focus of trying to provide indicative outcomes given a beyond 4°C world. In §2, the science of sea-level rise is reviewed, with special consideration of post-AR4 sea-level-rise scenarios. These are synthesized to develop a potential range of rise by 2100 that is broadly consistent with a beyond 4°C scenario. In §3, the paper develops indicative estimates of the impacts both with and without adaptation. It uses the framework of the Dynamic Interactive Vulnerability Assessment (DIVA) model [13] for this purpose and creates scenarios consistent with the pessimistic and optimistic views that have been defined above. In §4, these results are reviewed in the light of the new synthesis of sea-level rise. Particular attention is addressed to key issues such as vulnerable hotspots in small islands, deltas and coastal cities. Section 5 is a conclusion.

2. Sea-level-rise scenarios for the twenty-first century

(a) *What does the Intergovernmental Panel on Climate Change Fourth Assessment Report tell us?*

In the IPCC AR4, the global surface temperatures at the end of the twenty-first century (2090–2099) are projected to reach higher than 4°C relative to 1980–1999² in three of the Special Report on Emission Scenarios (SRES) emission scenarios:

¹Forced displacement is a (reactive) last-resort retreat response. However, more proactive approaches to adaptation would be preferred which would avoid the large costs and potential conflicts that such forced displacement would engender.

²This is a 4.5°C rise above pre-industrial temperatures.

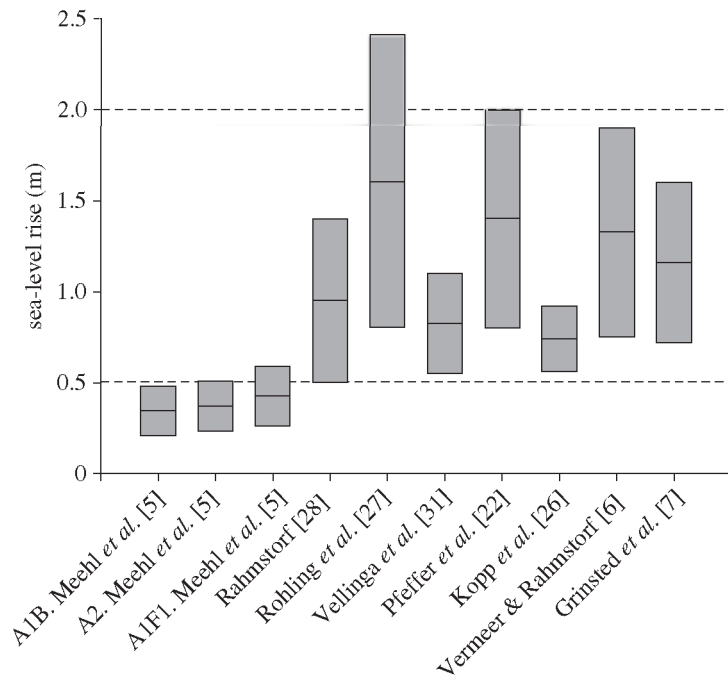


Figure 1. A graphical summary of the range of IPCC AR4 [5] sea-level-rise scenarios (for 2090–2099) and post-AR4 projections (see table 1) possible in a 4°C world. The dotted lines represent the minimum (0.5 m) and maximum (2.0 m) bounds considered in terms of impacts in this study.

A1B, A2 and A1FI [14]. The upper bounds of the temperature in these scenarios are within the range of 4.4°C (A1B scenario) to 6.4°C (A1FI scenario). The upper bounds of projected sea-level rise for these same emission scenarios ranged from 48 to 59 cm (figure 1).³ In those models, a significant portion of this sea-level rise (around 66%) is attributable to thermal expansion, with the contribution from glaciers and small ice caps being the next biggest term. For the A1B scenario, the contribution of the Greenland ice sheet is estimated to be 8 cm, while the contribution from Antarctica is negative at –2 cm owing to the accumulation of extra precipitation on the ice sheet. Thus, the sea-level-rise contributions from ice sheets are considered to be small in these AR4 model projections.

However, prior to the publication of IPCC AR4, some rapid changes were observed on the Greenland and Antarctic continental ice sheets ([14], later published by Rignot *et al.* [15] and van de Wal *et al.* [16]), but in Greenland these high rates were not sustained from 2006 to 2008 [17]. In 2007, these observations of rapid change could not be reproduced by state-of-the-art ice sheet models, forced by outputs from climate models (temperature, precipitation), because there was limited understanding of some key processes and feedbacks between the local climate and the ice sheets. The response of the IPCC was to include an often-overlooked statement that the ‘understanding of some important effects driving sea level rise is too limited ... [to] provide a best estimate or an upper bound for sea level rise’ during the twenty-first century ([18], p. 45). They also provided an illustrative scenario such that if the discharge term was to increase linearly with

³This is based on the 95th percentile from table 10.7 in Meehl *et al.* [5].

temperature, then it could add around 0.1–0.2 m to the projected upper bound for sea-level rise in 2100. This raised the projected upper bounds for the A1B scenario to 61 cm, and that for A1FI to 76 cm, and this has often been interpreted as an upper limit to sea-level rise during the twenty-first century, despite the IPCC statement on the undefined nature of this upper bound. This approach generated extended debates, mainly because the scaled-up values may not fully consider the feedbacks between ice-sheet melting/disintegration and sea level, and hence underestimate the ice-sheet contribution.

A further key question to ask of the IPCC AR4 analysis is how well do the methods reproduce the observed climate change? The observations for the period 1961–2003 are $1.8 \pm 0.5 \text{ mm yr}^{-1}$, while for the period 1993–2003, they are $3.1 \pm 0.7 \text{ mm yr}^{-1}$: the corresponding sums of the simulated sea-level components being 1.1 ± 0.5 and $2.8 \pm 0.7 \text{ mm yr}^{-1}$, respectively, are below these observations [19]. The more satisfactory agreement for the more recent period, during which individual terms are better known and satellite altimetry is available, indicates improvement in understanding. It should also be noted that the observed sea-level rise is following a trajectory at the high end of the SRES projections made in the IPCC Third Assessment Report in 2001 [20,21].

Hence, while we cannot link sea-level rise and temperature rise in a simple manner, a pragmatic choice is to consider 48 cm (or in round terms, 50 cm) as a lower range for the twenty-first century sea-level rise in a beyond 4°C world. In §3, we consider additional evidence to develop an upper estimate of sea-level rise under such warming.

(b) *Why might global mean sea-level rise exceed the Intergovernmental Panel on Climate Change Fourth Assessment Report projection?*

The most often cited mechanism that could cause sea level to increase significantly beyond the IPCC AR4 projected range is the acceleration of ice-sheet discharge above the linear rate used in Meehl *et al.* [5]. Several recent studies have considered this possibility using alternative approaches.

Pfeffer *et al.* [22] explored the kinematic constraints on the contribution of ice-sheet outlet glaciers and ice streams to sea-level rise, comparing the rates required to give more than 2 m of sea-level rise with potential glacier rates. They concluded that an increase of up to 2 m for the twenty-first century cannot be excluded, but a rise of 0.8 m is more likely. Pfeffer *et al.* [22] use simple physical considerations and some extrapolation of the combinations of contributions from Greenland and Antarctica based on varying glacier velocities. Therefore, their estimates should be regarded not as projections, but only as an indication of the physical constraint to the upper bound of global average sea-level rise. For instance, the earlier acceleration of some of the southeast Greenland glaciers had reversed by 2006 [17]. This revived the debate as to whether the recent rates of mass loss are transient or not, and whether they should be extrapolated into the future.

An alternative approach is to examine sea-level rise from a previous epoch when the ice sheets had some similarity with present configurations, and temperatures were similar to those expected during the twenty-first century. One such epoch is the last interglacial period (the Eemian), which occurred between 130 000 and 116 000 years ago. Ice-core data suggest that during the Eemian, global

mean temperature was 2–3°C higher than in the present, while the regional temperatures in Greenland and Antarctic were about 5°C higher [23]. Palaeo-evidence suggests that during the Eemian, the Greenland ice sheet was about 30 per cent smaller than today [24], but with sea levels several metres higher than at present. There is evidence that the Antarctica ice sheet also contributed to this sea-level rise (e.g. [25]). Kopp *et al.* [26] estimated higher Eemian sea levels at between 6 and 9 m above present, with both the Greenland ice sheet and the Antarctic ice sheets significantly smaller than today.

The information from the Eemian is more useful if ice sheet and sea-level estimates can be dated with sufficient accuracy. Based on their palaeo-studies, Kopp *et al.* [26] estimate that the present ice sheets could also contribute about 0.92 m to global sea-level rise per century (with the possibility of higher rates for shorter periods), and this rate could be sustained for centuries. A further estimate of Eemian sea-level rise was provided by Rohling *et al.* [27] using a proxy record from the Red Sea. This reconstruction suggests that sea level rose with rates of 1.6 ± 0.8 m per century providing a constraint on the maximum rate of rise.

(c) The most recent twenty-first century projections

The kinematic and palaeo-studies cited above do not provide projections for the sea-level behaviour in a ‘beyond 4°C’ world. Rather, they provide a guide to the potential maximum rate of sea-level rise under conditions that might be realized during the twenty-first century.

Since the completion of the IPCC AR4, a number of semi-empirical model projections of sea-level rise have been developed. These use present relationships between temperature and sea-level rise combined with climate-model projections of future warming to give an alternative set of future sea-level projections (e.g. [28]). Many of these studies suggest that the upper end of the range of sea-level-rise projections in 2100 could be significantly higher than the IPCC projections (figure 1). However, it must be kept in mind that the semi-empirical approaches assume that the observed relationship between temperature and sea level will continue in the future, given much more rapid warming, yet this may not be the case [29].

Using the correlation between observations of past changes in sea level with temperature changes since the pre-industrial era, Rahmstorf [28] projected a 0.5–1.4 m rise of sea level by 2100, relative to the 1990 level. Vermeer & Rahmstorf [6] refined the method, adding a rapid-response term, which gives an upper value of 1.90 m in 2100 (excluding the uncertainty of the statistical fit of $\pm 7\%$). Other semi-empirical approaches are also available that use slightly different formulations and statistical methods, such as Grinsted *et al.* [7]. These authors also include palaeo-constraints from preceding centuries, and project a future increase in sea level of up to 1.6 m for the twenty-first century for the SRES A1FI emissions scenario.

Some studies have been undertaken to directly support long-term flood-management responses to sea-level rise. In The Netherlands, the Delta Commission [30] requested an international assessment to explore the upper boundaries of the possible rise and to develop low-probability/high-impact scenarios for the years 2050, 2100 and 2200. This used both modelling and expert-judgement approaches, and assumed a large temperature rise of 6°C by 2100 [31].

Table 1. Range of global sea-level rise (metre per century) according to post-AR4 research.

sea-level rise (metre per century)	methodological approach	source
0.5–1.4	semi-empirical projection ^b	Rahmstorf [28]
0.8–2.4 ^a	palaeo-climate analogue	Rohling <i>et al.</i> [27]
0.55–1.10	synthesis ^b	Vellinga <i>et al.</i> [31]
0.8–2.0	physical-constraint analysis ^b	Pfeffer <i>et al.</i> [22]
0.56–0.92 ^a	palaeo-climate analogue	Kopp <i>et al.</i> [26]
0.75–1.90	semi-empirical projection ^b	Vermeer & Rahmstorf [6]
0.72–1.60 ^c	semi-empirical projection ^b	Grinsted <i>et al.</i> [7]

^aHigher rates are possible for shorter periods.

^bFor the twenty-first century.

^cFor the best palaeo-temperature record.

Expert judgement is a useful technique as it provides a mechanism to capture important, but poorly understood, processes such as the ice-sheet response (cf. [32]), although it often expands the uncertainties. As a starting point, Vellinga *et al.* [31] used recent observations which imply that higher contributions from the two ice sheets are possible and took the palaeo-reconstruction of Rohling *et al.* [27] as an upper constraint. They concluded that plausible global sea-level-rise scenarios were 0.55–1.10 m in 2100, and 1.5–3.5 m in 2200 (these estimates were then used as a base for developing local sea-level-rise scenarios for The Netherlands by taking into consideration other components such as geoidal changes, vertical land movement and storm surges).

The UK Met Office also developed a low-probability, high-impact range of sea-level rise scenarios, called the H++ scenario, to explore impacts and adaptation responses above the IPCC AR4 range. This was applied in the Thames Estuary 2100 Project (TE2100), which concerned the future flooding of London, and then adopted to national scenario guidance [33]. It used research from Rohling *et al.* [27] and Pfeffer *et al.* [22] as constraints, and accounted for the recent observed rapid changes in the two ice sheets. Overall, it adopted a maximum global rise of 2.5 m by 2100. (Allowing for geoidal changes (the necessity of which is discussed by Mitrovica *et al.* [34]) resulted in a sea-level rise around the UK of between 0.93 and 1.9 m during the twenty-first century.) However, Lowe *et al.* [33] also concluded that there is evidence that such a large increase should be considered very unlikely to occur during the next 100 years (see also [29]).

Based on a selection of the recent studies we have considered, table 1 summarizes the range of estimates for century-scale sea-level rise from a range of methods. While such estimates are possible, this should not be interpreted as being likely. What is likely, however, is that higher rates of sea-level rise will result from warmer temperatures.

The possibility of reversibility of large changes in ice sheets, and their corresponding contribution to sea level, is also important. Gregory *et al.* [35] concluded that a local warming of above $2.7 \pm 0.5^\circ\text{C}$ (average annual temperature rise related to 1990) would cause irreversible loss of the Greenland ice sheet. The approximate magnitude for this threshold is supported by results from the last

interglacial period when temperatures were a few degrees warmer than today, and the Greenland ice sheet was smaller (see §2*a*), although Hansen [36] suggests that a lower threshold should be used. A recent study by Ridley *et al.* [37] suggests that a higher warming could be sustained, but only for a short period of time. Because of the presence of large uncertainties, AR4 did not assign a temperature threshold for the irreversible melt of the vulnerable west Antarctic ice sheet. However, Lenton *et al.* [38] suggested that it would be in the range of 5–8°C local warming, corresponding to 3–5°C global warming, if evidence, such as the disintegration of ice shelves along the Antarctic Peninsula and the crevasse/meltwater hypothesis [39,40], were taken into consideration. Equally, marine ice-sheet instability may be triggered by (ocean) temperature rise, but once started, it may be rather insensitive to the actual atmospheric temperature rise that is achieved [41].

(*d*) Summary

Our review of high-end post-AR4 sea-level projections suggests that a credible upper bound of twenty-first century sea-level rise is of the order of 2 m. Combined with the earlier estimates of sea-level-rise scenarios from the AR4, this suggests a pragmatic range of 0.5–2 m for twenty-first century sea-level rise, assuming a 4°C or more rise in temperature. However, since it is not certain that recent observed increases in ice discharge from the ice sheets will continue to accelerate, we must also be clear that the upper part of this range is considered unlikely to be realized. As advocated by Solomon *et al.* [14] and Lowe & Gregory [29], among others, while such uncertainty remains, it is fundamental to continue monitoring sea level to detect any large or unexpected accelerations of rise. In parallel, developments of process-based models could improve the robustness of projections. We also note the conclusions of Rahmstorf *et al.* [20] and Pielke ([21], p. 206) that ‘Once published, projections should not be forgotten but should be rigorously compared with evolving observations’.

Finally, we have focused on the range of uncertainty in the recent rate of global mean sea-level rise. The IPCC AR4 analysis also highlighted the significant spread in projected spatial patterns of sea-level rise. While there is a growing understanding of what drives regional sea-level rise [42], there still remains a large spread in the deviations of regional sea-level rise from the global mean value [43]. The uncertainty in oceanic density changes could be up to several tens of centimetres from the global mean value, depending on the location. A further local contribution would be required in scenarios with larger ice melt owing to gravitational changes [34,44–46]. Finally, the non-climate component of sea-level rise owing to subsidence could also be substantial (e.g. due to water abstraction), most especially in susceptible deltas where human groundwater withdrawal and sediment starvation can be greatly enhanced [11,47,48], and this also needs to be considered.

3. Sea-level-rise impacts and adaptation responses

The previous section showed that a global rise in sea level of 0.5–2.0 m by 2100 is consistent with a beyond 4°C world. To explore the possible impacts with and without a protection response, the potential impacts of a 0.5 and 2 m global mean rise in sea level by 2100 are now assessed as bounding cases using the DIVA

model framework. These sea-level-rise scenarios are downscaled using estimates of glacial isostatic adjustment from Peltier [49,50] and natural subsidence in deltas, assumed as 2 mm yr^{-1} . It is recognized that using a global-mean scenario is an idealized assumption. However, it follows all previous published impact assessments, and hence is broadly comparable with these earlier results. Further, unpublished results, which have examined impacts under a range of realistic sea-level-rise patterns, indicate that while the uncertainty in the impacts rises when this factor is considered, there is little systematic change to the results (e.g. [51,52]). The results are most sensitive to deviations around south, southeast and east Asia, as this is the region where the largest coastal population occurs. Hence, the use of global-mean scenarios is an appropriate simplification for this exploratory analysis. In all cases, the sea-level-rise scenarios are combined with a temperature scenario exceeding a 4°C rise and with the A1B⁴ socioeconomic scenario in all cases [53].

In the analysis, impacts and adaptation costs are both assessed for assumptions that are consistent with the pessimist's and optimist's perspectives, respectively. The 'pessimists' and the 'optimists' generally accept the high-impact potential of sea-level rise, although pessimists may stress larger rise scenarios. They disagree much more on adaptation, especially protection. Pessimists view protection as being infeasible and likely to fail. Hence, actual impacts are similar to the exposure, leading to high impacts, numerous disasters, and an unplanned and forced retreat. In contrast, optimists view protection as likely to be applied in developed areas and likely to be successful. Hence, actual impacts are much smaller than the potential impacts, but there are significant adaptation costs. Below, impacts without and with adaptation are compared to illustrate the pessimistic and optimistic views, respectively.

(a) The Dynamic Interactive Vulnerability Assessment model

The DIVA model is an integrated model of coastal systems that assesses biophysical and socioeconomic impacts driven by climate change and socioeconomic development⁵ ([13,54]; <http://diva-model.net>). The climatic scenarios comprise temperature and most importantly, sea-level change, while the socioeconomic scenarios comprise coastal population, gross domestic product (GDP) and land-use change. In DIVA, there are an explicit range of adaptation options. Hence, unlike most published assessments of sea-level rise (e.g. [55]), impacts do not solely depend upon the selected climatic and socioeconomic scenarios, but also on the selected adaptation strategy, with a no upgrade/adaptation strategy being one option. Here, only the flooding/submergence and erosion aspects of DIVA are considered. These are

⁴The A1T, A1B and A1FI population and GDP scenarios are essentially the same, with a major difference being assumptions about the main energy sources. The A1 population peaks in 2050 and declines thereafter. The B1 population scenario is the same as the A1 population. The B2 and especially the A2 socioeconomic scenarios have larger populations and hence would give a larger coastal population.

⁵Here, DIVA v. 2.0.4 is used combined with DIVA database v. 1.3, where elevation is derived from the GTOPO30 dataset.

discussed in more detail by Tol *et al.* [56] and Hinkel *et al.* [57], respectively, while the underlying model database and spatial structure are explained by Vafeidis *et al.* [58].

Both direct and indirect coastal erosion are assessed. The direct effect of sea-level rise on coastal erosion is estimated using the Bruun rule (e.g. [59]). Sea-level rise also affects coastal erosion indirectly as tidal basins become sediment sinks under rising sea level, trapping sediments from the nearby open coast into tidal basins [60]. This indirect erosion is calculated using a simplified version of the aggregated scale morphological interaction between a tidal basin and the adjacent coast (ASMITA) model (e.g. [61]). About 200 of the largest tidal basins around the world are considered. DIVA considers beach/shore nourishment as the adaptation response to erosion. In beach nourishment, the sand is placed directly on the intertidal beach, while in shore nourishment, the sand is placed below low tide, where the sand is expected to progressively feed onshore owing to wave action, following the recent Dutch practice [62]. The way these options are applied is discussed further below.

The flooding and submergence of the coastal zone caused by mean sea-level rise and associated storm surges is assessed for both sea and river floods. Large parts of the coastal zone are already threatened by extreme sea levels produced during storms, such as shown by Hurricane Katrina (USA, 2005), Cyclone Nagris (Burma, 2008) and Storm Xynthia (France, 2010). These extreme events are produced by a combination of storm surges and astronomical tides, and the return period of extreme sea levels is reduced by higher mean sea levels. Sea-level rise also raises water levels in the coastal parts of rivers (via the backwater effect), increasing the probability of extreme water levels. DIVA considers both these flooding mechanisms. In the analysis, the present storm-surge characteristics are displaced upwards with the rising sea level, which implies no change to the intensity or frequency of coastal storms or interaction between sea level and tidal and surge characteristics. This assumption follows twentieth and early twenty-first century observations of mean and extreme sea level (e.g. [63–66]). Taking into account the effect of dikes, flood areas for different return periods are estimated. This is done by estimating the change in safety, assuming that a dike system is present (cf. [67,68]), and dike construction/upgrade is the adaptation option for flooding and submergence. There is no empirical data on the baseline level of safety at a global level, so a demand for safety function is used as explained below, and the safety is assumed to be provided by dikes. Based on dike height, land elevation and relative sea level, the frequency of flooding can be estimated over time. This is further converted into people flooded and economic flood damages based on population density and GDP (see below). River flooding is evaluated in a similar fashion along 115 major rivers.

DIVA also estimates the social and economic consequences of the physical impacts described above. For this paper, the *number of people displaced* by sea-level rise can be estimated owing to a combination of erosion and increased flooding. In the case of flooding, a threshold return level needs to be assumed to define abandonment. This has been set at a greater than a 1 in 1 year frequency of flooding. If a lower frequency of flooding (e.g. 1 in 10 year) was selected, the land area lost and the number of people displaced would be reduced.

DIVA computes impacts both without and with adaptation. Without adaptation, DIVA computes potential impacts in a traditional impact-analysis manner. In this case, dike heights are maintained at 1995 levels, but not raised, so flood risk rises with time as relative sea level rises. Beaches and shores are not nourished. With adaptation, dikes are raised based on the demand function for safety [69], which is increasing in *per capita* income and population density, but decreasing in the costs of dike building [70]. Dikes are not applied where there is very low population density (less than 1 person km⁻²), and above this population threshold, an increasing proportion of the demand for safety is applied. Half of the demand for safety is applied at a population density of 20 persons km⁻² and 90 per cent at a population density of 200 persons km⁻².

With adaptation, beaches and shores are nourished according to a cost-benefit analysis that balances costs and benefits (in terms of avoided damages) of adaptation. Shore nourishment has lower costs than beach nourishment, but is not widely practised at present and has the disadvantage of not immediately enhancing the sub-aerial beach. Beach nourishment is therefore the preferred adaptation option, but only if the tourism revenue is sufficient to justify the extra costs. The number of tourists and their spending follows the Hamburg tourism model (HTM), an econometric model of tourism flows [71,72]. In the HTM, tourism numbers increase with population and income. Climate change pushes tourists towards the poles and up the mountains.

Adaptation costs are estimated for the two adaptation options considered: dike building and beach nourishment. Initially, unit dike costs are taken from the global vulnerability assessment carried out by Hoozemans *et al.* [67]. Given that sea-level rise is up to 2 m, the dike costs for this scenario are raised offline to take account of the larger cross section that is required: a dike required in response to a 2 m rise in sea level is assumed to be four times the cost of that required for a 1 m rise in sea level (it is assumed that dikes of up to 1 m in height have a similar cost; cf. [73]). DIVA only considers the capital cost of dike construction, but maintenance costs are approximately 1 per cent per annum, and as the capital stock grows, so the maintenance costs can become significant. Hence, maintenance costs are considered here as an offline calculation. The costs of beach nourishment were derived by expert consultation with Delatares (formerly Delft Hydraulics). Different cost classes are applied, depending on how far the sand for nourishment needs to be transported, as this is a significant determinant of such costs. It is assumed that sufficient sand resources are available for nourishment purposes throughout the twenty-first century.

It is important to note that the purpose of the adaptation strategies described above is not to compute an optimal adaptation policy, but to model how coastal managers could respond to sea level rise. The complementary adaptation strategies serve the same purpose as the climate and socioeconomic scenarios, i.e. to explore possible futures. DIVA's different adaptation strategies show how different assumptions made about the behaviour of coastal planners translate into differences in impacts and adaptation costs. This interpretation can be enriched using the results from the climate framework for uncertainty, negotiation and distribution (FUND) model [74], which employs a benefit-cost approach. FUND estimated that 25 per cent of the developed coastal zone is abandoned if the costs of protection increased fourfold [73], and this correction is applied for the 2 m rise scenario.

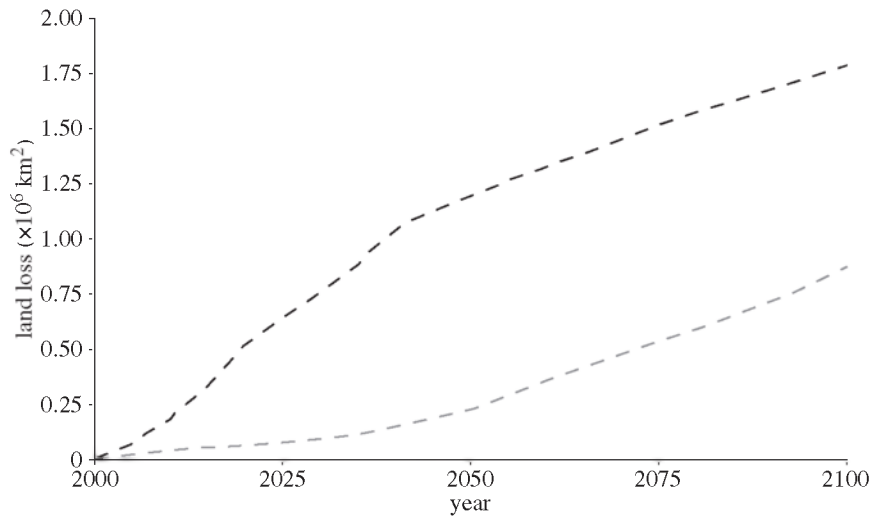


Figure 2. Global dryland losses according to the DIVA model assuming no adaptation for a 0.5 m (grey lines) and a 2.0 m (black lines) rise in sea level by 2100.

(b) *The pessimist's versus the optimist's view*

Results for a world where adaptation is not implemented/fails versus a world with successful adaptation are now contrasted for selected parameters.

Assuming no adaptation, of the two land-loss mechanisms considered in DIVA, submergence is a much larger contribution to the loss than erosion. Under these conditions, land loss amounts to a total of 877 000–1 789 000 km² for a 0.5 and 2.0 m rise in sea level, respectively (figure 2). This amounts to approximately 0.6–1.2% of the global land area. The net population displaced by this rise is more significant, being estimated at 72 and 187 million people over the century, respectively (roughly 0.9–2.4% of the global population). This reflects the high population density in coastal areas.⁶ The results are consistent with the literature on environmental refugees (e.g. [75]), which forecasts large population displacements owing to sea-level rise. Most of the threatened people are concentrated in three regions in Asia: east, southeast and south Asia (figure 3). Given 0.5–2 m rise in sea level, a total of 53–125 million people are estimated to be displaced over the century from these three regions alone. In the three small-island regions (Caribbean, Indian Ocean and Pacific Ocean), 1.2–2.2 million people are displaced over the century, with all three regions contributing significantly. It is noteworthy that impacts in some regions such as north and west Europe and the North America Atlantic Coast, impacts are much greater for a 2.0 m scenario than for a 0.5 m scenario. This reflects that pre-existing defences provide benefits for a 0.5 m rise, but are overwhelmed by a 2.0 m rise.

⁶Note that the socioeconomic scenarios used here assume no coastward migration: if coastward migration does continue in the coming decades, the impact potential would be amplified.

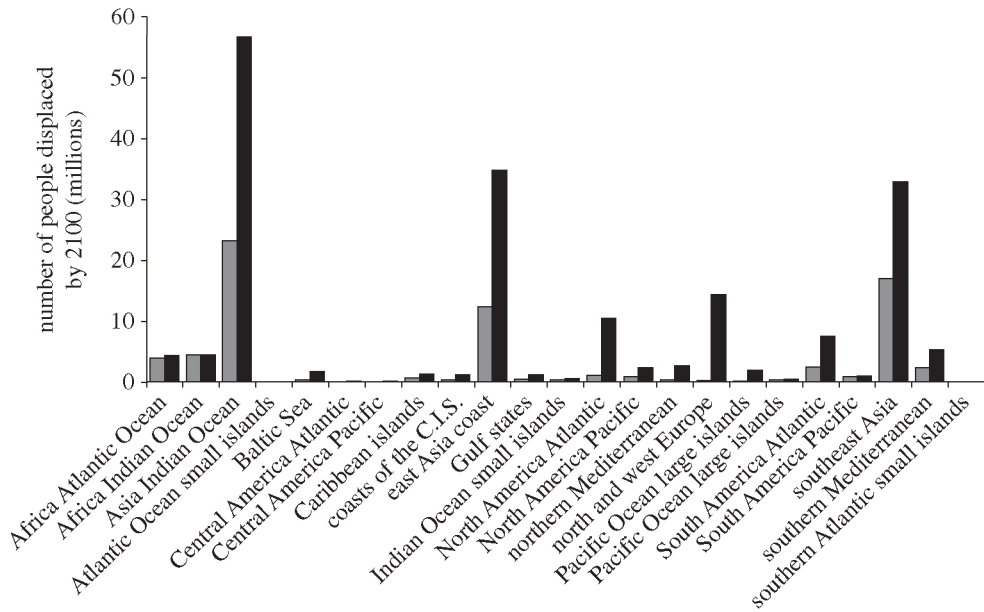


Figure 3. The distribution of net population displacement over the twenty-first century by region assuming no protection for a 0.5 m (grey bars) and a 2.0 m (black bars) rise in sea level. C.I.S., Commonwealth of Independent States.

If we assume protection with dikes and nourishment, the number of displaced people falls dramatically to comparatively minor levels of 41 000–305 000 people displaced over the twenty-first century. Hence, in contrast to the no-protection scenario, the problem of environmental refugees almost disappears.

The costs of protection are zero if we assume no protection. In contrast, the dike and nourishment responses have substantial costs. The incremental adaptation costs⁷ are estimated at roughly between US \$25 and \$270 billion (1995 values) per annum for 0.5 and 2.0 m in 2100, respectively. Dike costs dominate these response costs, and dike maintenance becomes an increasing component of the costs over time. This illustrates an important long-term consequence of a widespread protection response to sea-level rise that will continue to grow beyond 2100. In 2100, the relative mix of nourishment, dike construction/upgrade and dike maintenance costs is 36, 39 and 25 per cent; and 13, 51 and 37 per cent for the 0.5 and 2.0 m rise in sea level, respectively. The regional spread of these costs is quite variable with east Asia, North America Atlantic, North America Pacific, north and west Europe and South America Atlantic being the five regions with the highest costs (figure 4). In terms of avoided human displacement as a function of protection investment, not surprisingly, the benefits are highest in the regions with most threatened people: east Asia, south Asia and southeast Asia. It directly affects those on the coast, but also has knock-on effects further inland.

⁷Hence, these results assume an existing adaptation infrastructure that can be upgraded. If this is not the case, this is termed an ‘adaptation deficit’, which will require further investment to address [76,77].

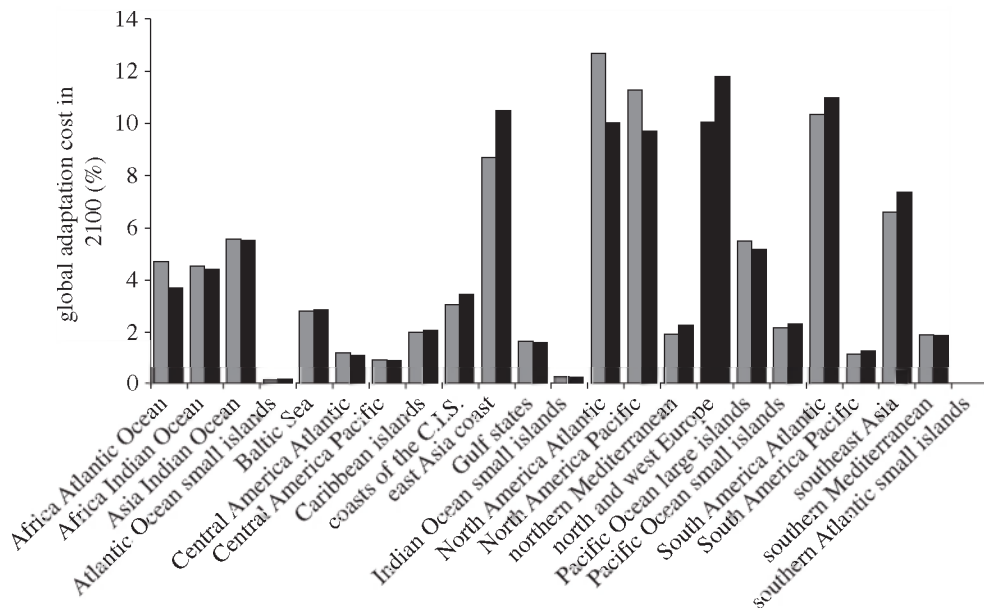


Figure 4. The annual protection cost by coastal region in 2100, as a percentage of global protection investment for a 0.5 m (grey bars) and a 2.0 m (black bars) rise in sea level by 2100.

4. Discussion

Section 2 showed that a sea-level rise of between 0.5 and 2.0 m is not an implausible range of climate-induced global rise in sea level in a 4°C world. Owing to our poor understanding of the underlying processes driving climate-induced sea-level rise, we cannot associate any likelihood with this range, and we conclude that rises above 0.5 m and especially 1 m by 2100 are possible, rather than inevitable. However, it is important to consider what would happen and what responses are available if such large changes did occur: in effect, there is a poorly understood potential for a high-consequence rise in global sea-level rise that is of significant interest to those concerned about coastal impacts and adaptation.

The results presented in §3 investigate the issue of impacts and adaptation assuming a rise in sea level between 0.5 and 2.0 m with or without upgraded protection by 2100. The results are indicative and are designed to provide an overview of their implications: they bracket the range of impacts and adaptation costs that might occur with intermediate sea-level-rise scenarios and partial-protection scenarios. They show that in addition to the uncertainty about sea-level rise, the outcome is very sensitive to our assumptions about protection. Without further upgrade to protection (no adaptation), sea-level rise will erode and more particularly flood and submerge extensive low-lying coastal areas displacing tens to millions of people or more by 2100. This would be a highly undesirable future world with many millions of forced environmental refugees owing to sea-level rise alone. In contrast, assuming a protection response, the impact of sea-level rise is mainly felt in terms of increasing protection costs. Hence, in developed coastal areas, a higher rise in sea level translates into a

larger protection cost. While the residual impacts would also rise, this is minor in magnitude when compared with a no-protection scenario (cf. [10]), and this is not evaluated here. So in conclusion, there is great uncertainty about the magnitude and sources of impacts and costs under high sea-level-rise scenarios.

Climate mitigation remains a viable strategy to avoid the 4°C world considered in this paper [78]. Reducing temperature rise reduces the magnitude of sea-level rise, although importantly, stabilizing global temperatures does not stabilize sea level. Rather, it stabilizes the rate of sea-level rise, a process that has been termed the ‘commitment to sea-level rise’ [5]. Hence, a need to adapt to sea-level rise would remain even under mitigation, and mitigation and adaptation policies are more effective when combined in coastal areas: mitigation reduces the rate of sea-level rise to a manageable level and adaptation is required for the remaining rise [2]. At present, the appropriate mix of mitigation and adaptation is not well understood, partly because scenarios of sea-level rise under different stabilization trajectories are poorly developed as already discussed, and partly because of uncertainty about adaptation. Combined with the uncertainties in sea level already discussed in §2, this is an important area for further research.

Without mitigation, the fundamentally different outcomes come down to how successful adaptation, and protection in particular, might be. While there is extensive literature in both the camps, which this paper has termed the ‘pessimists’ and the ‘optimists’, respectively, there has been little attempt to reconcile these two perspectives and really understand coastal adaptation as a systematic process [10,12]. The ‘pessimists’ seem to take it as read that adaptation will either fail or people will not even try to adapt. In contrast, the ‘optimists’ appear overly confident that benefit–cost approaches describe human behaviour in response to threats such as sea-level rise [3,10]. Both views can find empirical evidence to support them. In particular, the response to relative sea-level rise in subsiding coastal cities support the optimist’s perspective as they have all been protected, rather than fully or even partially abandoned. This includes cities in developing countries such as Bangkok in Thailand. However, adaptation failure cannot be ruled out, and major disasters such as Hurricane Katrina in 2005 and its impact on New Orleans certainly suggest caution. New Orleans’ defences are now largely rebuilt and upgraded to a much higher standard than before Katrina at a cost of US \$15 billion [79], but it is too early to assess the long-term effect of Katrina on the city (cf. [80]). In more general terms, it is certainly plausible that extreme events can trigger a cycle of decline and ultimately coastal abandonment [81]. Much more research on adaptation in coastal areas, including protection, is required. Historical analogue studies could be especially valuable.

Vulnerability to sea-level rise is not uniform and small islands, Africa and south, southeast and east Asia are recognized as the most vulnerable regions [11]. This reflects their high and growing exposure and low adaptive capacity. These regions are the areas where protection is most likely to not occur or fail, and they collectively contain a significant proportion of potential environmental refugees, especially the Asian regions (figure 3). Many of the people in Asia live in deltas, which are extensive and often subsiding coastal lowlands, amplifying global changes and making them more challenging environments for adaptation [47,48,82]. Small islands have relatively small population and given that implementing protection could also present significant problems, forced abandonment seems a feasible outcome for small changes in sea level (e.g. [83]).

Hence, the threats to these vulnerable regions provide some of the strongest arguments for mitigation to avoid a 4°C world. In addition, adaptive capacity needs to be enhanced in these vulnerable regions, regardless of the magnitude of sea-level rise. Realistic assessments of responses are required across the spectrum of adaptation: at the extreme, planned retreat is to be preferred to forced abandonment.

To date, there are only two strategic attempts to plan long-term adaptation to sea-level rise and these are both in the developed world: (i) the Thames Estuary 2100 (TE2100) Project [33], which considers flood management in London and its environs, and (ii) the Delta Commission [30], which considers the future of The Netherlands under sea-level rise. As already noted, both studies were prepared to consider quite large rises in sea level—much larger rises than quantified in the IPCC AR4. In both cases, the problem was constructed as one where high uncertainty is inherent, and it is fundamental to evaluate the low-probability high-consequence scenarios. In TE2100, a scenario-neutral analysis was followed, where the flood-management system was tested against sea-level-rise scenarios of up to 5 m, without worrying about the timing of this rise. Hence, a progressive sequence of adaptation measures could be identified that would manage the range of sea-level rise. Issues of the timing of adaptation have been analysed subsequently. The Delta Commission took a slightly different approach and looked to 2200 and estimated that sea levels might be up to 3.5 m higher than today [31]. However, both studies came to the conclusion that improved/upgraded protection was the best approach in their study sites, although both projects aspire to work with, and mimic nature as much as possible within this goal. The principles illustrated here should be applied much more widely—coastal cities with a large exposure to flooding are widespread, especially in Asia and North America [73]. More generic analyses of adaptation are also useful such as the World Bank [77] assessment of the economics of adaptation to climate change. Broad-scale studies could also be more developed, including responding to large rises in sea level as considered in this paper.

5. Conclusions

Climate-induced rise of relative sea level during the twenty-first century could be larger than the widely reported absolute numbers published by the IPCC AR4 [5,18], and a rise of up to 2 m is not implausible but of unquantifiable probability. In essence, there is a low-probability/high-consequence tail to the sea-level scenarios, although we have no basis to evaluate what that probability might be. While the IPCC AR4 report also acknowledges this fact, the presentation failed to communicate this important point effectively, and most readers of the IPCC assessments failed to notice this caveat concerning the published scenarios. From the perspective of those interested in impact and adaptation assessments, this is an important failure that we hope the next IPCC assessment will explicitly address.

Linking sea-level rise to temperature rise is difficult and there is not a simple relationship between the two factors. Hence, the sea-level-rise scenarios for a 4°C rise in temperature is uncertain, and a 0.5–2.0 m global rise in sea level has been selected as a pragmatic range to associate with such a temperature rise.

The human exposure is very large, reflecting the high population density in the coastal zone. Assuming no or failed adaptation, this exposure translates into catastrophic impacts with tens of millions or even more people being turned into environmental refugees owing to sea-level rise. In contrast, a protection response suggests that most of the threatened population would be protected, and the main consequence of a large rise in sea level is a larger investment in protection infrastructure. This analysis shows that it is incorrect to automatically assume a global-scale population displacement owing to a large rise in sea level, and coastal populations may have more choices than widely assumed. However, the more vulnerable locations such as small islands and populated deltas will be severely challenged by large rises in sea level, and the most appropriate adaptation responses, including protection, require more analysis.

Nicholls *et al.* [2] argued that the response to sea-level rise required a combination of adaptation for the inevitable rise, and mitigation to limit the inevitable rise of sea level to manageable magnitudes. This reflects the large inertia of sea-level rise, which means stabilizing global temperature in order to stabilize the rate of rise. Even so, rising sea levels will continue for centuries into the future. This analysis supports this view, as adaptation is more likely to succeed for smaller rises in sea level consistent with stringent mitigation. Better quantification of future sea levels and their links to temperature rise, including the role of the large ice sheets, is clearly important. Coastal adaptation requires more planning and there will be a debate about what allowances should be made for sea-level rise. The long-term vision of the Thames Estuary 2100 project [33] and the Delta Commission [30] are to be commended. These schemes are establishing a flexible approach to management where there is some upgrading of defences and a logical sequence of additional measures to reduce risk. This will be combined with monitoring of sea level so that the timing of further upgrades can be optimized. This type of adaptation planning needs to be applied much more widely in terms of developing a coherent strategy to deal with an uncertain rise in sea level over the next 100–200 years.

R.J.N. and S.B. were partly supported by the UK Natural Environment Research Council (NERC), under the QUEST programme (grant number NE/E001882/1). R.J.N., S.B., J.H. and R.S.J.T. were partly supported by the European Commission (DG Research) Seventh Framework Programme, as part of the Climate Cost Project (Full Costs of Climate Change, grant agreement 212774), www.climatecost.eu. N.M. and P.V. were supported by the Dutch KB2 programme 'IPOP Zee en Kust'. J.A.L. and D.d.G. were supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme (GA01101).

References

- 1 McGranahan, G., Balk, D. & Anderson, B. 2007 The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urbanisation* **19**, 17–37. (doi:10.1177/0956247807076960)
- 2 Nicholls, R. J., Wong, P. P., Burkett, V. R., Codignotto, J. O., Hay, J. E., McLean, R. F., Ragoonaden, S. & Woodroffe, C. D. 2007 Coastal systems and low-lying areas. In *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), pp. 315–357. Cambridge, UK: Cambridge University Press.
- 3 Nicholls, R. J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Chateau, J. & Muir-Wood, R. 2008 Ranking port cities with high exposure and vulnerability

- to climate extremes: exposure estimates. Environment working paper no. 1. Organization for Economic Co-operation and Development, Paris.
- 4 Mimura, N., Nurse, L., McLean, R. F., Agard, J., Briguglio, L., Lefale, P., Payet, R. & Sem, G. 2007 Small islands. In *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), pp. 687–716. Cambridge, UK: Cambridge University Press.
 - 5 Meehl, G. A. *et al.* 2007 Global climate projections. In *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller), pp. 433–497. Cambridge, UK: Cambridge University Press.
 - 6 Vermeer, M. & Rahmstorf, S. 2009 Global sea level linked to global temperature. *Proc. Natl Acad. Sci. USA* **106**, 21 527–21 532. (doi:10.1073/pnas.0907765106)
 - 7 Grinsted, A., Moore, J. C. & Jevrejeva, S. 2009 Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Clim. Dyn.* **34**, 461–472. (doi:10.1007/s00382-008-0507-2)
 - 8 Klein, R. J. T., Nicholls, R. J., Ragoonaden, S., Capobianco, M., Aston, J. & Buckley, E. H. 2001 Technological options for adaptation to climate change in coastal zone. *J. Coastal Res.* **17**, 531–543.
 - 9 Sugiyama, M., Nicholls, R. J., Vafeidis, A. T. 2008 Estimating the economic cost of sea-level rise. MIT global change joint program publications, report no. 156. See http://mit.edu/global_change/www/MITJPSPGC_Rpt156.pdf.
 - 10 Anthoff, D., Nicholls, R. J. & Tol, R. S. J. 2010 The economic impact of substantial sea-level rise. *Mitigation Adaptation Strat. Glob. Change* **15**, 321–335. (doi:10.1007/s11027-010-9220-7)
 - 11 Nicholls, R. J. & Cazenave, A. 2010 Sea-level rise and its impact on coastal zones. *Science* **328**, 1517–1520. (doi:10.1126/science.1185782)
 - 12 Nicholls, R. J. & Tol, R. S. J. 2006 Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. *Phil. Trans. R. Soc. A* **364**, 1073–1095. (doi:10.1098/rsta.2006.1754)
 - 13 DINAS-COAST Consortium. 2006 *DIVA 1.5.5*. Potsdam, Germany: Potsdam Institute for Climate Impact Research (on CD-ROM).
 - 14 Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L. (eds) 2007 *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
 - 15 Rignot, E., Bamber, J. L., van den Broeke, M. R., Davis, C., Li, Y., van de Berg, W. J. & van Meijgaard, E. 2008 Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nat. Geosci.* **1**, 106–110. (doi:10.1038/ngeo102)
 - 16 van de Wal, R. S. W., Boot, W., van den Broeke, M. R., Smeets, C. J. P. P., Reijmer, C. H., Donker, J. J. A. & Oerlemans, J. 2008 Large and rapid melt-induced velocity changes in the ablation zone of the Greenland ice sheet. *Science* **321**, 111–113. (doi:10.1126/science.1158540)
 - 17 Kerr, R. A. 2009 Galloping glaciers of Greenland have reined themselves in. *Science* **323**, 458. (doi:10.1126/science.323.5913.458a)
 - 18 Intergovernmental Panel on Climate Change (IPCC). 2007 *Climate change 2007: synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.
 - 19 Bindoff, N. L. *et al.* 2007 Observations: oceanic climate change and sea level. In *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller), pp. 385–432. Cambridge, UK: Cambridge University Press.
 - 20 Rahmstorf, S., Cazenave, A., Church, J., Hansen, J., Keeling, R., Parker, D. & Somerville, R. 2007 Recent climate observations compared to projections. *Science* **316**, 709. (doi:10.1126/science.1136843)

- 21 Pielke, R. 2008 Climate predictions and observations. *Nat. Geosci.* **1**, 206. (doi:10.1038/ngeo157)
- 22 Pfeffer, W., Harper, J. & O'Neel, S. 2008 Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* **321**, 1340–1343. (doi:10.1126/science.1159099)
- 23 Jansen, E. *et al.* 2007 Palaeoclimate. In *Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller), pp. 433–497. Cambridge, UK: Cambridge University Press.
- 24 Fleming, K. & Lambeck, K. 2004 Constraints on the Greenland ice sheet since the last Glacial maximum from sea-level observations and glacial-rebound models. *Q. Sci. Rev.* **23**, 1053–1077. (doi:10.1016/j.quascirev.2003.11.001)
- 25 Willerslev, E. *et al.* 2007 Ancient biomolecules from deep ice cores reveal a forested southern Greenland. *Science* **317**, 111–114. (doi:10.1126/science.1141758)
- 26 Kopp, R., Simons, F., Mitrovica, J., Maloof, A. & Oppenheimer, M. 2009 Probabilistic assessment of sea level during the last interglacial stage. *Nature* **462**, 863–867. (doi:10.1038/nature08686)
- 27 Rohling, E., Grant, K., Hemleben, C., Siddall, M., Hoogakker, B., Bolshaw, M. & Kucera, M. 2008 High rates of sea-level rise during the last interglacial period. *Nat. Geosci.* **1**, 38–42. (doi:10.1038/ngeo.2007.28)
- 28 Rahmstorf, S. 2007 A semi-empirical approach to projecting future sea-level rise. *Science* **315**, 368–370. (doi:10.1126/science.1135456)
- 29 Lowe, J. A. & Gregory, J. M. 2010 A sea of uncertainty. *Nat. Climate Rep.* **4**, 42–43. (doi:10.1038/climate.2010.30)
- 30 Delta Commission. 2008 Working together with water. A living land builds for its future. Findings of the Deltacommissie 2008. See http://www.deltacommissie.com/doc/deltareport_full.pdf.
- 31 Vellinga, P. *et al.* 2008 Exploring high-end climate change scenarios for flood protection of The Netherlands. International Scientific Assessment carried out at request of the Delta Committee. Scientific report WR-2009-05. KNMI, Alterra, The Netherlands. See <http://www.knmi.nl/bibliotheek/knmipubWR/WR2009-05.pdf>.
- 32 Vaughan, D. G. & Spouge, J. R. 2002 Risk estimation of collapse of the west Antarctic ice sheet. *Clim. Change* **52**, 65–91. (doi:10.1023/A:1013038920600)
- 33 Lowe, J. A. *et al.* 2009 *UK Climate projections science report: marine and coastal projections*. Exeter, UK: Met Office Hadley Centre. See http://ukclimateprojections.defra.gov.uk/images/stories/marine_pdfs/UKP09_Marine_report.pdf.
- 34 Mitrovica, J. X., Gomez, N. & Clark, P. U. 2009 The sea-level fingerprint of west Antarctic collapse. *Science* **323**, 753. (doi:10.1126/science.1166510)
- 35 Gregory, J. M., Huybrechts, P. & Raper, S. C. B. 2004 Threatened loss of the Greenland ice-sheet. *Nature* **428**, 616. (doi:10.1038/428616a)
- 36 Hansen, J. E. 2007 Scientific reticence and sea level rise. *Environ. Res. Lett.* **2**, 024002. (doi:10.1088/1748-9326/2/2/024002)
- 37 Ridley, J., Gregory, J. M., Huybrechts, P. & Lowe, J. A. In press. Thresholds for irreversible decline of the Greenland ice sheet. *Clim. Dyn.* (doi:10.1007/s00382-009-0646-0)
- 38 Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. & Schellnhuber, H. J. 2008 Tipping elements in the Earth's climate system. *Proc. Natl Acad. Sci. USA* **105**, 1786–1793. (doi:10.1073/pnas.0705414105)
- 39 Oppenheimer, M. & Alley, R. B. 2004 The west Antarctic ice sheet and long term climate policy. *Clim. Change* **64**, 1–10. (doi:10.1023/B:CLIM.0000024792.06802.31)
- 40 Vaughan, D. G., Marshall, G. J., Connolley, W. M., Parkinson, C., Mulvaney, R., Hodgson, D. A., King, J. C., Pudsey, C. J. & Turner, J. 2003 Recent rapid regional climate warming on the Antarctic Peninsula. *Clim. Change* **60**, 243–274. (doi:10.1023/A:1026021217991)
- 41 Vaughan, D. G. 2008 West Antarctic ice sheet collapse—the fall and rise of a paradigm. *Clim. Change* **91**, 65–79. (doi:10.1007/s10584-008-9448-3)
- 42 Lowe, J. A. & Gregory, J. M. 2006 Understanding projections of sea level rise in a Hadley centre coupled climate model. *J. Geophys. Res.* **111**, C11014. (doi:10.1029/2005JC003421)

- 43 Pardaens, A. K., Gregory, J. M. & Lowe, J. A. In press. A model study of factors influencing projected changes in regional sea level over the twenty-first century. *Clim. Dyn.* (doi:10.1007/s00382-009-0738-x)
- 44 Mitrovica, J. X., Tamisiea, M. E., Davis, J. L. & Milne, G. A. 2001 Recent mass balance of polar ice sheets inferred from patterns of global sea level change. *Nature* **409**, 1026–1029. (doi:10.1038/35059054)
- 45 Clark, P. U., Mitrovica, J. X., Milne, G. A. & Tamisiea, M. E. 2002 Sea-level fingerprinting as a direct test for the source of global melt water pulse 1A. *Science* **295**, 2438–2441. (doi:10.1126/science.1068797)
- 46 Milne, G. A., Gehrels, W. R., Hughes, C. W. & Tamisiea, M. E. 2009 Identifying the causes for sea-level change. *Nat. Geosci.* **2**, 471–478. (doi:10.1038/NGEO544)
- 47 Ericson, J. P., Vorosmarty, C. J., Dingman, S. L., Ward, L. G. & Meybeck, M. 2006 Effective sea-level rise and deltas: causes of change and human dimension implications. *Glob. Planet Change* **50**, 63–82. (doi:10.1016/j.gloplacha.2005.07.004)
- 48 Syvitski, J. P. M. *et al.* 2009 Sinking deltas due to human activities. *Nat. Geosci.* **2**, 681–686. (doi:10.1038/ngeo629)
- 49 Peltier, W. R. 2000 Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In *Sea level rise: history and consequences* (eds B. C. Douglas, M. S. Kearny & S. P. Leatherman), pp. 65–95. San Diego, CA: Academic Press.
- 50 Peltier, W. R. 2000 ICE4G (VM2) Glacial isostatic adjustment corrections. In *Sea level rise: history and consequences* (eds B. C. Douglas, M. S. Kearny & S. P. Leatherman). San Diego, CA: Academic Press.
- 51 Pardaens, A. K., Lowe, J. A., Brown, S., Nicholls, R. J. & de Gusmão, D. Submitted. Sea-level rise projections under a future scenario with large greenhouse gas emission reductions. *Geophys. Res. Lett.*
- 52 Brown, S., Nicholls, R. J., Lowe, J. A. & Hinkel, J. In preparation. Spatial variations in sea level rise and global impacts: an application of DIVA.
- 53 Nakicenovic, N. & Swart, R. (eds) 2000 *Emissions scenarios. Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- 54 Hinkel, J. & Klein, R. J. T. 2009 Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. *Glob. Environ. Change* **19**, 384–395. (doi:10.1016/j.gloenvcha.2009.03.002)
- 55 Dasgupta, S., Laplante, B., Meisner, C., Wheeler, D. & Yan, J. 2009 The impact of sea level rise on developing countries: a comparative analysis. *Clim. Change* **93**, 379–388. (doi:10.1007/s10584-008-9499-5)
- 56 Tol, R. S. J. *et al.* In preparation. Flooding and sea level rise: an application of DIVA.
- 57 Hinkel, J. *et al.* In preparation. A global analysis of coastal erosion of beaches due to sea-level rise: an application of DIVA.
- 58 Vafeidis, A. T., Nicholls, R. J., McFadden, L., Tol, R. S. J., Hinkel, J., Spencer, T., Grashoff, P. S., Boot, G. & Klein, R. 2008 A new global coastal database for impact and vulnerability analysis to sea-level rise. *J. Coastal Res.* **24**, 917–924. (doi:10.2112/06-0725.1)
- 59 Zhang, K., Douglas, B. C. & Leatherman, S. P. 2004 Global warming and coastal erosion. *Clim. Change* **64**, 41–58. (doi:10.1023/B:CLIM.0000024690.32682.48)
- 60 Stive, M. J. F. 2004 How important is global warming for coastal erosion? *Clim. Change* **64**, 27–39. (doi:10.1023/B:CLIM.0000024785.91858.1d)
- 61 van Goor, M., Zitman, T., Wang, Z. & Stive, M. 2003 Impact of sea-level rise on the morphological equilibrium state of tidal inlets. *Mar. Geol.* **202**, 211–227. (doi:10.1016/S0025-3227(03)00262-7)
- 62 van Koningsveld, M., Mulder, J. P. M., Stive, M. J. F., van der Valk, L. & van der Weck, L. W. 2008 Living with sea-level rise and climate change: a case study of The Netherlands. *J. Coastal Res.* **24**, 367–379. (doi:10.2112/07A-0010.1)
- 63 Zhang, K., Douglas, B. C. & Leatherman, S. P. 2000 Twentieth-century storm activity along the US east coast. *J. Clim.* **13**, 1748–1761. (doi:10.1175/1520-0442(2000)013<1748:TCSAAT>2.0.CO;2)

- 64 Woodworth, P. L. & Blackman, D. L. 2004 Evidence for systematic changes in extreme high waters since the mid-1970s. *J. Clim.* **17**, 1190–1197. (doi:10.1175/1520-0442(2004)017<1190:EFSCIE>2.0.CO;2)
- 65 Haigh, I., Nicholls, R. & Wells, N. 2010 Assessing changes in extreme sea levels: application to the English Channel, 1900–2006. *Cont. Shelf Res.* **30**, 1042–1055. (doi:10.1016/j.csr.2010.02.002)
- 66 Menendez, M. & Woodworth, P. L. In press. Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *J. Geophys. Res.* (doi:10.1029/2009JC005997)
- 67 Hoozemans, F. J., Marchand, M. & Pennekamp, H. 1993 *Sea level rise: a global vulnerability assessment: vulnerability assessments for population, coastal wetlands and rice production on a global scale*, revised edn. The Hague, The Netherlands: Delft Hydraulics and Rijkswaterstaat.
- 68 Nicholls, R. J. 2004 Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Glob. Environ. Change* **14**, 69–86. (doi:10.1016/j.gloenvcha.2003.10.007)
- 69 Tol, R. S. J. & Yohe, G. W. 2007 The weakest link hypothesis for adaptive capacity: an empirical test. *Glob. Environ. Change* **17**, 218–227. (doi:10.1016/j.gloenvcha.2006.08.001)
- 70 Tol, R. S. J. 2006 The DIVA model: socio-economic scenarios, impacts and adaptation and world heritage. In *DINAS-COAST Consortium 2006*. DIVA 1.5.5, Potsdam Institute for Climate Impact Research, Potsdam, Germany. See <http://www.pik-potsdam.de/diva>.
- 71 Hamilton, J. M., Maddison, D. J. & Tol, R. S. J. 2005 Climate change and international tourism: a simulation study. *Glob. Environ. Change* **15**, 253–266. (doi:10.1016/j.gloenvcha.2004.12.009)
- 72 Hamilton, J. M., Maddison, D. J. & Tol, R. S. J. 2005 Effects of climate change on international tourism. *Clim. Res.* **29**, 245–254. (doi:10.3354/cr029245)
- 73 Nicholls, R. J., Tol, R. S. J. & Vafeidis, A. T. 2008 Global estimates of the impact of a collapse of the west Antarctic ice sheet: an application of FUND. *Clim. Change* **91**, 171–191. (doi:10.1007/s10584-008-9424-y)
- 74 Tol, R. S. J. 2007 The double trade-off between adaptation and mitigation for sea-level rise: an application of FUND. *Mitigation Adaptation Strat. Glob. Change* **12**, 741–753. (doi:10.1007/s11027-007-9097-2)
- 75 Myers, N. 2001 Environmental refugees: our latest understanding. *Phil. Trans. R. Soc. Lond. B* **357**, 609–613. (doi:10.1098/rstb.2001.0953)
- 76 Parry, M. L. *et al.* 2009 *Assessing the costs of adaptation to climate change: a review of the UNFCCC and other recent estimates*. London, UK: International Institute for Environment and Development and Grantham Institute for Climate Change.
- 77 World Bank. 2010 The economics of adaptation to climate change. A synthesis report, final consultation draft. World Bank, Washington, DC. See http://siteresources.worldbank.org/EXTCC/Resources/EACC_FinalSynthesisReport0803_2010.pdf.
- 78 Betts, R. A., Collins, M., Hemming, D. L., Jones, C. D., Lowe, J. A. & Sanderson, M. G. 2010 When could global warming reach 4°C? *Phil. Trans. R. Soc. A* **368**, 67–84. (doi:10.1098/rsta.2010.0292)
- 79 Wynne, A. 2010 Evacuation remains essential to New Orleans flood plans/Post-Katrina project speeds to conclusion. *New Civ. Eng.* **02.09.10**, 5–7.
- 80 Grossi, P. & Muir-Wood, R. 2006 *Flood risk in New Orleans: implications for future management and insurability*. London, UK: Risk Management Solutions.
- 81 Franck, T. R. 2009 Coastal communities and climate change: a dynamic model of risk perception, storms, and adaptation. PhD thesis, Massachusetts Institute of Technology, Cambridge, MA.
- 82 Woodroffe, C. D., Nicholls, R. J., Saito, Y., Chen, Z. & Goodbred, S. L. 2006 Landscape variability and the response of Asian megadeltas to environmental change. In *Global change implications for coasts in the Asia-Pacific region* (ed. N. Harvey), pp. 277–314. London, UK: Springer.
- 83 Barnett, J. & Adger, W. N. 2003 Climate dangers and atoll countries. *Clim. Change* **61**, 321–337. (doi:10.1023/B:CLIM.0000004559.08755.88)