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Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses

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Abstract

To develop improved estimates of (1) flooding due to storm surges, and (2) wetland losses due to accelerated sea-level rise, the work of Hoozemans et al. (1993) is extended to a dynamic analysis. It considers the effects of several simultaneously changing factors, including: (1) global sea-level rise and subsidence; (2) increasing coastal population; and (3) improving standards of flood defence (using GNP/capita as an "ability-to-pay" parameter). The global sea-level rise scenarios are derived from two General Circulation Model (GCM) experiments of the Hadley Centre: (1) the HadCM2 greenhouse gas only ensemble experiment and (2) the more recent HadCM3 greenhouse gas only experiment. In all cases there is a global rise in sea level of about 38 cm from 1990 to the 2080s. No other climate change is considered. Relative to an evolving reference scenario without sea-level rise, this analysis suggests that the number of people flooded by storm surge in a typical year will be more than five times higher due to sea-level rise by the 2080s. Many of these people will experience annual or more frequent flooding, suggesting that the increase in flood frequency will be more than nuisance level and some response (increased protection, migration, etc.) will be required. In absolute terms, the areas most vulnerable to flooding are the southern Mediterranean, Africa, and most particularly, South and South-east Asia where there is a concentration of low-lying populated deltas. However, the Caribbean, the Indian Ocean islands and the Pacific Ocean small islands may experience the largest relative increase in flood risk. By the 2080s, sea-level rise could cause the loss of up to 22% of the world's coastal wetlands. When combined with other losses due to direct human action, up to 70% of the world's coastal wetlands could be lost by the 2080s, although there is considerable uncertainty. Therefore, sea-level rise would reinforce other adverse trends of wetland loss. The largest losses due to sea-level rise will be around the Mediterranean and Baltic and to a lesser extent on the Atlantic coast of Central and North America and the smaller islands of the Caribbean. Collectively, these results show that a relatively small global rise in sea level could have significant adverse impacts if there is no adaptive response. Given the "commitment to sea-level rise" irrespective of any realistic future emissions policy, there is a need to start strategic planning of appropriate responses now. Given that coastal flooding and wetland loss are already important problems, such planning could have immediate benefits.

Keywords: Costs; Climate change; Impacts; Adaption

1. Introduction

The balance of scientific evidence now suggests that anthropogenic emissions of greenhouse gases are having a discernible effect on the earth's climate (Houghton et al., 1996). These effects are expected to intensify in the 21st Century with a range of climatic effects, including an acceleration in global sea-level rise (Warrick et al., 1996). Regional and global perspectives on the potential impacts of climate change are required for a range of purposes, including communicating the likely implications of different climate change scenarios to a non-specialist audience, examining the costs and benefits of different combinations of mitigation–adaptation policies, and identifying regions where collective action could be beneficial (Nicholls and Mimura, 1998). Given that 21% the world's population already live within 30 km of the coast (Gommes et al., 1997) and these populations are growing at twice the global average (Bijlsma et al., 1996), the potential impacts of sea-level rise are an important focus for such assessments.

The DETR-funded Fast Track Programme has examined the potential regional and global impacts of climate change on terrestrial ecosystems, human health, water

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resources, food supply and coastal areas (Parry et al., editorial, 1999). This paper presents details of the coastal analysis, which uses two models for improved analyses of the potential impacts of global sea-level rise scenarios for:

(1) Coastal flooding due to storm surges; and
(2) Loss of coastal wetlands.

For the purposes of this analysis, all other climate factors are assumed to be constant. However, it is recognised that both regional variations in sea-level rise and changes in surge characteristics could have important influences on these impacts (cf. Warrick et al., 1996). In addition to climate change, increases in population and the standard of flood protection (using gross national product per capita (GNP/capita) as an "ability-to-pay" parameter) are considered. This allows the climate change scenario to be imposed upon a world that is evolving without climate change (i.e., an evolving reference scenario). In both cases, relative and absolute impacts are evaluated for 2025, 2055 and 2085, representing the 2020s, 2050s and 2080s, respectively.

The Second Assessment report of Working Group II of the Intergovernmental Panel on Climate Change (IPCC) concluded that accelerated sea-level rise due to greenhouse gas-induced changes of climate could have important impacts on coastal populations and ecosystems (Bijlsma et al., 1996). According to Hoozemans and Hulsbergen (1995), about 200 million people lived in the coastal flood plain (defined as beneath the 1 in 1000 year storm surge elevation) in 1990. In the developed world, people in such locations are generally protected from flooding by structural measures such as dikes and flood barriers. However, many people in such locations in the developing world are subjected to regular flooding with consequent disruption and economic loss, and at the extreme, severe loss of life as occurred in Bangladesh in 1970 and 1991 (see Nicholls et al., 1995a).

In the 21st century, global sea-level rise will raise flood levels and hence increase flood risk (Hoozemans et al., 1993; Hoozemans and Hulsbergen, 1995; Bijlsma et al., 1996). The number of people who experience flooding will also be affected by other factors such as increasing populations within the coastal flood plain. As already noted, coastal populations are already large and growing rapidly, often in urban settings (Nicholls, 1995a). Subsidence (which produces a local to regional relative sea-level rise) also enhances coastal flooding and in certain geological settings it is often exacerbated by human activity (Holzer and Johnson, 1985). Osaka, Tokyo, and Shanghai have subsided several metres during the 20th Century due to excessive groundwater withdrawal, and similar problems are now recognised in other large coastal cities such as Tianjin, Jakarta and Bangkok (Nicholls, 1995a). Such changes are expected to continue into the 21st Century. However, these increases in flood risk can be offset or even reversed if flood protection of these vulnerable populations is upgraded, or other approaches to flood management are implemented. Such changes are already happening without any consideration of sea-level rise and climate change — they are simply an adaptation to *present* climate variability. For example, the incidence of coastal flooding in the United Kingdom has declined substantially during the 20th Century (compare Steers, 1953; Steers et al., 1979). Similar trends are apparent in other developed countries. It is useful to distinguish such changes from adaptation to global sea-level rise induced by climate change, which would involve additional action.

Coastal wetlands (collectively comprising saltmarshes, mangroves and intertidal areas) could experience substantial losses given sea-level rise (Hoozemans et al., 1993; Bijlsma et al., 1996). These areas are highly productive and provide a number of important functions such as flood protection, waste assimilation, nursery areas for fisheries and nature conservation. Therefore, wetland loss has a high human cost. This is not widely perceived and wetland areas are already declining: about 1% of the global coastal wetland stock is lost each year, primarily by direct human reclamation (Hoozemans et al., 1993). Significant losses are likely to continue without climate change, but they will be exacerbated by sea-level rise.

2. Previous studies

The Global Vulnerability Assessment (or GVA) was conducted to provide a first worldwide estimate of socio-economic and ecological implications of accelerated sea level rise (Hoozemans and Hulsbergen, 1995; Hoozemans et al., 1993). It used the IPCC Common Methodology (IPCC CZMS, 1992). In consideration of data and modelling constraints, among others, the GVA was limited to the impacts of sea-level rise on three elements of the coastal zone:

(1) coastal flooding, including (a) *population at risk* (i.e. the number of people subject to flooding by storm surge in a typical year), and (b) *protection cost* estimates to counter increased flooding;
(2) *wetlands at loss* (i.e. the ecologically valuable coastal wetland area under a serious threat of loss);
(3) *rice production at change* (i.e. the changes in coastal rice yields due to less favourable conditions due to accelerated sea level rise) (for South, Southeast and East Asia only).

These parameters were selected to embrace factors concerning people, land use, the environment and the economy. It needs to be stressed that much of the underlying data and many of the assumptions about physical processes, as well as the physical and socio-economic boundary conditions limit the accuracy of the results. While

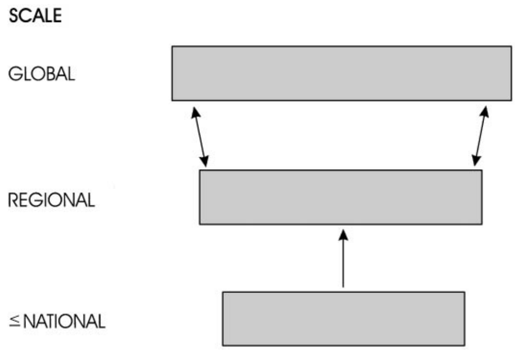

Fig. 1. The relationship between national, regional and global scales.

most calculations are conducted at a national scale, only results aggregated to a regional or global level are valid (Fig. 1). A validation of the regional GVA results against national-scale vulnerability assessments for flooding and wetland losses showed that the results of the two sets of studies were consistent, as far as they could be tested (Nicholls, 1995b). This gives confidence in improving and extending the GVA results, as presented in this paper.

Globally, Hoozemans et al. (1993) estimated that 46 million people were affected by flooding in 1990 and assuming a 1-m rise in sea level by 2100 and no other changes, this would rise to 60 million people/y. This estimate does not include the increased flood risk to the population within the existing coastal flood plain. The Asian coast, particularly South Asia, the African coast, including the southern Mediterranean; and the island states of the Caribbean and the Indian and Pacific oceans appeared particularly vulnerable to increased flooding. Globally there were at least 300,000 km^2 of coastal wetlands of international importance in 1990. In combination with human activities, a 1-m rise in sea level could threaten half of these coastal wetlands, while those that survive could be substantially changed. In some areas, valuable coastal wetlands could be virtually eliminated because their ability to migrate inland is limited by human infrastructure and/or the rapid rate of change. Coastal wetland decline is expected to be greater than average for the Atlantic coast of North America, the Mediterranean, the African Atlantic coast, South Asia and Australia and Papua New Guinea.

Baarse (1995) used the results of Hoozemans et al. (1993) to refine estimates of the population at risk. The analysis included the increasing flood risk to the population within the existing flood plain as sea level rises. It is estimated that the number of people flooded in a typical year by storm surges would roughly double and treble given a 0.5 and 1-m rise in global sea levels, respectively, and *no other changes*. More than 90% of these people would experience annual or more frequent flooding, suggesting that some response (migration, increased protection, etc.) would be essential. This shows that sea-level rise could have serious consequences. (No regional analysis is possible with Baarse's method).

These results provide a useful first-order perspective on the potential impacts of sea-level rise. However, given the focus on a 1-m global sea-level rise scenario impacting the 1990 (and 2020) socio-economic situation, these results may overstate the impacts of sea-level rise and understate the implications of other changes (see Klein and Nicholls, 1999). This is investigated below.

3. Methodology

Building on the earlier global analyses of Hoozemans et al. (1993), the potential impact of sea-level rise is investigated for (1) coastal flooding and (2) coastal wetland losses. The coastal flood model is adjusted to better reflect the existing risk of flooding due to storm surges and how it will increase with sea-level rise. For coastal wetlands, a dynamic non-linear model of losses is developed, including uncertainties which are expressed as a range. The results are presented for the 2020s, 2050s and 2080s both as global aggregates, and for selected regions.

3.1. Scenarios

Three different types of scenarios were used: (1) global sea-level rise; (2) population change; (3) gross national product (GNP) change (Hulme et al., 1999). In addition, scenarios of human-induced losses of coastal wetlands are also considered to place the impacts of sea-level rise in context. As a general principle, present trends are projected into the future if this seems sensible and plausible.

The global sea-level rise scenarios are from the Hadley Centre (the HadCM2 ensemble simulations and the HadCM3 simulation for greenhouse gas only forcing — see Hulme et al. (1999)) and are summarised in Table 1. The climate forcing assumes a growth in CO_2 concentrations from 354 ppmv (in 1990) to 731 ppmv for HadCM2 and 642 ppmv for HadCM3 (in the 2080s). Thermal expansion is derived directly from the model experiment, while ice melt contributions are derived directly using an offline ice-melt model driven by the temperature field from the model experiment (Gregory and Oerlemans, 1998). This represents a significant improvement to the global sea-level rise scenarios and also reduces them relative to earlier ice-melt estimates scaled from the IS92a scenario. The scenarios were referenced to a 1961 to 1990 average sea level (i.e. 1975). As tide gauges suggest that global sea levels have been rising at between 1 and 2.5 mm/yr (Warrick et al., 1996; Douglas, 1997), a reduction of 2.7 cm (or 1.8 mm/yr) has been applied to all the values in Table 1 to reference them to 1990. There is little between-scenario variation with a rise in global sea level from 1990 to the 2080s in the range 37 to 38 cm.

Table 1
Global sea-level rise and population change scenarios used in the study. (1. Sea-level rise from the 1961–1990 mean to 1990 is assumed to be 2.7 cm – see text)

Year	Sea-level rise scenarios (cm)					Global population (billions)
	HadCM2 ensemble				HadCM 3 GGa	
	GGa1	GGa2	GGa3	GGa4		
1961–1990	0.0	0.0	0.0	0.0	0.0	n.a.
1990[1]	2.7	2.7	2.7	2.7	2.7	5.27
2020s	12.3	12.2	12.6	12.2	12.1	8.12
2050s	24.8	24.1	24.8	24.7	24.1	9.76
2080s	40.8	40.4	40.8	40.7	39.8	10.67

For reference, the IS92a emissions scenario assuming constant 1990 aerosols produced a mid estimate of a 45-cm rise by 2085, with a range of 19-cm to 80-cm rise (Warrick et al., 1996).

Changes in population are taken from the World Bank 1994/95 global population scenario which provide national estimates to 2150 (Bos et al., 1994). Global values are included in Table 1.

Changes in gross domestic product (GDP) are taken from the Energy Modelling Forum 14 GDP/capita scenario (EMF WP 14.1, 1995). This provides aggregated scenarios of GDP growth rates to 2200 for six regions. The forecast net increase in GDP/capita from 1990 to 2085 is substantial: (1) USA — 448%, (2) EU — 457%, (3) other OECD — 462%, (4) former Soviet Union — 926%, (5) China — 1400%, (6) other non-OECD — 916%.

The reference scenario is the same scenario without global sea-level rise in all cases.

3.2. Flood risk due to storm surge

Fig. 2 shows the different risk zones to flooding that exist on any low-lying coast. Sea-level rise will move these risk zones upward and landward and hence increase the population vulnerable to flooding, and increase the flood risk of the population within the pre-existing flood plain (Fig. 3). A method to calculate the changes in flood risk is outlined in Fig. 4. Three output parameters related to human exposure to such flooding are derived:

(i) *People in the hazard zone* (*PHZ*): the number of people living below the 1000-year storm surge elevation (H_{1000} in Fig. 2) — the population potentially at risk of flooding by storms surges, ignoring sea defences;
(ii) *Average annual people flooded* (*AAPF*): the average annual number of people who experience flooding by storm surge, including the influence of sea defences (In previous analyses, this parameter was termed *people at risk* (IPCC CZMS, 1992; Hoozemans et al., 1993; Bijlsma et al., 1996). To make the terminology more consistent with the other fast track studies, the new term is preferred). Note that there is no distinction between different depths and magnitudes of flooding;
(iii) *People to respond* (*PTR*): the average annual number of people who experience flooding by storm surge more than once per year, including the influence of sea defences. This gives an indication of the population that would be affected by flooding so frequently that some response (upgrade flood protection, migrate, etc.) might be expected. For 1990, people to respond is defined as zero. (In previous studies this parameter has been termed *people to be moved*. This term is avoided as it implies a response).

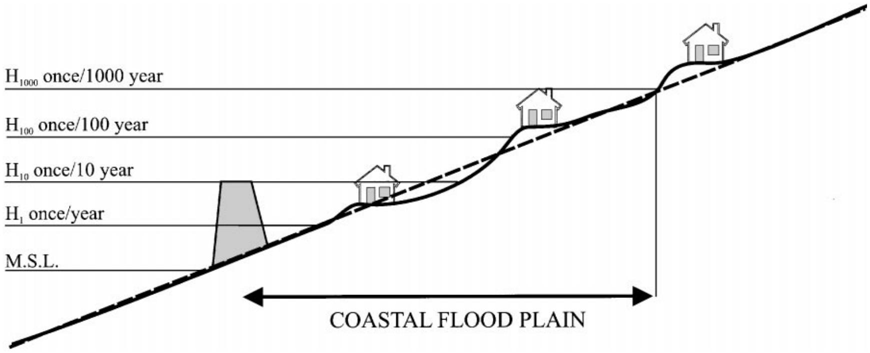

Fig. 2. The coastal flood plain, including different storm surge levels and corresponding risk zones.

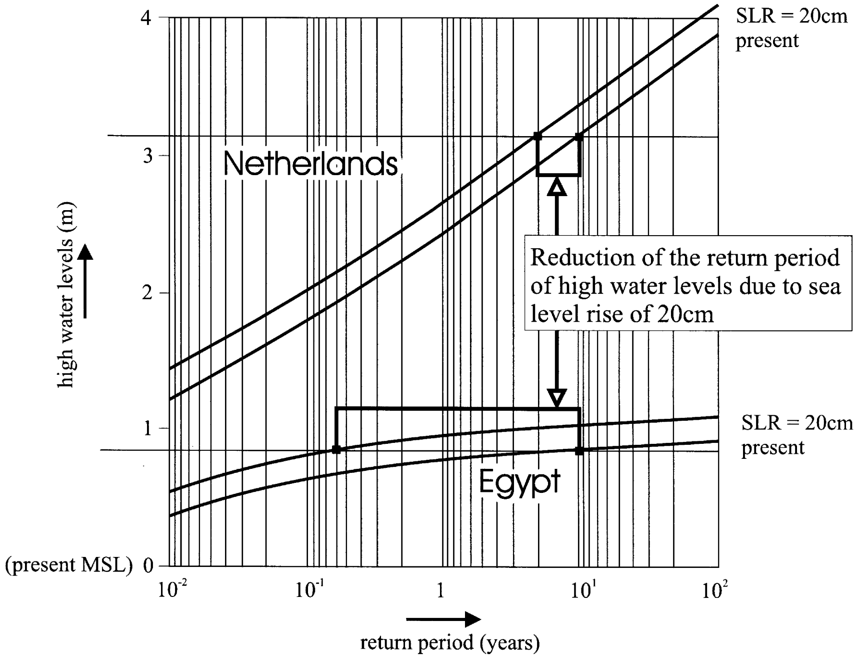

Fig. 3. The influence of sea-level rise on the return period of flood elevations.

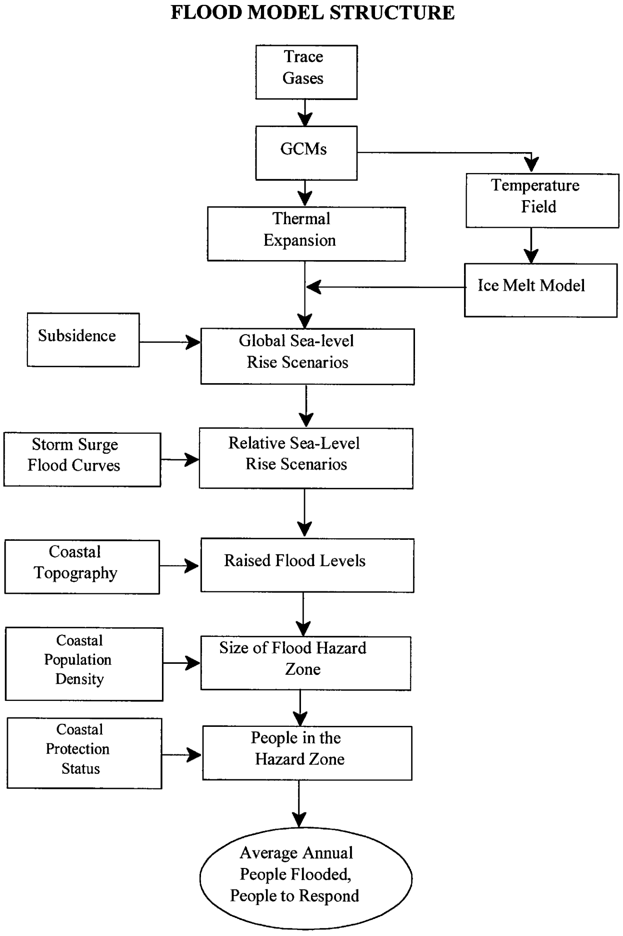

Fig. 4. The flood model algorithm.

The values of all three parameters will be changed by any human response to flooding, including migration out of the flood plain. It is beyond the scope of this analysis to consider such responses, except to note that the individual response to flooding could take several forms and is uncertain (Hoozemans et al., 1993). Therefore, these parameters are evaluated assuming no response. Average annual people flooded and, more particularly, people to respond are best seen as a cumulative total from 1990 to the time period being considered, rather than as an instantaneous value.

Hoozemans et al. (1993) provides a database of the five factors we need to apply the method in Fig. 4:

(1) the maximum area of the coastal flood plain after sea-level rise;
(2) the flood exceedance curve for storm surges from a 1 in 1 yr event to a 1 in 1000 yr event;
(3) the average coastal population density;
(4) the occurrence or absence of subsidence; and
(5) the standard of coastal protection.

It should be stressed that these data are at a coarse spatial resolution and several important assumptions about the characteristics of the flood plain and the occurrence of flooding are necessary to utilise it. The data are available for 192 coastal polygons of varying size. Most polygons represent the coastal areas of an individual country, although some countries which have more than one coastal area separated by land or sea areas (e.g. the Atlantic and Mediterranean coast of France) are split into two or more polygons. Three fundamental assumptions are that (1) the coastal flood plain has a constant slope, and (2) the population is distributed uniformly across the coastal zone, and (3) if a sea defence is exceeded by a surge, the entire area behind the sea defence is flooded.

Calculations proceed as shown in Fig. 4. Estimates of four storm surge elevations (1 in 1 yr, 1 in 10 yr, 1 in 100 yr, and 1 in 1000 yr) are raised by the relative sea-level rise scenario and converted to the corresponding land areas threatened by these different probability floods assuming a uniform coastal slope. These areas are then converted to people in the hazard zone using the average population density for the coastal area. Lastly, the standard of protection is used to calculate average annual people flooded and people to respond. These national estimates are then aggregated to regional and global results. Given the limited resolution of the underlying databases and the simplifying assumptions employed in the calculations, only the regional and global results are considered to be valid.

The 1990 population density was increased (or decreased) at twice the rate of national growth. This is simply projecting present trends (WCC'93, 1994; Bijlsma et al., 1996). Coastal areas where coastal subsidence is occurring are noted by Hoozemans et al. (1993) and a uniform subsidence of 15 cm/century was applied to the entire coastal area. Most of these coastal areas include deltaic areas, at least in part. The same assumption is made here, although it is recognised that subsidence varies greatly within coastal areas and this is only a first approximation. (Based on the historical experience discussed in the Introduction, the actual subsidence may be significantly larger in many urban areas on the coast.) In the original GVA, no global data bases on the level of flood protection were identified and this parameter was estimated indirectly using the GNP/capita in 1989 as an "ability-to-pay" parameter. It utilised the World Bank classification of less developed, middle and high developed nations (slightly amended based on expert judgement by Hoozemans et al., 1993) (Table 2).

In the new results, the same concept was used to determine the level of flood protection, but the algorithm was improved to reflect:

(1) the greater costs of protecting deltaic areas against flooding;
(2) the increasing risk of flooding within the coastal flood plain as sea levels rise.

It is well known that deltaic areas are more expensive to protect from flooding than non-deltaic areas. This is due to the much longer land–water interface within deltas, and the additional need for extensive water management within the extensive low-lying areas that are protected. This approach to flood control within deltas is most developed within the Netherlands, but many other deltaic areas are protected in a similar manner (Day et al., 1993; Rodenhuis, 1992; Oudshoord et al., 1999). Based on expert judgement we have selected the protection classes for deltaic areas shown in Table 3. Table 4 gives the 16 coastal areas that were considered deltaic for this analysis. These coastal areas were selected based on deltas containing a large proportion of the coastal population so they make a significant contribution to the national flood risk. On this basis, countries which have large, but sparsely populated deltas such as Argentina, Brazil and Venezuela are not considered deltaic for the purposes of this flood analysis. Seven of the countries in Table 4 are from south, south-east and east Asia, reflecting the concentration of populated deltas in this region (cf. Nicholls et al., 1995a).

The increase in flood risk produced by sea-level rise is estimated by reducing the selected the protection class (i.e., the standard of protection) as defined in Table 5. The protection class is reduced in integer steps by up to four steps, giving a protection class of 0, which is a 1 in 1 yr or lower standard of protection. A range of factors including storm parameters and coastal configuration controls the shape and slope of flood exceedance curves. Increases in flood risk due to sea-level rise are greater for lower slopes (Fig. 3), or flood envelopes (E_{flood}):

$$E_{\text{flood}} = H_{1000} - H_{1}, \quad (1)$$

Table 2
Protection classes used by Hoozemans et al. (1993)

GNP/capita (US$) (or ability-to-pay)	Protection class (PC)	Protection status	Design frequency
< 600	PC 1	Low	1/1 to 1/10
600–2400	PC 2	Medium	1/10 to 1/100
> 2400	PC 3	High	1/100 to 1/1000

Table 3
Revised protection classes used in this study, allowing for deltaic and non-deltaic coasts

GNP/capita (US$)		Protection class (PC)	Protection status	Design frequency
If deltaic coast	If non-deltaic coast			
< 2400	< 600	PC 1	Low	1/10
2400–5000	600–2400	PC 2	Medium	1/100
> 5000	2400–5000	PC 3	High	1/1000
—	> 5000	PC 4	Very high	1/1000

Table 4
Coastal countries and areas considered deltaic when assigning protection class (see Table 3)

Bangladesh, Burma, China, Egypt, France (Mediterranean coast), French Guyana, Guyana, India, Iraq, Italy, Netherlands, Nigeria, Pakistan, Surinam, Thailand, Vietnam.

Table 5
Algorithm for the reduction in standard of protection with sea-level rise

	Algorithm (SLR — sea-level rise) (E_{Flood} — flood envelope) (see Eq. (1))	Original protection class			
		1	2	3	4
New protection class	If SLR $< 1/3 * E_{\text{Flood}}$	1	2	3	4
	If SLR $> 1/3 * E_{\text{Flood}}$	0	1	2	3
	If SLR $> 2/3 * E_{\text{Flood}}$	0	0	1	2
	If SLR $> E_{\text{Flood}}$	0	0	0	1
	If SLR $> 4/3 * E_{\text{Flood}}$	0	0	0	0

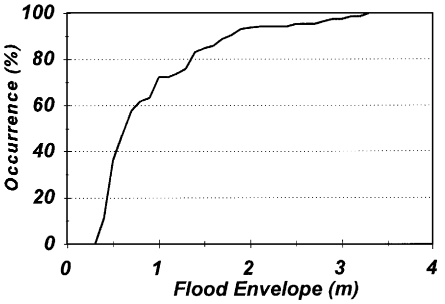

Fig. 5. Cumulative probability distribution for the flood envelopes (E_{flood}) by coastal area.

where H_{1000} is the 1 in 1000 yr flood elevation and H_1 is the 1 in 1 yr flood elevation (Fig. 2). A relative rise in sea level equal to E_{flood} reduces a 1 in 1,000 yr standard to a 1 in 1 yr standard of protection. As E_{flood} is less than 1 m on much of the world's coast (Fig. 5), rises in sea level of the magnitude considered in this paper can produce a large increase in the flood risk.

Lastly, it was assumed that the minimum standard of protection in 1990 was 1 in 10 yr. This significantly reduces average annual people flooded in 1990 compared to the estimates of Hoozemans et al. (1993), and appears justified (see Validation later).

Two protection scenarios are considered:

(1) constant protection (i.e., constant 1990 levels); and
(2) evolving protection in phase with increasing GNP/capita.

A constant protection scenario follows many previous analyses (Nicholls, 1995b), while the evolving protection scenario is more realistic based on historic trends in developed countries during the 20th Century. It should be noted that evolving protection only includes measures that would be implemented without sea-level rise — i.e. there are no proactive adaptation measures to anticipate sea-level rise. These two protection scenarios allow us to examine how such changes might reduce vulnerability to sea-level rise.

3.3. Coastal wetlands

In this analysis, coastal wetlands comprise saltmarshes, mangroves and intertidal areas (and excludes other biogenic features such as coral reefs). Wetlands are sensitive to long-term sea-level change as their location is intimately linked to sea level. However, wetlands are not passive elements of the landscape (Bijlsma et al., 1996; Cahoon et al., 1995; Cahoon and Lynch, 1997). As sea level rises, so the surface of a coastal wetland shows increased vertical accretion due to increased sediment and organic matter input. If vertical accretion equals sea-level rise, the coastal wetland will grow upwards in place. However, if the rate of vertical accretion is less than the rate of sea-level rise, the coastal wetland steadily loses elevation relative to sea level. Vegetated wetlands are submerged during a tidal cycle for progressively longer periods and may die due to waterlogging, causing a change to bare sediment, or even open water. Unvegetated intertidal areas are just progressively submerged. Therefore, coastal wetlands show a dynamic and non-linear response to sea-level rise. All the evidence shows that coastal areas with a small tidal range are more vulnerable than similar areas with a large tidal range. Direct losses of coastal wetland due to sea-level rise can be offset by inland wetland migration (upland conversion to wetland). As sea level rises, so low-lying coastal areas become suitable for the growth of wetland plants (Bijlsma et al., 1996). In areas without low-lying coastal areas, or in low-lying areas that are protected by humans to stop coastal flooding, wetland migration cannot occur, producing a coastal squeeze.

A database of the type, area and location of most coastal wetlands of international importance was created for the analysis of Hoozemans et al. (1993) mainly comprising RAMSAR sites. The coverage is not global: there are no data for Canada, the Gulf States, the CIS and the small islands in the Atlantic, Indian and Pacific Oceans (except Bermuda and the Falklands). Hoozemans et al. (1993) considered the impacts of a 1-m rise in sea level. As wetland response to sea-level rise is non-linear, these existing results cannot be linearly scaled. To handle smaller sea-level rise scenarios, a new non-linear model of coastal wetland response to sea-level rise was developed (Fig. 6). The modelling effort is split into two parts (1) vertical accretion and (2) wetland migration. Ideally, we would like site-specific information on the potential for vertical accretion and landward migration for each wetland site, including factors such as sediment availability. Unfortunately, this is unavailable and the more aggregated approach shown in Fig. 6 must be used. National assessments of wetland losses and changes for policy purposes have used similar approaches (e.g., Titus et al., 1991; Lee, 1998).

To model vertical accretion, a generalised threshold approach similar to Nicholls et al. (1995b) is used (Fig. 7).

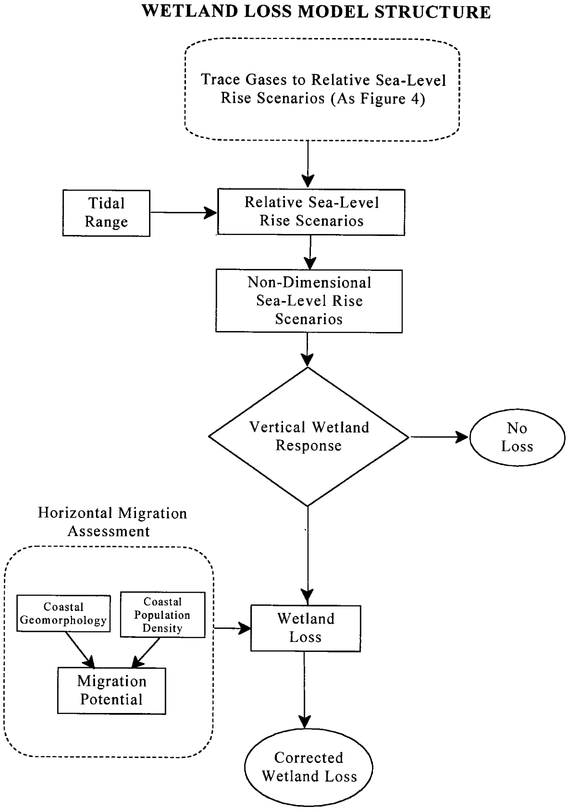

Fig. 6. Wetland loss model algorithm.

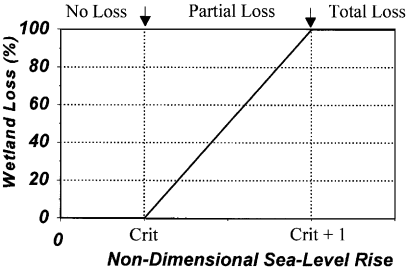

Fig. 7. The threshold approach used to determine the vertical wetland response to sea-level rise.

The availability of sediment/biomass for vertical accretion is parameterised using critical values of non-dimensional relative sea-level rise (RSLR*):

$$\mathrm{RSLR}^* = \mathrm{RSLR}/\mathrm{TR}, \tag{2}$$

where RSLR is the relative sea-level rise scenario and TR is the tidal range on spring tides. This means that wetlands in areas with a low tidal range are more vulnerable to sea-level rise than wetlands in areas with a higher tidal range, all other factors being equal. (The rate of relative sea-level rise is implicit being defined by the 95 year period of interest). A critical value of RSLR* ($\mathrm{RSLR}^*_{\mathrm{crit}}$) distinguishes two distinct wetland responses to sea-level rise in terms of vertical accretion (see Fig. 7):

(1) $\mathrm{RSLR}^* \leqslant \mathrm{RSLR}^*_{\mathrm{crit}}$, No wetland loss as wetland accretion $\geqslant$ sea-level rise; and
(2) $\mathrm{RSLR}^* > \mathrm{RSLR}^*_{\mathrm{crit}}$, Partial or total wetland loss as wetland accretion $<$ sea-level rise.

If wetland loss occurs, it is modelled linearly using the excess sea-level rise up to $\mathrm{RSLR}^* = \mathrm{RSLR}^*_{\mathrm{crit}} + 1$. Above this rise, (near-) total loss is assumed and wetlands will only continue to survive if there is inland wetland migration. This simple model captures the non-linear response of wetland systems to sea-level rise and the association of increasing tidal range with lower losses. (cf. Stevenson et al., 1986; Bijlsma et al., 1996). Some indication of appropriate critical values is available in the literature, although this also stresses the existing uncertainties concerning quantitative wetland response to sea-level rise (e.g., Ellison and Stoddart, 1991; Snedaker et al., 1994; Parkinson et al., 1994). Given this uncertainty, a range of values for $\mathrm{RSLR}^*_{\mathrm{crit}}$ from 0.18 to 0.5 were selected. This encompasses the available information, but further investigations of the appropriate value of these parameters are essential. Tidal range was measured using Admiralty Tide Tables. The wetland sites are aggregated to the 192 coastal areas defined in the flood analysis, except for eight continuous national coasts that were subdivided because of the large variation in tidal range within these areas (Argentina, Australia, Brazil, India, North Korea, South Korea, Malaysia and Morocco).

To model wetland migration, the approach of Hoozemans et al. (1993) was used. The natural potential for the migration of the coastal wetlands under sea-level rise was evaluated for each wetland site using the global coastal geomorphic map of Valentin (1954). Five possible responses are considered:

(1) no or hardly any change;
(2) a retreat of the coastline, combined with an inland migration of coastal wetlands;
(3) a retreat of the coastline, without possibilities for an inland migration of coastal wetlands due to topography;
(4) a possible retreat of the coastline and increase of the flooded area (ponding) landward of the coastline; and
(5) total loss of the coastal wetlands.

These five classes are then further reduced to two classes: (1) migration is possible; or (2) migration is impossible. It is uncertain to what extent wetlands in deltaic and barrier areas might migrate inland. Therefore, losses were calculated assuming both migration and no migration and this contributes to the uncertainty between the low and high range of the results. In areas where migration is possible, the 1990 population density landward of the wetland was estimated using Times Books (1994). This

1990 population estimate was projected to a 2080s population in a similar manner to the coastal flooding analysis. Following Hoozemans et al. (1993), it was assumed that if the 2080s population density exceeded 10 inhabitants/km^2, wetland migration would be prevented by flood protection and other human activities (even low standard flood defences can impede wetland migration under sea-level rise). Due to the large, growing population around most of the world's coasts, the potential for wetland migration is significantly reduced compared to the situation in earlier geological periods of rapid sea-level rise. In areas where wetland migration is possible, wetland losses are assumed to be zero (i.e. wetland migration compensates for any losses due to inundation).

In addition to the effects of sea-level rise on coastal wetlands, we must consider an appropriate reference scenario which reflects non-climate change trends. Giving the existing loss of wetlands, further losses are to be expected. However, it seems likely that the loss of coastal wetlands will decline with time due to both increasing rarity, and rising living standards that give the environment a higher "value". Two possible models for human-induced loss scenarios are considered to define a range of possible losses (Hoozemans et al., 1993):

(1) Model 1: 1%/year, which is the present rate of loss;
(2) Model 2: 0.4%/year, representing immediate moves to more effective conservation;

These scenarios leads to the loss of 32–62% of the wetland stock in 1990 by the 2080s without any consideration of sea-level rise.

4. Flood model validation

An important, but difficult step is model validation. In the present case, there is only limited information with which to compare the new model results. Nicholls (1995b) supported Hoozemans et al. (1993) for both people in the hazard zone and the losses of wetlands given a 1-m rise in sea level. However, average annual people flooded was not validated.

Table 6
Coastal flood model validation. Aggregated average annual people flooded for Egypt, Germany, Guyana, Netherlands, Poland and Vietnam from different assessments

Assessment	Aggregated average annual people flooded based on 1990 population (millions)	
	No sea-level rise	1-m sea-level rise
National studies	1.2	23.5
Hoozemans et al. (1993)	5.5	10.1
These results	1.2	14.2

Six national studies: Egypt (Delft Hydraulics et al., 1992); Germany (Sterr and Simmering, 1996; Ebenhoeh et al., 1997); Guyana (Kahn and Sturm, 1995); Netherlands (Baarse et al., 1994); Poland (Zeidler and Toms, 1994; Zeidler, 1997); and Vietnam (Toms et al., 1996) have estimated average annual people flooded for the 1990 situation given (1) the present situation and (2) a 1-m rise in sea level. The corresponding national estimates of Hoozemans et al. (1993) and the upgraded flood model presented here are compared with these national estimates in Table 6 and Fig. 8. Compared to the national studies, Hoozemans et al. (1993) tends to overestimate the estimated flood risk in 1990, and underestimate the flood risk after a 1-m rise in sea level. The new model produces improved estimates of average annual people flooded for both the 1990 situation and after a 1-m rise in sea level. The relative error is smallest for those nations

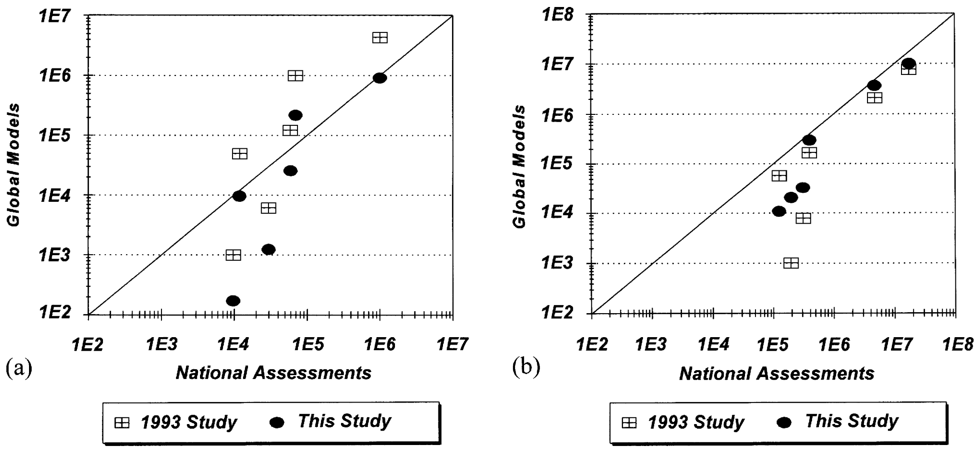

Fig. 8. Validation of the flood model. National estimates of the average annual people flooded derived from the 1993 global study (Hoozemans et al., 1993) and this global study are plotted against the results of national-scale assessments for six countries: Egypt, Germany, Guyana, the Netherlands, Poland and Vietnam. The climate scenarios are (a) no sea-level rise, and (b) an instantaneous 1-m sea-level rise, and no other change. See text for sources.

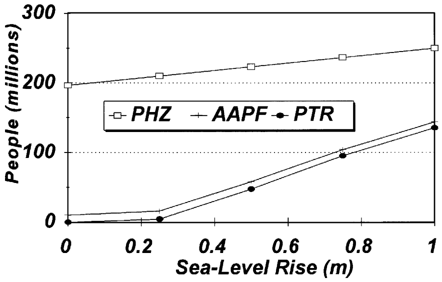

Fig. 9. Response surface for people in the hazard zone (PHZ), average annual people flooded (AAPF), and people to respond (PTR) for an instantaneous global rise in sea level on the 1990 world.

with a high number of average annual people flooded (Fig. 8) — these are the results that most strongly influence the regional and global estimates (Fig. 1).

Therefore, the new flood model appears to produce results of the right order of magnitude for average annual people flooded and represent an improvement over earlier estimates.

5. Results

5.1. Coastal flooding

5.1.1. Response surfaces for sea-level rise

Before examining the implications of the HadCM2 and HadCM3 scenarios, it is useful to examine the broad properties of the new flood model. Fig. 9 shows global estimates of people in the hazard zone, average annual people flooded and people to respond assuming an instantaneous rise in sea level on the 1990 situation. While this is an artificial scenario, it is comparable with much earlier work at both the national and global scale (see Flood Model Validation above). Presently there are about 200 million people living in the hazard zone and this increases with sea-level rise by about 25% for a 1-m rise scenario. Average annual people flooded increases more rapidly above a 0.25-m rise scenario, and then shows a more rapid increase than people in the hazard zone. There is a 14-fold increase in average annual people flooded for a 1-m rise scenario relative to the reference scenario. This is mainly due to the increased frequency of flooding within the flood plain as sea level rises, with the expansion of the size of the flood plain being a smaller effect. People to respond is zero for no sea-level rise (by definition) and closely follows average annual people flooded. For a 1-m rise scenario, more than 90% of the average annual people flooded would experience flooding more than once per year, which is similar to the results of Baarse (1995).

5.1.2. HadCM2/HadCM3 scenarios — global impacts

Table 7 summarises the results for the reference scenario and the HadCM2 and HadCM3 climate change scenarios. The absolute impacts of all the HadCM2 scenarios are almost identical. The impacts from the HadCM3 scenario fall within the range of the HadCM2 ensembles, except for the 2080s when the HadCM3 scenario produces slightly smaller impacts. The variation within the HadCM2 ensemble gives some indication of the likely variation of impact magnitude due to climate variability (see Hulme et al., this issue). The sea-level rise scenarios show very little variation indicating that global sea-level rise is insensitive to climate variability. The impact results further demonstrate that the influence of

Table 7
People in the hazard zone (PHZ), average annual people flooded (AAPF) and cumulative people to respond (PTR) for the different sea-level rise and protection scenarios. The results for the HadCM2 ensemble include 95% confidence intervals.

Scenario	Time	PHZ	AAPF	PTR	AAPF	PTR
			Constant protection		Evolving protection	
		(In millions of people)				
Reference (no global sea-level rise)	1990	197	10	0	10	0
	2020s	399	23	0	22	0
	2050s	511	32	0	27	0
	2080s	575	36	0	13	0
HadCM2 GGa ensemble	2020s	410	30	5	26	3
(mean ± 95% confidence interval)	2050s	542 ± 1	79 ± 1	46 ± 1	51 ± 1	20 ± 1
	2080s	636 ± 1	237 ± 4	205 ± 4	93 ± 2	70 ± 2
HadCM3 GGa	2020s	409	29	5	26	2
	2050s	542	78	45	50	20
	2080s	634	228	195	88	65

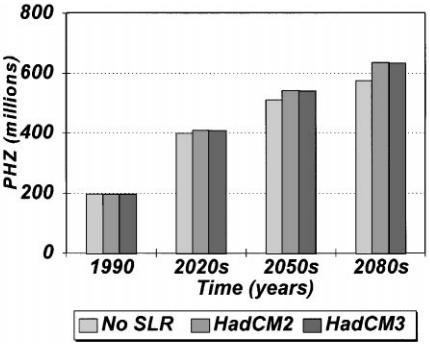

Fig. 10. The number of people in the hazard zone (PHZ) for (1) no global sea-level rise (No SLR), (2) the HadCM2 (mean), and (3) the HadCM3 climate change scenarios.

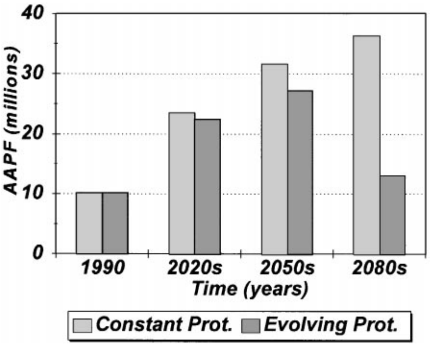

Fig. 11. Average annual people flooded (AAPF) without global sea-level rise (the reference scenarios).

climate variability is negligible for the flood impacts of a global sea-level rise. Therefore, all the subsequent discussion concerns the HadCM2 (mean) and the HadCM3 scenarios only.

In 1990, about 200 million people lived beneath the 1 in 1000 year storm surge (or people in the hazard zone). This nearly trebles to 575 million people in the 2080s without any rise in sea level (Fig. 10). Sea-level rise causes a modest increase in this number to 630 to 640 million people, or an increase of about 10% above the reference scenario.

In 1990, the number of average annual people flooded was 10 million, rising to 36 million in the 2080s under constant (1990) flood protection and no global sea-level rise (but allowing for subsidence). Assuming evolving protection, the number of average annual people flooded first increases to 27 million in the 2050s and then decreases to 13 million people in the 2080s (i.e. rising standard of flood protection becomes more important than population increase (and subsidence) after the 2050s). This different behaviour shows the importance of considering the changes that might occur without any specific adaptation for sea-level rise. These changes are illustrated in Fig. 11. Given sea-level rise, the average annual people flooded parameter increases more than 5-fold relative to the reference scenario in all cases by the 2080s (Fig. 12). The broad pattern of the results is independent of assumptions about protection if the appropriate reference scenario is used. In other words, the relative increase in flood risk is largely independent of the standard of protection. However, in terms of absolute impacts, the standard of protection is of great importance and average annual people flooded is reduced from 237 to 93 million people (about 60%) when comparing constant to evolving protection for the 2080s.

As sea levels rise, increasing numbers of people will experience frequent flooding and so will have to respond

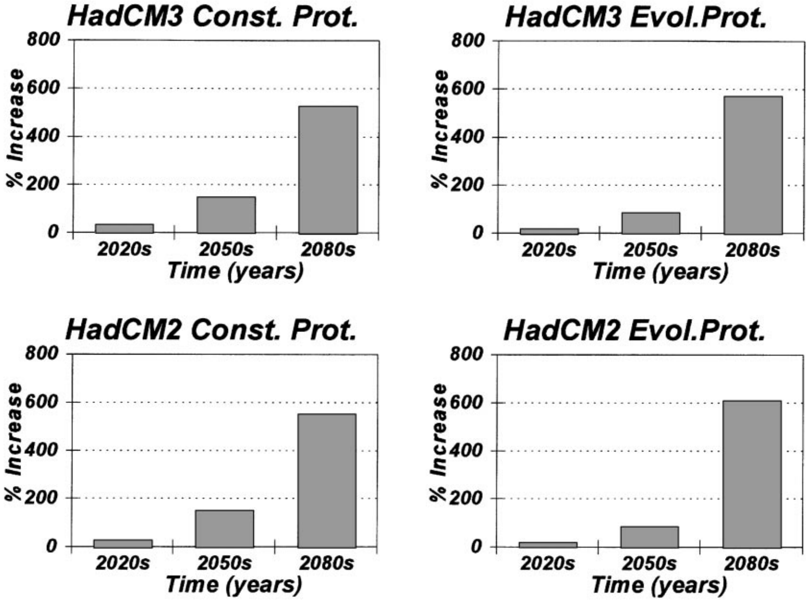

Fig. 12. Relative increase in average annual people flooded (AAPF) above the appropriate reference scenario (see Table 7 and Fig. 11) given the HadCM2 (mean) and HadCM3 climate change scenarios, and constant and evolving protection.

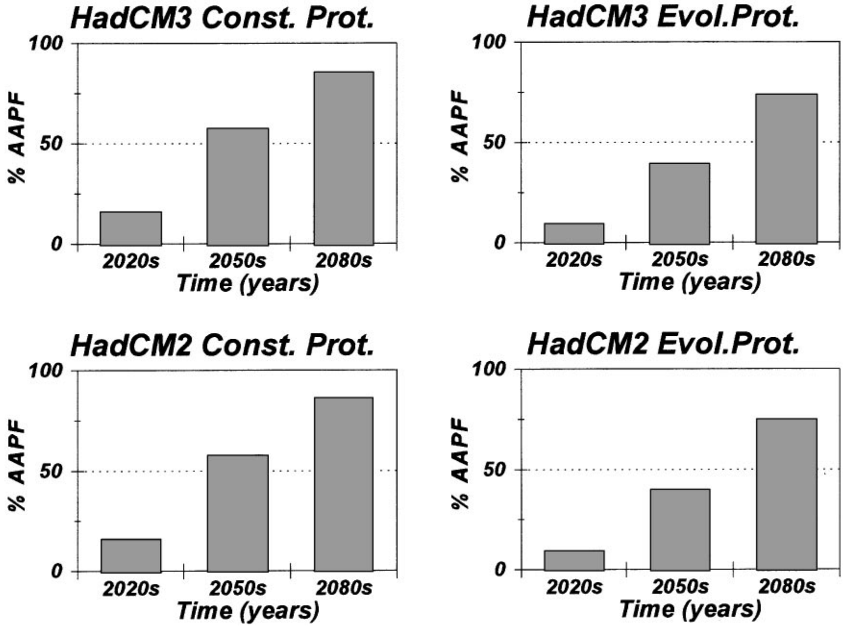

Fig. 13. Cumulative number of people to respond as a percentage of average annual people flooded (AAPF) given the HadCM2 (mean) and HadCM3 climate change scenarios, and constant and evolving protection.

Table 8
The five regions most vulnerable to coastal flooding given the HadCM2 (mean) scenario

Region	Average annual people flooded (millions)		
	1990	2080s	
		Constant protection	Evolving protection
Southern Mediterranean (Turkey to Algeria)	0.2	13	6
West Africa (Morocco to Namibia)	0.4	36	3
East Africa (South Africa to Sudan)	0.6	33	5
South Asia (Pakistan to Burma, including Sri Lanka)	4.3	98	55
South-east Asia (Thailand to Vietnam, including Indonesia and the Philippines)	1.7	43	21

in some way to the flood hazard. Here we present the cumulative total of people to respond, starting in 1990. However, as already noted, a continuous ongoing and growing response to flooding is likely and at any time the instantaneous number of people to respond is expected to be less than the results show in Table 7. Fig. 13 shows that the cumulative number of people to respond increases significantly in all cases, being about 70 and 200 million people under constant and evolving protection, respectively (or more than 70% of average annual people flooded) by the 2080s. This result suggests that the flooding produced by sea-level rise will be more than a trivial problem and many of the people living in the coastal flood plain will need to respond in some way.

5.1.3. HadCM2/HadCM3 scenarios — regional impacts

Most of the people flooded in the 2080s are concentrated in a few regions, particularly the Southern Mediterranean, West Africa, East Africa, South Asia and South-East Asia (see Table 8 and Fig. 14). These five regions contain more than 90% of the average annual people flooded, irrespective of the protection scenario considered. (For reference, in 1990, these five regions contained 70% of the average annual people flooded). South Asia is particularly noteworthy as it contains at least 40% of the global population at risk irrespective of the scenario considered. The large population at risk in South Asia and South-East Asia can be attributed to the concentration of low-lying, densely populated deltas in

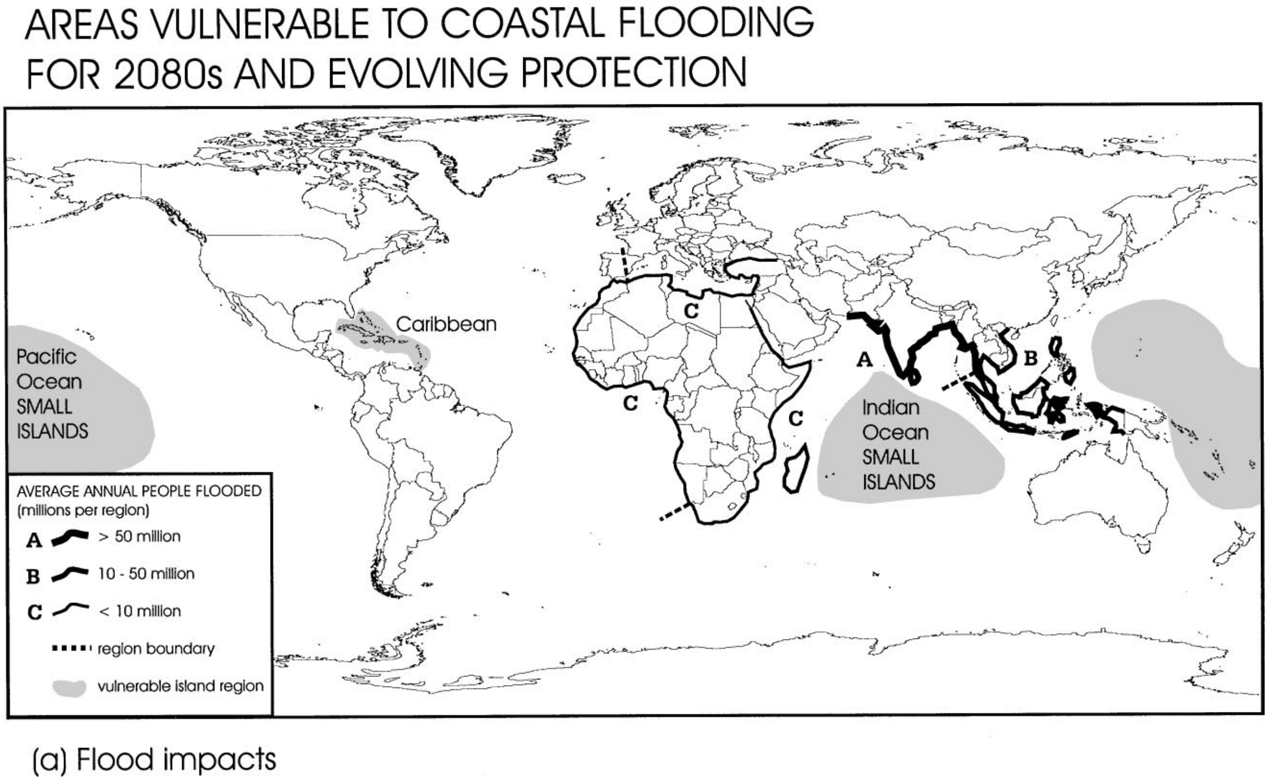

Fig. 14. Regional implications of sea-level rise — the regions most affected by flood impacts given the HadCM2 (mean) scenario for the 2080s.

these regions (Nicholls and Mimura, 1998). In Africa, the coastal population is expanding rapidly, but the means to provide high standards of protection from flooding is less available than in most other regions (Hoozemans et al., 1993; Nicholls and Mimura, 1998). East Asia is noteworthy in its relatively low increase in flood risk, despite containing a number of large populated deltas, particularly in China. Under evolving protection, average annual people flooded is about one million in the 2080s.

In addition to the absolute results, large relative increases in the number of people flooded are noted in a number of regions. This includes the main regions comprised of small islands: the Caribbean and the Indian Ocean and Pacific Ocean small islands (see Table 9). Under evolving protection, these three regions experience the largest relative increase in flood risk of any region. By the 2080s, the average annual people flooded has increased more than 200 times the reference scenario in all cases. This emphasises the high vulnerability of small islands to sea-level rise, including the "high" islands of the Caribbean (Bijlsma et al., 1996; Nurse et al., 1998).

Table 9
Small island regions and coastal flooding for the HadCM2 (mean) scenario

Region	Average annual people flooded (thousands)		
	1990	2080s	
		Constant protection	Evolving protection
Caribbean	10	1350	560
Indian Ocean	9	920	460
Pacific Ocean	4	290	160

5.2. Coastal wetlands

5.2.1. Response surfaces for sea-level rise

Fig. 15 shows the range of the response surfaces that result from the wetland loss model. There is considerable uncertainty about the actual response between the two surfaces shown. Most losses occur above a 0.2-m rise in sea level. Given a 1-m rise in sea level, in the worst case, it is estimated that 46% of the world's coastal wetlands could be lost. This is similar to the estimates of Hoozemans et al. (1993) that 55% of the world's coastal wetlands could be threatened by a 1-m global sea-level rise.

5.2.2. HadCM2/HadCM3 scenarios — global impacts

Table 10 shows the predicted losses of coastal wetlands to relative sea-level rise alone. Again, the HadCM2 scenario and the HadCM3 scenario produce very similar

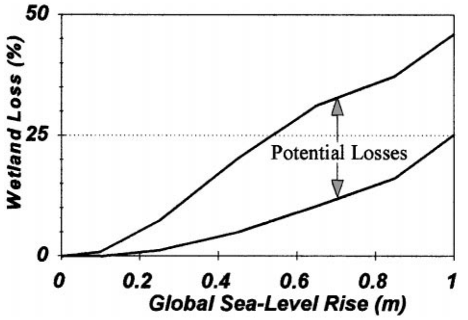

Fig. 15. The range of possible response surfaces for wetland loss as a function of global sea-level rise over a century. Note that there is no consideration of subsidence or other loss factors.

Table 10
Global losses of coastal wetlands due to sea-level rise only

Year	HadCM2 ensemble scenarios		HadCM3 scenario	
	High loss (%)	Low loss (%)	High loss (%)	Low loss (%)
2020s	2.3 ± 0.1	0.0	2.3	0
2050s	10.5 ± 0.4	1.9 ± 0.1	10.1	1.8
2080s	22.2 ± 0.1	5.7 ± 0.1	21.8	5.5

impacts. As with the coastal flooding, the impacts in the 2080s for the HadCM3 fall out of the range defined by the HadCM2 impacts. However, given the uncertainties in the analysis, little significance should be attached to this small difference. As with the flood analysis, all subsequent results concentrate on the HadCM2 (mean) and the HadCM3 scenarios. The losses due to sea-level rise are negligible before the 2020s and then increase significantly. By the 2080s, between 6% and 22% of the world's coastal wetlands could be lost (Fig. 16). When combined with the direct loss scenarios due to direct human destruction, in the worst case, 36% to 70% of the world's wetlands (up to 210,000 km^2) could be lost by the 2080s (Table 11).

Table 11
Combined global losses considering both sea-level rise and direct human destruction for the HadCM2 (mean) scenario

Year	High loss (%)	Low loss (%)
2020s	15–31	13–30
2050s	31–53	24–49
2080s	47–70	36–64

5.2.3. *HadCM2/HadCM3 scenarios — regional impacts*

Losses vary substantially from region-to-region: the Atlantic coast of North and Central America, the Mediterranean and the Baltic are projected to have the highest losses of wetlands due to sea-level rise (as distinct from other loss mechanisms) (Fig. 17). These wetlands are particularly vulnerable to sea-level rise due to the low tidal range in these areas. By the 2080s, most of the wetlands around the Mediterranean and Baltic could be lost. Coastal wetlands around the smaller islands in the Caribbean also appear to be threatened with large losses. While other areas with small islands are excluded from the analysis, similar impacts are likely due to the low tidal range of most of these areas and the limited opportunity for landward migration of the wetlands, among other factors.

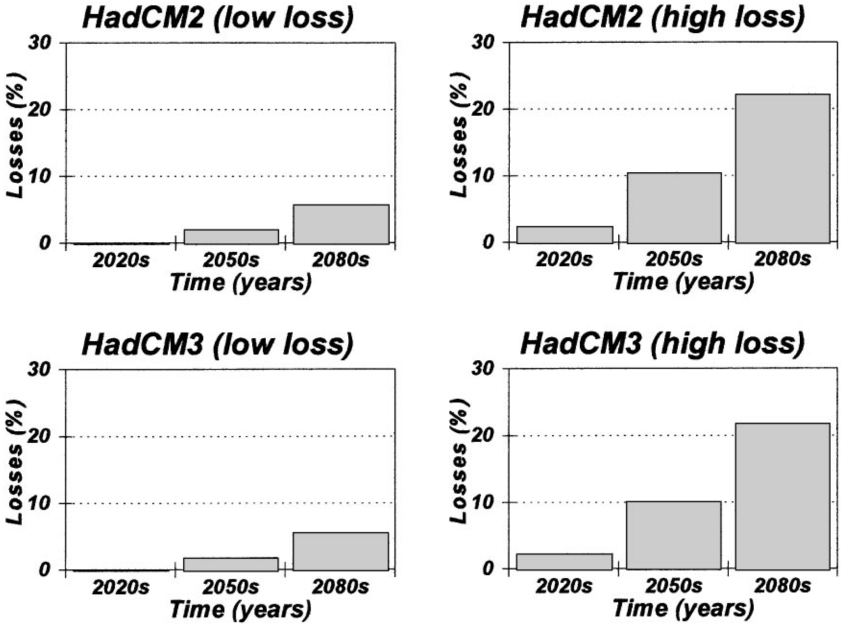

Fig. 16. Low and high estimates of additional wetland loss due to the HadCM2 (mean) and HadCM3 scenarios.

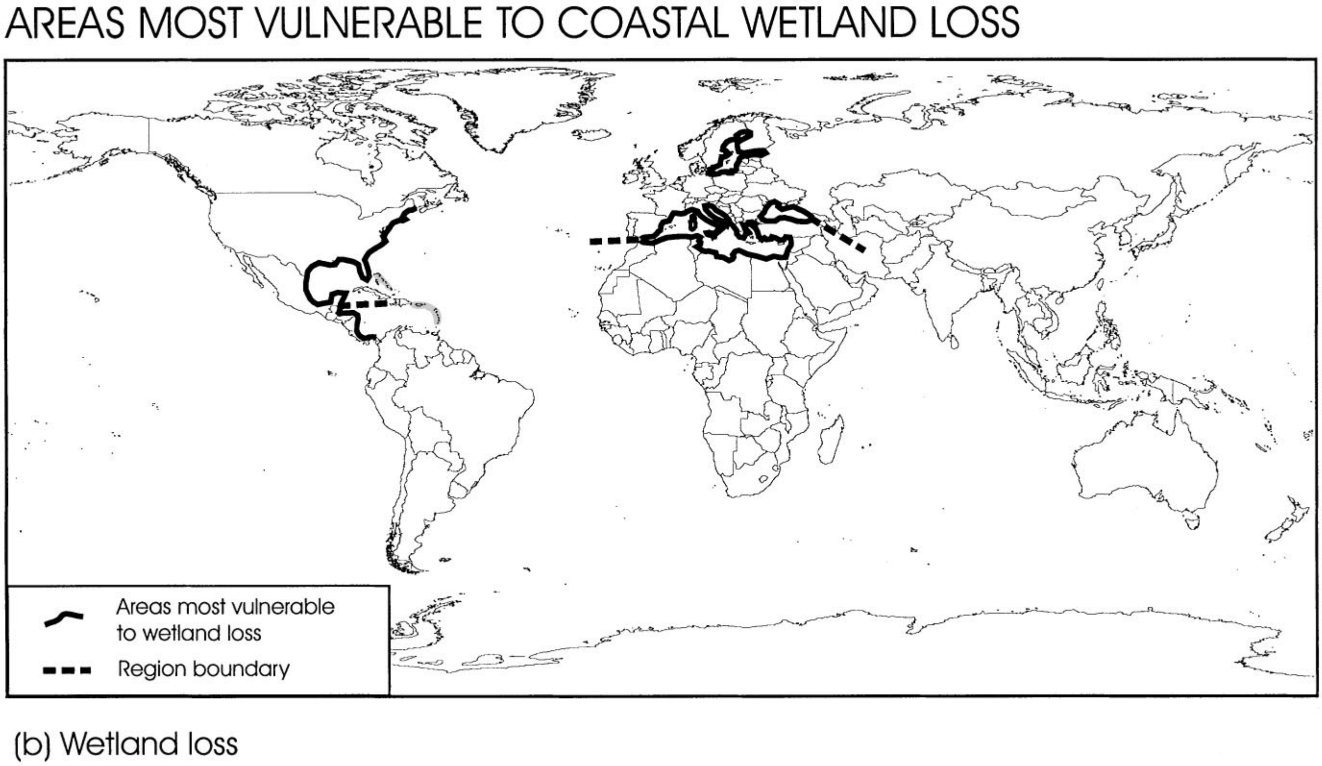

Fig. 17. Regional implications of sea-level rise — the regions where wetland losses may exceed 65% due to the HadCM2 (mean) scenario by the 2080s.

6. Discussion

6.1. Flood risk

Collectively, these results show larger relative and absolute increases in flood risk as sea levels rise than described in earlier work (Hoozemans et al., 1993; Hoozemans and Hulsbergen, 1995; Baarse, 1995), or by the IPCC Second Assessment Working Group II report (Bijlsma et al., 1996). This reflects a more realistic estimate of the 1990 level of protection and the calculation of increased flood risk within the 1990 flood plain as sea levels rise. The latter effect is much more important than the expansion of the flood plain due to sea-level rise. In addition, the impact of increased flooding is significantly reduced by the likely evolution of protection against climate variability when compared to an (unrealistic) scenario of constant protection. However, the absolute and relative flood impacts are still significant under an evolving protection scenario, and some adaptive response would be essential given the HadCM2 and HadCM3 climate change scenarios considered in this paper.

Other than evolving protection, the analysis has not considered potential autonomous adaptation to the flood impacts of sea-level rise. Autonomous adaptation comprises spontaneous changes in coastal resource use and management that occur without changes in policy, or prior knowledge or awareness of climate change (Carter et al., 1994; Klein and Nicholls, 1998). The present path of development around the world is placing ever greater amounts of fixed infrastructure and economic activity within the coastal zone. This present trend seems to offer limited scope for such adjustments against sea-level rise. Therefore, without a specific planned adaptation measures, sea-level rise will cause significant flooding impacts in the coastal zone. Certain regions are particularly vulnerable to sea-level rise in absolute or relative terms: Western Africa, Eastern Africa, the southern Mediterranean, south Asia, south-east Asia, the Caribbean and the Indian ocean and Pacific small islands. In all these vulnerable regions, the best adaptation options remain unclear (Nicholls and Mimura, 1998).

It should be remembered that the flood results are derived from limited data and make several important assumptions about the characteristics of the flood plain and the occurrence of flooding. However, the validation of these results against independent national studies gives some confidence in the broad patterns that have been defined, particularly the relative results. Nonetheless, there are a range of potential improvements to the flood analyses presented here. Most fundamentally, the resolution and types of underlying data should be improved, combined with further development and calibration of the methods employed. The impact of other aspects of climate change could also be considered, including an analysis of sea-level rise taking account of the spatial variation in thermal expansion (Gregory, 1993; Warrick et al., 1996) and possible regional changes in storminess and hence storm surge regime (e.g., Lowe and Gregory, 1998). Changes in storminess often attract more interest and concern than sea-level rise. The potential role of subsidence (and uplift) in future rates of relative sea-level rise could be more closely analysed as many coastal areas will see significant relative rises in sea level without any climate change. Lastly, the interaction of river flooding and sea-level rise could be considered as this could produce substantial increases in flood risk above those evaluated here (Nicholls, 1995b; see also Arnell, 1999).

6.2. Coastal wetlands

Coastal wetlands are threatened by sea-level rise, particularly as direct human destruction is likely to substantially reduce the existing global stock. While it has not been assessed, surviving wetlands may be significantly altered. These impacts will be particularly severe in certain regions such as the Mediterranean and the Baltic where coastal wetlands could almost completely disappear by the 2080s due to sea-level rise alone. (In the northern Baltic post-glacial rebound (i.e. land uplift) will offset global sea-level rise, but few wetlands exist in this area). In addition, significant wetland losses are expected to continue after the 2080s if sea levels continue to rise, but again this has not been evaluated. Losses of wetlands will impact many sectors and functions including food production (loss of nursery areas for fisheries), flood and storm protection (storm surges will penetrate further inland), waste treatment and nutrient cycling functions, and as habitat for wildlife. Broadly similar results have been reported previously (Hoozemans et al., 1993; Nicholls, 1995b; Bijlsma et al., 1996). Thus, the already poor prognosis for coastal wetlands is significantly worsened by accelerated sea-level rise.

However, as with the flood analysis, it is important to remember that there are significant uncertainties in the analysis. While similar approaches have been used in national assessments of coastal wetland response to sea-level rise for policy purposes, the method used is difficult to validate. This point of caution stresses that good policy requires continuing research on wetland response to sea-level rise at a range of scales, from local to regional/global, as well as an improved understanding of the linkage between these different scales. At the global scale, improved spatial resolution of the coastal typology and the distribution of coastal population would be particularly useful, combined with data on additional factors such as sediment availability.

6.3. Policy implications

This study suggests the need for a policy response to the projected impacts of sea-level rise. Mitigation of greenhouse gas emissions is one important response to the threats identified in this paper. Lower emissions of greenhouse gases will translate into less climate change and sea-level rise. However, mitigation policies would slow, but not stop the expected rise in sea level even given stabilisation of greenhouse forcing in the next few decades (which seems an optimistic scenario). This has been termed the "commitment to sea-level rise" (Warrick and Oerlemans, 1990; Wigley, 1995). Analysis using several impact models (food, water and coastal flooding) suggests that the benefits of mitigation policies lie well in the future (beyond the 2050s) (Parry et al., 1998). Therefore, adaptation to global sea-level rise will also be essential during the next century. Given that large numbers of people are already flooded every year and coastal wetlands are already declining, proactive measures to deal with these issues could give immediate benefits.

Reducing flood impacts is often interpreted as meaning new or upgraded structural protection. The terminology used in the flood analysis methodology in this paper makes the same implication. However, three broad strategies are available to reduce flood impacts due to sea-level rise: (1) planned retreat (e.g., vulnerable areas could be zoned as unsuitable for development); (2) accommodation (e.g., new homes could be flood-proofed or elevated above the flood levels expected during their design life); or (3) protection (e.g., flood walls could be raised as they are renewed or upgraded) (IPCC CZMS, 1990; Bijlsma et al., 1996; Klein and Nicholls, 1998). To be successful, all of these responses imply some anticipation of sea-level rise, particularly the retreat and accommodate strategies. The type of analysis presented in this paper is unsuitable to determine which strategy is most suitable for a given area: this needs to be the subject of more detailed local and national assessments. However, it should be noted that large-scale use of protection will maintain or increase coastal squeeze and hence will enhance wetland losses. This stresses that responses to sea-level rise should not happen in isolation: they need to be assessed together with other implications of climate change, and the wider goals of coastal zone management (Bijlsma et al., 1996; Cicin-Sain et al., 1997; Klein et al., 1999).

The results certainly stress the need for more effective wetland conservation worldwide. With or without sea-level rise the prognosis for coastal wetlands is poor and it is important to stop or greatly reduce the direct destruction of these systems. We also need to plan to promote and encourage wetland survival under a rising sea level. Two possible responses to minimise wetland losses due to sea-level rise are (1) maintaining sediment supplies to coastal wetlands so they can grow in place (by improving catchment management, allowing coastal erosion to continue, etc.) and (2) selective use of planned retreat and accommodation to create space for wetland migration to occur (cf. Working Group on Sea level Rise and Wetland Systems, 1997). Given the varied threats to coastal wetlands, the most realistic policy goal may be to minimise wetland losses rather than maintain the existing stock.

6.4. Other uncertainties

A number of uncertainties within the impact modelling have been briefly raised and possible improvements have been discussed. In addition, it is important to remember that the climate change scenarios used here do not encompass the full uncertainties concerning future climate (Hulme et al., 1999). Based on the IPCC Second Assessment, the range of uncertainty in sea-level rise for the IS92a emissions scenario (which is similar to the HadCM2 and HadCM3 emission scenarios) is a 19–80-cm global rise. Similarly, the socio-economic scenarios we have used have a large uncertainty. The impacts we have estimated are sensitive to all these scenarios, emphasising the need to better understand and interpret the full range of uncertainty.

7. Conclusions

The analyses presented here shows that without an adaptive response, a global sea-level rise of only 37–38 cm by the 2080s could greatly enhance the occurrence of coastal flooding and increase the decline of coastal wetlands. The impacts are not uniform around the globe and some regions will be more adversely affected than others will. For coastal flooding, the southern Mediterranean, Africa, South and South-East Asia are most vulnerable in absolute terms, while the Caribbean, Indian Ocean islands and the Pacific Ocean small islands will see large relative increases in flood impacts. The largest losses of coastal wetlands is expected around the Atlantic coast of Central and North America, the small Caribbean islands, and most particularly the Mediterranean and Baltic.

These results suggest that it would be prudent to begin proactive planning for the potential impacts of sea-level rise now. This is particularly important given “the commitment to sea-level rise” regardless of any realistic future emissions policy. Given that sea-level rise will generally exacerbate existing problems, such planning could have immediate benefits.

Acknowledgements

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