PERGAMON

Physics and Chemistry of the Earth 27 (2002) 1455–1466

PHYSICS and CHEMISTRY of the EARTH

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Analysis of global impacts of sea-level rise: a case study of flooding

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Abstract

Analysis of the response to climate change and sea-level rise requires a link from climate change science to the resulting impacts and their policy implications. This paper explores the impacts of sea-level rise, particularly increased coastal flooding due to storm surges. In particular, it asks the simple question "how much will projected global sea-level rise exacerbate coastal flood problems, if ignored?" This is an important question to the intergovernmental process considering climate change. Further many countries presently ignore sea-level rise in long-term coastal planning, even though global sea levels are presently slowly rising.

Using the model of Nicholls et al. [Global Environmental Change 9 (1999) S69], the analysis considers the flood impacts of sea-level rise on an "IS92a world" based on a consistent set of scenarios of global-mean sea-level rise, subsidence (where appropriate), coastal population change (usually increase), and flood defence standards (derived from GDP/capita). Two of the protection scenarios consider the possible upgrade of flood defences, but no allowance for global-mean sea-level rise is allowed to ensure consistency with the question being investigated. This model has been validated against national- and regional-scale assessments indicating that the relative results are reasonable, and the absolute results are of the right order of magnitude.

The model estimates that 10 million people experienced flooding annually in 1990. It also predicts that the incidence of flooding will change without sea-level rise due to changes to the other three factors. Taking the full range of scenarios considered by 2100 the number of people flooded could be from 0.4 to 39 million/year. All the sea-level rise scenarios would cause an increase in flooding during the 21st century if measures to adapt to sea-level rise are not taken. However, there are significant uncertainties and the number of people who are estimated to experience flooding in 2100 is 16–388 million for the mid (55-cm) global-mean sea-level rise scenarios, and up to 510 million people/year for the high (96-cm) scenario. These results suggest that sea-level rise could be a significant problem if it is ignored, and hence it needs to be considered within the policy process considering climate change in terms of mitigation (reducing greenhouse gas emissions) and adaptation (improved coastal management and planning) needs.

Keywords: Sea-level rise; Impacts; Vulnerability; Flooding; Scenarios; Adaptation; Coastal management

1. Introduction

Sea-level rise was one of the issues that first triggered widespread concern about the potentially adverse effects of anthropogenically-induced climate change (e.g., Schneider and Chen, 1980; Barth and Titus, 1984; Broadus et al., 1986; Commonwealth Secretariat, 1989). While the expectations concerning the likely magnitude of sea-level rise during the 21st century have been reduced, the implications of a rise of sea level remain an important element in determining the overall policy response to climate change as well as informing long-term coastal management needs. Therefore, it is important to link climate and sea-level rise scenarios to the impacts that might result. However, this linkage is not simple as it depends on both the exposure and adaptive capacity to a given change in climate (as reviewed by Smit et al. (2001)).

A rise in sea level would produce four major biogeophysical impacts in coastal areas: (1) inundate and displace wetlands and lowlands; (2) erode shorelines; (3) exacerbate storm flooding and damage; and (4) increase the salinity of estuaries and threaten freshwater aquifers (Bijlsma et al., 1996). In turn, these will have socio-economic consequences producing a cascade of impacts and responses through the coupled biogeophysical-socio-economic coastal system (Klein and Nicholls, 1999). A series of global assessments suggest that the impacts of sea-level rise could be significant during the 21st century, unless there is an appropriate adaptive

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PII: S1474-7065(02)00090-6

response (e.g., Hoozemans et al., 1993; Nicholls et al., 1999). Large populations could experience more frequent flooding and storm damage, rice production in Asian deltas could be significantly reduced by hydrological and salinity changes, and coastal wetlands will be further degraded by sea-level rise. The potential to adapt is variable, with some developing world regions facing the greatest burdens. Further, adaptation for human systems may exacerbate other impacts (e.g., flood defences may exacerbate coastal squeeze of ecosystems (Nicholls, 2000a)).

This paper examines one of these impacts: the potential impacts of global sea-level rise on coastal flooding due to storm surges. The increase in extreme water levels will threaten all coastal lowlands and the increased flooding is a precursor to the permanent inundation and submergence of low-lying land by sea-level rise which has captured so much attention (e.g., for Bangladesh see Broadus et al., 1986; Huq et al., 1995). Most of the discussion concerns the flood model described by Nicholls et al. (1999) and Nicholls (2000b). Using scenarios that are consistent with an IS92a world, the potential impacts of sea-level rise are evaluated. The main focus of the analysis is on answering the simple question: "how much will projected global sea-level rise exacerbate coastal flood problems, if ignored?" This is a realistic question when considering what response is required for climate change and further, many countries presently ignore sea-level rise in long-term coastal planning.

2. Climate change, sea-level rise and the coast

During the 20th century, greenhouse gas concentrations increased significantly due to the burning of fossil fuels, while global temperatures increased about 0.6 °C and global sea levels rose 10–20 cm (Houghton et al., 2001). There is increasing scientific evidence that these observations are linked and the anthropogenic emissions of greenhouse gases are having a discernible effect on the earth's climate (Houghton et al., 2001). This human influence on climate is expected to intensify during the 21st century. Given the large and growing population in coastal areas (Nicholls, 1995a; Nicholls and Small, 2002), the potential implications of sea-level rise and other climate change is of great concern.

The certainty of these climate changes varies from factor to factor. A global rise in sea level is of high certainty: the observed rise of the 20th century is expected to continue and probably accelerate during the 21st century. The Intergovernmental Panel on Climate Change (IPCC) Second Assessment estimated global-mean sea-level rise from 1990 to 2100 to be in the range 23–96 cm (Warrick et al., 1996). The most recent IPCC estimate has reduced the expected global-mean rise to between 9 and 88 cm (Church et al., 2001). Regionally sea-level rise will depart from the global-mean trend due to a range of meteorological, oceanographic and geological effects. However, apart from some geological effects (e.g., Shennan, 1989; Peltier, 2000), the patterns of this change remain uncertain. Importantly, sea levels are expected to continue to rise beyond 2100 for hundreds or more years into the future, even if global climate is stabilised in the next few decades.

The influence of climate change on the long-term tracks, intensity and frequency of coastal storms is much less certain (Warrick et al., 2000; Church et al., 2001). It receives considerable attention due to the high impact potential and erroneous comments about the certainty of an increase in storminess. Given the high interannual and interdecadal variability of storm occurrence (e.g. WASA Group, 1998; Zhang et al., 2000) it may be difficult to discern any long-term changes in the presence of natural variability. Given these uncertainties, most assessments of climate change in coastal areas have focussed on assessing the impacts of global-mean sea-level rise and no other climate change. The work discussed here follows the same assumption. However, it is recognised that both regional variations in sea-level rise and changes in storm and surge characteristics could have important influences on these impacts.

3. Coastal flooding and sea-level rise

Coastal flooding is the result of infrequent extreme sea levels produced by storms (or significant run-off from the land). Fig. 1 shows the different zones at risk of flooding that exist on any low-lying coast. Fig. 2 shows two sample flood exceedance curves: the different slopes reflect variation in both the storm characteristics and the shelf-sea/coastal configuration.

The first-order effect of sea-level rise (and no other change) is to displace the flood exceedance curves upward (Fig. 2). Hence, the risk zones move upward and landward and (1) increase the flood risk within the existing floodplain and (2) expand the floodplain landward. In a natural situation, this landward expansion of the floodplain would tend to be compensated by inundation (i.e., permanent submergence) at the seaward margin, but if there are artificial flood defences present, this process may only occur if the defences are rendered completely ineffective. As shown in Fig. 2, for the same rise in sea-level rise, the decrease in the return period of high waters for Egypt is much greater than for the Netherlands: a 10-year high water event is reduced to a 6-month event and a 9-year event, respectively. Therefore, coastal areas with low gradient flood curves like Egypt will see a larger increase in the frequency of flooding due to sea-level rise. However, the exposure to

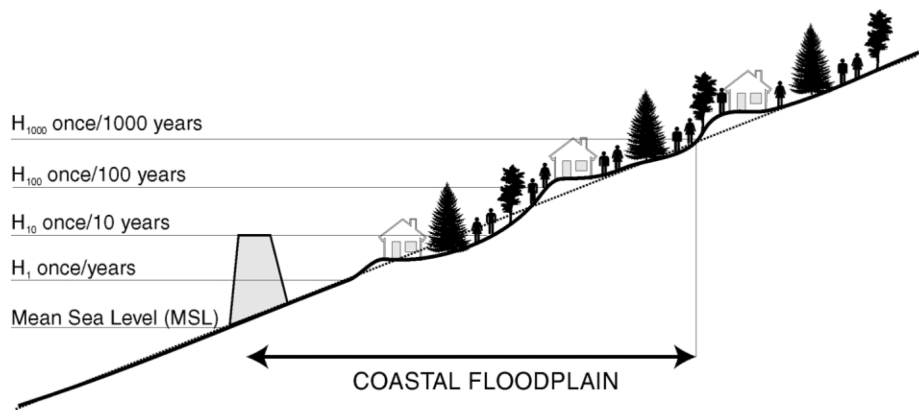

Fig. 1. The coastal floodplain, including different storm surge levels up to the 1000-year surge elevation (H_{1000}).

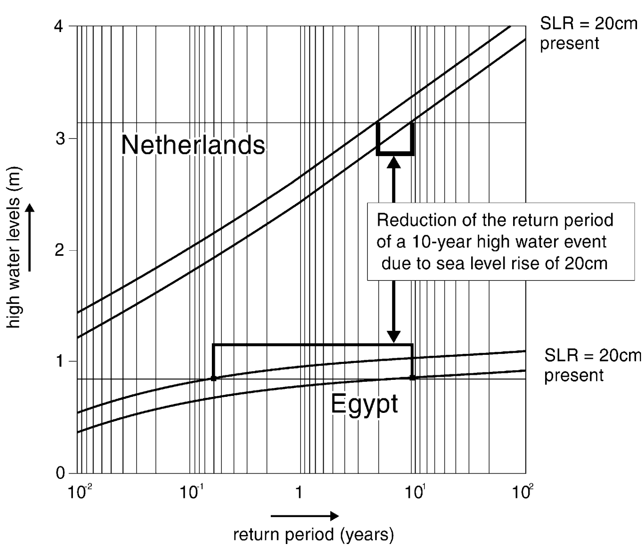

Fig. 2. Examples of the influence of a 20-cm relative rise in sea level on the return period of flood (or high water) elevations (adapted from Hoozemans et al., 1993).

flood events in areas with large surges such as the Netherlands also needs to be considered.

Secondary effects of sea-level rise on flood risk are erosion of the coast and the degradation and destruction of coastal ecosystems. This reduces the natural protection against a surge and the associated wave action could propagate inland more easily. Hence, the return period of high water events would be further decreased (Nicholls, 2002).

4. History of global assessments

In 1990, IPCC Coastal Zone Management Sub-Group (CZMS) (1990) published a global estimate of protection costs against a 1-m rise in sea level. Since then, there have been a series of studies using the same underlying data, but progressively improving the analytical methods. The first global vulnerability analysis was completed in 1992 using the IPCC Common Methodology (IPCC CZMS, 1992). This included evaluating increased flood risk and potential response costs assuming a 1-m global rise in sea level on the 1990 and (projected) 2020 worlds (Hoozemans et al., 1992). This was rapidly updated with a second edition (Hoozemans et al., 1993). These results were made available to the United Nations Conference on Environment and Development (Rio de Janeiro, Brazil, 1992) (IPCC CZMS, 1992), and the World Coast Conference (Noordwijk, the Netherlands, 1993) (WCC'93, 1994). They are also included in the IPCC Second Assessment Report (Bijlsma et al., 1996), including improvements to the flood analysis by Baarse (1995).

Subsequently, the flood analysis was upgraded to a dynamic form, including improved impact algorithms (Nicholls et al., 1999; Nicholls, 2000b). This can consider the implications of a range of sea-level rise scenarios combined with the interacting effects of increased coastal populations, and rising living standards on defense standards. This more recent work is widely cited within the IPCC Third Assessment Report (McCarthy et al., 2001) and has also contributed to a series of sectoral impact studies based on common climate and socio-economic scenarios (Parry and Livermore, 1999; Arnell et al., 2002; Parry et al., 2001).

5. Methodology

A range of parameters could be used to describe the exposure and risk of flooding. Here the coastal population is used as an input to derive three parameters (Nicholls et al., 1999):

- *People in the hazard zone (PHZ)*: the number of people exposed to flooding by storm surges ignoring sea defences. This is defined as the people living below the 1000-year storm surge elevation (Fig. 1);

- *Average annual people flooded (AAPF)*: the average annual number of people who experience flooding by storm surge, including the benefits of sea defences (note that this parameter has been widely referred to as *people at risk*);
- *People to respond (PTR)*: the average annual number of people who experience flooding by storm surge more than once per year, including the benefits of sea defences. This gives an indication of the population that would be affected by flooding so frequently that a significant response (upgrade flood protection, migrate, etc.) is expected.

However, note that the calculation of these parameters assume no human response to increased flooding, because this is difficult to model. Thus, the estimates can be considered as cumulative impacts, which is an important point to remember during the interpretation of the results. The relative magnitude of the parameters is as follows:

$$\mathrm{PTR} \leqslant \mathrm{AAPF} \leqslant \mathrm{PHZ} \qquad (1)$$

The methodology used to calculate these parameters is outlined in Fig. 3, and has been described in detail previously (Nicholls et al., 1999). It evaluates the first-order potential impact of sea-level rise on coastal flooding due to storm surges. Hoozemans et al. (1993) provides a database of the four factors we need to apply this method (1990 is the base year):

(1) the maximum area of the coastal floodplain after a 3-m relative rise in sea level;
(2) the flood exceedance curve for storm surges under base conditions;
(3) the average coastal population density in the base year;
(4) geological characteristics in terms of the occurrence or absence of subsidence.

It should be stressed that this database has a coarse spatial resolution and several important assumptions about the characteristics of the floodplain and the occurrence of flooding are necessary for the calculations (see Hoozemans et al., 1993; Nicholls et al., 1999). The database comprises 192 coastal polygons of variable size, largely corresponding to the coastal areas of the countries that existed around 1990. Three fundamental assumptions are that (1) the coastal floodplain has a constant slope, (2) the population distribution within the coastal flood plain is uniform, and (3) when a sea defence is exceeded by a surge, it fails totally. Also note that the second-order effects of sea-level rise such as erosion and wetland loss are not considered.

Calculations proceed as shown in Fig. 3. Estimates of the storm surge elevations are raised by the *relative* sea-level rise scenario (i.e. global rise plus estimated subsidence) and converted to the corresponding land areas threatened by these different probability floods. These areas are then converted to PHZ using the average population density for the coastal area. Lastly, the standard of protection (i.e. the level of risk) is used to calculate AAPF and PTR. These national estimates are then aggregated to regional and global results. Given the limited resolution of the underlying databases and the simplified assumptions used in the calculations, only the aggregated regional and global results are valid (Hoozemans et al., 1993; Nicholls et al., 1999).

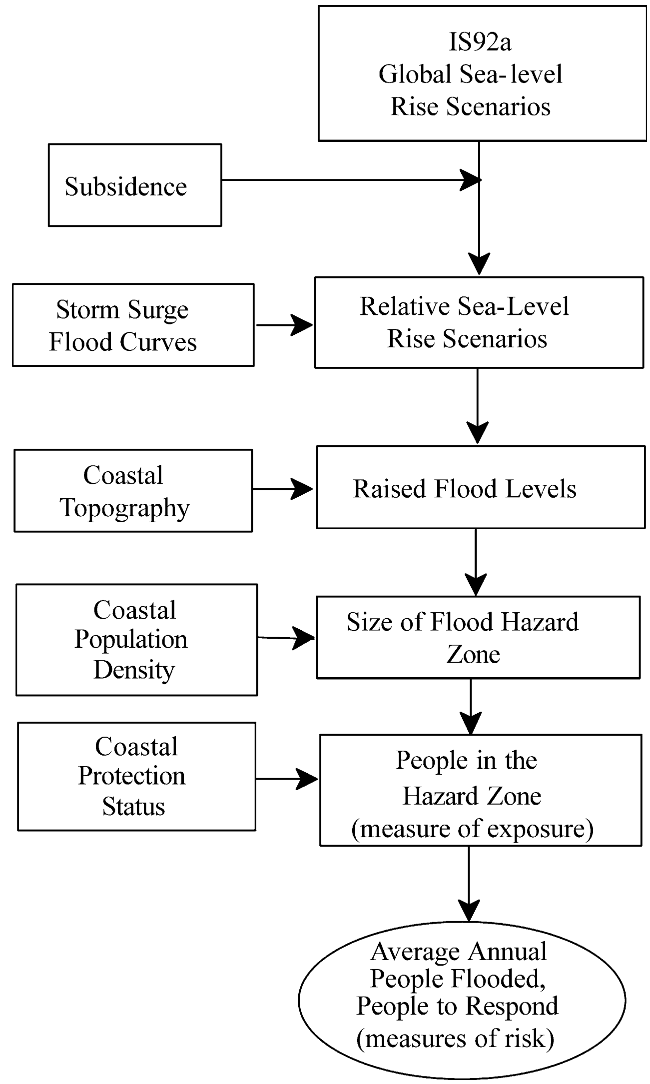

Fig. 3. Flow diagram illustrating the flood model algorithm.

There are no global databases on the level of flood protection, so the standard of protection was estimated indirectly using per capita GNP (or GDP) as an "ability-to-pay" parameter. Based on empirical observations, the assumptions are that (1) wealthy nations enjoy better protection and (2) deltaic areas are more expensive to protect. Following earlier analyses and expert judgement, Nicholls et al. (1999) linked different levels of

Table 1
Selection of PC, allowing for deltaic and non-deltaic coasts

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

Table 2
Reduction in PC as a function of RSLR and flood envelope (E_{Flood}) (Eq. (1))

If RSLR $< 1/3 * E_{\mathrm{Flood}}$,	No change
If RSLR $> 1/3 * E_{\mathrm{Flood}}$,	PC = PC-1
If RSLR $> 2/3 * E_{\mathrm{Flood}}$,	PC = PC-2
If RSLR $> E_{\mathrm{Flood}}$,	PC = PC-3
If RSLR $> 4/3 * E_{\mathrm{Flood}}$,	PC = PC-4

GNP/capita to protection classes (PCs) (and design frequencies) shown in Table 1 for deltaic and non-deltaic areas. The selection of deltaic areas was based on areas where the deltaic population made a significant contribution to the overall flood risk of the area under consideration. They are Bangladesh, Burma, China, Egypt, France (Mediterranean coast), French Guyana, Guyana, India, Iraq, Italy, Netherlands, Nigeria, Pakistan, Surinam, Thailand, and Vietnam.

The minimum standard of protection in 1990 was selected as 1 in 10 years based on the observation that coastal populations do not appear to accept more frequent flooding. This means that in 1990, PTR is zero by definition. The increase in flood risk produced by sea-level rise within the pre-existing floodplain is estimated by reducing the PC as defined in Table 2. The PC is reduced in integer steps up to four classes. The lowest PC is 0, which is a 1 in 1 year or lower standard of protection. As already noted, the shape and slope of the flood exceedance curves control how much a given rise in sea level reduces flood risk, all other factors being equal. The increase in flood risk due to sea-level rise is controlled by the flood envelope (E_{flood}):

$$E_{\mathrm{flood}} = H_{1000} - H_1 \tag{2}$$

where H_{1000} is the 1 in 1000 year flood elevation and H_1 is the 1 in 1 year flood elevation (Fig. 1). A relative rise in sea level equal to E_{flood} reduces a 1 in 1000 year standard to a 1 in 1 year standard of protection. As E_{flood} is less than 1 m on much of the world's coast, the sea-level rise scenarios considered in this chapter result in a large increase in the flood risk (Nicholls et al., 1999).

6. Scenarios of change

Most impact studies consider the impacts of sea-level rise by 2100 on the present socio-economic situation (Nicholls, 1995b; Nicholls and Mimura, 1998). At most, socio-economic scenarios are developed for 30 years in the future (e.g., Hoozemans et al., 1993). Such results may understate the importance of non-climate change factors, which could compensate or exacerbate the effects of climate change. Here we examine the implications of sea-level rise on a dynamic future world, including the influence of relevant evolving climate and non-climate change factors. Consistent and meaningful natural system and socio-economic scenarios are required and this analysis is based on assumptions consistent with the IS92a world where greenhouse gases increase at 1% per annum through to 2100 and constant 1990 aerosols (Houghton et al., 1996; Hulme et al., 1999). The reference scenario is the same scenario without global sea-level rise in all cases.

Scenarios of four factors reflecting relevant climate and non-climate change are used (Tables 3 and 4). The global-mean sea-level rise has a large range of uncertainty that is expressed by low, mid and high scenarios (Warrick et al., 1996). Most of this uncertainty is due to uncertainty in the climate sensitivity (Wigley, 1999). The scenarios are a mid estimate of a 45-cm rise by the 2080s, with a range of 19–80-cm rise, relative to 1990. In addition, it is assumed that subsiding areas are experiencing a relative sea-level rise (RSLR) of 15 cm/century, while elsewhere there is no change.

Changes in national population are taken from the World Bank (Bos et al., 1994): global population more than doubles from 1990 to the 2080s (5.3–10.7 billion people). This implies a large increase in the population

Table 3
Scenarios used in the analysis (following the classification of Klein and Nicholls, 1999)

	Environmental changes	Socio-economic developments
Climate-induced	Global-mean sea level	GDP/capita (upgrade of flood defenses to climate variability, but not climate change)
Not climate-induced	Vertical land movement	Population

Table 4
The scenario values used in this study

Year	Global-mean sea-level rise (cm)			Subsidence (cm/century)	Global population (10^9)	Global GDP(10^{12} 1990 US$)
	Low	Mid	High			
1990	0	0	0	0 or 15	5.3	20
2020s	4	11	22	0 or 15	8.1	65
2050s	10	27	49	0 or 15	9.8	113
2080s	19	45	80	0 or 15	10.7	164
2100	23	55	96	0 or 15	11.0	189

See text for sources.

of coastal areas. To apply these national scenarios to the coastal zone, two scenarios are developed:

- Population scenario one: coastal populations increase at the same rate as national population;
- Population scenario two: coastal populations increase at twice the rate of national population.

The present trend is widely reported as being consistent with scenario two, although the available data is poor and there is limited systematic analysis. Earlier analyses (Nicholls et al., 1999; Nicholls, 2000b) only focussed on the second scenario.

The standard of protection is derived from GDP/capita forecasts of the Energy Modelling Forum (1995). This provides aggregated scenarios of GDP growth rates for six groups of countries. To distinguish the potential for autonomous upgrade of protection to offset sea-level rise, three protection scenarios are considered:

(1) constant protection (i.e., constant 1990 levels);
(2) evolving protection in phase with increasing GDP/capita;
(3) full-upgrade protection (for 2100 only).

Evolving protection only includes measures that would be implemented without any sea-level rise—i.e. there are no proactive adaptation measures to anticipate sea-level rise. This helps to assess how much autonomous processes that are likely to occur without sea-level rise might reduce the impacts. The GDP/capita scenarios show a substantial increase for all countries, particularly for developing countries. This implies a large upgrade in the standard of defence in countries which presently do not enjoy high defence standards. The evolving protection assumption is also consistent with the main question that the study is addressing, and follows current practise in many parts of the world, which treats sea level as constant. The most optimistic situation in a world that ignores sea-level rise would be for all flood defences to be upgraded to a 1 in 1000 year standard based on 1990 surge conditions. This might happen if national resources were focused on flood defence. This 'full-upgrade' protection scenario is considered for comparative purposes for 2100.

7. Model validation

When conducting analyses of this type, the first thing to evaluate is the validity and accuracy of the results. Given the simple, first-order approach, the simplifying assumptions employed and the coarse spatial resolution of the data, there is considerable potential for inaccuracy. Aggregation is one approach to reduce unbiased errors and all the results considered are aggregated to a supra-national level. Beyond this, independent validation of the model is an important and difficult step. For this purpose, a data set of national values for the three flood impact parameters has been derived from national-scale vulnerability assessments wherever possible (Nicholls, 2000b). While these national-scale results consider the impacts of sea-level rise on the 1990 world without any socio-economic changes, the results can be used to validate the global flood model. The aggregated results are presented in Table 5 (following the comment above). For comparative purposes, the results of Hoozemans et al. (1993) are also shown.

Considering 12 national studies, PHZ is broadly similar with 109 million people in the national studies and 68 million people in this study. Compared to the national studies, Hoozemans et al. (1993) tends to overestimate the AAPF in 1990, and underestimate the flood risk after a 1-m rise in sea level. This study produces improved estimates of AAPF for both present conditions (no sea-level rise) and after a 1-m rise in sea level. PTR is also similar for a 1-m global rise in sea level with >39 million people in the three national studies,

Table 5
Model validation

Assessment	PHZ	AAPF		PTR
		No SLR	SLR = 1 m	SLR = 1 m
		(millions of people)		
Countries	Japan, Netherlands, China, Egypt, Germany, Poland, Antigua, Belize, Benin, Marshall Islands, Mauritius, Nigeria (Total: 12)	Egypt, Germany, Guyana, Netherlands, Poland, Vietnam (Total: 6)		Bangladesh, India, Vietnam (Total: 3)
National studies	109.2	1.2	23.5	>39.0
Hoozemans et al. (1993)	68.1	5.5	10.1	Not reported
This study	68.1	1.2	14.2	50.0

Aggregated results from selected national assessments compared with Hoozemans et al. (1993) and this study, assuming 1990 population (from Nicholls, 2000b).

Table 6
Comparison between this study and Mimura (2000) for people in the hazard zone in the Asia–pacific region

Study	PHZ (millions)		
	No SLR (1994 world)	SLR = 1 m (1994 world)	SLR = 1 m (2100 world)
This study	139	171	319
Mimura (2000)	207	270	450

compared to 50 million in this study. Given the limited sample, this parameter is the least well validated.

Independent of this study, Mimura (2000) produced estimates of PHZ during 1994 for the Asian–Pacific Region using more detailed data than employed here. The results are compared in Table 6. The numbers in this study tend to be smaller than those estimated by Mimura (2000), but are comparable in magnitude.

Therefore, the model validation suggests that the results are broadly in line with the available national-scale and regional-scale assessments. This gives confidence in the validity of the patterns in the relative results, and the order-of-magnitude of the absolute results. It also represents an improvement over the earlier estimates of Hoozemans et al. (1993) and Baarse (1995) for AAPF.

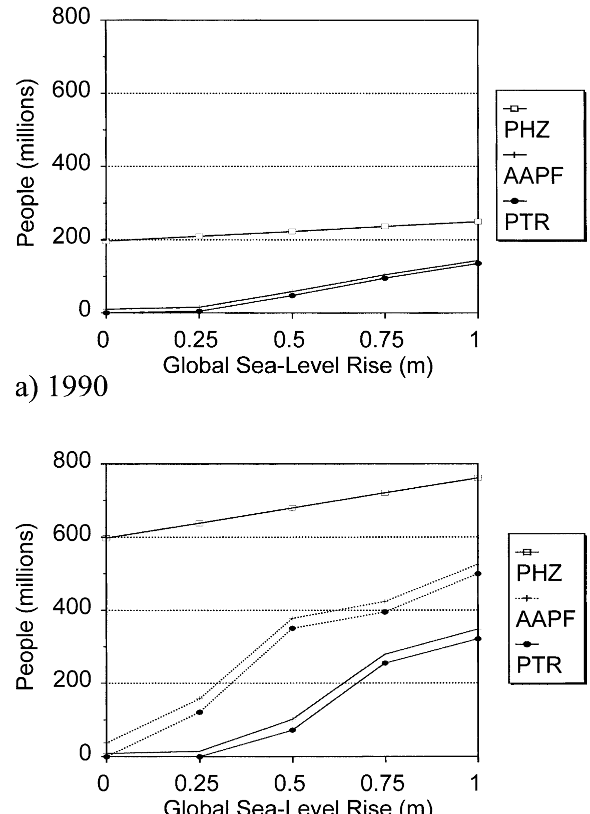

Fig. 4. (a) Response surfaces from the model for 1990 and (b) 2100 under population scenario two, contrasting the situation assuming evolving protection (solid line) and constant protection (dotted line). Note that there is only a single value for PHZ in 2100.

8. Results

Some of the results have been considered before (Nicholls, 2000b), and what is presented are new results, avoiding unnecessary duplication. First, the general results of the model are considered in terms of the characteristics of the response surfaces to sea-level rise under IS92a conditions, and how they evolve over time. Then, the potential impacts for the IS92a sea-level rise scenarios in Table 4 are discussed.

8.1. Response surface characteristics

Fig. 4 shows the response surfaces for the global estimates of the three population parameters in 1990, and in 2100 given constant and evolving protection. Only results for population scenario two (where population change in the coastal flood plain is double the national change) are shown to keep Fig. 4 simple. The main effect of considering population scenario one is to act as a scale factor and reduce all population numbers by the same amount. In 1990 there were about 200 million people living in the hazard zone and this increases given sea-level rise by about 25% for a 1-m rise scenario. By 2100, this exposure has increased 3-fold to nearly 600 million people, and the proportional response to sea-level rise is the same.

In contrast, AAPF and PTR show more variation in their response to sea-level rise. For 1990 population and protection estimates, numbers increase more rapidly above a 0.25-m rise scenario. There is a 14-fold increase in AAPF for a 1-m rise scenario relative to the reference scenario (to 140 million people flooded per year). 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. PTR is zero for no sea-level rise (by definition) and closely follows AAPF. For a 1-m rise scenario, more than 90% of the AAPF would experience flooding more than once per year, which is similar to the results of Baarse (1995).

For 2100 population and protection scenarios, the response to a given sea-level rise scenario is much greater than in 1990, reflecting the growth in coastal population. Under constant protection, the results are similar to those for 1990, scaled upward by the growth in population (reaching about 530 million people flooded per year under the 1-m rise scenario). Under evolving protection, the results are more complex. Impacts are slightly lower than in 1990 up to a 0.25-m rise, and then rise more rapidly. There is a 39-fold increase in AAPF for a 1-m rise scenario relative to the reference scenario (to about 350 million people flooded per year).

Therefore, while the absolute numbers of people flooded are lower, the increase relative to the reference scenario is generally much greater.

Lastly, it is important to remember that these surfaces represent variations based on one world future—the IS92a world. These response surfaces could look quite different under different sets of socio-economic scenarios. Faster population growth in the coastal zone would increase human exposure to flooding, while faster economic growth potentially creates increased resources to upgrade flood defences, and vice versa. Thus impacts of sea-level rise and climate change and our vulnerability to them are conditioned by the evolving socio-economic context. This may be an obvious point to many impact scientists, but it has often been overlooked in earlier impact and vulnerability assessments.

8.2. Detailed impacts

Tables 7 and 8, and Figs. 5 and 6 summarise the global results for each set of scenarios summarised in Table 4 from 1990 to 2100. The 2020s, 2050s, and 2080s correspond to 2025, 2055, and 2085, respectively. These results supersede those previously published by Nicholls (2000b) as they consider a wider range of population scenarios, and consider an additional time period (2100). As might be expected from the discussion of the response surface characteristics, there are significant changes to the occurrence of coastal flooding under all the considered futures. They also emphasise the large uncertainties concerning future conditions.

Table 8
AAPF and cumulative PTR in 2100 assuming the full-upgrade protection scenario

Sea-level scenario	AAPF	PTR
	($\times 10^6$ people)	
Reference	0.4–0.6	0
Low	0.5–0.8	0
Mid	16–25	11–18
High	73–113	64–97

The range in each column indicates the range due to the two population scenarios.

In summary, some of the main results are as follows:

- The global incidence of flooding will increase without any climate change due to increasing coastal populations. However, as global population growth slows in the middle of the 21st century, the progressive upgrade of defences due to rising living standards could start to reduce the occurrence of flooding, ultimately reducing it to levels below that experienced in 1990.
- The increase in the incidence of flooding varies greatly. There are relatively minor increases for the low estimate sea-level rise scenario, particularly under evolving protection; and significant increases for the mid and high estimates irrespective of the protection scenario. This includes the full-upgrade protection scenario shown in Table 8.
- The absolute impacts of sea-level rise are significantly reduced by the likely evolution of protection against climate variability when compared to a (less realistic) scenario of constant (unchanged) protection.

Table 7
PHZ, AAPF and cumulative PTR for the different sea-level rise, population and protection scenarios

Time (years)	Sea-level scenario	PHZ	Constant protection		Evolving protection	
			AAPF	PTR	AAPF	PTR
			($\times 10^6$ people)			
1990		197	10	0	10	0
2020s	Reference	299–399	17–23	0	16–22	0
	Low	302–403	17–24	0	17–23	0
	Mid	328–411	18–25	1	17–24	0
	High	358–423	25–36	7–10	22–30	4–5
2050s	Reference	356–511	23–32	0	18–27	0
	Low	366–525	24–34	1	19–28	0
	Mid	382–550	66–97	42–64	41–64	21–34
	High	404–581	147–213	125–183	113–176	94–149
2080s	Reference	388–575	23–36	0	9–13	0
	Low	409–605	47–77	25–38	11–17	0–1
	Mid	436–647	193–310	194–281	86–133	67–107
	High	474–702	270–426	278–399	228–353	208–332
2100	Reference	399–598	25–39	0	6–9	0
	Low	424–635	83–140	59–104	9–14	0
	Mid	459–688	241–388	223–360	86–138	68–109
	High	503–755	326–510	309–484	211–337	195–311

The range in each column indicates the range due to the two population scenarios.

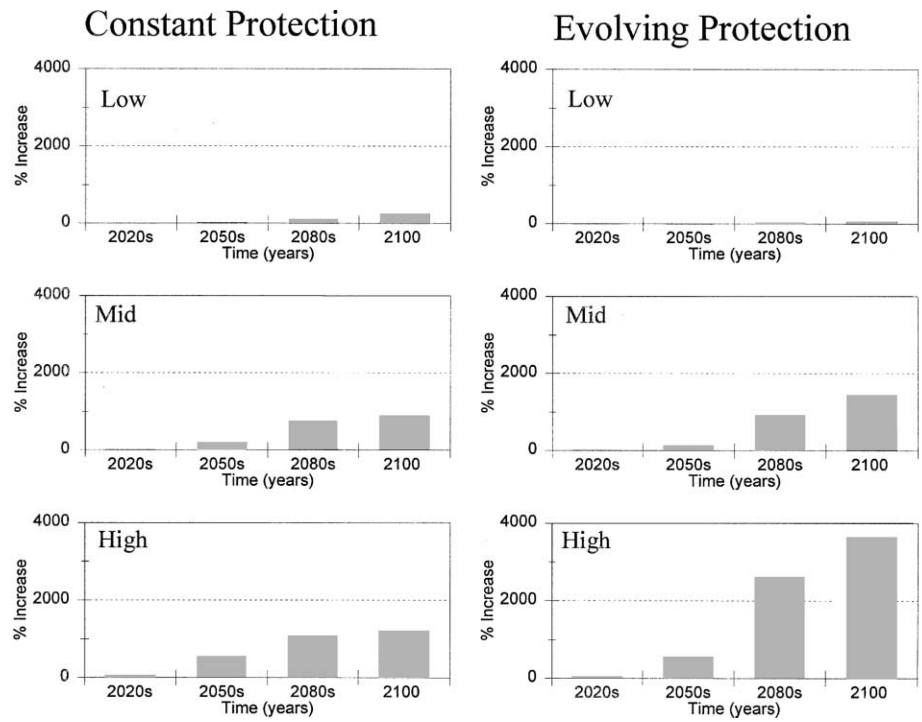

Fig. 5. Relative increase in average annual number of people flooded above the appropriate reference scenario for each IS92a sea-level rise scenario. Assumes constant and evolving protection and the high population growth scenario.

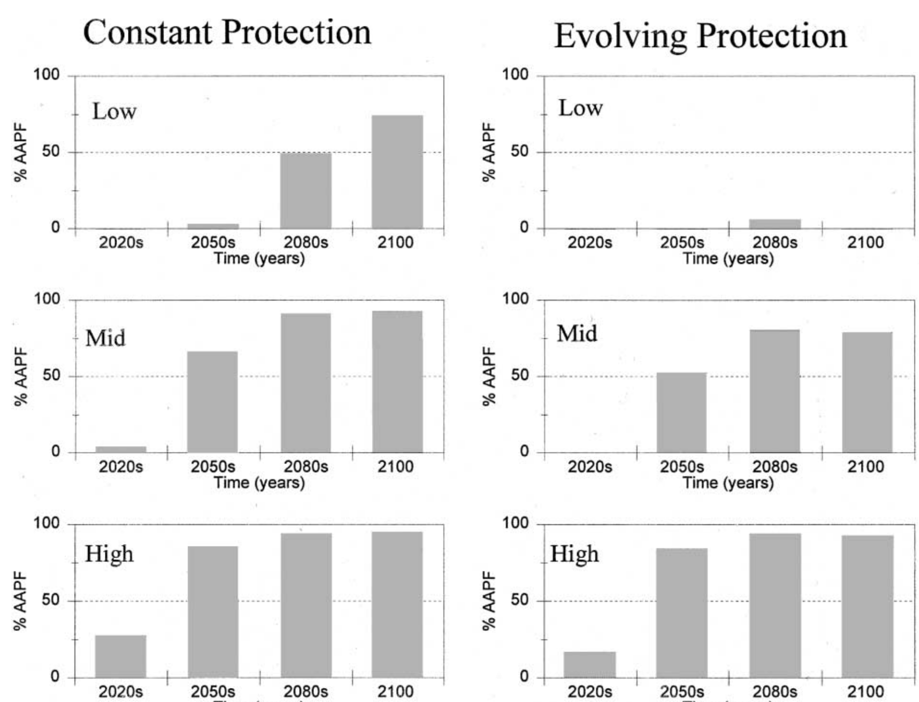

Fig. 6. Cumulative number of PTR as a percentage of AAPF for each IS92a sea-level rise scenario. Assumes constant and evolving protection and the high population growth scenario.

- The uncertainty concerning the future flood impacts of sea-level rise is very large. In 2100, the AAPF is 83–510 million people/year and 9–337 million people/year under constant and evolving protection, respectively.
- Under the mid and high estimate scenarios, there are significant numbers of PTR under constant, evolving and full-upgrade protection scenarios. This suggests that sea-level rise has the potential to produce

significant impacts during the 21st century, unless there is an adaptive response to sea-level rise.

- Increased flooding due to sea-level rise shows significant regional variations. In absolute terms, West Africa, East Africa, the southern Mediterranean, Southeast Asia, and most particularly South Asia have the greatest incidence of flooding. However, the island regions of the Caribbean, the Indian Ocean and the Pacific experience the largest relative increases in flooding.

9. Discussion

This work has focussed on trying to understand the implications of sea-level rise on flooding due to storm surges. The results show that if sea-level rise is ignored, the incidence of flooding may increase significantly. Given the large potential impacts of sea-level rise, the less certain threat from other climate change factors such as storminess, and the continued development of the world's coastal zones, some proactive response would be prudent (Nicholls, 2000b). Historically, our response to flooding has tended to be reactive, so this represents a significant challenge. The four factors in Table 3 suggest four broad actions that would reduce future flood impacts:

- Reduce global-mean sea-level rise. This could be reduced (or mitigated) with other climate change by reducing greenhouse gas emissions. However, there appears to be a substantial commitment to sea-level rise independent of future emissions, so some sea-level rise is to be expected during the 21st century, and beyond (Wigley, 1999; Church et al., 2001);
- Avoid human enhancement of subsidence. This is a long-term geological process, but in many coastal cities, groundwater withdrawal is enhancing subsidence which has significant implications for the incidence of flooding (Nicholls, 1995a);
- Upgrade protection against flooding, including additional freeboard for sea-level rise;
- Control growth in exposure by encouraging the expanding coastal population and economy to avoid locating in the coastal floodplain unless absolutely necessary.

Many other adaptation options are available (Klein et al., 2000, 2001). As we are already committed to global-mean sea-level rise in the future due to historic and near-future greenhouse gas emissions, for coastal areas some combination of mitigation and adaptation would seem most prudent (Nicholls, 2000b; Parry et al., 1998, 2001). Accepting the need for adaptation, linking climate change issues to wider coastal management and planning issues becomes critical. Sea-level rise has been seen by many as one possible trigger for integrated coastal zone management (WCC'93, 1994; Cicin-Sain et al., 1997). Linking any coastal adaptation to wider coastal management is essential for its success, as the management of changing hazards such as flooding is the key issue.

To help support and inform these processes, there is an ongoing requirement to improve regional and global perspectives on the potential impacts of climate change as presented here. Potential applications include:

- communicating the implications of different climate change scenarios to a non-specialist audience;
- examining the costs and benefits of different combinations of mitigation–adaptation policies;
- identifying regions where collective action could be beneficial.

There are a range of potential improvements to the flood analyses presented here. Most fundamentally, the spatial resolution of the underlying data should be greatly improved, combined with further development, calibration and extension of the methods employed. The DINAS-COAST Project is pursuing this goal for the erosion, flood, salinisation and ecosystem effects of sea-level rise (http://www.pik-potsdam.de/~richardk/dinas-coast/). The Special Report on Emission Scenarios (SRES) provides an improved framework for evaluating a wider range of possible future than considered here (Nakicenovic et al., 2000; Gaffin, 2001), although coupled climate-impact assessments for the SRES worlds remain to be completed.

These developments will increase our capacity to analyse the implications and responses to sea-level rise, and will allow improved climate change scenarios to be rapidly interpreted in impact, vulnerability and policy terms.

10. Conclusions

The analysis presented here shows that without an adaptive response, global sea-level rise in an IS92a world could greatly enhance the occurrence of coastal flooding due to storm surges, among other adverse impacts. While the upgrade of defences reduces absolute impacts, the relative change due to sea-level rise is increased. Given the mid-estimate rise (55 cm by 2100), the number of people experiencing flooding could be 9- to 14-times higher than the case without sea-level rise: under the full-upgrade protection scenario impacts are 39-times higher.

These results suggest that it would be prudent to both explore the benefits of climate change mitigation and begin proactive planning for the potential impacts of sea-level rise (and more broadly climate change) now.

Noting the need for adaptation is important given that there is a 'commitment to sea-level rise' regardless of any realistic future emissions policy on greenhouse gases. This raises a range of questions such as the appropriate mix of adaptation and mitigation, the most appropriate timing for adaptation and the most appropriate broad approaches to adaptation (retreat, accommodate, or protect?). Developments of the model approaches described can support and inform this debate. Importantly, they allow new climate scenarios to be rapidly translated into a range of policy-useful forms.

Acknowledgement

The author would like to acknowledge a Leverhulme Trust Fellowship which allowed this paper to be prepared.

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