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Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios

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Abstract

This paper considers the implications of a range of global-mean sea-level rise and socio-economic scenarios on: (1) changes in flooding by storm surges; and (2) potential losses of coastal wetlands through the 21st century. These scenarios are derived from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES). Four different storylines are analysed: the A1FI, A2, B1 and B2 'worlds'. The climate scenarios are derived from the HadCM3 climate model driven by the SRES emission scenarios. The SRES scenarios for global-mean sea-level rise range from 22 cm (B1 world) to 34 cm (A1FI world) by the 2080s, relative to 1990. All other climate factors, including storm characteristics, are assumed to remain constant in the long term. Population and GDP scenarios are downscaled from the SRES regional analyses supplemented with other relevant scenarios for each impact analysis.

The flood model predicts that about 10 million people/year experienced coastal flooding due to surges in 1990. The incidence of flooding will change without sea-level rise, but these changes are strongly controlled by assumptions on protection. Assuming that defence standards improve with growth in GDP/capita (lagged by 30 years), flood incidence increases in all four cases to the 2020s due to the growing exposed population. Then to the 2080s, the incidence of flooding declined significantly to $\leqslant 5$ million people/ year in the B2 world, $\leqslant 2$ million people/year in the B1 world and $\leqslant 1$ million people/year in the A1FI world due to improving defence standards. In contrast, flood incidence continues to increase in the A2 world to the 2050s, and in the 2080s it is still 18–30 million people/year. This reflects the greater exposure and more limited adaptive capacity of the A2 world, compared to the other SRES storylines.

Sea-level rise increases the flood impacts in all cases although significant impacts are not apparent until the 2080s when the *additional* people flooded are 7–10 million, 29–50 million, 2–3 million and 16–27 million people/year under the A1FI, A2, B1 and B2 worlds, respectively. Hence, the A2 world also experiences the highest increase in the incidence of flooding. This is true under all the realistic scenario combinations that were considered demonstrating that socio-economic factors can greatly influence vulnerability to sea-level rise. The trends of the results also suggest that flood impacts due to sea-level rise could become much more severe through the 22nd century in all cases, especially in the A1FI world. Note that impacts using a climate model with a higher climate sensitivity would produce larger impacts than HadCM3.

Coastal wetlands will be lost due to sea-level rise in all world futures with 5–20% losses by the 2080s in the A1FI world. However, these losses are relatively small compared to the potential for direct and indirect human destruction. Thus, the difference in environmental attitudes between the A1/A2 worlds and the B1/B2 worlds would seem to have more important implications for the future of coastal wetlands, than the magnitude of the sea-level rise scenarios during the 21st Century.

These results should be seen as broad analysis of the sensitivity of the coastal system to the HadCM3 SRES global-mean sea-level rise scenarios. While these impact estimates are only for one climate model, for both impact factors they stress the importance of socio-economic conditions and other non-climate factors as a fundamental control on the magnitude of impacts both with and without sea-level rise. The A2 world experiences the largest impacts during the 21st century, while the B1 world has the smallest impacts, with the differences more reflecting socio-economic factors than climate change. This suggests that the role of development pathways in influencing the impacts of climate change needs to be given more attention.

Keywords: Climate change; Coastal vulnerability; Flood risk; Coastal ecosystems

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) concluded that global-mean sea-level rise will rise through the 21st century and beyond due to greenhouse gas-induced changes of climate (Church et al., 2001) and that this could have important impacts on coastal populations and coastal ecosystems (McLean et al., 2001). The aim of this paper is to explore some of the regional and global impacts for four of the Special Report on Emission Scenarios (SRES) worlds (A1FI, B1, A2 and B2) (Nakicenovic et al., 2000). The analysis considers global-mean sea-level rise scenarios produced by the HadCM3 coupled atmosphere-ocean climate model using the SRES emission scenarios (Johns et al., 2003). The SRES framework also defines a range of other aspects of each world, including socio-economic factors and prevailing values, and hence allows the impacts of climate change to be imposed on the evolving "world" that produced the climate change. For more information on the details of the SRES scenarios used here, see Arnell et al. (2003).

The methods build on earlier work which explored sea-level rise impacts based on scenarios developed by unmitigated and mitigated emission experiments consistent with the "IS92a" world, using both the HadCM2 and HadCM3 models (Nicholls et al., 1999; Arnell et al., 2002). The research is part of a larger study of climate change impacts using common scenarios, which additionally consider terrestrial vegetation, water resources, food supply and human health (see other papers in this issue).

The core question which is explored for each set of scenarios is:

> "are the global-mean sea-level rise scenarios a problem if we ignore them?

Sea-level rise would cause a range of impacts (Nicholls, 2002a), two of which are considered here:

- Changes to flooding by storm surges (a human-system impact); and
- Loss of coastal wetlands (an ecosystem impact).

All impacts are evaluated for 2025, 2055 and 2085, representing the 2020s, 2050s and 2080s, respectively. Assessments include both changes in impacts in a world without climate change (the baseline), and with climate change, so that the relative effect of climate change can be assessed. A more detailed analysis and interpretation of these results than in earlier assessments is made possible by the SRES "storylines".

In addition to assessing the potential impacts of sea-level rise, this work also raises broader questions about how the coastal zone might develop over the 21st century and beyond that are pertinent to the goal of sustainable development.

2. Background

Large populations live in the coastal areas where they are exposed to a range of hazards, including coastal flooding (Small et al., 2000; Small and Nicholls, 2003). In the developed world, most exposed populations are protected from flooding by various structural measures (e.g., London, UK, the Netherlands and Japan). In the developing world, flood defences are less developed and the exposed populations are more often subject to flooding with consequent disruption, economic loss, and in the worst cases—loss of life—as illustrated by the 1999 super-cyclone in Orissa, India (UNEP, 2002).

In the 21st century, the incidence of flooding and number of people affected in coastal areas will change due to a variety of causes, related to changes in:

1. flood levels,
2. human exposure to flooding, and
3. the standard of flood management infrastructure.

Rising sea levels will raise flood levels, all other things being equal (Smith and Ward, 1998). For instance, it is estimated that the number of people flooded in a typical year by storm surges would increase 6-times and 14-times given a 0.5 and 1.0 m rise in global sea levels, respectively, and *no other changes* (Nicholls et al., 1999). The number of people who are affected by flooding will also increase due to growing coastal populations, including net coastward migration across the globe (e.g., WCC'93, 1994; Bijlsma et al., 1996). Widespread subsidence (falling land levels) will also enhance flooding, and natural subsidence is often exacerbated by drainage and/or excessive groundwater withdrawal, especially in urban centres (Nicholls, 1995). However, these potential increases in the incidence of flooding and number of people affected will be offset or even reversed by improving flood management and protection. Such changes are happening without any consideration of sea-level rise and climate change—they have occurred through the 20th century (e.g., Nicholls, 2000) and are simply an adaptation to the *present* climate and its variation. It is important to distinguish the effect of such changes from adaptation to long-term sea-level rise, which would involve additional action.

Coastal areas are highly productive at a global scale (Holligan and de Boois, 1993). As an example of one of the ecological components, coastal wetlands (collectively comprising saltmarshes, mangroves and associated unvegetated intertidal areas) could experience substantial changes and losses due to sea-level rise. These areas provide a number of important functions such as waste assimilation, nursery areas for fisheries, flood protection and nature conservation. Therefore, wetland loss can have a significant human cost, even if this is not always directly perceived by those affected. In combination with human activities, it is estimated that a 1-m rise in sea level could threaten up to half of the world's coastal wetlands which are designated as of international importance (>168,000 km^2), while those that survive could be substantially changed (Hoozemans et al., 1993; Nicholls et al., 1999). However, wetland areas are already under multiple stresses and are declining rapidly: about 1% of the global coastal wetland stock was being lost each year in the late 20th century, primarily by direct human reclamation, although a variety of loss mechanisms are apparent (Hoozemans et al., 1993). Hence, significant losses are possible without climate change, but they will be exacerbated by human-induced sea-level rise.

3. The SRES scenarios

3.1. The SRES storylines

The SRES report supersedes the IS92 emission scenarios (Nakicenovic et al., 2000) and is considered in more detail in this issue by Arnell et al. (2003). This report develops a range of possible future world states based on plausible storylines. Hence, it develops quantitative estimates of the socio-economic drivers of greenhouse and aerosol emissions, including factors such as population, GDP and technology and in turn emission scenarios. This provides a consistent input to both climate models and impact assessment models.

The SRES scenarios are presented as four "storylines" which represent mutually consistent characterisations of how the world might evolve during the 21st century. Each storyline is a short narrative of a possible pathway of future development from today's world. They explore what might happen if political, economic, technical and social developments took specific alternative directions at the global level, including considering potential regional differences and interactions. The results are four families (the 'A1', 'B1', 'A2' and 'B2' worlds) of self-consistent social and emission scenarios which are considered to be equally plausible (Table 1). In this paper, scenarios from four of these storylines are analysed: A1FI, A2, B1 and B2. Henceforth, they are referred to as the A1FI, A2, B1 and B2 worlds, respectively.

3.2. Global-mean sea-level rise scenarios

The global-mean sea-level rise scenarios have been described in outline by Johns et al. (2003) and are summarised in Table 2. Global-mean sea-level rise estimates encompass components due to thermal expansion, ice sheet mass balance changes and land glacier melt are derived from the model experiment (Gregory and Lowe, 2000). Thermal expansion, glaciers and small ice-caps provide a positive contribution to global-mean sea-level rise, while the contributions of Greenland and Antarctica are near-equal and opposite and hence the net effect is minimal. (The ice mass of Greenland is predicted to decline, while the ice mass of Antarctica is predicted to increase under global warming due to increased snowfall without any increase in ice melting.) The model outputs all commence in 1860 and the scenarios were all referenced to a 1990 30-year average sea level using this simulation.

Table 1
A summary of the most important characteristics of each SRES storyline

"A1 world"	"B1 world"
Increasing globalisation/ convergence	Increasing global co-operation/ convergence
Rapid global economic growth	Environmental priority
Materialist/consumerist	Clean and efficient technologies
Rapid uniform technological innovation	
"A2 world"	"B2 world"
Heterogeneous world	Heterogeneous world/local emphasis
Rapid regional economic growth	Environmental priority
Materialist/consumerist	Clean and efficient technologies
Diverse technological innovation	

Table 2
Global-mean sea-level rise scenarios (cm) used in the study (referenced to 1990)

Year	IS92a	SRES (HadCM3)					Full SRES scenario range (Church et al., 2001)
	GGa1	A1FI	A2	B1	B2	Range	
2020s	9	5	5	5	6	1	10 (4–14)
2050s	21	16	14	13	14	3	29 (7–36)
2080s	37	34	28	22	25	13	60 (9–69)

The IS92a GGa1 scenario and the range of SRES scenarios provided by Church et al. (2001) are included for reference purposes.

While there are ensemble runs for the A2 and B2 cases, for global-mean sea-level rise the difference is so small that only one case is used. Compared to the GGa1 scenario, which was driven by the IS92a emissions scenario, all the SRES climate sea-level scenarios show a smaller global-mean rise (Table 2). This reflects both lower greenhouse gas emission scenarios and higher aerosol emissions, which are explicit parts of the SRES scenarios. For all practical purposes, the SRES scenarios are almost identical for both the 2020s and the 2050s, with significant departure only being apparent by the 2080s. A1FI has the greatest rise and B1 has the smallest rise.

All other climate factors are considered constant over time. While changes in storms could have important implications for coastal areas and hence attract considerable attention, historical data shows large inter-annual and inter-decadal variation, but suggest stability over the last 100 years (WASA Group, 1998; Zhang et al., 2000). Further, while possible changes in surge under climate change have been developed for a few cases (e.g., Lowe et al., 2001), credible future scenarios at the global scale pertinent to this study remain to be developed. However, a rise in mean sea level also raises the extreme levels of the sea which have the potential to cause floods (e.g., Dixon and Tawn, 1997; Smith and Ward, 1998). Therefore, increases in the frequency of given flood elevations (i.e., increases in extreme events) is an explicit element of the flood analysis.

3.3. National socio-economic scenarios

The SRES scenarios are only quantified in Nakicenovic et al. (2000) at a global and regional scale. The global aggregates for these scenarios in the 2080s are outlined in Table 3. Population growth by the 2080s is relatively modest under A1FI/B1, and the world population is falling from a peak in the 2050s of 8.7 billion people (64% above 1990 totals). In contrast, under A2 the population growth to the 2080s is large (167% relative to 1990) and still growing. GDP grows substantially in all cases, but the net differences by the 2080s are substantial: A1FI is the wealthiest world both in absolute and per capita terms, while A2 is the poorest in both terms. Given the large population under A2, the per capita incomes are particularly reduced only being 25% of those under A1FI. The difference in GDP between world regions also reduces in all cases, but again at differing rates.

The impact models require national estimates of each parameter. The Centre for International Earth Science Information Network (CIESIN) has conducted the first national downscaling exercise for the SRES population and GDP scenarios for the IPCC Data Distribution Centre (DDC). These scenarios were downloaded from the DDC blue pages (ipcc-ddc.cru.uea.ac.uk) in summer 2002 for processing and analysis. Small countries with a population of less than 150,000 in 1990 are not included in the scenarios, including many small island states. Population and GDP scenarios were developed for all the missing cases using the regional change apparent in the larger countries in each island region (e.g., Caribbean, Indian Ocean or Pacific Ocean) (Arnell et al., 2003).

Table 3
The SRES socio-economic scenarios for the 2080s: a global summary

Year and scenario	Population (billions)	GDP (trillion US 1990 $)	GDP/capita (thousands US 1990 $)
1990	5.3	20.1	3.8
2080s			
A1	7.9	416	52.6
A2	14.2	185	13.0
B1	7.9	289	36.6
B2	10.2	204	20.0

4. Methodology

All the analysis below is based on 192 polygons, which correspond to the coastal countries in the early 1990s (see Hoozemans et al., 1993). Each polygon is assumed to respond uniformly to the changes described below. This aggregation of processes is an important element of the analysis and it places limits on the interpretation of the results (see Model Validation).

4.1. Flooding due to storm surge

The basic model used here to predict flood impacts has already been outlined by Nicholls et al. (1999). Here it is slightly modified as described later to better describe the increase risk of flooding due to rising sea level. In addition, a wider range of scenarios are explored to better define the broad sensitivities of coastal populations to flood impacts under rising sea levels and other realistic change. Therefore, the broad model details are discussed, including the improvements that have been implemented.

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 two impact parameters:

- *People in the hazard zone (PHZ)*: the number of people living below the 1000-year storm surge elevation (i.e., the exposed population ignoring sea defences);
- *Average annual people flooded (AAPF)*: the average number of people who experience flooding by storm surge per year, including the benefits of sea defences (note that this parameter has been also been referred to as *people at risk* in earlier studies).

Note that the calculation of these parameters assumes that there is no human response to the increased flooding. The relative magnitude of the parameters is as follows:

$$AAPF \leqslant PHZ. \tag{1}$$

The methodology used to calculate these parameters is outlined in Fig. 1. 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 people in the hazard zone using the average population density for the coastal area.

Lastly, the standard of protection (i.e., the estimated level of flood risk) is used to calculate average annual people flooded. These national estimates are then aggregated to regional and global results. 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 (see Hoozemans et al., 1993; Nicholls et al., 1999; Nicholls, 2002b). Further, only the aggregated regional and global results are valid.

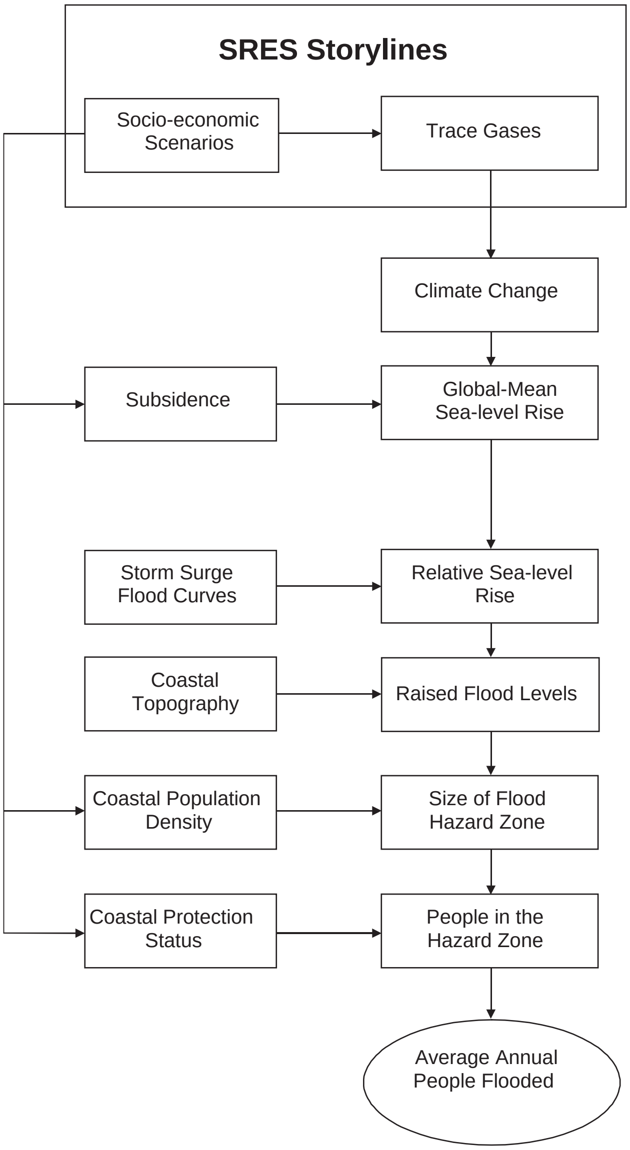

Fig. 1. The flood model algorithm showing how the SRES socio-economic and climate scenarios were used.

There are no global databases on the level of flood protection, so the standard of protection was estimated indirectly using national GDP/capita as a direct measure of adaptive capacity. Table 4 links GDP/capita to three protection classes 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 and comprise 17 countries. The minimum standard of protection in 1990 was selected as 1 in 10 years (Protection Class 1) based on empirical observation. The increase in flood risk produced by sea-level rise within the pre-existing floodplain is estimated by reducing the protection class as defined in Table 5. As sea levels rise, so the protection class is reduced in integer steps to a standard of protection of $\leqslant 1$ in 1 year (which is Protection Class 0). Note that the form of Tables 4 and 5 is a simplification compared to earlier model applications, which validation suggests is an improvement.

In this analysis, ranges of scenarios are used as defined in Table 6. Those scenarios that were used by Nicholls et al. (1999) and those scenarios that have been introduced as part of the SRES analysis are distinguished. The relationship of these different scenarios to the different SRES storylines is presented in Table 7 and are discussed below.

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

	Algorithm (SLR—sea-level rise) (HM—1 in 1000 year flood level) (HO—1 in 1 year flood level)	Original protection class		
		1	2	3
New protection class	If $\mathrm{SLR} < 1/3^{*}\mathrm{HM{-}HO}$	1	2	3
	If $\mathrm{SLR} > 1/3^{*}\mathrm{HM{-}HO}$	0	1	2
	If $\mathrm{SLR} > 2/3^{*}\mathrm{HM{-}HO}$	0	0	1
	If $\mathrm{SLR} > \mathrm{HM{-}HO}$	0	0	0

Protection class 0 is $a \leqslant 1$ in 1 year design frequency.

Table 4
Protection classes used for deltaic and non-deltaic coasts

GDP/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	$\geqslant 2400$	PC 3	High	1/1000

Table 6
Scenarios used in the flood modelling

Subsidence		
1. Natural subsidence (in subsiding areas)	15 cm/century	
2. Human-induced subsidence (due to groundwater extraction in subsiding areas)	45 cm/century	x
Coastal population change		
1. Low growth (uniform national change assumption)	As national population change	x
2. High growth (populations are attracted to coastal areas)	Increases at double the population increase (and decreases at half any population decrease)	x
Protection standards		
1. Constant protection	Fixed (1990) protection standards	
2. In phase evolving protection	Protection standards improve in phase with GDP/capita, but only considering 1990 surge levels (i.e. sea-level rise is not considered)	
3. Lagged evolving protection	As in phase evolving protection, except protection standard improvements occur with a 30-year time lag behind GDP/capita change.	x

x indicates scenarios not used in previous analyses.

Table 7
Qualitative assessment of flood issues (Population trends, subsidence, adaptation lags and hazard management) under the SRES storylines

"A1 world"	"B1 world"
Coastal population change: higher Human-induced subsidence: more likely Adaptation lag time: longer Hazard management—lower priority	Coastal population change: higher Human-induced subsidence: less likely Adaptation lag time: shorter Hazard management—higher priority
"A2 world"	"B2 world"
Coastal population change: lower Human-induced subsidence: more likely Adaptation lag time: longer Hazard management—lower priority	Coastal population change: lower Human-induced subsidence: less likely Adaptation lag time: medium Hazard management—higher priority

In countries where coastal subsidence is occurring, two subsidence scenarios are applied to estimate relative sea-level rise scenarios. The low subsidence scenario (15 cm/century) corresponds to natural subsidence, while the high subsidence scenario includes additional human-induced subsidence due to groundwater withdrawal, which appears likely under some SRES storylines (Table 7). The subsidence scenarios allow the interaction of global-mean sea-level rise with more local changes to be considered.

For coastal population density, two scenarios of change are considered which bound the likely change (Table 6). The high growth scenario difference is similar to the single population scenario used in previous assessments (Nicholls et al., 1999), but it is modified here so that people are relatively attracted to the coast even in the case of falling national populations. The degree of 'coastal attraction' is likely to differ between the different SRES worlds, with greater relative movement to the coast in the A1FI/A2 worlds, given their greater trends towards globalisation and mobility (Table 7).

Scenarios of protection standards are the most problematic parameters to estimate as they have a large effect on *AAPF*. Here it is assumed (reasonably) that it is strongly related to GDP/capita. The class boundaries in Table 4 are based on expert judgement (Nicholls et al., 1999) and they are only approximations. If the numbers in Table 4 were raised, some defences might be of a lower standard and estimates of people flooded per year might increase, and vice versa. In addition, factors other than GDP/capita will probably influence the adaptive capacity of coastal societies (Smit et al., 2001; Yohe and Tol, 2002). Therefore, three different protection scenarios are developed to encompass the likely evolution of protection standards (Table 6). The evolving protection scenarios only include measures that would be implemented in response to 1990 surge conditions, and they ignore relative sea-level rise. This assumption is consistent with the core question posed in this paper. It is also consistent with current behaviour, as few countries are considering sea-level rise in coastal management and planning. Collectively, the Constant Protection, Lagged Evolving Protection and In Phase Evolving Protection scenarios can be seen as extremely pessimistic, fairly realistic and extremely optimistic scenarios of protection upgrade, respectively, but always in the absence of any specific adaptation for sea-level rise.

The 30-year time lag under *lagged evolving protection*, is based on the time scale required for major flood defence projects to be implemented around the world.

Examples include the Thames Barrier (Gilbert and Horner, 1984), the Dutch delta works (Smith and Ward, 1998), and Shanghai (Han et al., 1995; Wang et al., 1995). While a constant lag time (30 years) is used in lagged evolving protection for the sake of simplicity of the scenarios, there is likely to be a difference in lag time in each of the SRES worlds before collective investments such as flood defence are implemented. Looking at the present situation, coastal cities in Northern Europe enjoy much higher defence standards than coastal cities in the USA, even though the latter country enjoys a higher GDP/capita. For example, both New Orleans and New York appear quite vulnerable to existing floods and there is limited preparation for climate change (e.g., Nicholls and Leatherman, 1995; Rosensweig and Solecki, 2001). In contrast, London, the Netherlands and Germany have defences of a higher standard ($\geqslant 1$ in 1000 standard), making flooding highly unlikely (e.g., Gilbert and Horner, 1984; Kelly, 1991), and are already planning upgraded defences for higher sea levels to 2100 (Tol et al., 2004). Following this rationale, different 'worlds' may experience different lag times (Table 7). Other factors such as the history and experience of flooding are likely to be important, but this is not considered here.

As all the GDP/capita scenarios show substantial growth in all countries from 1990 to the 2080s, under both evolving protection scenarios, the protection standards progressively improve towards the highest possible standard—protection class 3 or defence against a 1 in 1000 year event in 1990 (Table 4). In reality, economic development may act to increase vulnerability to coastal hazards due to destruction of natural protection (e.g., mangroves), increased exposure of populations and assets, and more subtle social processes such as a possible decline in the effectiveness of collective behaviour which can lead to a decline in flood defence maintenance and hence increased risk of their failure (e.g., Adger et al., 2001). Importantly, in such cases this analysis will underestimate the increase in flood risk so the results presented here might be considered as minimum estimates of the number of people likely to affected by sea-level rise.

4.2. *Loss of coastal wetlands*

In this study, coastal wetlands comprise saltmarshes, mangroves and associated unvegetated intertidal areas (and exclude coral reefs). Wetlands are sensitive to sea-level rise as their location is intimately linked to sea level. However, wetlands are not passive elements of the landscape (e.g., Cahoon et al., 1995, 1999; McLean et al., 2001), and their vertical response shows a dynamic and non-linear response to sea-level rise. Hence, losses only occur above some threshold rate of rise (Nicholls et al., 1999). The available evidence shows that wetlands experiencing a small tidal range are more vulnerable to relative sea-level rise than those experiencing a large tidal range. Direct losses of coastal wetland due to sea-level rise can be offset by inland wetland migration (dryland conversion to wetland). As sea level rises, so low-lying coastal areas adjacent to wetlands may become suitable for the growth of wetland plants (Titus and Richman, 2001; McLean et al., 2001). In areas without low-lying coastal areas, or in low-lying areas which are protected to stop coastal flooding, wetland migration cannot occur, causing what is termed a coastal squeeze between the rising sea level and the fixed shoreline (French, 1997).

The wetlands that are considered here are contained in a database of wetland type, area and location that was developed by Hoozemans et al. (1993). In many parts of the world it only comprises sites designated under the Ramsar Wetlands Convention (i.e., sites agreed to be of international importance). Therefore, this database omits some wetlands and further there is no data for Canada, the Gulf States, the former Soviet Union and the small islands in the Indian and Pacific Oceans.

Based on the available data, Nicholls et al. (1999) developed a non-linear model of coastal wetland response to sea-level rise. The modelling effort is split into an assessment of the two dimensions of the wetland system response: (1) vertical accretion; and (2) wetland migration. Here vertical accretion is based on the *rate* of relative sea-level rise, rather than the absolute rise. Sea-level rise triggers coastal wetland loss when the rate of sea-level rise exceeds a defined threshold, taking account of any system lags (see also Nicholls and Wilson, 2001).

To model vertical response, a lagged threshold approach is used. The availability of sediment/biomass for vertical accretion is parameterised using critical values of the $RSLR^*$ parameter, which is defined as

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

where $RSLR$ is the *rate* of relative sea-level rise in metres/century and TR is the mean tidal range on spring tides in metres.

A critical value of $RSLR^*$ ($RSLR^*_{crit}$) distinguishes the onset of loss due to sea-level rise. If wetland loss is predicted, it is modelled linearly as a function of $RSLR^*$. 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. Based on the available literature, $RSLR^*_{crit}$ was assumed to range from 0.18 to 0.5 (Nicholls et al., 1999). The response of a wetland to long-term sea-level rise is not instantaneous and based on geomorphic considerations, a 30-year time lag was applied in all the calculations.

To model horizontal response, migratory potential was assessed using the global coastal typology of Valentin (1954). 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). 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 range of the results. Additionally, if the population density exceeded 10 inhabitants/km^2, it is assumed that wetland migration is prevented (Nicholls et al., 1999). Owing 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 addition to the affects of sea-level rise on coastal wetlands, we must consider an appropriate baseline. Three models of wetland loss are considered which are consistent with the range from environmental indifference to environmental concern:

- Model 1: 1% per year, which is the present rate of loss;
- Model 2: 0.4% per year, representing immediate moves to more effective conservation.
- Model 3: 0.4% per year from 1990 to 2020, followed by zero loss, implying that all losses are compensated by habitat recreation.

These models lead to the loss of 62%, 32% and 11% of the present wetland stock by 2080s, respectively, without any consideration of sea-level rise. To define the likely non-climate losses of wetlands, a range defined by two out of the three loss models are defined for each SRES storyline as shown in Table 8.

Table 8
Likely range of non-climate losses for coastal wetlands assumed for each SRES world

"A1 world"	"B1 world"
Models 1–2	Models 2–3
"A2 world"	"B2 world"
Models 1–2	Models 2–3

In terms of the scenarios used in the analysis (Table 6), only the low subsidence scenario and the high population growth scenarios are used, following the earlier analysis of Nicholls et al. (1999).

5. Model validation

When conducting analyses of this type, the first thing to evaluate is the validity and accuracy of the results. The models make a range of assumptions and also operate at a coarse spatial scale. While Nicholls et al. (1999) validated the flood model, the version used here has been modified slightly and there is new validation data. Aggregation to a regional or global scale is one approach to reduce unbiased errors. Beyond this, independent validation of the impact models is an important and difficult step.

5.1. Flood model

A data set of national values for both flood impact parameters has been derived from independent national-scale vulnerability assessments (Nicholls, 2000, 2002b) and supplemented with further results here. While these national-scale results consider the impacts of sea-level rise on the 1990 world without any socio-economic changes, they can be used to validate the global flood model. The aggregated results are presented in Table 9.

Considering people in the hazard zone, the model data is smaller than those estimated by the national studies, but comparable in magnitude: 154 million people in the national studies and 109 million people in this study. This study produces reasonable estimates of average annual people flooded for both present conditions (no sea-level rise) and after a 1-m rise in sea level (Fig. 2). Results using lagged GDP/capita to determine protection standards gives the same results, although the lagged GDP/capita remains a more attractive approach as a 'best estimate' from a conceptual perspective. Additionally, it is estimated in this study that globally there were about 200 million

Table 9
Flood model validation

	People in the Hazard Zone (PHZ) (millions)	Average annual people flooded (AAPF) (millions/year)	
		No SLR	SLR = 1 m
Countries	Antigua, Bangladesh, Belize, Benin, China, Egypt, Germany, Japan, Marshall Islands, Mauritius, Netherlands, Nigeria, Poland, Suriname, United Kingdom, Vietnam	Egypt, Germany, Guyana, Netherlands, Poland, Suriname, Vietnam	
National Studies	154	1.2	23.7
This study	109	1.2	14.7

Aggregated results from selected national assessments compared with the model results of Nicholls et al. (1999) and this study. The socio-economic scenario being impacted is the 1990 situation in all cases.

people (or 4% of the world's 1990 population) living beneath the 1 in 1000 year storm surge in 1990. This is consistent with Small and Nicholls (2003) who estimated that 450 million people lived beneath the 10-m contour above sea level in 1990.

Therefore, the results are broadly in line with independent assessments. This gives confidence in the validity of the patterns in the relative results, and the order-of-magnitude of the absolute results.

5.2. *Wetland loss model*

Nicholls et al. (1999) noted that the wetland model is more difficult to validate as most national scale studies have assumed no wetland response to sea-level rise. Hence, these national results are overestimates of the likely losses given by sea-level rise. Improved validation of the wetland loss model remains an important issue for future research.

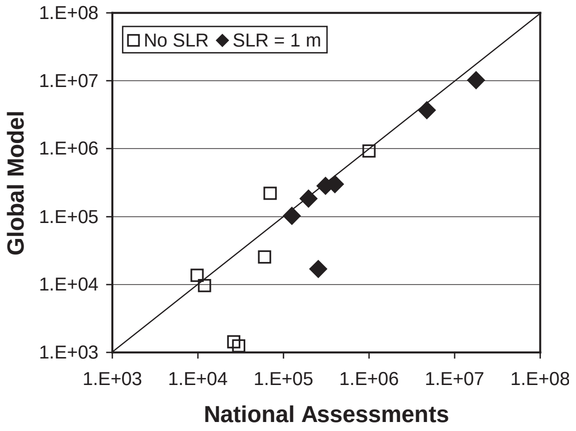

Fig. 2. Validation of the flood model for seven countries: Egypt, Germany, Guyana, the Netherlands, Poland, Suriname and Vietnam, assuming the 1990 world and (a) no sea-level rise (No SLR) and (b) an instantaneous 1-m sea-level rise and no other change (1-m SLR).

6. Results

6.1. *Coastal flooding*

6.1.1. *Baseline conditions (no climate change)*

Table 10 summarises the results for the reference scenario of no climate-induced sea-level rise and low subsidence. In 1990, it is estimated that about 200 million people lived beneath the 1 in 1000 year storm surge (i.e., people in the hazard zone). This shows large increases in all cases reflecting the large increase in population in all the SRES worlds, although under the A1FI and B1 cases, the population in the hazard zone may decline from the 2050s to the 2080s, reflecting a global decline in population. The largest population in the hazard zone is under A2, when it reaches about 520–840 million people by the 2080s (an increase of up to 326% on 1990 values under the higher population growth scenario).

In 1990, it is estimated that about 10 million/year experienced flooding (Fig. 3). Assuming constant (1990) protection, this increases in all cases as the exposed population grows (and relative sea-level rise due to subsidence occurs), reaching 30–49 million/year under the A2 world in the 2080s. Assuming in phase evolving protection, the number of people flooded increases to

Table 10
Global results for coastal flooding without climate change

Scenario	Time	PHZ (millions)		AAPF (millions/year)					
				Constant protection		In-phase evolving protection		Lagged evolving protection	
	1990	197	197	10	10	10	10	10	10
A1FI	2020s	293	387	16	22	10	14	16	22
	2050s	317	445	18	26	0	1	11	16
	2080s	286	439	15	25	0	0	0	1
A2	2020s	324	449	18	26	17	24	18	26
	2050s	434	668	25	40	16	26	23	37
	2080s	521	840	30	49	11	19	18	30
B1	2020s	293	387	16	22	13	18	16	22
	2050s	317	445	18	26	2	2	14	20
	2080s	286	439	15	25	0	0	1	2
B2	2020s	297	395	17	23	12	17	17	23
	2050s	349	501	21	31	3	4	16	24
	2080s	374	552	22	34	1	1	3	5

A comparison of people in the hazard zone (PHZ) and average annual people flooded (AAPF) in the SRES worlds assuming that there is *no* climate-induced sea-level rise. The low subsidence scenario is assumed and the range indicates the values from the low and high population growth scenarios.

the 2020s in all cases, but subsequent behaviour shows significant variation. Due to the rapid rise in living standards and hence the assumed improvement in flood defences within the flood model, the number of people being flooded diminishes from the 2020s to the 2080s under the A1FI , B1 and B2 worlds to levels well below those in 1990. In particular, in the A1FI and B1 worlds, the estimated number of people flooded is less than 500,000 people/year (or <5% of the 1990 estimates). In contrast, in the A2 world, people flooded increases to 16–28 million/year in the 2050s and then decreases to 11–19 million people/year in the 2080s. This reflects a larger exposed population and lower living standards and hence capacity to raise flood defences. In the A1FI world, the entire world's population enjoys the highest standard of flood defences that the model will allow. In contrast, under the A2 world some populous countries such as India, Nigeria, Bangladesh and Vietnam have lower standard defences. The B2 and B1 worlds are intermediate.

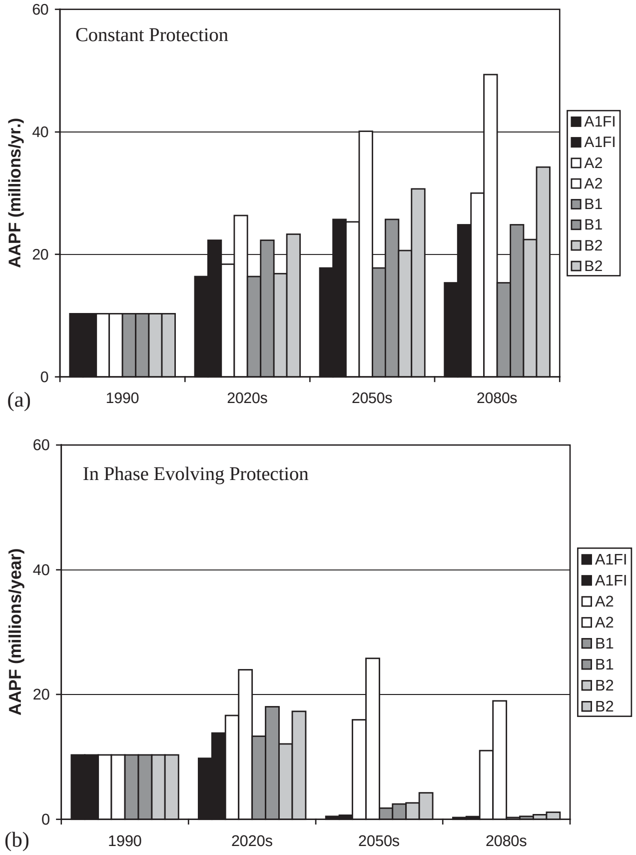

Fig. 3. Average annual people flooded under baseline conditions (no climate change) and (a) constant protection and (b) in-phase evolving protection. The paired values for each storyline represent the low and high population growth scenarios, respectively. The low subsidence scenario is assumed.

Assuming lagged evolving protection, the incidence of flooding is less reduced but the general results are the same with the number of people affected by flooding by the 2080s still being greatly reduced compared to 1990 levels in the B2 world, particularly in the A1FI and B1 worlds. In contrast, the A2 world experiences a two- to three-fold increase in the number of people flooded per year in the 2080s compared to 1990.

Table 11 presents the results assuming the high subsidence scenario for the 2080s only. The increased rate of relative sea-level rise produced by the subsidence increases the impacts in all cases, most dramatically under constant protection: in the B2 world the increase in people flooded compared to the low subsidence baseline could exceed 100 million people/year. The evolving protection scenarios greatly reduce these additional impacts. Under the in phase evolving protection, the largest increase is 11 million people flooded per year in the A2 world.

6.1.2. SRES global impacts

Table 12 summarises the results given by global-mean sea-level rise under the SRES scenarios and low subsidence. Global-mean sea-level rise causes a modest increase in the number of people in the hazard zone in all cases, with an increase of about 9% above the reference scenario for the A1FI scenario in the 2080s (which represents the largest sea-level rise scenario).

When considering the actual incidence of flooding, these results show that global-mean sea-level rise could have significant impacts on coastal areas, but the additional impacts take some time to become manifest (Figs. 4 and 5). Taking the pessimistic view (constant protection), impacts are apparent by the 2050s and by the 2080s, there is a three- to five-fold increase in the incidence of flooding compared to the reference scenario (Fig. 4a). The biggest relative increase in the incidence of

Table 11
Global results for coastal flooding with no global-mean sea-level rise and the high subsidence scenario for the 2080s only

Scenario	PHZ (millions)		AAPF (millions/year)					
			Constant protection		In-phase evolving protection		Lagged evolving protection	
A1FI	302	464	51	86	2	3	2	3
A2	549	886	85	144	18	30	44	74
B1	302	464	51	86	2	3	3	5
B2	395	585	81	137	4	6	20	35

The range indicates the values from the low and high population growth scenarios.

Table 12
Global results for coastal flooding showing the additional impacts due to sea-level rise for people in the hazard zone (PHZ) and average annual people flooded (AAPF)

Scenario	Time	PHZ (millions)		AAPF (millions/year)					
				Constant protection		In phase evolving protection		Lagged evolving protection	
A1FI	2020s	4	6	1	1	0	0	1	1
	2050s	14	20	9	14	1	0	2	3
	2080s	28	43	63	102	6	10	7	10
A2	2020s	4	6	1	1	0	1	1	1
	2050s	16	26	10	16	2	3	6	10
	2080s	41	67	70	120	9	15	29	50
B1	2020s	4	6	1	1	0	0	1	1
	2050s	12	15	5	7	0	1	2	3
	2080s	18	27	33	54	2	3	2	3
B2	2020s	4	6	0	1	0	1	0	1
	2050s	13	20	7	11	0	1	3	6
	2080s	25	39	55	93	3	5	16	27

The low subsidence scenario is assumed and the range indicates the values from the low and high population growth scenarios.

flooding occurs under the largest sea-level rise scenario (A1FI). However, the additional number of people flooded is largest under the A2 scenario reflecting a combination of sea-level rise, a large increase in the exposed population, and lower standards of flood protection. Taking the optimistic view (in phase evolving protection), impacts are not apparent until the 2050s for the A2 world, and the 2080s in the other cases. The magnitude of additional impacts is typically an order of magnitude lower than under constant protection. Taking the most realistic view (lagged evolving protection), impacts increase in all cases compared to In Phase Evolving Protection. However, the additional impacts show substantial variation from 27 to 50 million people being flooded per year in the A2 world, to only 2–3 million people per year being flooded in the B1 world.

The high subsidence scenario increases the number of people predicted to experience flooding and will exacerbate the impacts of climate-induced global-mean sea-level rise (e.g., Table 13). Considering In Phase Evolving Protection, the additional impacts vary from 167 to 277 million people being flooded per year in the A2 world, to only 21–34 million people per year being flooded in the B1 world. In other words, there is a five- to ten-fold increase compared to the low subsidence case. This shows how global sea-level rise might interact with other changes to exacerbate impacts and is indicative of how problems in the coastal zone may be produced by multiple stresses.

6.1.3. SRES regional impacts

The results for the SRES scenarios in the 2080s under lagged evolving protection, low population growth and low subsidence are presented in Table 14. The regions with the highest incidence of additional flooding due to sea-level rise are the African Atlantic Coast for the A1FI, B1 and B2 worlds, and South Asia for the A2 world. In the A2 world, the Southern Mediterranean and African Indian Ocean Coast are noteworthy with more than one million people/year flooded in both

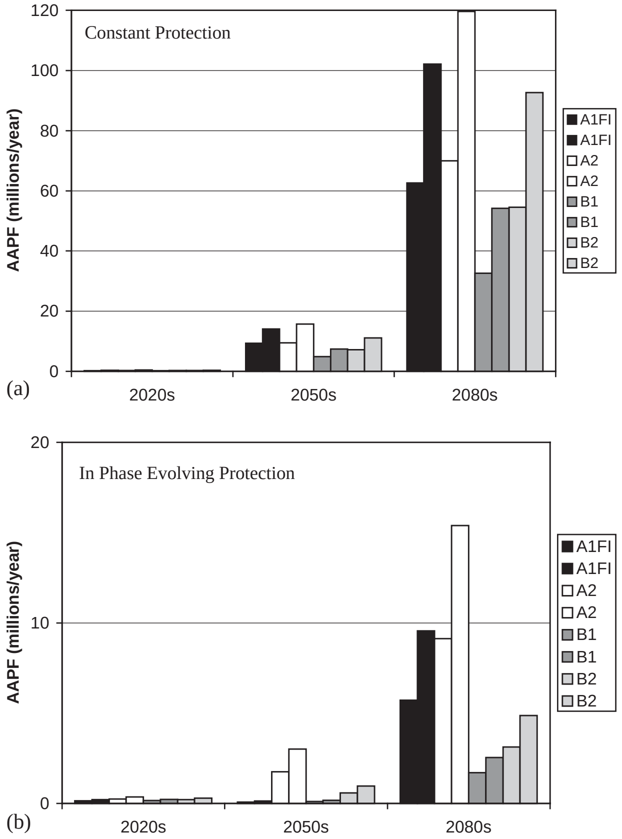

Fig. 4. Additional average annual people flooded due to sea-level rise under the SRES scenarios and (a) constant protection and (b) in-phase evolving protection. The paired values for each storyline represent the low and high population growth scenarios, respectively. The low subsidence scenario is assumed. Note the different scales.

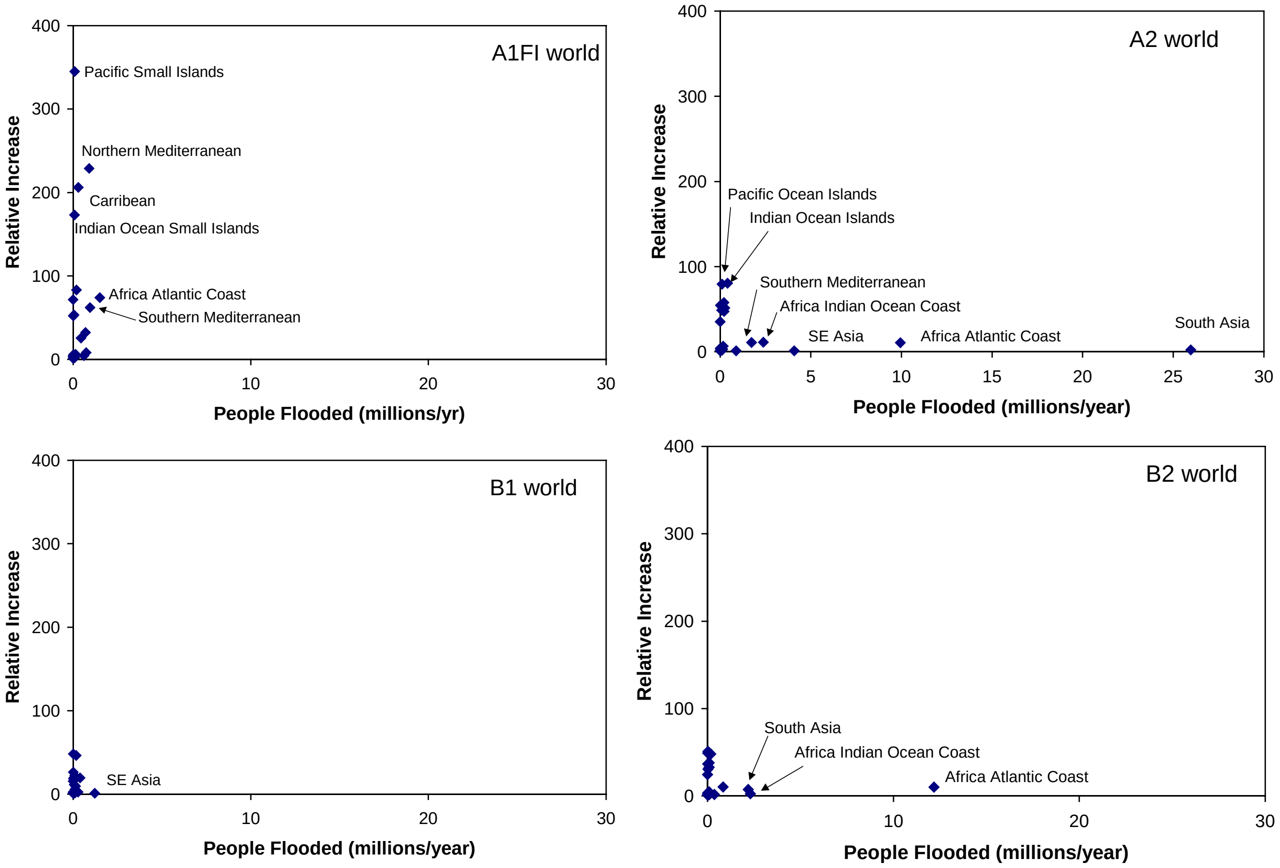

Fig. 5. Regional behaviour of flooding. The plots show the relative increase of flooding due to sea-level rise (a dimensionless ratio) versus the *total* number of people flooded (millions/year) in each region. The results are for the 2080s and assume lagged evolving protection and the low population growth and subsidence scenarios.

Table 13
Global results for coastal flooding showing the additional impacts due to sea-level rise for people in the hazard zone (*PHZ*) and average annual people flooded (*AAPF*) under the high subsidence scenario for the 2080s only

Scenario	PHZ (millions)		AAPF (millions/year)					
			Constant protection		In phase evolving protection		Lagged evolving protection	
A1FI	28	43	105	167	25	39	26	42
A2	41	67	179	294	144	245	167	277
B1	18	27	90	143	12	19	21	34
B2	25	38	124	186	25	41	41	66

The range indicates the values from the low and high population growth scenarios.

regions. Under the A1FI world, where protection standards are uniform and sea-level rise is largest, some developed world regions such as the Northern Mediterranean and North and West Europe start to see a significant proportion of the predicted impacts.

In addition to the absolute results, large relative increases in the number of people flooded are noted in a number of regions. Small island regions experienced the largest relative increases in the incidence of flooding in previous analyses (Nicholls et al., 1999). In these analyses, while the impacts are less dramatic, island regions still stand out in terms of their relative vulnerability, particularly in the A1FI world (Table 15). This result occurs in spite of an underlying assumption that the high defence standards on the islands can be achieved at the same cost as mainland countries (see Table 5). If this assumption is considered optimistic (cf. IPCC CZMS, 1990), it can be argued that this analysis is *underestimating* the flood impacts and hence the inherent vulnerability of these regions is greater than indicated here.

Fig. 5 synthesises the regional results for each of the worlds for the 2080s under the lagged evolving protection scenario and low subsidence. It characterises each

Table 14
Regional contributions to coastal flooding in the 2080s

Region	1990	A1FI		A2		B1		B2	
	B	B	SLR	B	SLR	B	SLR	B	SLR
North America	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0
Central America	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
South American Atlantic Coast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South American Pacific Coast	0.0	0.0	0.2	0.0	0.2	0.0	0.0	0.0	0.1
Caribbean	0.0	0.0	0.3	0.0	0.2	0.0	0.0	0.0	0.1
Atlantic Small Islands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North and West Europe	0.0	0.0	0.7	0.0	0.1	0.0	0.0	0.0	0.1
Baltic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North Mediterranean	0.0	0.0	0.9	0.0	0.2	0.0	0.2	0.0	0.2
South Mediterranean	0.2	0.0	0.9	0.2	1.6	0.0	0.1	0.1	0.8
Africa Atlantic Coast	0.3	0.0	1.5	0.9	9.0	0.0	0.4	1.2	10.9
Africa Indian Ocean Coast	0.6	0.0	0.4	0.2	2.2	0.0	0.1	0.3	1.9
Gulf States	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Asia	4.3	0.1	0.6	12.4	13.6	0.1	0.2	1.0	1.3
Indian Ocean Small Islands	0.0	0.0	0.1	0.0	0.4	0.0	0.0	0.0	0.0
South-East Asia	1.9	0.1	0.5	3.6	0.4	1.1	0.1	0.2	0.1
East Asia	2.9	0.0	0.0	0.8	0.1	0.0	0.0	0.1	0.0
Pacific Large Islands	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0
Pacific Small Islands	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0
Former USSR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SUM (millions)	10.3	0.4	6.6	18.4	28.3	1.4	1.4	3.0	15.6

The incidence of flooding (in millions/year) under the lagged evolving protection scenario. The low subsidence scenario and low population growth scenario is assumed. Columns marked B indicates the baseline conditions, while columns marked SLR indicate the additional people experiencing flooding due to sea-level rise. The 1990 regional pattern is shown for reference purposes.

Table 15
Vulnerable regions for coastal flooding—small islands

	1990	2080s							
		A1FI		A2		B1		B2	
		B	SLR	B	SLR	B	SLR	B	SLR
5. Caribbean	9.6	1.5	296.4	3.6	199.4	1.5	25.5	2.5	88.6
15. Indian Ocean	2.0	0.4	70.9	5.0	397.0	0.4	10.1	0.6	28.0
19. Pacific Ocean	3.2	0.2	82.8	1.3	102.2	5.2	54.4	0.3	10.3

The incidence of flooding (thousands/year) under the lagged evolving protection scenario. The low subsidence scenario and low population growth scenario is assumed. Columns marked B indicates the baseline conditions, while columns marked SLR indicate the additional people experiencing flooding due to sea-level rise. The 1990 results are shown for reference purposes.

region by the absolute magnitude of numbers of people flooded, and the relative increase in the incidence of flooding compared to a non-climate baseline. Hence, it distinguishes those regions that make large absolute contributions to the global results, and those regions that are most sensitive to sea-level rise. Five regions stand out in absolute terms: South-east Asia, Southern Mediterranean, Africa Indian Ocean Coast, South Asia and Africa Atlantic Coast, with the last two being most important. This is consistent with earlier analyses (Nicholls et al., 1999). There are also a number of regions which are quite sensitive to sea-level rise, although the absolute impacts are quite small, including the island regions discussed above, and the Northern Mediterranean. Hence, Fig. 5 conveys some important general characteristics on the range of regional response to sea-level rise in terms of the incidence of coastal flooding.

6.1.4. *Summary*

Table 16 ranks the four SRES worlds that are explored in this analysis in terms of average annual people flooded for a wide range of scenarios. In both the cases of climate change and no climate change, the A2 world experiences the greatest incidence of flooding. In the situation without climate change, the A1FI world experiences the lowest incidence of flooding, although this ranking is sometimes tied with the B1 world. With climate change, the ranking is changed, and the B1 world consistently experiences the lowest incidence of flooding. The main distinction with the A1FI world is the lower rate of sea-level rise (Table 2). However, even though the A1FI scenario produces the largest rise in global-mean sea level, the A2 world always has a greater incidence of flooding, as does the B2 world in nearly all cases.

Table 16 compares the same population, subsidence, climate change and protection scenarios. As discussed earlier and presented in Table 6, the SRES storylines

Table 16
Ranking of each SRES future world (A1FI , A2, B1 and B2) based on the magnitude of the global impacts in terms of annual average people flooded in the 2080s

Low subsidence scenario			High subsidence scenario		
(a) *No climate change*					
C Prot	IPE Prot	LE Prot	C Prot	IPE Prot	LE Prot
A2	A2	A2	A2	A2	A2
B2	B2	B2	B2	B2	B2
A1FI/B1 tie	A1FI/B1 tie	B1	A1FI/B1 tie	A1FI/B1 tie	B1
		A1FI			A1FI
(b) *With human-induced climate change*					
C Prot	IPE Prot	LE Prot	C Prot	IPE Prot	LE Prot
A2	A2	A2	A2	A2	A2
A1FI	A1FI	B2	B2	B2	B2
B2	B2	A1FI	A1FI	A1FI	A1FI
B1	B1	B1	B1	B1	B1

C Prot—Constant protection; IPE Prot—In phase evolving protection; LE Prot—Lagged evolving protection.

Table 17
The likely incidence of flooding under the in-phase protection scenario, selecting the preferred population and subsidence scenarios as defined in Table 6

	Baseline AAPF (no sea-level rise)	Additional AAPF (due to sea-level rise)
	Millions of people/year	
A1FI world	3	42
A2 world	44	167
B1 world	2	2
B2 world	3	16

suggest that the different worlds may show substantial differences in many important factors relevant to coastal flooding. Table 17 selects results following two factors as indicated, and it is noteworthy that the A2 world is still ranked highest, followed in this case by the A1FI world. The other factors identified in Table 7 concerning adaptation lag time and the priority given to hazard management would not change this ranking, and it would appear that the A2 world is always the most vulnerable to global-mean sea-level rise through the 21st century for the full range of scenario combinations.

Hence this analysis shows that the factors influencing exposure and adaptive capacity are critical in controlling vulnerability to climate change, in addition to the magnitude of climate change.

6.2. *Coastal wetlands*

Table 18 shows a low and a high loss estimate of the decline in the global stock of wetlands due to the sea-level rise scenarios. By 2080s, up to 20% of the world's coastal wetlands could be lost due to sea-level rise under the A1FI scenario. Significant additional losses are expected to continue after the 2080s, but this has not been evaluated.

Table 18
The range (low/high) of global losses of coastal wetlands due to global-mean sea-level rise only

	A1FI losses (%)		B1 losses (%)		A2 losses (%)		B2 losses (%)	
2020s	1	5	1	5	1	5	1	5
2050s	1	8	1	8	1	7	1	8
2080s	5	20	4	16	3	14	3	15

Table 19
Indicative net global losses by combining losses due to sea-level rise with possible human losses

	A1FI losses (%)		B1 losses (%)		A2 losses (%)		B2 losses (%)	
2020s	14	34	12	17	14	34	12	17
2050s	24	52	12	28	24	52	12	29
2080s	35	70	14	42	35	68	14	42

When combined with the appropriate direct loss scenarios for the SRES storyline (Table 8), much larger losses of coastal wetlands might occur than due to sea-level rise alone (Table 19). The worst loss is up to 70% of the world's coastal wetlands under the A1FI scenario. There is a clear distinction between the larger potential losses in the A1FI/A2 worlds compared to the B1/B2 worlds, reflecting their differing attitudes to the environment and sustainable development. This sets the role of sea-level rise impacts on coastal wetlands in context and suggests that these other factors would be more important in determining the fate of coastal wetlands during the 21st century. The impacts of climate change will be of most significance where coastal wetlands are protected from other human-induced pressures. Elsewhere, sea-level rise is simply exacerbating an already adverse situation.

In terms of regional change, wetland losses due to sea-level rise are expected to be most severe in a few regions as found by Nicholls et al. (1999). While the range of losses has a high degree of uncertainty, the Baltic, North Mediterranean, South Mediterranean, and the Atlantic coast of North and Central America could see substantial losses of wetlands due to sea-level rise by the 2080s. Therefore, even with the lowest human losses (i.e., Model 3 in Table 8), some regions could still see substantial wetland losses. It is also noteworthy that coastal wetland losses due to sea-level rise could be significant in parts of the European Union and the USA.

7. Discussion/conclusions

The SRES scenarios provide a more diverse and richer perspective on the different pathways of development that the world might follow through the 21st century and hence the implications of climate change and sea-level rise.

7.1. Coastal flooding

The different pathways of development lead to a wide range of vulnerability to coastal flooding. In the situation of no climate-induced sea-level rise, all four worlds experience an increase in the incidence of flooding to the 2020s, following widely reported observations of the increasing frequency of flood disasters through the late 20th century (Smith and Ward, 1998). In the model, this result mainly reflects the increased population of the flood plain in this period. After the 2020s under evolving protection, the impacts of flooding diverge as the A1FI, B1 and B2 worlds experience sufficient economic growth to adapt to coastal flooding in all locations. In contrast in the A2 world, coastal flooding remains a problem through to the 2080s. This reflects that it has the highest exposure to flooding due to the large population increase, and the smallest adaptive capacity due to the smallest increases in GDP/capita.

These differences are also apparent when we consider the additional impacts of sea-level rise on coastal flooding. The A2 world experiences by far the greatest impacts of sea-level rise. This reflects the same issues as above. In contrast, the A1FI world, which produces the largest rise in global-mean sea-level rise, has much lower absolute flood impacts. This reflects the lower population growth than the A2 world, and the larger adaptive capacity implied by the rapid growth in GDP/capita. Hence, the A2 world ranks highest in terms of the relative incidence of flooding throughout the 21st century, irrespective of the scenarios that are considered. This includes using the scenario combinations that are most consistent with the full narrative of the SRES storylines (Table 7).

While post-2080s changes were not analysed, when sea-level rise is considered, the flood impacts increase significantly from the 2050s to the 2080s, particularly for the A1FI and B2 worlds. This suggests that if the analysis continued, the 22nd century might experience more significant flood impacts due to sea-level rise than estimated for the 21st century. Given that the A1FI scenario is rising most rapidly at the end of the 21st century, its continuation into the 22nd century and beyond would generate the most significant flood impacts. This shows that only focussing on the 21st century may ignore important problems and issues for future generations. This is particularly true with global-mean sea-level rise as even with stabilisation of greenhouse forcing, it will continue for centuries or even millennia (Wigley and Raper, 1993; Church et al., 2001).

Small island regions stand out in all SRES futures to the 2080s as experiencing significant flood impacts, even including what could be considered optimistic assumptions about their potential for defence upgrade under evolving protection scenarios (e.g., Table 15). The worst impacts are predicted for the A2 and A1FI worlds. The possibility of post-2080s changes discussed above raise further concerns. This reinforces earlier conclusions about the vulnerability of these small island regions and the particular need to prepare for adaptation to sea-level rise in these regions (Nurse et al., 2001).

7.2. Coastal wetlands

While sea-level rise causes losses in all cases, the biggest factor influencing the future state of the world's coastal wetlands is the degree of direct and indirect human-induced destruction. This is linked to human attitudes to the environment. Thus, the difference between the attitudes and actions of the A1/A2 worlds which do not value the environment and the B1/B2 worlds which do value the environment would seem to have a much important influence on the future status of coastal wetlands than the magnitude of climate change during the 21st century. This places sea-level rise in an appropriate context as one factor in a set of multiple stresses on these systems. Looking beyond the 2080s, further losses of coastal wetlands due to sea-level rise look likely during the 22nd century, so climate change could become a more important loss factor even under scenarios of effective wetland conservation and management. This reiterates the need not to stop consideration of impacts at the 2080s.

7.3. Climate change and sustainable development

The diversity of the SRES socio-economic futures allows us to see that socio-economic factors often drive the impacts that we are studying more than the magnitude of climate change. This places dealing with climate change in the broader context of sustainable development. Certain pathways of development appear to be producing worlds that are less vulnerable to climate change than other development pathways and vice versa. Hence, in addition to encouraging development that is less dependent on carbon energy (mitigation), development should also be encouraging forms that are less vulnerable to climate change and variability. Based on the results of the two impact factors considered here, the A2 world appears to be the least desirable with or without climate change, as already stated (Table 20). In contrast, the B1 world would appear to give the lowest impacts in terms of coastal flooding and wetland loss, based on its lower population, higher GDP/capita and the lowest rise in global-mean sea level (and magnitude of climate change, in general). This conclusion is reinforced by the wider attitudes of this world to community, hazards and the environment (see Arnell et al., 2003).

The impacts presented here are lower than in earlier analyses of unmitigated sea-level rise (Nicholls et al., 1999; Arnell et al., 2002), so they could be taken to demonstrate that global-mean sea-level rise is not really a problem. This would be an over-interpretation of these results, which present broad sensitivities of the coastal system to change for one climate model (HadCM3). A key uncertainty that has not been addressed within the analysis is climate sensitivity, which continues to have a large range of uncertainty. The HadCM3 model has a climate uncertainty of 3.3°C (Hulme et al, 1999) and other climate models with larger climate sensitivities would estimate larger rises in sea level (e.g., Table 2), and hence larger impacts (e.g., Nicholls, 2002b). To explore this issue across the full range of climate sensitivity, Table 21 indicates results for flooding in the 2080s based on reasonable combinations of the SRES socio-economic scenarios with the low and high global-mean sea-level rise scenarios reported by Church et al. (2001) (see Table 2). For the B1/B2 worlds combined with the low scenario, the impacts are negligible, while for the A1FI/A2 worlds combined with the high scenario the impacts are dramatic as in earlier analyses examining the IS92a scenario (Nicholls, 2002b). For the coastal wetlands, the high global-mean sea-level rise scenario could lead to losses of 22–48% of global wetlands by the 2080s, just considering the effects of sea-level rise. As with Table 21, these losses are best linked to the A1FI and A2 worlds. Further analysis to systematically explore the range of impacts across the full range of possible scenarios, including the uncertainties in the climate projections, would be prudent to explore this effect in more detail.

Table 20
Synthesis ranking of the SRES worlds for magnitude of coastal flooding and wetland loss, with and without climate change

No climate change		Climate change	
Coastal flooding	Wetland loss	Coastal flooding	Wetland loss
A2	A1FI/A2	A2	A1FI/A2
B2		A1FI/B2	
A1FI/B1	B1/B2		B1/B2
		B1	

Table 21
The effect of climate sensitivity on additional average annual people flooded in the 2080s (millions/year)

Global-mean sea-level rise scenario	A1FI	A2	B1	B2
Low (9 cm)	n.c.	n.c.	0.2–0.3	0.8–1.4
High (69 cm)	56–88	271–453	n.c.	n.c.

This combines the low and high global-mean sea-level rise scenarios of Church et al. (2001) with appropriate socio-economic scenarios. Assumes low subsidence and lagged evolving protection, while the range describes the uncertainties due to the population scenarios. n.c.—combination not considered realistic.

The SRES socio-economic scenarios also generate a number of questions. One could argue that all the GDP scenarios are optimistic, as the whole world experiences significant GDP and GDP/capita growth in all four of the futures, but at varying rates. This does not agree with trends in sub-Saharan Africa over the last 50 years where GDP/capita has often been static or even falling (UNDP, 2003). This raises the possibility of climate change being imposed on a less equal world than any other considered here. This would translate into greater flood impacts in the poorer regions. Further analysis of such 'worst-case' socio-economic scenarios would be instructive for national and international policymakers.

7.4. Conclusions

These results should be seen as a broad analysis of the sensitivity of the coastal system to the SRES global-mean sea-level rise scenarios. The main conclusions are as follows:

(1) The incidence of coastal flooding will change due to factors other than sea-level rise and the four SRES worlds considered here have a range of vulnerability to such flooding. Without any global-mean sea-level rise, the incidence of flooding increases from 1990 to the 2020s. Subsequently, the incidence of flooding diminishes in all cases, except for the A2 world, which is the most vulnerable to coastal flooding.
(2) Under the global-mean sea-level rise scenarios, additional impacts are not apparent until the 2050s or even 2080s, but the same vulnerabilities are apparent. The A2 world is again predicted to experience the greatest flood impacts, even though the largest rise in sea level occurs in the A1FI world.
(3) While not quantitatively analysed here, the trend of the results suggest much larger impacts of sea-level rise on coastal flooding in the 22nd century, particularly under the A1FI scenario. This shows that discussions on climate policy should not simply focus on impacts in the 21st century.
(4) Small island regions appear to be particularly vulnerable to increased flooding during the 21st century under all the SRES worlds.
(5) Impacts of sea-level rise on coastal wetlands could be significant, but human-induced direct and indirect effects are potentially much larger based on existing trends. Therefore, the distinction between the A1/A2 worlds (little environmental concern) and the B1/B2 worlds (high environmental concern) appears to be more important than sea-level rise for the status of coastal wetlands during the 21st century.

(6) Summarising the impacts, the A2 world would appear to be most vulnerable to both sea-level rise, and other change factors, while the B1 world is least vulnerable to sea-level rise.
(7) The results show the importance of the socio-economic conditions as a fundamental control of impacts both with and without climate change. This suggests that more consideration of the role of development pathway on impacts and adaptation to climate change could be useful.
(8) Further work on coastal impacts in the SRES world should include more analysis of:

    - Impacts for a range of climate models, including the full range of climate sensitivity;
    - Long-term impacts into the 22nd century and beyond;
    - Impacts of worst-case socio-economic storylines developed to supplement the SRES storylines;
    - The benefits and feasibility of different combinations of stabilisation (cf. Swart et al., 2002) and adaptation.

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