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Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century

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Taking the Special Report on Emission Scenarios (SRES) climate and socio-economic scenarios (A1FI, A2, B1 and B2 'future worlds'), the potential impacts of sea-level rise through the twenty-first century are explored using complementary impact and economic analysis methods at the global scale. These methods have never been explored together previously. In all scenarios, the exposure and hence the impact potential due to increased flooding by sea-level rise increases significantly compared to the base year (1990). While mitigation reduces impacts, due to the lagged response of sea-level rise to atmospheric temperature rise, impacts cannot be avoided during the twenty-first century by this response alone. Cost–benefit analyses suggest that widespread protection will be an economically rational response to land loss due to sea-level rise in the four SRES futures that are considered. The most vulnerable future worlds to sea-level rise appear to be the A2 and B2 scenarios, which primarily reflects differences in the socio-economic situation (coastal population, Gross Domestic Product (GDP) and GDP/capita), rather than the magnitude of sea-level rise. Small islands and deltaic settings stand out as being more vulnerable as shown in many earlier analyses. Collectively, these results suggest that human societies will have more choice in how they respond to sea-level rise than is often assumed. However, this conclusion needs to be tempered by recognition that we still do not understand these choices and significant impacts remain possible. Future worlds which experience larger rises in sea-level than considered here (above 35 cm), more extreme events, a reactive rather than proactive approach to adaptation, and where GDP growth is slower or more unequal than in the SRES futures remain a concern. There is considerable scope for further research to better understand these diverse issues.

Keywords: coasts; climate change; sea-level rise; flooding; climate policy; adaptation

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One contribution of 20 to a Theme Issue 'Sea level science'.

1. Introduction

One of the more certain consequences of human-induced climate change through the twenty-first century is a global-mean rise in sea-level of up to 1 m (Church & Gregory 2001). While the impacts of sea-level rise are confined to coastal areas, these are the most densely populated land areas on earth, and they support important and productive ecosystems that are sensitive to sea-level changes. However, the significance of sea-level rise remains uncertain and contested. In part, this reflects a mixture of confusion and different interpretations concerning *potential impacts* and *actual impacts* (see Nicholls 2002 for a further discussion). Potential impacts are the consequences of sea-level rise and climate change before considering adaptation, while actual impacts represent the impacts including any adaptation. Successful adaptation will reduce impacts and hence the difference between potential and actual impacts reflects the effectiveness of adaptation measures[1]. Based on the differing interpretations of the same knowledge base, 'optimists' argued that human adaptation will reduce the magnitude of impacts to a level where sea-level rise is almost a trivial problem (e.g. Lomborg 2002), while 'pessimists' argue that sea-level rise (and climate change in general) are a major threat for the twenty-first century (e.g. New Economics Foundation & Greenpeace 2004).

This paper explores these conflicting optimistic and pessimistic interpretations over the twenty-first century using two global models of the impacts of sea-level rise, including exploring the opportunities for response to this threat by mitigation (reducing greenhouse gas forcing) and adaptation (to moderate the impacts of sea-level rise) (see Nicholls & Lowe 2004, 2006; Tol 2004). Previous global studies have tended to either consider (i) the potential impacts of sea-level rise (e.g. number of people affected) (Hoozemans *et al.* 1993; Nicholls 2004), or (ii) the economic implications of sea-level rise (e.g. impact and adaptation costs) (Fankhauser 1994; Tol 2004). For the first time, in this paper, these two complementary approaches are examined together to develop a more comprehensive and integrated perspective on the implications of sea-level rise. New model analyses explore both stabilization and adaptation under the SRES[2] scenarios. More general remarks about the impacts and responses to sea-level rise and the broader factors that need to be considered in future analyses conclude.

2. Assessments of sea-level rise

Relative sea-level rise produces a range of impacts on the coastal zone, and there is a range of possible responses to each impact (table 1). It is important to recognize that all existing analyses only consider aspects of these impacts and responses due to data and model limitations. Through the paper, these limitations are defined to the reader.

The challenges for analysis at the global scale are significant, and studies require consistent global datasets and scenarios, appropriate analytical tools and answerable questions. Despite major and continuing improvements in the

[1] The term maladaptation is used in cases where adaptation increases adverse impacts.

[2] SRES—the Special Report on Emission Scenarios (Nakicenovic & Swart 2000).

Table 1. The main natural system effects of relative sea-level rise, including examples of possible adaptation responses.

natural system effect		possible adaptation responses
1. inundation, flood and storm damage	a. surge (sea)	dikes/surge barriers, building codes/floodwise buildings, land use planning/hazard delineation
	b. backwater effect (river)	
2. wetland loss (and change)		land use planning, managed realignment/forbid hard defences, nourishment/sediment management.
3. erosion (direct and indirect morphological change)		coast defences, nourishment, building setbacks
4. saltwater intrusion	a. surface waters	saltwater intrusion barriers, change water abstraction
	b. ground-water	freshwater injection, change water abstraction
5. rising water tables/impeded drainage		upgrade drainage systems, polders, change land use, land use planning/hazard delineation

available physical, ecological and socio-economic datasets, the availability of high resolution and consistent data remains a major constraint on such analyses (as an example, see Small & Nicholls 2003 for a discussion of uncertainty in global data for relatively high-quality coastal population data). Therefore, the validity of the results is scale dependent and they will provide more robust results at more aggregated scales (Hoozemans *et al.* 1993).

To date, one of the most influential and widely used[3] regional to global assessments of coastal zones has been the Global Vulnerability Assessment (GVA) and its derivatives (Nicholls & Hoozemans 2005). After considering the limitations outlined earlier, the GVA evaluated fairly simple parameters (Hoozemans *et al.* 1993) based on an assessment based on 192 coastal polygons, essentially comprising the world's coastal countries at the time. The impact parameters comprised of potential impacts of 1 m sea-level rise on three distinct elements of the coastal system and one possible adaptive response:

(i) *Population risk*. Population at risk of flooding by storm surges (and potential upgrade costs for dikes, as discussed later) (natural system effect 1a in table 1).
(ii) *Ecosystem loss*. Coastal wetlands of international importance at loss (natural system effect 2 in table 1).
(iii) *Agricultural impacts*. Rice production at change (for South, Southeast and East Asia only) (relating to natural system effects 1, 4 and 5 in table 1).

All the results were only considered meaningful when aggregated to 20 regions, and the globe.

[3] The underlying data in direct or modified form is the basis for most subsequent global assessments (e.g. Nicholls 2004; Nicholls & Lowe 2004; Tol 2004).

Table 2. Summary of the SRES storylines.

'A1 world'	'B1 world'
increasing globalization/convergence	increasing global cooperation/convergence
materialist/consumerist	environmental priority
rapid uniform technological innovation	clean and efficient technologies
'A2 world'	'B2 world'
heterogeneous world	heterogeneous world/local emphasis
materialist/consumerist	environmental priority
diverse technological innovation	clean and efficient technologies

3. The SRES scenarios

In this paper, we analyse the well-known SRES scenarios (Nakicenovic & Swart 2000), which developed a range of emission scenarios (and hence climate change and sea-level rise scenarios) from a diverse set of socio-economic pathways for the twenty-first century. While these scenarios have generated a significant debate (e.g. Castles & Henderson 2003; Grübler *et al.* 2004), they are still useful to explore the broad sensitivities of impacts and responses to contrasting sea-level rise and socio-economic scenarios.

The SRES scenarios are presented as four 'storylines', which represent mutually consistent characterizations of how the world might evolve during the twenty-first century. Each storyline is a short narrative of alternative pathways of future global development from today's world in terms of political, economic, technical and social developments (termed the 'A1', 'B1', 'A2' and 'B2' worlds). From these storylines, self-consistent scenarios were developed, which are considered equally plausible by the SRES originators (table 2). In this paper, four pairs of climate and socio-economic scenarios are analysed: A1FI[4], A2, B1 and B2. Henceforth, they are referred to as the A1FI, A2, B1 and B2 worlds, respectively.

The global-mean sea-level rise scenarios for each SRES world are derived from experiments using the HadCM3-coupled ocean–atmosphere model (Johns *et al.* 2003) using the methods described by Gregory & Lowe (2000). The effective climate sensitivity of HadCM3 is 3 °C. Global-mean sea-level rise estimates encompass components due to thermal expansion, ice sheet mass balance changes and land glacier melt. Thermal expansion is derived directly from the HadCM3 model, while the ice melt components are derived from offline models. Each scenario was referenced to 1990 based on a 30-year running average. The largest sea-level rise is under the A1FI scenario, and smallest under the B1 scenario (figure 1).

The SRES socio-economic scenarios are only quantified at a global and regional scale (e.g. 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. In contrast, under A2 and B2, the population growth continues to the 2080s, reaching over 2.5 times 1990 levels for A2. Gross Domestic Product (GDP) and GDP/capita grow substantially in all cases, and all developing countries become much richer under all scenarios, reducing the gap between

[4] A1 socio-economics in a carbon-based fuel intensive (FI) world and hence high greenhouse gas emissions.

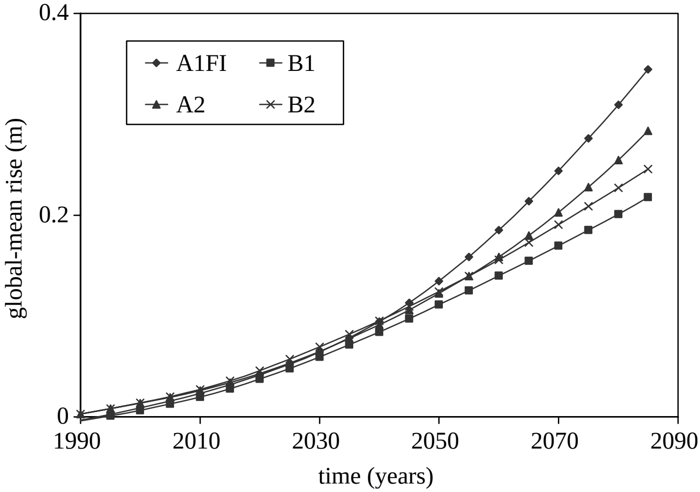

Figure 1. The SRES sea-level rise scenarios (after Johns *et al.* 2003).

developed and developing countries. However, the net differences between worlds 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 greatly reduced being only 25% of those under A1FI.

Both the models used in this paper require national estimates of population and GDP. Slightly different assumptions have been made. For the impact analyses, the SRES population and GDP scenarios from the IPCC Data Distribution Centre (DDC)[5] were used (Nicholls 2004). The economic analysis uses the scenarios developed by the IMAGE Team (2001), applied homogonously to the countries within each of 17 regions[6] (Tol 2004).

4. Potential impacts of coastal flooding

Coastal flooding due to storm surges[7] is a long-standing problem as shown by Medieval flooding around the southern North Sea and twentieth century floods in the Bay of Bengal, especially in Bangladesh. Historical data suggest that surges have been constant over the long-term on the US East Coast and the north-western Atlantic, but with high interannual and interdecadal variability (WASA Group 1998; Zhang *et al.* 2000). In the future, some models suggest systematic

[5] The Centre for International Earth Science Information Network (CIESIN) 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. Small countries with a population of less than 150 000 in 1990 are not included, including many small island states which are important in coastal studies. Population and GDP scenarios were developed for all the missing cases using the regional change for the larger countries in each island region (e.g. Caribbean, Indian Ocean or Pacific Ocean) (Arnell *et al.* 2004).

[6] Small rich countries in poor regions were shifted to neighbouring richer regions (e.g. the Bahamas and Singapore have the same relative growth as the USA and Japan, respectively, rather than Central America and Southeast Asia, respectively).

[7] Natural system effect 1a (table 1).

Table 3. Global SRES socio-economic and sea-level rise scenarios for the 2080s.

year and scenario		population (billions)	GDP (trillion US 1990 $)	GDP/capita (thousands US 1990 $)	global-mean sea-level rise (cm)
1990		5.3	20.1	3.8	0
2080s	A1	7.9	416	52.6	34
	A2	14.2	185	13.0	28
	B1	7.9	289	36.6	22
	B2	10.2	204	20.0	25

change in surge characteristics (e.g. Lowe *et al.* 2001), but the uncertainties remain large and there are no global-scale scenarios.

Sea-level rise, and more frequent and more intense storms will increase the potential impacts of coastal flooding. In the absence of any credible scenarios, in this paper, storm surge characteristics are assumed constant over time, and only the effects of sea-level rise in raising these surges are considered.

(*a*) *Methods*

The analysis of coastal flooding due to surges uses the methods described by Nicholls (2004). The analysis proceeds at the scale of coastal countries, which are considered to be homogeneous and examines the competing influence of:

(i) relative sea-level rise (due to local subsidence and global-mean rise),
(ii) coastal population change[8], and
(iii) improving flood protection (via changing dike standards), estimated using GDP/capita[9].

Figure 2 summarizes the overall method.

Sea-level rise and changes in coastal population are unconstrained. In all scenarios, there are large potential increases in coastal population, which is reinforced by the assumption of coastal attraction of population. The effect of sea-level rise on extreme water levels (i.e. surge height) is an explicit part of the analysis: relative sea-level rise simply displaces these extreme water levels upwards. Exposure is measured as a function of the population living below the 1 in 1000-year storm surge[10]. Following the GVA, risk is measured using the average number of people flooded per year (Hoozemans *et al.* 1993). In countries where coastal subsidence is known to be occurring, a uniform subsidence scenario of 15 cm per century was assumed, consistent with the scale of analysis.

[8] The potential impact results reported here assume coastal attraction and that population changes in coastal areas are double the national increase (or half the national decrease) (Nicholls 2004).
[9] To facilitate the analysis, all protection against coastal flooding is treated as dike construction, although it is acknowledged that other protection approaches are possible, such as beach and dune nourishment. This point is revisited in §6.
[10] All the base data in the GVA, including surge height estimates, were developed by Delft Hydraulics for every coastal country (Hoozemans *et al.* 1993).

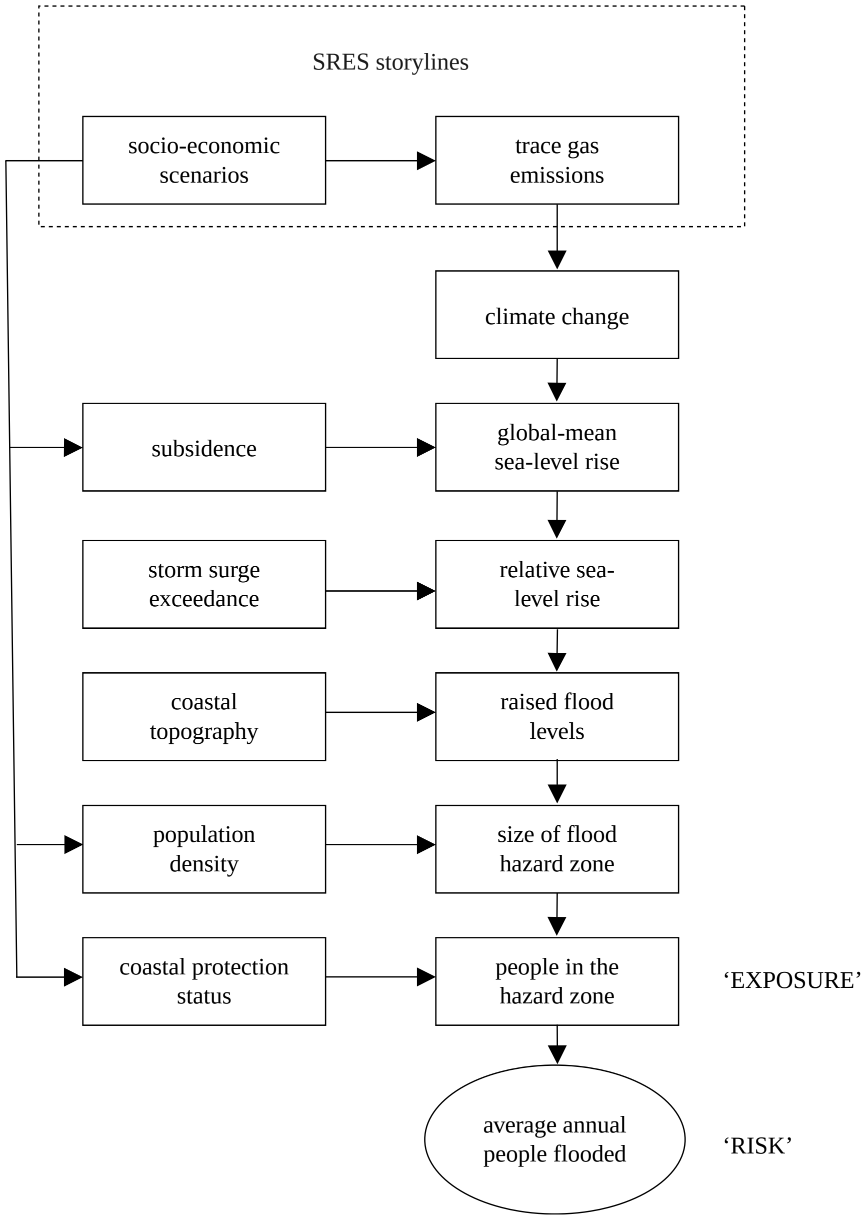

Figure 2. Summary of the method for flood analysis.

Scenarios of protection standards are the most problematic parameter to estimate, as they have a large effect on the number of people flooded. Here it is assumed that attitudes to risk are controlled by wealth, and GDP/capita is linked to dike standards in a similar manner to Hoozemans *et al.* (1993) (table 4). Yohe & Tol (2002) show that this is a reasonable first-order assumption. Four different protection scenarios are considered to encompass the likely evolution of protection standards (table 5), ranging from Constant Protection in

Table 4. Protection classes as applied by Hoozemans *et al.* (1993) and Nicholls (2004).

protection class (and status)	Hoozemans *et al.* (1993) GDP/capita (US$)	Hoozemans *et al.* (1993) design frequency	Nicholls (2004) GDP/capita (US$) if deltaic coast	Nicholls (2004) GDP/capita (US$) if non-deltaic coast	Nicholls (2004) design frequency
1. low	<600	1/1 to 1/10	<2400	<600	1/10
2. medium	600 to 2400	1/10 to 1/100	2400 to 5000	600 to 2400	1/100
3. high	>2400	1/100 to 1/1000	>5000	>2400	1/1000

Table 5. Protection scenarios including upgraded protection assumptions.

protection scenario	adaptation to sea-level rise	definition
Constant Protection	no	Fixed (1990) Protection Class
In Phase Evolving Protection	no	Protection Class improves in phase with GDP/capita, but only considering 1990 surge levels (i.e. relative sea-level rise is not considered)
Upgraded Constant Protection	yes	Constant Protection upgraded by one protection class (see table 4)
Upgraded In Phase Evolving Protection	yes	In Phase Evolving Protection upgraded by one protection class (see table 4)

the base year (1990) to significant upgrade under In Phase Evolving Protection with Upgrade, reflecting the rising GDP/capita across the entire world in the SRES scenarios (table 3).

Coastal population is used to describe the exposure and risk of flooding as follows (figure 2):

(i) *People in the hazard zone*. The number of people living below the 1000-year storm surge elevation (i.e. the exposed population ignoring dikes).
(ii) *Average annual people flooded*. The average number of people who experience flooding by storm surge per year, including the effects of dikes in risk reduction (note that this parameter has also been referred to as *people at risk*).

It is fundamental to note that the calculation of these parameters assumes that there is no human response to flooding and population change continues irrespective of other changes.

For climate stabilization, the analysis by Nicholls & Lowe (2004) is developed to also consider the benefits of adaptation as outlined earlier. While the SRES scenarios were not designed as stabilization scenarios, Swart *et al.* (2002) demonstrated that the twenty-first century changes in the SRES B2 and B1

scenarios are consistent with stabilization during the twenty-second century at concentrations of about 650 ppm CO_2 and 550 ppm CO_2 (henceforth termed the S650 and S550 scenarios, respectively). Hence, these SRES climate scenarios were linked to the appropriate SRES socio-economic scenarios (A1FI, A2, etc.) to create stabilization scenarios as discussed in Nicholls & Lowe (2004)[11].

(*b*) *Previous results*

Hoozemans *et al.* (1993) estimated that about 200 million people lived in the coastal flood plain (below the 1 in 1000-year surge-flood elevation) in 1990, or about 4% of the world's population. Based on this data, Nicholls *et al.* (1999) estimated that on average 10 million people per year experienced flooding due to storm surge in 1990. Collectively, Nicholls (2004) and Nicholls & Lowe (2004) showed a number of important points:

- (i) Without global sea-level rise, the number of people flooded per year is still dynamic due to competing socio-economic change (growing populations, and increasing protection standards) (as well as subsidence).
- (ii) While sea-level rise is a slow onset hazard, in the long-term its potential impacts are significant, threatening many millions of people. However, the uncertainty about potential impacts is large and increases with time.
- (iii) Due to the slow response of sea-level rise to mitigation (termed the 'commitment to sea-level rise'; Wigley & Raper 1993), the impacts of flooding increase with time under all the emission scenarios that are considered, including significant mitigation scenarios that stabilize greenhouse gas concentrations as low as 550 ppm CO_2. Thus, it is unclear what impacts are avoided and what impacts are delayed due to mitigation.
- (iv) Potential impacts depend on future development pathways as well as on climate change: climate stabilization has no effect on this relative vulnerability.
- (v) Potential impacts vary regionally: the three small island regions of the Caribbean, Indian Ocean and Pacific Ocean are most vulnerable in relative terms, while absolute increases in flooding are largest in the southern Mediterranean, West Africa, East Africa, South Asia and Southeast Asia.

(*c*) *New results under stabilization and adaptation scenarios*

Figure 3 shows the number of people living in the hazard zone (coastal flood plain) under the SRES futures. From about 200 million in 1990, the number rises significantly in all cases to the 2050s, and then diverges by the 2080s, as the A2 and to a lesser extent the B2 worlds continue to experience population growth, while the A1FI and B1 worlds experience a decline in population. This illustrates the high exposure to coastal flooding that exists without sea-level rise. Sea-level rise only causes a relatively small increase of the exposed population (6–10% by the 2080s), but it does have the potential to increase the risk of flooding for the exposed population as discussed later.

[11] Note that mitigation here is assumed not to change GDP/capita.

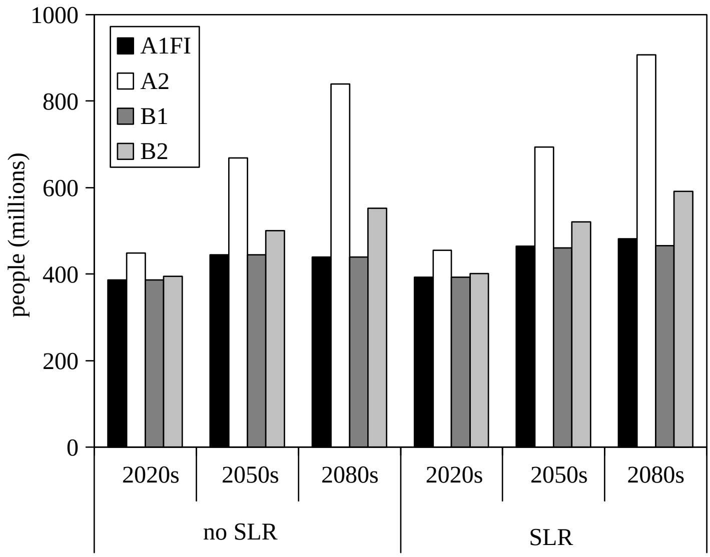

Figure 3. People in the hazard zone under the four SRES worlds and with and without sea-level rise (SLR and no SLR, respectively). This assumes that coastal attraction is double national increases (or half national decreases) following Nicholls (2004).

The *additional* number of people flooded annually under the different stabilization and protection options in the 2080s is shown in figure 4. The potential impacts are significant and largest for the A2 world, being over 100 million people per year under Constant Protection, and over 30 million people per year under In Phase Evolving Protection. Stabilization reduces the impacts for each SRES world, and especially for the A1FI world, which has the largest unmitigated sea-level rise. However, the benefits of stabilization in terms of reduced impacts are smaller than the benefits of upgraded protection. Unsurprisingly, the more protection that occurs, the smaller the benefits of stabilization. The A2 world has the highest impacts in all cases, reflecting its higher vulnerability to flood impacts in general, while the B1 world has the lowest impacts, which is consistent with Nicholls (2004).

Figure 5 shows the effects of adaptation on impacts over time, including an additional scenario of high subsidence induced by groundwater withdrawal in areas that are already subject to subsidence (at 45 cm per century). The impacts increase with time, but given Upgraded In Phase Evolving Protection, the additional impacts due to sea-level rise are at almost negligible levels by the 2080s (less than 1 million people per year), except for the A2 world. The impact of additional human-induced subsidence is also significant as shown by the high subsidence scenario for the 2080s where the *additional* impacts of global-mean sea-level rise are significantly amplified. Hence, in addition to global mitigation of sea-level rise and climate change, more local measures to avoid enhancing subsidence would be prudent (see Nicholls 1995, 2004).

This analysis shows that mitigation of climate change reduces the flooding impacts of sea-level rise, but suggests that protection could be more effective in managing coastal flooding. Of course, these policies can be combined as

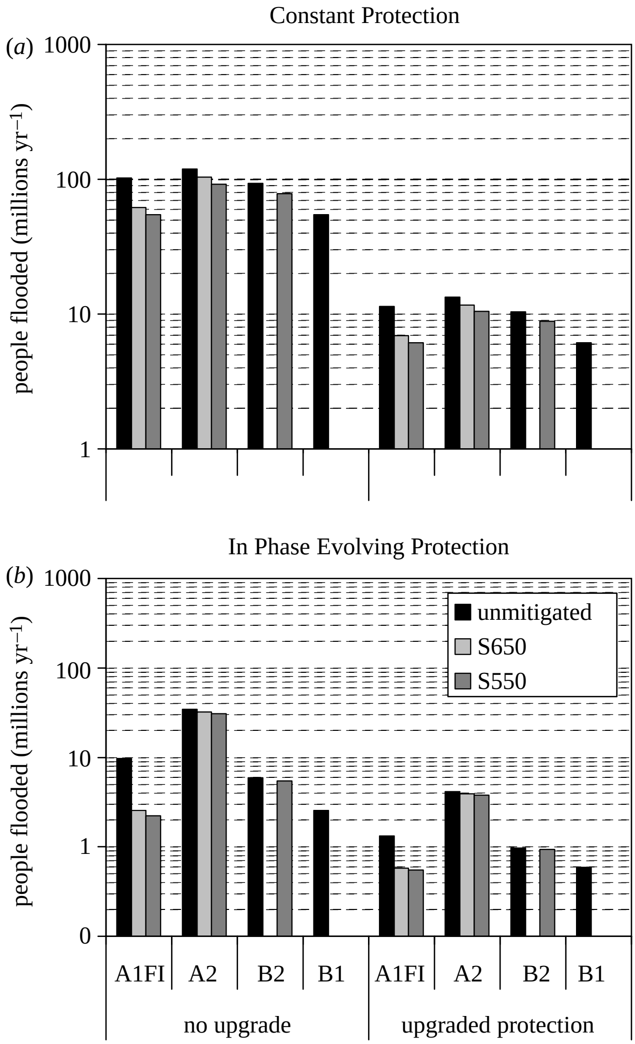

Figure 4. Additional people flooded due to sea-level rise in the 2080s for unmitigated emissions and stabilization of climate at concentrations of about 650 ppm CO_2 (S650) and 550 ppm CO_2 (S550), respectively, combined with the full range of protection scenarios. (*a*) Constant Protection, including upgraded protection. (*b*) In Phase Evolving Protection, including upgraded protection.

illustrated in figure 4. While the analysis shows the effectiveness of protection, it does not show where it might be economically feasible to implement.

5. Economic analysis of coastal impacts

This analysis considers a subset of the effects of sea-level rise comprising land loss[12], coastal protection via dike construction and wetland loss[13] within the

[12] This is the net effect of inundation and erosion, although inundation generally dominates in terms of potential area loss (natural system effects 1 and 3 in table 1).
[13] Natural system effect 2 in table 1.

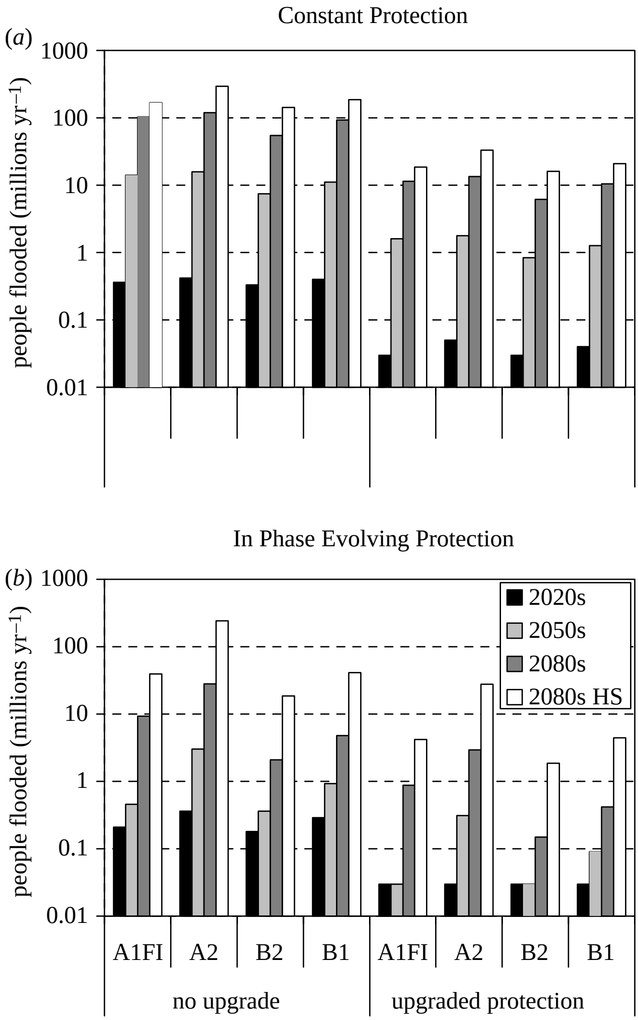

Figure 5. Additional people at risk due to unmitigated sea-level rise through time under (*a*) Constant Protection and (*b*) In Phase Evolving Protection, including upgraded protection scenarios. HS refers to the high subsidence scenario.

integrated framework of the FUND[14] model (figure 6). Note that this approach is conceptually different to the preceding analysis, which was considering exposure and risk rather than loss. The data that is used to estimate these impacts mainly comes from the GVA (Hoozemans *et al.* 1993) concerning wetland losses, length of low-lying developed (and hence vulnerable) coasts and costs of dike upgrade. Land losses are not reported in the GVA, but they are provided by Bijlsma (1996) for 18 countries. The GVA reports people-at-risk, which is the number of people living in the 1 in 1000-year flood plain

[14] The model used is v. 2.8 (national resolution) of the FUND (*Climate Framework for Uncertainty, Negotiation and Distribution*) model, an integrated assessment model of a wide range of climate change impacts (Tol 2004). Here we only analyse the impacts of sea-level rise.

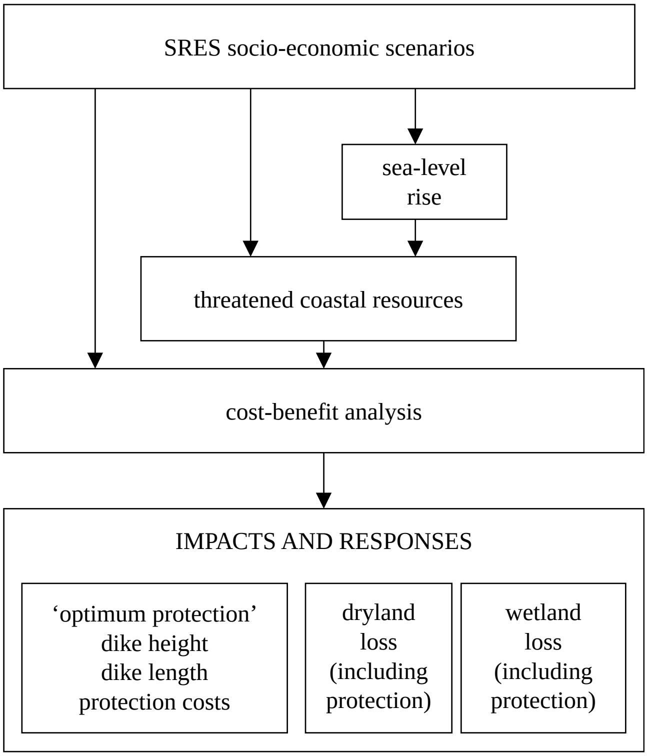

Figure 6. Summary of the sea-level rise impact assessment within the FUND model.

multiplied by the probability of flooding. Combining this parameter with the GVA's coastal population densities, allows area-at-risk to be estimated (see Tol 2004). These areas describe the developed areas that are threatened, and threatened areas with negligible population and economic activity are not included. The direct costs of sea-level rise, and the length and cost of protection are evaluated for each SRES future.

Direct cost estimates are the sum of the direct costs of adaptation and residual impacts. The GVA contains one of the first, global direct cost estimates for sea-level rise: the costs of dike building against coastal flooding assuming a 1 m global-mean rise in sea-level, allowing for variable surge magnitude (Hoozemans *et al.* 1993). It suggests that the costs of coastal protection are small compared to the GDP in most countries. However, in countries that have a long coastline relative to land area and countries that are relatively poor, coastal protection will tend to be more expensive, possibly restricting its implementation. This situation particularly applies to small and poor island nations (cf. Bijlsma 1996; Nurse & Sem 2001). Fankhauser (1994) extends the global estimates of the direct cost estimates of the GVA to the loss of land and wetlands. Again, the conclusion is that a protection response to sea-level rise will be widespread. While the data are quite uncertain, this remains the best available approach to estimate direct costs at the global scale.

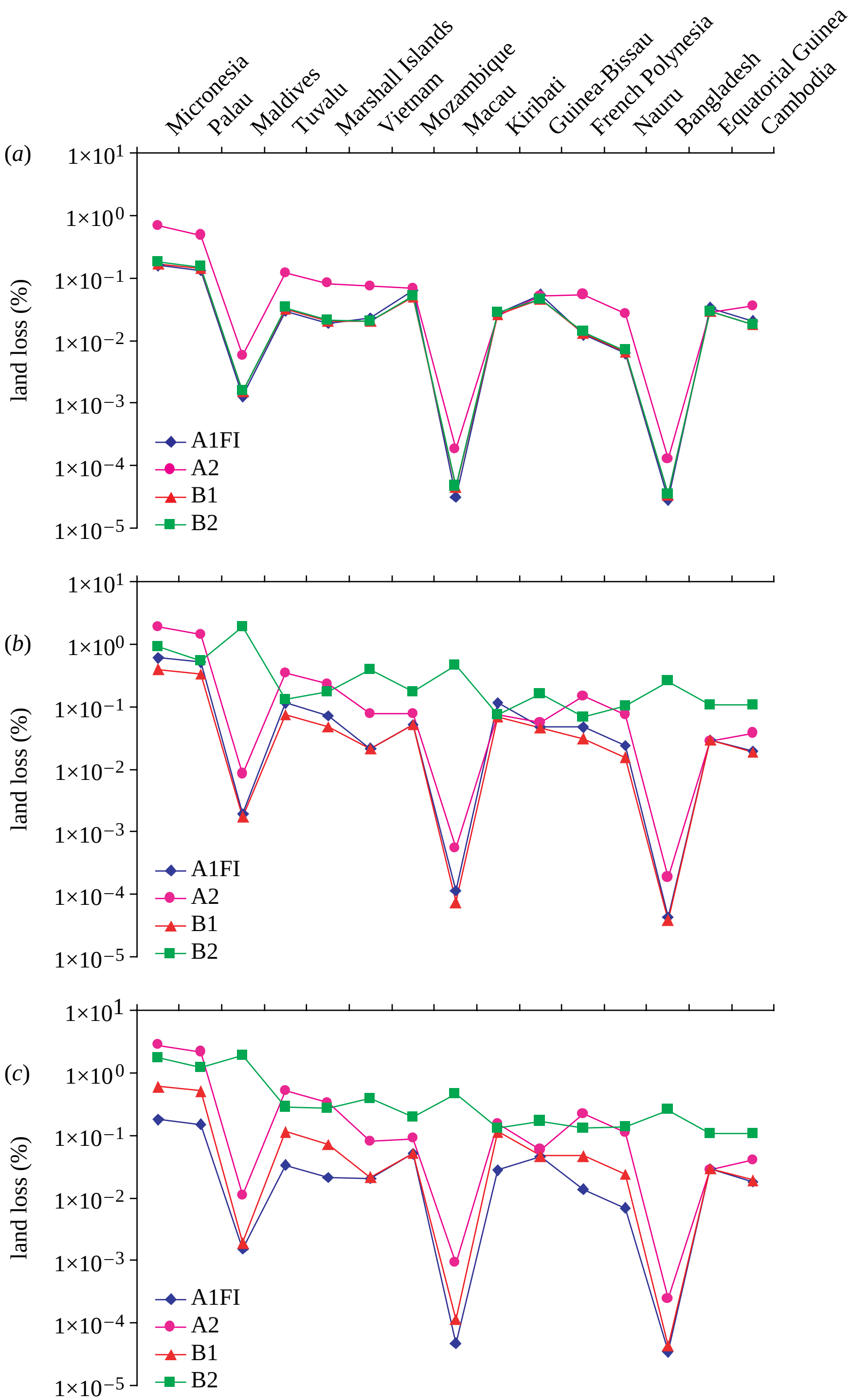

Figure 7. Land loss after considering coastal protection as a percentage of land area in 1990 for the 15 most affected countries under the four SRES worlds (A1FI, A2, B1, B2): 2020s (*a*), 2050s (*b*) and 2080s (*c*).

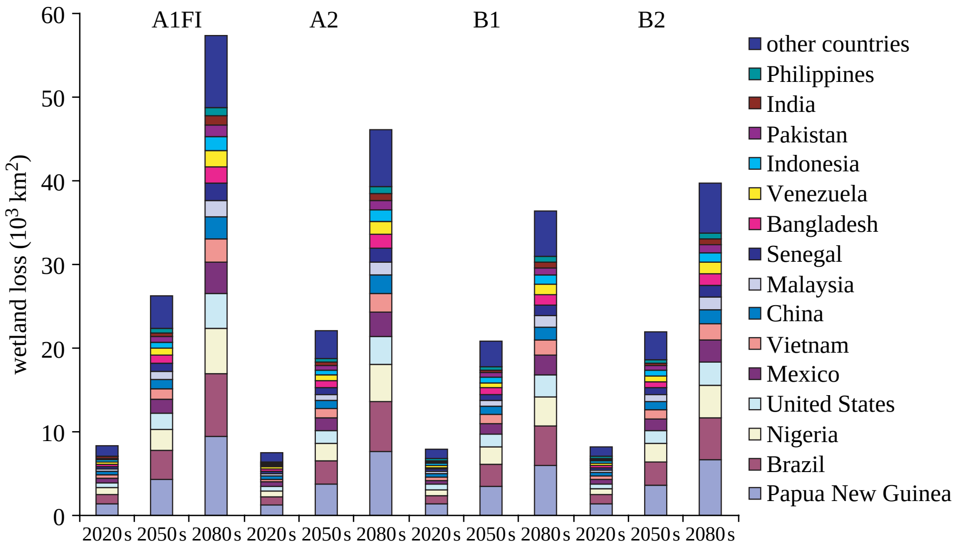

Figure 8. Global wetland losses due to sea-level rise and coastal protection in thousands of square kilometres under the four SRES worlds (A1FI, A2, B1, B2) for the 2020s, 2050s and 2080s. The losses in the 15 most impacted countries are distinguished.

In this paper, we extend the direct cost estimates of Tol (2004) for the A1B scenario[15], to direct costs per country for the A1FI, A2, B1 and B2 SRES scenarios. The model estimates land loss and wetland loss as a linear function of sea-level rise. The economic values are derived from Tol (1995), while the model of Fankhauser (1994) is used to estimate the extent of coastal protection. Essentially, coastal protection is driven by the ratio of projected and discounted protection costs and the projected and discounted land losses. Coastal protection also enhances wetland losses, due to coastal squeeze. However, wetland values are generally low in developing countries so their influence on direct costs is relatively small.

To analyse adaptation, Fankhauser (1994) selects the level of protection based on an analysis of the costs of a single coastal protection option (dike construction) and its benefits (the avoided costs of land loss). The model assesses height and length of a dike and hence its costs, using the national GVA costs. Ignoring sea-level variability and possible increases in local wave height due to increasing water depths, the optimal dike height equals the magnitude of sea-level rise. Fankhauser (1994) assumes that income and capital goods are equally distributed across the population of a country. He also assumes that there is a linear gradient in population density varying from twice the average to zero. This implies that the benefits of coastal protection are linear in population density. Fankhauser (1994) uses dynamic programming (with an analytical solution) to determine the optimal fraction of vulnerable coast to be protected. Hence, unlike the GVA or the earlier impact analyses (table 4), the protection standard is not uniform across a country.

[15] A1B has the same economic and demographic development as A1FI, but lower emissions and hence a smaller sea-level rise.

Tol (2004) combined Fankhauser's (1994) adaptation model with the land loss and wetland loss models that were just discussed. This extended form adaptation model is used here.

(a) Direct costs of sea-level rise

Figure 7 shows land loss in low-lying developed areas over time, including the effect of coastal protection, for the 15 most impacted countries. These 15 countries were selected on the basis of the relative land loss averaged over time and over scenarios. Note that they include eight small islands and three countries with large deltaic areas. In the 2020s, land loss is always less than 1%, rising to a maximum loss of 2.8% for Micronesia in the 2080s in the A2 world, which is still a modest land loss compared to the potential impacts without protection. The different scenarios become increasingly distinct over time, mainly reflecting the different socio-economics in each future, rather than the different amount of sea-level rise. The A2 world stands out for its higher impacts, even in the 2020s, reflecting that it experiences the slowest economic growth, which reduces the ability to protect. This effect is enhanced by the 2050s, and the B2 world also becomes distinct, because countries such as the Maldives and Bangladesh opt for less protection (see later). This is because these countries are less wealthy in the B2 world than in the A1FI/B1 worlds. Under the A2 world, they are even less wealthy, but sea-level rise is higher (and hence potential land losses are greater), and this threat sometimes triggers a higher degree of optimum protection in the A2 world. In the 2080s, the pattern is essentially the same, with the richest A1FI world also becoming distinct from the B1 world.

Figure 8 shows the total wetland loss, including distinguishing the losses in the 15 most impacted countries in the 2020s, 2050s and 2080s[16]. Losses increase over time, and are highest in the A1FI world (amounting to about 18% of the 1990 stock of coastal wetlands by the 2080s), because the level of coastal protection and sea-level rise are highest. The A2 world has the second highest impacts, followed by the B2 and B1 world. These impacts reflect both the magnitude of sea-level rise scenarios, and the length of protection, and are within the same range as reported by Nicholls (2004).

(b) Adaptation to sea-level rise

Figure 9 shows the optimal fraction of the coast that should be protected based on cost–benefit analysis for the 15 least protected countries, using the Tol (2004) adaptation model. For all other countries, the optimal fraction of protection approaches 100 per cent (of their low-lying developed coasts as defined by Hoozemans *et al.* (1993)—low-lying undeveloped coasts such as Arctic Russia, Canada or Alaska are assumed to be undefended). There are a few developed countries (e.g. New Zealand, Sweden) among these least protected countries, all of which have relatively long coastal lengths and low population densities. In the 2020s, the fraction of protected coast is lowest under the A2 scenario, reflecting the slowest economic growth. In the 2050s and 2080s, the A2 and B2 scenarios compete for lowest fraction of protected coast. While A2 is poorer than B2,

[16] The wetland data comes from the GVA which is an incomplete global dataset (Hoozemans *et al.* 1993; Nicholls 2004).

sea-level rise is faster and hence the need for protection is greater, as already discussed for land loss. By the 2080s, the model estimates that almost all low-lying developed coasts are optimally protected against sea-level rise in most coastal countries independent of the SRES future.

Figure 10 shows the relative costs of coastal protection, for the 15 countries that invest the largest share of their income towards coastal protection. These countries include nine small islands, and three countries with significant deltaic areas (Guyana, Mozambique and Vietnam) reflecting the higher burden that protection will mean to such settings. For most countries, the annual cost of coastal protection is below 0.1% of GDP, regardless of the time-step or scenario. The main exceptions are the low island countries of Micronesia, Palau and Tuvalu (figure 10); in Micronesia, annual protection costs are up to 0.7% of GDP by the 2080s, which represents a significant economic burden.

6. Discussion/conclusion

Before discussing the results, it is worth remembering their limitations. They are all based on national scale calculations and quite uncertain underlying datasets. Hence, the results are only meaningful in an aggregated sense: for groups of countries and the globe. Further, emphasis should be placed on the relative changes and the order of magnitude of the results, rather than focussing on numbers and their details.

The impact analysis demonstrates significant potential coastal impacts of sea-level rise due to flooding, and also shows that these impacts are sensitive to human choice in terms of mitigation of climate change or protection against sea-level rise. While climate stabilization reduces the potential impacts, stabilization alone is not a sufficient response and there is a remaining need to adapt to sea-level rise. For the SRES scenarios considered here (22- to 34-cm rise by the 2080s), the upgraded protection options have a significant potential to manage the human impacts of sea-level rise and reduce the additional impacts of sea-level rise to almost negligible levels. The A2 world consistently has the highest potential impacts even though it does not experience the largest rise in sea-level, while the B1 world has the lowest potential impacts. This shows the importance of the development pathway: worlds with higher population growth and lower economic growth will tend to be more vulnerable to coastal flooding and *vice versa*. Lastly, human-induced subsidence in susceptible coastal lowlands due to groundwater withdrawal could exacerbate the global impacts of climate-induced sea-level rise: therefore, managing subsidence in coastal lowlands is a useful strategy to reduce vulnerability to global-mean sea-level rise. This is of particular relevance to the densely populated deltas in East, South and Southeast Asia (Woodroffe *et al.* in press).

The economic analysis suggests that the optimum cost–benefit response to land loss due to sea-level rise would be widespread protection rather than abandoning populated and exposed coastal land. This suggests that for the four SRES worlds considered here, adaptation to sea-level rise will be widespread. It might be argued that the assumptions that are used are optimistic, as economic growth instantaneously translates into the potential to build dikes, and actual adaptation will be more costly than the protection options considered here as the full range of

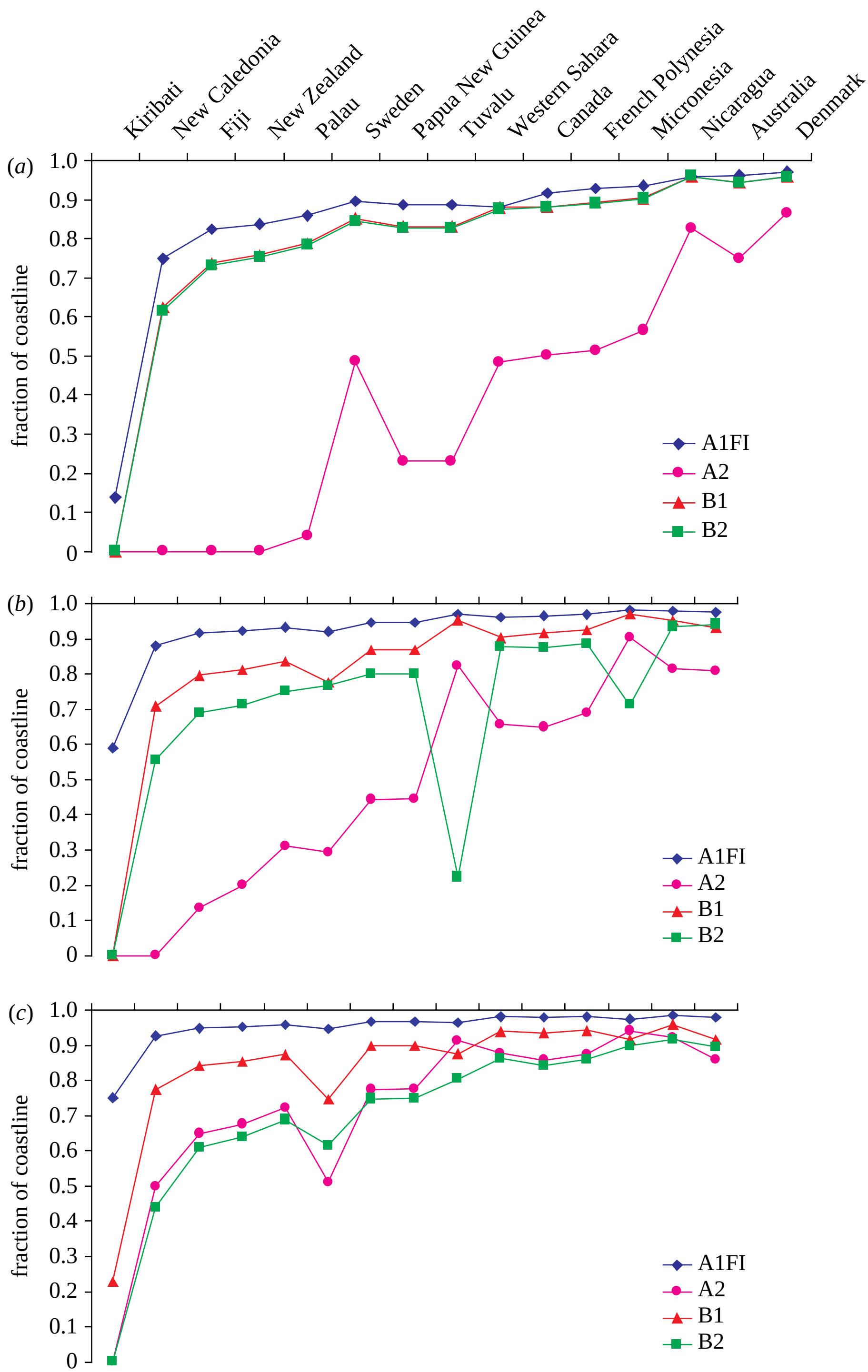

Figure 9. Model estimated optimal level of coastal protection as a fraction of the developed low-lying coastline as identified by Hoozemans *et al* (1993) for the 15 least protected countries under the four SRES worlds (A1FI, A2, B1, B2): 2020s (*a*), 2050s (*b*) and 2080s (*c*).

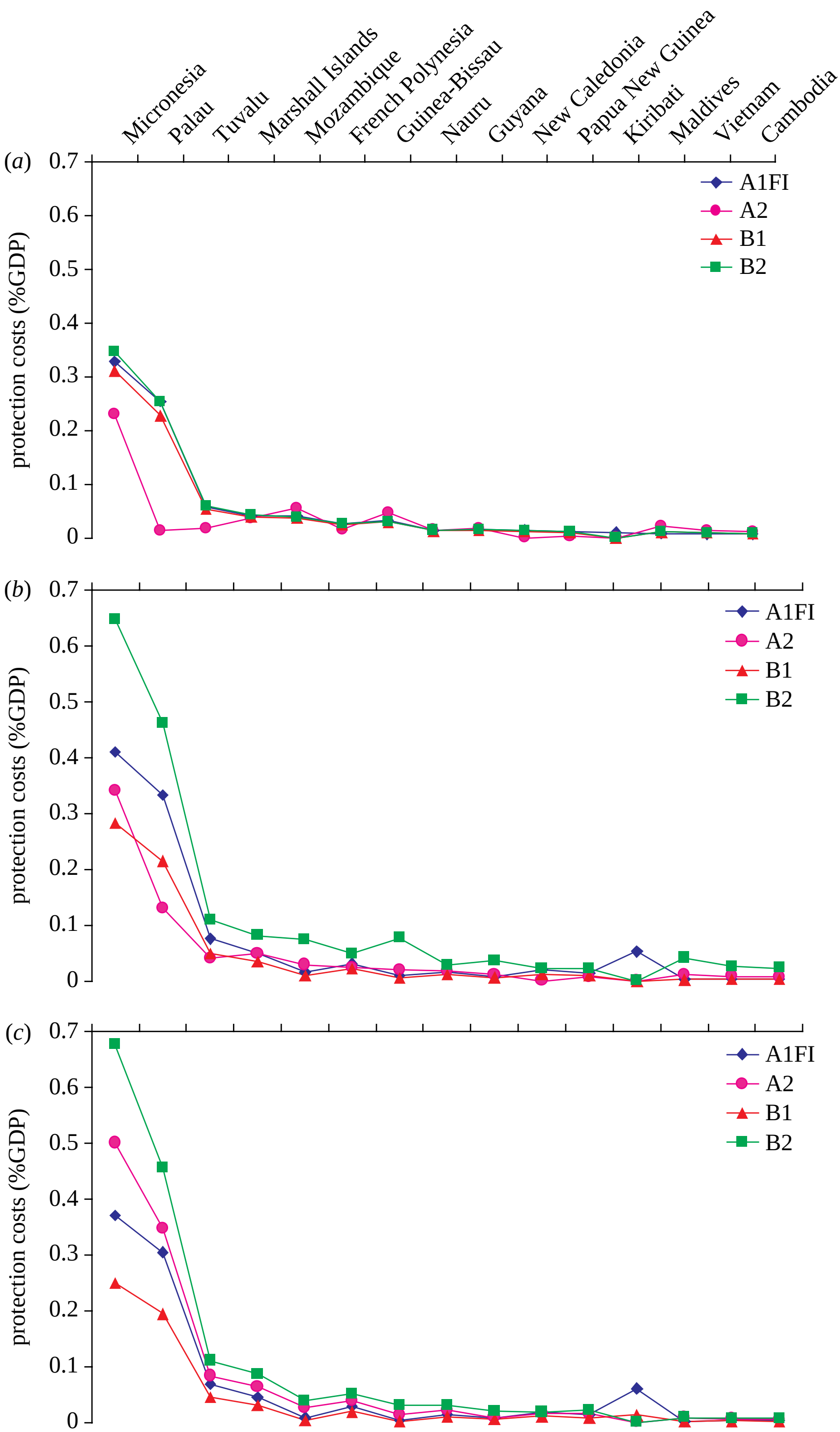

Figure 10. Protection costs as a percentage of current gross domestic product for the 15 most affected countries under the four SRES worlds (A1FI, A2, B1, B2): 2020s (*a*), 2050s (*b*) and 2080s (*c*).

impacts of sea-level rise will require adaptation (table 1). However, these deficiencies are unlikely to qualitatively change the important result that hard (and soft) protection is likely to be widespread given sea-level rise, although this will require widespread additional investment in coastal protection around the world (Tol 2004). Small island and deltaic settings appear to have the lowest capacity to adapt, reflecting their relatively small area to coastal length ratio among other factors. The relative vulnerability of these two settings has long been recognized (e.g. IPCC CZMS 1992; Bijlsma 1996). Further, the feasibility and implications of adaptation is least understood for small islands and large deltas, and the protection costs used here may be systematically underestimated compared to other coasts. Of the SRES worlds, the A2 and B2 worlds have the largest land loss as they have lowest capacity to protect, reflecting the important control of socio-economic conditions on impacts in addition to the magnitude of sea-level rise.

Coastal wetlands are threatened directly and indirectly by sea-level rise and coastal protection/squeeze. Moreover, they are also threatened by a host of other human-induced stresses (e.g. Hoozemans *et al.* 1993; Viles & Spencer 1995) and human attitudes to the environment may be more important than sea-level rise through the twenty-first century (Nicholls 2004).

Both the impact and economic analyses consider only one adaptation response (dikes) at national scales, while there are a multitude of adaptation options to sea-level rise (Klein *et al.* 2001), and decisions on which areas to protect have been found to be scale dependent (Turner *et al.* 1995). Thus, in practise, coastal management will exploit this wide range of options across the range of scales, rather than universally build dikes or do nothing. Hence, actual adaptation will vary at spatial scales below those resolved in this analysis and this requires more detailed assessment (e.g. Evans *et al.* 2004; Nicholls *et al.* in press). Thus, an expert interpretation of the economic analysis suggests that it means that coastal populations will have much more choice in their response to sea-level rise, and other coastal hazards, than is popularly assumed. This view is supported by historical experience. Several coastal megacities in Asia that subsided several metres or more during the twentieth century (representing a relative sea-level rise of the same magnitude) were all protected rather than abandoned (Nicholls 1995). Around the southern North Sea, the overall response to coastal flooding has again been massive investment in defences and a net coastal advance due to land claim (Smith & Ward 1998; French 2001). This is not to endorse such a protection approach, but to recognize the important human role in influencing coastal change and the impacts of sea-level rise (Klein & Nicholls 1999).

Returning to the competing optimistic and pessimistic views on the future with sea-level rise raised at the beginning of this paper, these results suggest that both perspectives are meaningful within our current understanding. Supporting the optimists, adaptation is likely to be widespread, and coastal populations are likely to have a range of choices given sea-level rise, especially in future worlds with favourable development pathways. However, pessimists can raise a number of cautionary warnings. The four SRES scenarios include significant economic growth across the world, even for the most adverse A2 world. Lower growth and/or greater regional differences in development, such as the continued failure of development for Africa, would almost certainly lead to more adverse situations than considered in this paper (Nicholls 2004), even if greenhouse gas emissions and hence sea-level rise was consequently reduced. Further, the process of

effective adaptation is not automatic, and presently much of the world is ignoring sea-level rise in coastal management, even in Europe (Tol *et al.* forthcoming). This suggests that adaptation could often be a reactive process to real rather than forecast events. This view of the future suggests a higher incidence of coastal impacts and disasters through the twenty-first century, than if a proactive approach was adopted. Therefore, a pathway of ultimately successful adaptation is not automatically painless, excluding the investment required for adaptation. Protection costs may have been underestimated, especially for deltas and small islands, and the potential for more extreme events, which were not evaluated here, also need to be considered. Hence, there are a diverse set of reasons for the concerns of pessimists to remain justified.

In conclusion, rather than taking sides in the debate between the optimists and the pessimists, this study shows how much more we need to know before we can really understand the consequences of sea-level rise. However, a major insight of the analysis presented here is the important choices that coastal societies face through the twenty-first century in managing the risks and responses to sea-level rise.

While this analysis may seem to be stressing adaptation as a response to coastal flooding, the results do not contradict Nicholls & Lowe (2004) and Tol (2004), who argued that stabilization and adaptation need to be considered together in coastal areas. While adaptation can deal with the relatively moderate global-mean sea-level rise scenarios considered here (less than 35 cm by the 2080s), climate stabilization would slow the rise and give more time for adaptation, including post-2080s impacts (Nicholls 2004). Most importantly, stabilization also reduces the risk of an extreme rise in sea-level due to the decline of the Greenland or Antarctica ice sheets over the twenty-first century and beyond (e.g. Tol *et al.* in press). Assessing the overall response that is required for sea-level rise (and climate change in general) remains a major challenge.

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