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Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of *FUND*

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Abstract The threat of an abrupt and extreme rise in sea level is widely discussed in the media, but little understood in practise, especially the likely impacts of such a rise including a potential adaptation response. This paper explores for the first time the global impacts of extreme sea-level rise, triggered by a hypothetical collapse of the West Antarctic Ice Sheet (WAIS). As the potential contributions remain uncertain, a wide range of scenarios are explored: WAIS contributions to sea-level rise of between 0.5 and 5 m/century. Together with other business-as-usual sea-level contributions, in the worst case this gives an approximately 6-m rise of global-mean sea level from 2030 to 2130. Global exposure to extreme sea-level rise is significant: it is estimated that roughly 400 million people (or about 8% of global population) are threatened by a 5-m rise in sea level, just based on 1995 data. The coastal module within the *Climate Framework for Uncertainty, Negotiation and Distribution (FUND)* model is tuned with global data on coastal zone characteristics concerning population, land areas and land use, and then used for impact analysis under the extreme sea-level rise scenarios. The model considers the interaction of (dry)land loss, wetland loss, protection costs and human displacement, assuming perfect adaptation based on cost-benefit analysis. Unlike earlier analyses, response costs are represented in a non-

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linear manner, including a sensitivity analysis based on response costs. It is found that much of the world's coast would be abandoned given these extreme scenarios, although according to the global model, significant lengths of the world's coast are worth defending even in the most extreme case. This suggests that actual population displacement would be a small fraction of the potential population displacement, and is consistent with the present distribution of coastal population, which is heavily concentrated in specific areas. Hence, a partial defence can protect most of the world's coastal population. However, protection costs rise substantially diverting large amounts of investment from other sectors, and large areas of (dry)land and coastal wetlands are still predicted to be lost. Detailed case studies of the WAIS collapse in the Netherlands, Thames Estuary and the Rhone delta suggest greater abandonment than shown by the global model, probably because the model assumes perfect implementation of coastal protection and does not account for negative feedbacks when implementation is imperfect. The significant impacts found in the global model together with the potential for greater impacts as found in the detailed case studies shows that the response to abrupt sea-level rise is worthy of further research.

1 Introduction

Low probability, high impact climate-induced events have been used in climate policy and climate policy advice to argue for stringent greenhouse gas emission reduction. Examples of such events include the shutdown of the thermohaline circulation, the release of methyl hydrates from the deep ocean, or the collapse of the West-Antarctic Ice Sheet (WAIS). In most cases, the "high impact" is known in physical terms, but human dimensions are essentially speculative. Taking the WAIS collapse example, it will impact coastal areas where average population densities are highest and there is a concentration of urban areas (Small and Nicholls 2003), so there is clearly a high impact potential. Conventional wisdom often assumes universal coastal abandonment under such a scenario, but prior to the Atlantis Project,[1] this has only been systematically investigated in two national-scale national assessments (Schneider and Chen 1980; Rijkswaterstaat 1986). In this paper, we attempt a first estimate of the global impacts of a WAIS collapse in an integrated analysis of dryland[2] loss, wetland loss, coastal protection, and human displacement. These results are then compared to the outcomes of the three detailed European case studies (Olsthoorn et al. 2008; Lonsdale et al. 2008; Poumadere et al. 2008).

Any global analysis is an ambitious goal, and we do not claim to have gone beyond a first, crude estimate of the order of magnitude of change. The goal is so ambitious because the conventional methods of climate change impact analysis breakdown under large changes such as the impact of a 5-m sea-level rise (Nicholls et al. 2006). A 1-m sea-level rise, the maximum scenario considered in the vast majority of studies, can be considered as a marginal change, not in the sense of not being important, but in the formal, mathematical sense of the word. That is, a 1-m sea-level rise would perturb the current situation, and the size of the perturbation can be studied with an essentially linear model. On the other hand, a 5-m rise of sea level would have impacts that extend beyond the coastal zone, and alter the coastal zone in a dramatic manner. For instance, the analysis of Olsthoorn et al. (2008)

[1] The Atlantis project was a collaborative European project. It aimed to estimate the impact of extreme sea-level rise. The current paper and several others in this special issue report on the results.

[2] Henceforth dryland loss is simply referred to as land loss

suggests that the harbour of Rotterdam (and by implication the harbours of Antwerp and Bremen) may be abandoned under a 5-m sea-level rise, which would radically change transport patterns in the whole of Western Europe. In contrast, a 1-m sea-level rise would increase costs in Rotterdam Harbour, but would not fundamentally affect its operations, and its competitors are similarly affected.

In this paper, we approach this problem in two distinct ways. Firstly, we examine the basic data on exposure to sea-level rise. Whereas a 1-m sea-level rise has about twice the impact potential as a 0.5-m sea-level rise, a 5-m sea-level rise does not have ten times the impact potential. Using a recent digital elevation model, we estimate population distribution up to 10 m elevation. Secondly, we take an existing model of the costs of coastal protection and made it non-linear. This immediately affects the associated model of the level of coastal protection, which is now also non-linear. We do not pretend that these two changes solve all problems, but the work presented below is more than a simple extrapolation of previous work for smaller rises in sea level to a 5-m rise.

To our knowledge, this is the third paper analysing the impacts of a 5-m sea-level rise and the first to consider global impacts. The first paper (Schneider and Chen 1980) is based on now outdated methods and observations and only considers the United States. The method used also only considers exposure based on elevation. The second paper (Rijkswaterstaat 1986) is limited to the Netherlands; its methods are more advanced than those of Schneider and Chen (1980), and it concludes that the Netherlands could be maintained in the face of 5-m sea-level rise over 200 years (see Olsthoorn et al. 2008). Note that there are numerous previous results for global impacts of sea-level rise up to a 1-m rise scenario (e.g., Hoozemans et al. 1993; Fankhauser 1994; Nicholls 2004; Tol 2007; Nicholls and Tol 2006), and some national results for impacts up to a 2-m rise scenario (e.g., Titus et al. 1991; Nicholls and Leatherman 1995a).

The paper proceeds as follows. In “Section 2”, we briefly survey the Literature on the West-Antarctic Ice Sheet and its possible collapse. In “Sections 3 and 4”, we describe the potential exposure of land, population, gross domestic product (GDP) and land use to extreme sea-level rise scenarios. In “Section 5”, we present the impact model and its modifications for nonlinear impacts under extreme sea-level rise. In “Section 6”, we discuss the impact results, while “Sections 7 and 8” discusses the overall results and concludes.

2 Previous literature

The WAIS comprises about 10% by volume of the entire Antarctic ice sheet, and in volume is equivalent to a 5- to 6-m rise in sea level (Vaughan and Spouge 2002; Oppenheimer and Alley 2004; Overpeck et al. 2006). It is maintained by a balance of precipitation across the sheet, and seaward flow across the ice sheet, to the floating ice shelves. Here there is melting on the underside of the ice shelf, or iceberg calving at the periphery. Mercer (1978) caught the attention of policymakers when he speculated that human-induced global warming could cause the ice shelves of West Antarctica to disintegrate during the 21st Century, allowing the ice sheet to be catastrophically released into the ocean by a sliding mechanism (see also Oppenheimer 1998). This would raise global-mean sea level by displacement alone, and there is no requirement for the ice to melt. Thus, the resulting rise could be much faster than for example the loss of the Greenland ice sheet, which would require melting of the ice to raise sea level, taking many hundreds or even thousands of years (Gregory et al. 2004). (Note that the WAIS would also take a long time to melt, hundreds or thousands of years, even if the ice were floating). Recent observations of the break up of smaller ice shelves in Antarctica have maintained concern about WAIS collapse (Oppenheimer and Alley 2004).

Having established this risk, there was widespread concern about the likelihood of extreme sea-level rise, and the maximum rate of rise that might be possible (see Kasperson et al. 2005 for a more detailed review). There are widely divergent views ranging from considering the mechanism to be almost impossible, to expectations that WAIS collapse may begin in the 21st Century, with WAIS collapse being strongly equated to 'dangerous climate change' (Smith et al. 2001; Oppenheimer and Alley 2004). Vaughan and Spouge (2002) recently conducted a formal risk assessment of the WAIS collapse, including using a Delphi technique and a panel of experts to explore these uncertainties and estimate the resulting risk. The complexity of the collapse mechanism is captured in their Fig. 2, illustrating the range of processes of interest when trying to understand WAIS collapse. They concluded that there is a 5% probability of the WAIS causing a sea-level rise of at least 10 mm/yr (or 1 m/century) within 200 years. In terms of total rise due to the WAIS contribution, they estimated a 5% probability of a rise greater than about 0.5 m by 2100 (averaging 0.5 m/century), about 2.3 m by 2500 (averaging 0.46 m/century), and about 3.2 m rise by 4000. Hence, none of these estimates equate to a total WAIS collapse. Kasperson et al. (2005) also emphasizes the uncertainties and disagreements between experts that the Vaughan and Spouge analysis reveals.

The goal of the Atlantis Project was to examine an extreme scenario, and especially to understand the societal response to such an extreme change. Given the current status of scientific knowledge, including discussions with relevant glaciologists, the total collapse of the WAIS in relatively short time scales of 100 to 200 years cannot presently be stated as impossible. Given the limited resources available for the three detailed case studies, it was decided that we would learn most about the response by considering the most extreme scenario—a 5-m rise in 100 years due to the WAIS collapse. The scenario was kept deliberately simple and was applied linearly from 2030 for all the three case studies. In 2130, the rise ceases, as abruptly as it began. Even if this extreme Atlantis scenario were demonstrated to be totally impossible, the intellectual exercise of thinking through an extreme scenario to impacts and especially responses has been very valuable and informative, both for coastal impacts and more generally to understanding extreme climate change (Tol et al. 2006). This might be an important lesson to others studying extreme climate change.

Unlike the detailed case studies in the rest of the project, the model-based global analysis was able to explore a much wider range of scenarios of WAIS contribution to sea-level rise, ranging from a 0.5 up to a 5 m/century scenario, with a maximum contribution of 5 m from the WAIS in all cases.

3 Exposure analysis

3.1 Data sources

The exposure analysis was based on a series of global datasets on population (two data sets), elevation, tidal range and administrative unit boundaries. These data sources are now discussed in turn.

3.1.1 Population data

The Gridded Population of the World, version 3 (GPW3; CIESIN and CIAT 2004) and Landscan (2003; see also Dobson et al. 2000) were compared in the analysis, as there are considerable uncertainties in such data (e.g., Small and Nicholls 2003). The LandScan dataset is a worldwide population database compiled on a 30×30 arc sec latitude/longitude grid (about 1 km at the equator). Census counts (at sub-national level) were apportioned to each grid cell based on likelihood coefficients derived from a series of variables such as proximity to roads, slope, land cover, night time lights, and other data.

The GPW3 is the latest update of the GPW dataset: earlier versions have been extensively employed in a range of global population studies (e.g., Cohen et al. 1997; Small and Nicholls 2003). GPW adopts a simple population distribution algorithm gridded at the same scale as Landscan, but putting more emphasis on the collection of the input data rather than modelling distributions (Nelson and Balk 2003).

3.1.2 Elevation data

The elevation dataset that was employed is the Shuttle Radar Topography Mission 30 (SRTM30) Enhanced Global Map developed by ISciences (2003). The dataset has a *spatial* resolution of 30 arc sec (around 1 km at the equator) and is based on the raw data acquired from the SRTM, which cover 80% of the earth's land surface at a 3 arc sec resolution. These data were supplemented with elevation data from the *GTOPO30 digital elevation model* (*30 arc sec resolution*) for land areas that are *not* covered in the SRTM30 dataset and also with ocean bathymetry data from ETOPO2 (*2 min spatial resolution*) *to create the SRTM30 enhanced global dataset.*

The nominal vertical accuracy of the original SRTM 3-arc-sec data is 16 m. However, vertical accuracy of the dataset has a considerable spatial variation depending on parameters such as terrain elevation and aspect and the resolution of the employed dataset. Accuracy issues are explained in detail by Rodriguez et al. (2005) who also present maps of the spatial distribution of accuracy of the SRTM elevation dataset. From these maps it can be seen that accuracy of the dataset is considerably higher in coastal regions. For this reason, the SRTM data were used for terrain analysis after the 2004 tsunami in Southeast Asia (Blumberg et al. 2005). Furthermore, Gorokhovich and Voustianiouk (2006) found significantly higher accuracies than the nominal 16 m when comparing SRTM data with field data in the US and Thailand.

Considering the quality of the original data, the enhancements and the corrections that have been made and the uncertainties associated with global datasets of moderate resolution, the elevation data employed in the present study is one the best available datasets for producing a first-order indicative assessment of the impacts of a large rise in sea level.

3.1.3 Tidal range data

The tidal range dataset is a 1-degree resolution global dataset compiled according to the small-scale map of Davies (1980) containing a global overview of tidal range classes. The data used is derived from the Land Ocean Interactions in the Coastal Zone typology dataset (Maxwell and Buddemeier 2003). Tidal range is presented as five classes, which were interpreted as average tidal range values and hence high water (tidal range/2).

3.1.4 Administrative unit boundaries

The Geographic Information System (GIS) dataset of 1095 first-level subnational administrative boundaries that is included in the Digital Chart of the World (DCW) was employed in the present study (ESRI 2002; Deichmann et al. 2001). The DCW has been partially employed for the generation of the GPW3, which ensures consistency in our analysis.

3.1.5 Land use data

Land use was derived from a dataset that was developed by the IMAGE Team (2002). This dataset contains the global distribution of 19 principal land use types at 0.5°×0.5° resolution.

3.2 Data processing and analysis

Data processing was performed within a GIS, which provided the environment for the storage, the spatial analysis and the cartographic display of the geo-referenced datasets. Zonal statistical functions and data overlays were employed within the context of the spatial analysis that was performed in a series of steps. This included defining the population and land use by elevation up to 10-m above mean sea level. Then potential impacts defined relative to high water were considered. In the first step average tidal range values were estimated for all coastal administrative units. Then, based on these values and using the elevation dataset, land loss as a function of sea-level rise was calculated for each administrative unit and for two scenarios of sea-level rise: a 1- and 5-m rise scenario, respectively. In this step, low-lying inland areas and water bodies were masked out. In the final step, resident coastal population counts for the areas lost were estimated using the GPW3 and Landscan datasets.

4 Results

Figure 1 shows key aspects of the global exposure to sea-level rise as a simple function of elevation above mean sea level. This includes the land area, the population, and their total income (measured at market exchange rates (MER) as well as at purchasing power parity (PPP)). Given the large uncertainties in the input global datasets, it is important not to over-interpret the results, and they should only be considered indicative (Small and Nicholls 2003). The distributions are broadly linear up to a 10-m rise, with the exception of land area which increases more rapidly from 0- to 1-m elevation, probably reflecting coastal wetlands and areas of land claim which both tend to be concentrated near mean sea level. The GPW3 and Landscan data are remarkably similar—Landscan estimates a larger population below 10-m elevation. (However, if we had used GPW2, then the exposure would have been estimated as much higher.) Economic exposure is less when measured in MER than in PPP, indicating that a substantial part of the exposure is in developing countries.

Figure 2 shows the exposed land area again, but this time split up by land use. The exposed area consists mostly of agricultural land, boreal forest, and tundra. Residential areas only make a small contribution to the exposed area. Note that given the coarse resolution of the IMAGE data, these results are again indicative. Based on more detailed data, 20 out of 30 of the world's biggest cities are threatened and there is a concentration of smaller cities in vulnerable locations (Small and Nicholls 2003).

Table 1 shows the *minimum* impact given a 1- and 5-m sea-level rise on area, population and total income assuming no coastal protection. These impacts are based on change relative to high water and hence are larger than those in Fig. 1. It is assumed (reasonably) that all assets and population in this area are lost or forced to move. These estimates are minimum as they

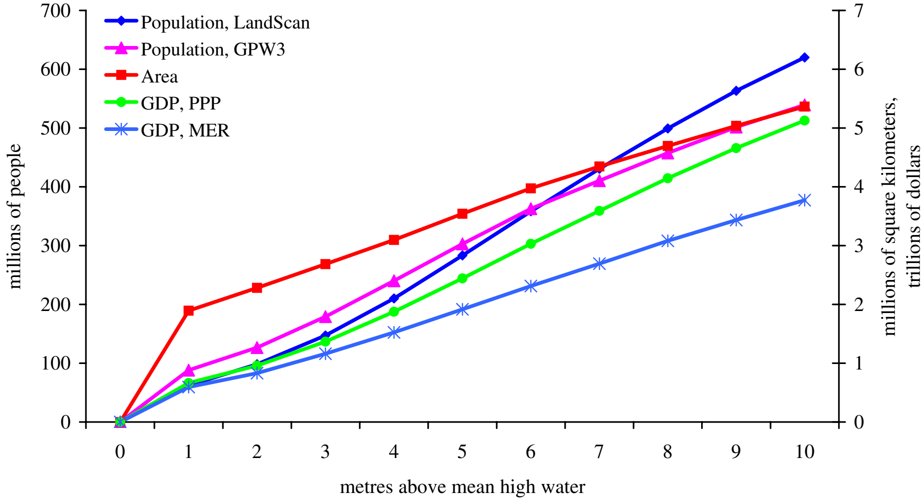


Fig. 1 Population, land area and GDP as a function of elevation above mean sea level, based on 1995 data

only consider the impacts below high water and there would be additional potential impacts above high water, as mentioned below. The data suggests that area is less than linear, GDP slightly less than linear, and population more than linear as a function of sea-level rise.

5 The impact model

The impact model considers impacts taking account of coastal protection, and uses version 2.8n of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.8n is different in many ways from previous versions. However, in this paper, only

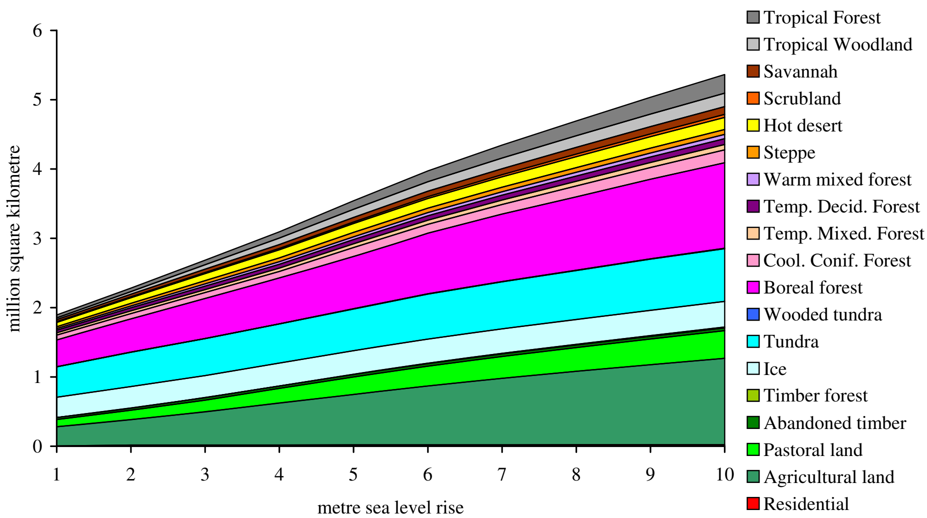


Fig. 2 Land area by land use type, as a function of elevation above mean sea level, for 1995 data

Table 1 The global exposure of population, land area and total income as a function of sea-level rise, calculated relative to high water

	1-m rise	5-m rise
Population (millions)	131	410
Land area (thousand Km^2)	2,463	4,107
GDP, N, MER (billions US $)	1,015	2,425
GDP, R, MER (billions US $)	1,009	2,482
GDP, N, PPP (billions US $)	1,132	2,959
GDP, R, PPP (billions US $)	1,239	3,342

Based on 2000 data

coastal impacts are considered as described in Tol (2002a, b). The essential features are outlined below. Version 2.8n differs from version 2.8 (Link and Tol 2004) in that version 2.8n resolves 207 countries; while version 2.8 has only 16 aggregated regions.

Essentially, *FUND*2.8n consists of a set of exogenous scenarios on which impacts are calculated. The model from 1995 to 2100 in time steps of 5 years. Population and economic growth follow the *FUND* scenario, which is close to the IS92a scenario (Leggett et al. 1992). Carbon dioxide concentrations, global mean temperature and sea-level rise are calculated with the *FUND*2.8 model (Link and Tol 2004).

In this paper, the following impacts of sea-level rise are considered: (1) land loss, (2) wetland loss, (3) protection costs, and (4) forced migration, all assuming perfect adaptation based on cost-benefit analysis. These impacts interact with one another. For example, if land were fully protected, no land would be lost, but the associated costs of protection would be maximised, and any adjacent wetlands experience greater losses due to coastal squeeze. The total impact of sea-level rise depends on the adaptive policy chosen, and hence so does the estimated damage. For instance, Hoozemans et al. (1993) uses the ad hoc rule that all land with a population density above ten people/km^2 will be protected, while Fankhauser (1994, 1995) and Yohe et al. (1995, 1996) employ models which choose the economically optimal level of protection. The resulting difference in estimated impacts and response costs can be substantial.

As this is an exploratory analysis, only the direct submergence/land loss effects of sea-level rise are considered. There are a number of other impacts of sea-level rise, including increased flood risk and saltwater intrusion (McLean et al. 2001), which may have significant additional impacts to those considered here.

The coastal length of all countries in the world was taken from the Global Vulnerability Assessment (GVA; Hoozemans et al. 1993). Other sources, such as the World Coast 1993 Conference (Bijlsma et al. 1994; Nicholls and Leatherman 1995a, b) and Fankhauser (1995), use (occasionally widely) different estimates of the length of the coast of particular countries. However, the length of a coast depends on the measurement procedure. The GVA is based on an internally consistent, globally comprehensive data-set, and is used here.

Wetland losses for a 1-m sea-level rise were taken from the GVA and, where available, replaced with results from country studies as reported by Bijlsma et al. (1996) plus Nicholls and Leatherman (1995a, b). The GVA reports wetland losses both with and without coastal protection; the country-specific ratio between the two was used to derive wetland losses with protection according to Bijlsma et al. (1996). Without coastal protection, following the GVA, wetland loss is assumed to be linear in sea-level rise, albeit it with a cap on total wetland loss. While the resulting wetland model is simple and based on incomplete data, it is well understood and hence used in this exploratory analysis. However, it may well be that the actual wetland response to sea-level rise is non-linear (e.g., McFadden et al. 2007), and our model results may be biased towards smaller losses.

Land losses are not reported in the GVA, but they are provided by Bijlsma et al. (1996) for 18 countries. The GVA reports people-at-risk, which is the number of people living in the one-in-1,000-year flood plain, weighted by the probability of flooding. Combining this parameter with the GVA's coastal population densities, allows area-at-risk to be estimated. The exponential of the geometric mean of the ratio between area-at-risk and land loss derived from the data in Bijlsma et al. (1996) was used to extrapolate land loss for all other countries. This procedure is more reliable than using a DEM, as the GVA includes more than just elevation in its (implicit) estimate of area-at-risk. In the GVA, without protection, land loss is assumed to be linear in sea-level rise. Here, we use a power function, $D=\alpha S^{\beta}$; α is such that the impacts are as in the GVA for $S=1$; β is estimated, for each country individually, from the data presented in "Section 4". On average, $\beta=0.39$, but it ranges from $\beta=0.00$ in Monaco and Nauru, where there is little land between 1 and 5 m, to $\beta=1.72$ in the Lebanon, where there is little land below 1 m.

The monetary value of the loss of 1 km^2 of land was on average \$4 million in Organisation for Economic Co-operation and Development (OECD) countries in 1990 (cf. Fankhauser 1994). Land value is assumed to be proportional to GDP per square kilometre. Wetland losses were valued at \$2 million per km^2 on average in the OECD in 1990 (cf. Fankhauser 1994). The wetland value is assumed to have logistic relation to per capita income, that is, it increases more than proportional to economic growth at low income levels, it is roughly linear in per capita income at the OECD average, and it grows only slowly at higher income levels.

Land loss is assumed to lead to forced migration, which is a major concern under scenarios of large rise in sea level, including WAIS collapse. Following Tol (1995), forced migration equals area lost times population density.

Coastal protection *against sea-level rise* is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze. The aim is to minimise the net present costs of dike building minus the costs of land loss. The level of protection is derived by Fankhauser (1994):

$$L_{c,t} = \min\left\{0, 1 - \frac{1}{2}\left(\frac{PC_{c,t} + WL_{c,t}}{DL_{c,t}}\right)\right\} \tag{1}$$

L is the fraction of the coastline of country c to be protected at time t. PC is the net present value of the protection if the whole coast were protected, and WL is the net present value of the wetlands loss due to protection. DL is the net present value of the land lost if there were no protection. Equation 1 thus balances the costs of protection (incl. wetland loss) with the costs of land lost. It is based on the following assumptions:

- Coastal protection decision makers *anticipate* a linear sea-level rise and linear land loss, even though these are not linear in actuality; if the anticipation were based on a non-linear model, Eq. 1 could not be written explicitly as a function, but would become the solution to a numerical optimisation problem;
- Dikes are raised just as high as sea-level rise (*i.e.* storms are ignored);
- Coastal protection is implemented without a lag, and dikes are raised every year;
- The gradient of population density is linear;
- Coastal protection comprises large infrastructural works which have a life of decades; and
- Considered costs are direct investments only, and the relevant technologies are mature.

Without these assumptions, the minimisation problem cannot be solved analytically, and we would have to resort to computationally-expensive numerical optimisation instead.

Throughout the analysis, a pure rate of time preference, ρ, of 1% per year is used. The actual discount rate lies thus 1% above the growth rate of the economy, g. The net present costs of protection PC thus equal

$$PC_{c,t} = \sum_{s=t}^{\infty}\left(\frac{1}{1+\rho+g_{c,t}}\right)^{s} P_c = \frac{1+\rho+g_{c,t}}{\rho+g_{c,t}} P_c \tag{2}$$

where P is the average annual costs of protection. The average annual costs are taken from the GVA. Again, the GVA assumes linearity. Because protection costs are at the heart of Eq. 1, we replace this with a bilinear equation: If sea-level rise were less than 1 cm per year, protection costs would be as the GVA; if not, they are ten times as high.

WL is the net present value of wetlands loss due to full coastal protection. Land values are assumed constant, reflecting current preferences about the value of non-marketed services and goods. The amount of wetland loss is assumed to increase linearly over time. The net present costs of wetland loss *WL* follow from

$$WL_{c,t} = \sum_{s=t}^{\infty} s\left(\frac{1}{1+\rho+g_{c,t}}\right)^{s} W_{c,t} = \frac{1+\rho+g_{c,t}}{\left(\rho+g_{c,t}\right)^{2}} W_{c,t} \tag{3}$$

where W denotes the value of wetland loss in the year of decision.

DL denotes the net present value of the land loss if no protection takes place. Land values are assumed to rise at the same pace as the economy grows. The amount of land loss is assumed to increase linearly over time. The net present costs of land loss *DL* are

$$DL_{c,t} = \sum_{s=t}^{\infty} s\left(\frac{1+g_{c,t}}{1+\rho+g_{c,t}}\right)^{s} D_{c,t} = \frac{\left(1+\rho+g_{c,t}\right)}{\rho^{2}} D_{c,t} \tag{4}$$

where D is the value of land loss in the year of decision.

The population and per capita income scenarios used are the *FUND* scenarios as shown up to 2300 in Table 2 (Link and Tol 2004). These projections are for 16 world regions. Population change and per capita growth were assumed to be uniform for all countries within a region.

Using the population and economic scenarios, as well as the corresponding scenarios on technological progress, the full *FUND* model, version 2.8,[3] was used to generate scenarios of climate change and sea-level rise. CO_2 concentrations rise to 870 ppm by 2100, the global mean temperature is 3.5°C above pre-industrial levels, and the global-mean sea level rises by 66 cm above 1990 levels.

For the WAIS collapse, we assume a wide range of scenarios ranging upwards from an additional contribution of 0.5 m/century up to the most extreme scenario of an additional sea-level rise of 5 m between 2030 and 2130. For the other scenarios, we do not vary the start date for the WAIS collapse, but move the end date of the 5-m rise to 2130, 2230, 2330, 2430, 2530 and 3030, respectively. For comparative purposes, the IS92a scenario is also shown. Figure 3 shows the assumed scenarios of global-mean sea-level rise, allowing for both the WAIS and other sea-level contributions. While the probability of these events remains poorly defined, the additional contribution of 0.5 m/century has a roughly 5%

[3] That is, the version with 16 regions rather than 207 countries.

Table 2 Scenarios for population (millions) and per capita income (Y/C, in 1995 US dollars) per region[a]

	USA	CAN	WEU	JPK	ANZ	EEU	FSU	MDE	CAM	SAM	SAS	SEA	CHI	NAF	SSA	SIS	World
Population																	
2000	278	31	387	174	20	125	291	237	129	352	1366	522	1311	143	636	46	6048
2050	299	34	396	218	27	127	294	461	189	507	2234	842	1649	306	1389	65	9037
2100	295	33	392	226	27	126	290	544	203	546	2633	993	1709	401	1816	70	10304
2150	295	33	392	226	27	126	290	545	203	546	2640	996	1709	405	1834	70	10337
2200	295	33	392	226	28	126	290	545	203	546	2640	996	1709	405	1833	70	10337
2250	295	33	392	226	28	126	290	545	203	546	2640	996	1709	405	1833	70	10337
2300	295	33	392	226	28	126	290	545	203	546	2640	996	1709	405	1833	70	10337
Y/C																	
2000	37406	26032	32496	49011	22300	3256	2162	2586	3008	3838	608	2096	2733	1490	475	1196	6981
2050	83217	57794	72694	110032	48630	13976	9599	7980	9302	11826	2146	7741	13154	4513	1446	4015	14786
2100	140136	99333	121566	187363	86444	32222	21538	26719	30773	38656	7057	25248	50002	14150	4662	13443	32350
2150	197437	140576	170191	267487	123481	49706	31145	56628	64542	81337	14762	52478	101183	27891	9562	27586	57268
2200	263285	188182	224431	360243	159179	71857	41255	91094	103483	132701	23650	84005	149672	42311	15155	41586	84316
2250	351336	251939	296173	483124	211250	98722	52128	138521	157419	206432	36013	128327	208417	62146	23016	58757	120095
2300	470014	337970	392745	647690	280536	129524	63797	191204	217571	291277	49849	178390	266268	83995	31889	75871	160814

The regions are the USA; Canada; Western Europe; Japan and South Korea; Eastern Europe; former Soviet Union; Middle East; Central America; South America; South Asia; Southeast Asia; China, Mongolia and North Korea; North Africa; Sub-Saharan Africa; and Small Islands States.

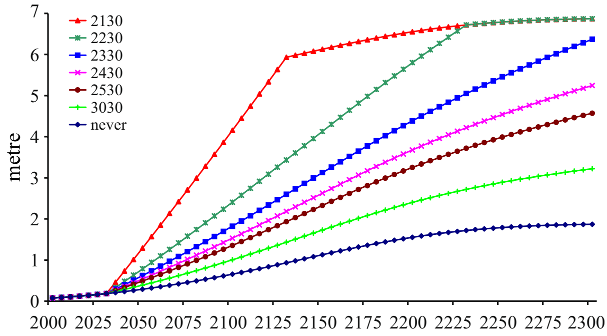


Fig. 3 The global-mean sea-level rise scenarios used in the analysis, including the baseline IS92a scenario without any significant contribution from Antarctica

chance during the 21st Century according to Vaughan and Spouge (2002), and the larger rises are less likely.

In all cases, calculations deliberately proceed beyond the arbitrary time limit of 2100 to the year 2300, so that we can see the complete response, at least for some of the more extreme scenarios.

6 Impact results

Figure 4 shows the fraction of the global coast that is protected for each scenario of sea-level rise. As soon as sea-level rise accelerates in 2030, the length of the world's coast that is protected declines from about 85% to about 50% of the exposed and populated coastline, reflecting that protection becomes too expensive in many areas. The threshold of sea-level rise to trigger higher protection costs is exceeded at the same time for all the WAIS collapse scenarios, except for the slowest scenario in which the collapse takes 1,000 years. As soon as the WAIS collapse ceases, the rate of sea-level rise slows dramatically, and the length of coastline that is economic to protect returns to the fraction that it was before the WAIS collapse. However, this does not imply that the lost land would be reclaimed; rather, the new inland coastal position would be protected. In the slowest WAIS collapse scenario, the rate of sea-level rise does not immediately rise above 1 cm/yr, and then falls below the same threshold shortly after 2200. Given the assumptions on protection costs used in this analysis, this strongly influences the predicted protection response.

Figure 5 shows the global costs of coastal protection as a function of time. Despite the drop in length of coast that is protected (cf. Fig. 4), the overall protection costs rise

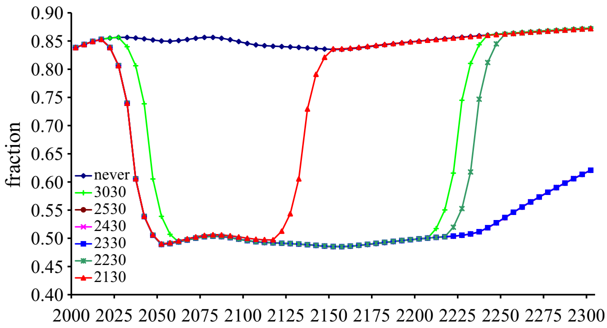
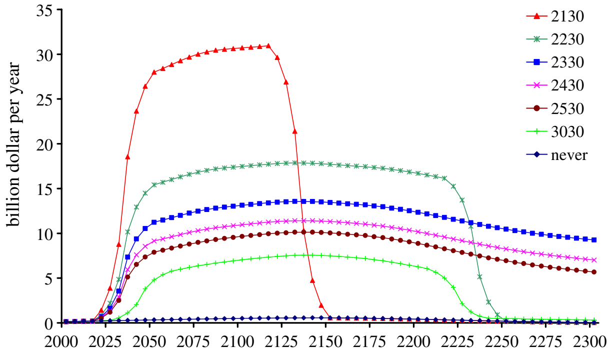


Fig. 4 The fraction of coastal protection of exposed and populated coasts at the global scale as a function of time and WAIS scenario

Fig. 5 The global annual costs of coastal protection as a function of time and WAIS scenario



dramatically in the largest scenario (by 15 times in 2100), and increase significantly even in the scenarios where the WAIS collapse takes 500 or 1,000 years. Thus, while the model suggests that it is beneficial to protect many coastal areas, this will be at the expense of other investment. In the slowest WAIS collapse scenario, the slower rate of sea-level rise influences the overall cost of defences, for the same reasons as outlined above. While the purpose of this analysis is not a national-scale view, it is worth noting that in a few cases, national protection costs are forecast to consume large proportions of national GDP (>1% GDP; 5% of investment). Hence, while it is economically rational to protect – the alternative would be an even greater loss—the burden may be more than the economy can bear (cf. Fankhauser and Tol 2005). The most vulnerable countries are general small island or deltaic nations, while African countries stand out due to the relative size of the economy.

Figure 6 shows the model estimates of cumulative land loss. Because sea-level rise is much faster, and the length of protected coast falls, land losses are much higher with a WAIS collapse than without this change. If it would take 1,000 years for the WAIS to collapse, land loss would increase threefold; if it would take 100 years, the increase would be eightfold; both relative to the losses without WAIS collapse. Although *potential* land loss itself is less than linear as a function of sea-level rise (cf. Fig. 1), when the effects are combined with coastal protection, *actual* land loss is more than linear.

Note that the numbers in Fig. 6 are much lower than those in Figs. 1, 2 and Table 1. This is due to two reasons. Firstly, the numbers in Fig. 6 include *additional* coastal protection as a response to sea-level rise, whereas the numbers in Figs. 1, 2 and Table 1 do not. Secondly, and more importantly, the numbers in Fig. 6 also include *current* coastal protection as estimated in the GVA by Hoozemans et al. (1993), whereas the numbers in Figs. 1, 2 and

Fig. 6 The global cumulative land loss as a function of time and WAIS scenario

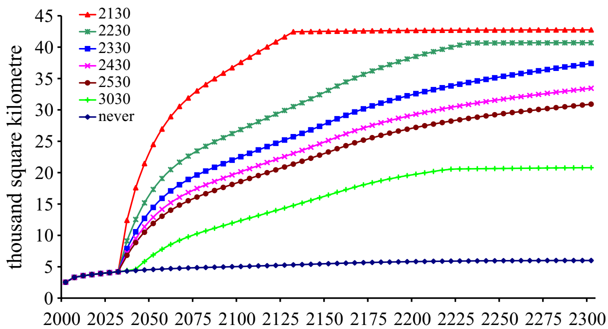


Table 1 do not. These differences stress the importance of considering relative rather than absolute results.

Figure 7 shows forced displacement of people. Note that displacement, like land loss, is by sea-level rise only; storms are not considered. Without a WAIS collapse, forced displacement starts at around 75,000 people per year, but rapidly falls to some 5,000 people in 2050 as defences standards progressively improve. Note the disproportionate reaction of forced migration to increased protection levels (cf. Fig. 4). With a WAIS collapse, forced migration soars. With a WAIS collapse in 100 years, the number of forced migrants peaks at around 350,000 a year, and stays at that level for a decade. The model suggests that about 15 million people in total are displaced by the most extreme collapse scenario (2030 to 2130). This is a significant impact and such population displacement would have major economic and other consequences. However, the numbers displaced are much smaller than the exposed population (Fig. 1), only being 2% to 3% of the total, showing that the model predicts that most of the coastal population is protected.

Figure 8 shows the model estimates of coastal wetland area over time. Without a WAIS collapse, wetland area falls because of a combination of sea-level rise and coastal protection (which removes areas for wetlands to migrate inland which is termed coastal squeeze). The annual rate of loss diminishes with time because a large number of wetlands have disappeared completely. With a WAIS collapse, coastal wetland area declines even more rapidly, showing that the impact of the additional sea-level rise outweighs the benefits of reduced coastal protection. In the scenario without WAIS collapse, about one third of global wetlands disappear with the most rapid WAIS collapse over 100 years causes about two thirds of global wetlands disappear. Given that wetland loss is a non-linear process (Nicholls 2004; McFadden et al. 2007), losses for the higher rates of change may be underestimated.

7 Sensitivity analysis

The above results are sensitive to our assumptions and the scenarios that we have used, as shown in earlier analyses (Tol 2002a, b, 2004). If emissions were higher, so would the resulting impacts. If people were richer, coastal protection would be more extensive and effective, and the impacts would be lower. If wetlands are more sensitive to sea-level rise, then impacts (losses) would be higher. If coastal protection were more expensive, the amount of protection would be lower, and impacts higher. Here we present two additional sensitivity analyses on the two parameters that were adjusted in *FUND* to make the analysis more realistic: (1) the shape of the protection cost function; and (2) the shape of the land-

Fig. 7 Global annual forced migration as a function of time and WAIS scenario

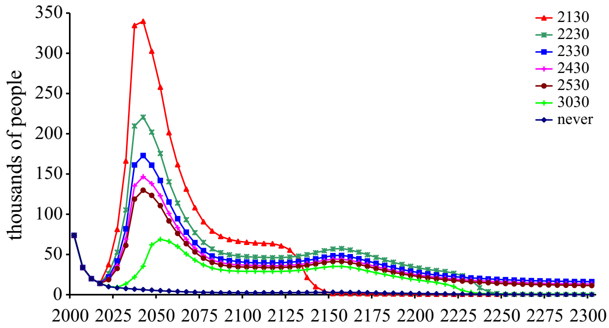
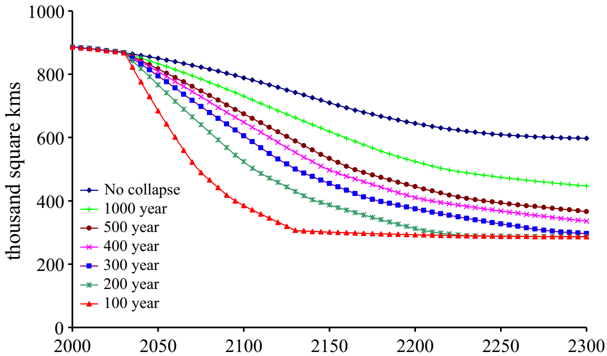


Fig. 8 The global wetland area as a function of time and WAIS scenario



loss function. Collectively, this illustrates key features of the response to the WAIS collapse We avoid results without protection, as this is unrealistic and easily misinterpreted by alarmist readers. The cost-benefit analysis is such that richer and more densely populated coasts are protected first, so the case without coastal protection would see dramatically higher impacts, as already discussed.

The cost of coastal protection is a crucial parameter in the analysis, because it strongly influences the extent of protection.[4] Protection costs are specified as a bilinear function of dike height, where the costs are 10 times higher if sea level rises faster than 1 cm per year; we refer to this as the *cost increase factor*. In Figs. 9 and 10, we show the results for cost increase factors of 5, 20 and 100.[5] We also show the case of a cost increase factor of 1, which is the original, linear model, unadjusted for extreme sea-level rise scenarios. Figure 9 shows the fraction of coast protected for the scenarios in which the WAIS collapses in 100 and in 500 years. As one would expect, higher costs leads to less protection. However, the amount of protection falls much more between a cost increase factor of 5 and 10, than between a cost increase factor of 10 and 20, and 20 and 100. Hence, the model suggests that even if the cost increase factor were 100,[6] roughly 35% of the world's coast would still be worth protecting. In effect, the analysis suggests that some coasts are so valuable that they will be protected regardless of the rise in sea level over the range that is physically plausible. Figure 10 shows the corresponding land loss. Here as well, the land loss response is less than linear in the cost increase factor, but this is less pronounced than for the protection level.

We had to make other adjustments to the *FUND* model in order to more realistically analyse extreme sea-level rise. In the original specification, land loss was proportional to sea-level rise. This was replaced with a non-linear land loss function, derived from the exposure analysis. Figures 9 and 10 show the difference in results. Coastal protection is hardly affected, as the decision makers assumed linearity anyway, regardless of the "actual" world (cf. Fig. 9). However, estimates of land loss are considerably higher with the original,

[4] Actually, what matters is the cost of protection relative to the value of land. We keep the latter constant and vary the former.

[5] Based on dike costs being quadratic, in round terms cost factors of 1, 5, 10 and 20 correspond to dike heights of 1-, 2-, 3- and 4.5-m, respectively, with the 1-m cost derived directly from the GVA.

[6] This is possible in some locations if we assume the worst-case sea-level rise scenario and the corresponding increase in wave heights as they break closer and closer to the shoreline (Townend 1994; Townend and Burgess 2004).

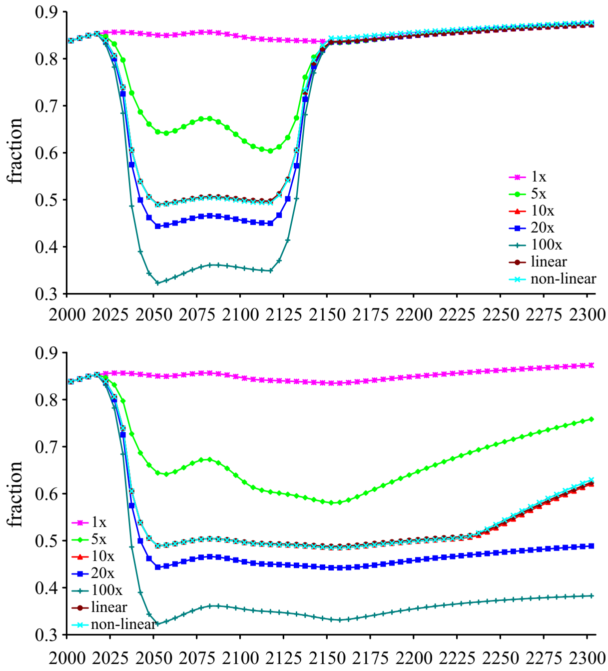


Fig. 9 The fraction of coastal protection on threatened coasts at the global scale over time; four alternative cost increase factors are used: *1*×, *5*×, *10*×, *20*× and *100*×; also shown are the results for a linear response of land loss to sea-level rise, and a response with a stronger non-linearity than in the base case (assuming cost increase factors of *10*×).; the results of these two cases are very close to "*10*×". The *top* (*bottom*) panel shows the results for a WAIS collapse between 2030 and 2130 (2530)

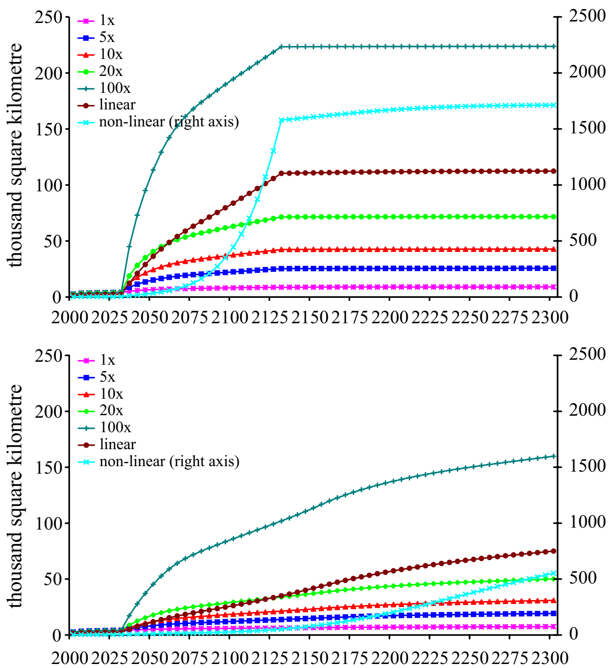


Fig. 10 The global cumulative land loss over time; five alternative cost increase factors are used: 1×, 5×, 10×, 20× and 100×; also shown are the results for a linear response of land loss to sea-level rise, and a response with a stronger non-linearity than in the base case (assuming cost increase factors of 10×). The top (bottom) panel shows the results for a WAIS collapse between 2030 and 2130 (2530)

linear specification. The original model would have overestimated the impacts of a WAIS collapse. This follows immediately from the exposure analysis, which shows that the coast is steeper between 1 and 5 m than between 0 and 1 m elevation.

We may also consider exposure of land area to extreme sea-level rise without additional protection. Above, we discuss the differences between Figs. 1, 2 and Table 1, on the one hand, and Fig. 6 on the other. We argue that the exposure analysis (Figs. 1, 2, 3) may overestimate the impact of a 1-m rise (Fig. 6) as the exposure analysis ignored current coastal protection. However, for a 5-m rise, current coastal protection is largely irrelevant as it would be submerged without upgrade. This suggests that the non-linearity of the response of land loss (without additional protection) should not be based on the exposure analysis for 1 and 5 m—as it was done above. The non-linearity should rather be based on the impact analysis (without additional protection) for 1 m and the exposure analysis for 5 m. As a result, the loss model would become *more* non-linear. Figures 9 and 10 show the results if we make this assumption. Coastal protection is hardly affected (Fig. 9), for the same reason as above. However, the estimates of land loss would be considerably higher, by a factor of about 20 (or 40) for a 5-m sea-level rise in 2530 (or 2130).

8 Discussion and conclusion

This analysis suggests that a significant acceleration of sea-level rise due to a WAIS collapse (or any other cause) could have a profound effect on the impacts of sea-level rise. In terms of a cost-benefit analysis and perfect adaptation, it suggests that it would be appropriate to abandon large lengths of the world's coasts, although about 30% to 50% of the world's coasts could still be optimally protected under such a cost-benefit analysis. The optimum amount of protection depends on the protection cost, and while optimum in a cost-benefit sense, the increased investment in protection would divert significant resources away from other investment needs.

Given the extent of protection that is predicted by the model, so the number of people displaced is also much lower than widely assumed. Up to 15 million people are estimated to be displaced from 2030 to 2130, although this number could increase with a higher cost increase factor. Population distribution in the near-coastal zone is known to be strongly non-uniform (Small and Nicholls 2003), and hence, relatively small lengths of defences can protect a significant fraction of the coastal population. Here 50% protection protects >95% of the coastal population. The length of protection required to achieve this goal might well fall further if the analysis were performed at sub-national scale as demonstrated for East Anglia, England by Turner et al. (1995), and this should be investigated.

On the other hand, the amount of protection suggested by the global model is surprising, as there is a widespread view that any large rise in sea level is beyond our capacity to adapt and a global retreat will result. Independent support for the model results presented here can be found from subsiding coastal cities during the 20th Century such as Tokyo which subsided up to 5-m due to groundwater withdrawal (Nicholls 1995). Nonetheless, the response to such large relative sea-level rise was always to protect, and coastal cities such as Tokyo, Tianjin, Shanghai, Rotterdam, Osaka, Bangkok and Amsterdam presently have large areas below normal tides which are dependent on flood defences and pumped drainage to avoid flooding. In contrast, the global model appears to conflict with the three detailed case studies of WAIS collapse, which all suggest a greater tendency towards coastal abandonment and retreat than the global model even in major urban areas such as London and Holland (see Table 3). This difference partly reflects factors that are not

Table 3 Summary of the response of three detailed case studies to the Atlantis sea-level rise scenario (5-m rise from 2030 to 2130)

Case Study	Impacts	Response	Source
Netherlands	>10 million people threatened together with one of the world's largest economies	Abandon the northwest and southwest of the Netherlands, but possibly protect the Ranstad (Amsterdam to Rotterdam area). Likelihood of intense political conflict and very large response costs in proportion to GDP	Olsthoorn et al. (2008)
Thames estuary	Two million people threatened with a rapidly increasing flood risk without a response, even allowing for expected upgrades. Also much of London's financial sector including Canary Wharf.	Indecision may lead to forced abandonment, but there are adaptation options—especially a new downstream barrier	Lonsdale et al. (2008) Dawson et al. (2005)
Rhone delta	Compared to the other case study sites, human impacts are minimal, but significant natural values are threatended	After an initial 'wait and see', abandon the delta	Poumadere et al. (2008)

considered in the global model, such as an overall loss of confidence due to the rapid sea-level rise, which in turn, may trigger a vicious cycle of decline. In the Netherlands, response costs where estimated at 3% to 4% of GDP, which was considered prohibitive in terms of other demands on the national economy. It was also observed in the Thames Estuary case study that paralysis, which might well delay an adaptation response too long for it to be effective, leave retreat as the only viable option. Again this process is not included in the global model which assumes perfect adaptation if it has an appropriate cost-benefit ratio. Although the Netherlands and the UK have the technological and economic wherewithal to adapt to extreme sea-level rise, the case studies suggest that this necessary condition is not a sufficient one, as assumed by the model. This is consistent with the results of Yohe and Tol (2002) and Tol and Yohe (2006).

Barnett and Adger (2003) discussed the role of social-ecological thresholds in triggering island abandonment, and an empirical analysis of an historic island abandonment in the Chesapeake Bay by Gibbons and Nicholls (2006) supports the validity of this concept. The different results for the global model and the case studies suggest that the notion of social-ecological thresholds may have widespread value when thinking about abrupt climate change. These differences also raise questions about the different controls on barriers to adaptation, which is important information to the climate policy process.

Therefore, collectively the Atlantis project results show that a WAIS collapse would have profound effects on the world's coasts, but it remains uncertain to what extent we would be able to respond.

Even with protection as widespread as suggested by a cost-benefit analysis, the impacts of even a slow WAIS collapse would be substantial. Protection costs would increase by a factor of 10 or more; land loss and forced migration would go up by a factor of 5 or more; wetland loss would double or more compared to a scenario without a WAIS collapse. Faster WAIS collapse would exacerbate all these impacts.

These results also illustrate that the impacts of sea-level rise are non-linear, even in a simple coupled model as used here. Potential land loss is less than linear in sea-level rise.

Actual land loss, in contrast, is more than linear, as coastal protection cannot keep up with higher rates of sea-level rise. For even higher sea-level rise, the response becomes again less than linear, as more and more of the most susceptible areas are abandoned.

The research presented here is only a first exploration of the global impacts of extreme sea-level rise, using a simple coupled model with a number of limiting assumptions and a comparison with detailed case studies. Our ability to protect is fundamental to the actual impacts of WAIS collapse and this remains uncertain as discussed above—this raises technical, economic and socio-political questions. Even in the most optimistic situation with widespread protection being possible, the overall consequences are sufficiently alarming to justify a range of further research (see also Kasperson et al. 2005). In physical terms, scenarios or even probabilities of WAIS collapse linked to different climate change scenarios are desirable, albeit extremely difficult to develop (Nicholls and Lowe 2004). In impact terms, the analysis discussed here could be refined with more detail in terms of coastal data, impact models and representation of adaptation. Such a study could yield important insights into the limits to adaptation, which are suggested here, including the full range of controls that influence these limits. This information is fundamental to understand how society may, or may not, be able to respond to abrupt climate change.

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