

GLOBAL ESTIMATES OF THE IMPACT OF A COLLAPSE OF THE WEST ANTARCTIC ICE SHEET

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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. This includes the likely impacts of such a rise. This paper explores for the first time the impacts of such an extreme sea-level rise, triggered by the collapse of the West Antarctic Ice Sheet (WAIS). Contributions to sea level of between 0.5m/century up to 5m/century are considered, together with other business-as-usual contributions, given in the worst case an approximately 6-m rise in global-mean sea level from 2030 to 2130. The FUND model is tuned with new global data concerning the coastal zone and then used for the analysis. This considers the interaction of dryland loss, wetland loss, protection costs and human displacement. Unlike earlier analyses, response costs are represented in a non-linear manner. It is found that significant lengths of the coast are abandoned given these extreme scenarios, although these preliminary results suggest that significant lengths of the world's coast would remain worth defending. However, protection costs rise substantially, and still very large areas of dryland and wetland are abandoned. When compared to the case studies, this study suggests more protection than they suggested: partial abandonment of the Netherlands and London seems possible based on these results. This suggests that more factors than simply cost-benefit analysis were driving the decisions in the detailed case studies.

Key words: Abrupt climate change, sea-level rise, coastal impacts, adaptation.

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 (to some approximation) only in physical terms. That the impact is also “high” in “human terms” is typically asserted but essentially speculative. In this paper, we attempt a first estimate of the impacts of a WAIS collapse in an integrated analysis of (dry)land loss, wetland loss, coastal protection, and human displacement. These results are then compared to the outcomes of the three European case studies. While the impacts of the WAIS collapse will only impact coastal areas, people are crowded into the coastal zone (e.g., Small and Nicholls, 2003), giving a high impact potential. Hence, coastal impacts are of global significance.

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. The goal is so ambitious because the conventional methods of climate change impact analysis crumble under large changes such as the impact of a 5 metre sea-level rise. A 1 metre sea-level rise, the maximum considered in the vast majority of studies, can be considered as marginal, not in the sense of not important, but in the formal, mathematical sense of the word. That is, a 1 metre 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 metre sea-level rise would have impacts that extend beyond the coastal zone, and alter the coastal zone in a dramatic manner. For instance, the analysis of Olsthoorn and Van der Werff (this volume) suggests that the harbour of Rotterdam (and by implication the harbours of Antwerp and Bremen) may disappear under a 5-m sea-level rise, which would radically change transport in the whole of Western Europe. A 1 metre sea-level rise would increase costs in Rotterdam Harbour, but not affect its operations very much.

In this paper, we approach this problem in two ways. Firstly, we went back to the data underlying sea-level rise impact studies. Whereas a 1 metre sea-level rise is about twice as bad as a 0.5 metre sea-level rise, a 5 metre sea-level rise is not 10 times as bad. Using a recent digital elevation model, we estimated exposure up to 10 metres sea-level rise. Secondly, we took 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 non-linear as well. We do not pretend that these two changes solve all problems, but the work presented below is more than a simple extrapolation to 5 metre sea-level rise of previous work for much smaller rises.

To our knowledge, this is the second paper analysing the impacts of a 5 metre sea-level rise and the first to consider global impacts. The first paper (Schneider and Chen, 1980) is based on outdated methods and observations and only considers the United States. The method used there is inappropriately simple (a digital elevation model only, no coastal defences). Note that there are previous results for global impacts of sea-level rise up to a 1-m rise scenario (e.g., Hoozemans *et al.*, 1993; Nicholls, 2004; Tol, 2004), and some national results for impacts up to a 2-m 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. In Section 3, we describe the data used. In Section 4, we present the model. In Section 5, we discuss the results. Section 6 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). 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 realise the sea-level rise equivalent 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, taking many hundreds or even thousands of years (Gregory *et al.*, 2004). The WAIS will also take a long time to melt, taking hundreds or thousands of years.

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. 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. 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 Figure 2, illustrating the range of processes of interest when trying to understand WAIS collapse. They concluded that there was 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 0.5 m rise by 2100, about 2.3 m by 2500, and about 3.2 m rise by 4000. Hence, none of these estimates equate to a total WAIS collapse.

The goal of the Atlantis Project was to look at an extreme scenario, and especially to understand the societal response to such an extreme change. Given the current status of scientific knowledge, the total collapse of the WAIS in relatively short time scales of 100 to 200 years cannot presently be stated as completely impossible. This is supported by discussions with several glaciologists who all thought such rapid collapse highly unlikely, but felt the system was not well enough understood to totally discount such a rapid change. Given the limited resources of the project, it was felt that we would learn most about the response by considering the most extreme scenario possible, and for the three detailed case studies the Atlantis Project decided to use a scenario of a 5-m rise in 100 years due to the WAIS collapse. This was kept deliberately simple and was applied linearly from 2030 for all the three case studies discussed below. In 2130, the rise ceases, as abruptly as it began. Even if the Atlantis scenario is later demonstrated to be impossible, which we recognise is quite possible, 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.*, 2005).

Unlike the detailed case studies, the global analysis was able to explore a wider range of scenarios of WAIS contribution to sea-level rise, ranging from a 0.5 m/century up to a 5 m/century scenario.

3. The data

Preliminary analysis was based on a series of global datasets on population, elevation, tidal range and administrative unit boundaries. These datasets include:

- an updated global population distribution model, the third version of the Gridded Population of the World (GPW3) dataset (CIESIN, 2004);
- the LandScan global population database (Landscan, 2003);
- global elevation and bathymetry data from the SRTM Enhanced Global Map (ISciences, 2003);
- tidal range data from the Land-Ocean Interactions in the Coastal Zone (LOICZ) typology dataset (LOICZ, undated);

- vector data on second-level administrative boundaries from the Digital Chart of the World (DCW) developed by ESRI (2002);
- land use data from the IMAGE Team (2002) datasets.

Data processing was performed within a Geographic Information System (GIS) which provided the environment for the storage, the spatial analysis and the cartographic display of the geo-referenced datasets.

The data

Population data

Two global population databases were used for the analysis, the GPW3 and LandScan. The LandScan dataset is a worldwide population database compiled on a 30"×30" latitude/longitude grid. 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, nighttime lights, and other data. LandScan was developed as part of the Oak Ridge National Laboratory (ORNL) Global Population Project for estimating ambient populations at risk.

The GPW3 is the latest update of the GPW and GPW2 datasets which have been extensively employed in various global population studies (Cohen et al., 1997; Small and Nicholls, 2003) in areas as diverse as climate change, urban studies, health and agriculture (see F.A.O., 2003). The GPW3 provides estimates of the population of the world on a 5km × 5km grid and includes improved boundary data and year 2000 population data. GPW adopts a simple population distribution algorithm putting more emphasis on the collection of the input data rather than on the modelling. Although the output resolution of the GPW is lower than the resolution of the LandScan dataset the input data are nearly three times more detailed (F.A.O., 2003)

Elevation data

The elevation dataset that has been employed is the SRTM Enhanced Global Map developed by ISciences (2003). The dataset has a resolution of 30 arc seconds (around 1km at the equator) and is based on data acquired from the Shuttle Radar Topography Mission (SRTM) which cover 80% of the earth's land surface and have been processed by NASA's Jet Propulsion Laboratory to 30 arc-second resolution. The data have been processed to identify and correct anomalies using best-source correction and specially-developed levelling techniques. Such anomalies included elevation "step" anomalies measuring in the tens to hundreds of meters, lake surface data anomalies, and inconsistently depressed areas. Finally, the SRTM data were supplemented with GTOPO30 elevation data for land areas that are covered in the SRTM30 dataset and also with ocean bathymetry data from ETOPO2.

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 LOICZ typology dataset (LOICZ, undated). Tidal range values are classified into five classes which were interpreted into average tidal range values based on expert judgement. From these values, the high water mark was approximated as (tidal

range)/2 . This estimate of the high tide mark was used as the reference against which any sea-level rise is measured.

Administrative unit boundaries

The GIS dataset of first-level subnational administrative boundaries that is included in the Digital Chart of the World (DCW) was employed in the present study. This dataset is a worldwide base map of administrative boundaries and is the most commonly-used template for GIS regional or global analysis (Deichmann et al., 2001). Furthermore the DCW has been partially employed for the generation of the GPW3 which ensures consistency in our analysis. The DCW second-level administrative units dataset consists of 1095 polygons and has been based primarily on the US Defense Mapping Agency (DMA) Operational Navigation Chart (ONC) series that are produced by the United States, Australia, Canada, and the United Kingdom. (ESRI, 1992). The ONCs have a nominal scale of 1:1,000,000.

Land use data

Land use was derived from a dataset that was developed within by the IMAGE Team (2002). This dataset contains the global distribution of 16 principal landuse types at $0.5^{\circ} \times 0.5^{\circ}$ resolution.

Data processing and analysis

The available datasets were processed within a GIS. Zonal statistical functions and overlays were employed within the context of the spatial analysis that was performed. This analysis produced average tidal range values for all coastal administrative units. 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-m and 5-m rise scenario, respectively. During this analysis, low-lying inland areas and water bodies were masked out. In the next step, resident coastal population counts for the areas lost were estimated using the GPW3 and Landscan datasets. Finally, the dominant land use for the areas at risk from the sea-level rise scenarios were calculated for each administrative unit.

4. The model

The model used is 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 coastal impacts are used, and these are as described in Tol (2002a; 2002b). The essentials are given below. Version 2.8n differs from version 2.8 (Link and Tol, 2004) in that version 2.8n runs at its maximum spatial resolution, that is, 207 countries; version 2.8 has only 16 regions.

Essentially, *FUND2.8n* consists of a set of exogenous scenarios based on which impacts are calculated. The model runs from 1995 to 2100 in time steps of five years. The scenarios are the SRES scenarios, as implemented by the IMAGE2 model (IMAGE Team, 2002). The scenarios concern the rate of population growth and economic growth, carbon dioxide concentrations, global mean temperature and sea-level rise.

The climate impact module is based on Tol (2002a; 2002b). The following impact categories of climate change are considered: agriculture, forestry, sea-level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhea, energy consumption, water resources, and unmanaged ecosystems. In this paper,

only the impacts of sea-level rise are considered, comprising (1) dryland loss, (2) wetland loss, (3) protection costs, and (4) forced migration.

The impacts of sea-level rise interact with one another. For example, if a piece of dryland is fully protected, no dryland will be lost, but the costs of protection will be high, and the adjacent wetland may be inundated. The total impact of sea-level rise depends on the adaptive policy chosen, and hence so does the estimated damage. For instance, IPCC CZMS (1992) uses the *ad hoc* rule that all dryland with a population density above 10 people per square meter will be protected while Fankhauser (1994, 1995) and Yohe *et al.* (1995, 1996) employ models which choose the economically optimal level of protection. The difference in estimated impacts can be substantial.

The coastal length of all countries in the world was taken from the Global Vulnerability Assessment (GVA) (Hoozemans *et al.*, 1993), an update of work earlier done for the IPCC (IPCC CZMS, 1990). Other sources, such as the proceedings of the 1993 World Coast Conference (Bijlsma *et al.*, 1994), Nicholls and Leatherman (1995a; 1995b) 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. Therefore, the GVA is used here.

Wetland losses for a 1 metre 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; 1995b). The reasons are: (i) the GVA is a desk study which occasionally shows signs of the great haste of its preparation; (ii) the country studies use local data; and (iii) land lost because of sea-level rise is more obviously estimated than coastal length. Bijlsma *et al.* (1996), however, only report wetland losses in the absence of coastal protection. 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. The resulting wetland model is crude and based on incomplete and older data. However, for want of a better model, it is used here.

Dryland losses are not reported in the GVA, but they are by Bijlsma *et al.* (1996). The GVA reports people-at-risk, which is the number of people living in the one-in-1000-year flood plain, weighted by the chance of inundation. Combining this with GVA's coastal population densities, area-at-risk results. The exponential of the geometric mean of the ratio between area-at-risk and land loss for the 18 countries in Bijlsma *et al.* (1996) was used as a correction factor to derive land loss for all other countries. In the GVA, without protection, dryland 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 3.

The monetary value of a loss of one square kilometer of dryland was on average \$4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometer. Wetland losses are valued at \$2 million per square kilometer on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income.

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 level of protection is derived by Fankhauser (1994):

$$L = \min \left\{ 0, 1 - \frac{1}{2} \left(\frac{PC + WL}{DL} \right) \right\} \quad (1)$$

L is the fraction of the coastline to be protected. PC is the net present value of the protection if the whole coast is protected. The GVA reports average costs per year over the next century. PC is calculated assuming annual costs to be constant. This is based on the following. Firstly, the 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, (1) could not be written explicitly as a function, but would in fact be the solution to a numerical optimisation problem. Secondly, coastal protection entails large infrastructural works which last for decades. Thirdly, the considered costs are direct investments only, and technologies for coastal protection are mature.

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

$$PC = \sum_{t=1}^{\infty} \left(\frac{1}{1 + \rho + g} \right)^t PC_a = \frac{1 + \rho + g}{\rho + g} PC_a \quad (2)$$

where PC_a is the average annual costs of protection. The average annual costs are taken from the GVA. Again, the GVA assumes linearity. Because the protection costs are at the heart of the coastal protection equation (1), we replace this with a bilinear equation: If sea-level rise is less than 1 cm per year, protection costs are as in the GVA; if not, they are 5 times as high.

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

$$WL = \sum_{t=0}^{\infty} t \left(\frac{1}{1 + \rho + g} \right)^t WL_0 = \frac{1 + \rho + g}{(\rho + g)^2} WL_0 \quad (3)$$

where WL_0 denotes the value of wetland loss in the first year.

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

$$DL = \sum_{t=0}^{\infty} t \left(\frac{1}{1 + \rho + g} \right)^t DL_0 = \frac{(1 + g)(1 + \rho + g)}{\rho^2} DL_0 \quad (4)$$

where DL_0 is the value of dryland loss in the first year.

The population scenario used is IPCC SRES A1/B1 scenario (Nakicenovic and Swart., 2001) as implemented in the *IMAGE 2.2* model (IMAGE Team, 2002). The *IMAGE* model has population projections for 17 world regions. Population growth was assumed to be the same for all countries within a region. The A1/B1 scenario has moderate population growth. The world population peak at 8.7 billion people in 2055, and falls to 7.0 billion in 2100.

The scenario for per capita income is the IPCC SRES A1B scenario, again as implemented in *IMAGE*. Per capita income growth within a region is assumed to be uniform. Economic growth is fairly rapid. Japan is the slowest grower, seeing its per capita income quadruple over the century, an average annual growth of 1.3%. The fastest growth is in South Asia, seeing its per capita income increase by a factor of 180, an average annual growth of 5.1%.

Using the population and economic scenarios, as well as the corresponding scenarios on technological progress, the full *FUND* model, version 2.8,¹ was used to generate scenarios of climate change and sea-level rise. CO₂ concentrations rise to 870 ppm by 2100, the global mean temperature to 3.5°C above pre-industrial levels, and the sea rises by 66 cm.

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 metres 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 2230, 2230, 2330, 2430, 2530 and 3030, respectively. For comparative purposes, the IS92a scenario is also shown. Figure 1 shows the assumed scenarios of global-mean sea-level rise, allowing for both the WAIS and other sea level contributions.

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

5. Results

Figure 2 shows key aspects of the global exposure as a function to sea-level rise in 1995. This includes the area above the mean high water level, the number of people living there, and their total income. Given the uncertainties in these global datasets, it is important not to over-interpret the results. 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, reflecting coastal wetlands and areas of land claim which all tend to exist near to mean sea level.

Figure 3 shows the impact based on the 1995 situation, without additional coastal protection, on area, population and total income as a function of sea level rise. 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.

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, the length of the world's coast that is protected drops from about 85% to about 50%, reflecting that protection becomes too expensive in many areas. The threshold is crossed at the same time for all the WAIS collapse scenarios, except for the slowest one in which the collapse takes 1,000 years. As soon as the WAIS has collapsed, the rate of sea-level rise slows again, and the length of coastal protection returns to the fraction that it was before the WAIS collapse. Note, however, that this does not imply that the lost land would be reclaimed; rather, the new coastline would be protected at its new location which is further inland. In the slowest WAIS collapse scenario, the rate of sea-level rise does not instantly rise above 1 cm/yr, and then falls below the threshold of 1 cm/yr shortly after 2200. Given the assumptions on protection costs 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. Figure 4), the overall protection costs soar, 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 reason.

Figure 6 shows the model estimates of cumulative loss of dryland. Because sea-level rise is much faster, and hence protection levels fall, dryland losses are much higher with a WAIS collapse than without this change. If it takes 1,000 years for the WAIS to collapse, dryland

¹ That is, the version with 16 regions rather than 207 countries.

loss increases threefold; if it takes 100 years, the increase is eightfold; both relative to the situation without WAIS collapse. Although potential dryland loss itself is less than linear as a function of sea-level rise (cf. Figure 1), when the effects are combined with coastal protection, actual dryland losses becomes more than linear.

Figure 7 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). 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 impacts of the additional sea-level rise outweighs the benefits of reduced coastal protection. In the scenario without WAIS collapse, about 1/3 of global wetlands disappears; with the most rapid WAIS collapse in 100 years causes about 2/3 of global wetlands disappears.

6. 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, it suggests that it would be appropriate to abandon protecting large lengths of the world's coasts, although about 50% of the world's coasts could still be protected at considerable cost. This latter result is surprising, as the widespread view is that any large rise in sea level is beyond our capacity to adapt and a global retreat will result. Support for the 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 was always to protect, and cities such as Tianjin, Shanghai, Tokyo, Osaka and Bangkok have large areas below mean sea level which are dependent on coastal protection and pumped drainage.

However, the results here appear to conflict with the three case studies of the Netherlands, Thames Estuary and the Rhone delta, which suggest a greater tendency towards abandonment than the global model. This difference may reflect non-economic factors that are not considered in the global model, such as an overall loss of confidence triggering a cycle of decline. 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, leaving retreat as the only viable option. Again this process is not included in the global model which assumes perfect adaptation where it has an appropriate cost benefit.

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

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References

- Bijlsma, L., Crawford, M., Ehler, C., Hoozemans, F. M. J., Jones, V., Klein, R. J. T., Mieremet, B., Mimura, N., Misdorp, R., Nicholls, R. J., Ries, K., Spradley, J., Stive, M., de Vrees, L., & Westmacott, S. (1994) "Preparing to Meet the Coastal Challenges of the 21st

- Century - Conference Report World Coast Conference 1993", Intergovernmental Panel on Climate Change/Ministry of Transport, Public Works and Water Management, The Hague.
- Bijlsma, L., Ehler, C. N., Klein, R. J. T., Kulshrestha, S. M., McLean, R. F., Mimura, N., Nicholls, R. J., Nurse, L. A., Perez Nieto, H., Stakhiv, E. Z., Turner, R. K., & Warrick, R. A. (1996), "Coastal Zones and Small Islands," in *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses -- Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, 1 edn, R. T. Watson, M. C. Zinyowera, & R. H. Moss, eds. (eds.), Cambridge University Press, Cambridge, pp. 289-324.
- Cohen, J.E., C. Small, A. Mellinger, J. Gallup, & J. Sachs (1997) Estimates Of Coastal Populations, *Science*, 278, 1211,
- Fankhauser, S. (1994), 'Protection vs. Retreat -- The Economic Costs of Sea Level Rise', *Environment and Planning A*, 27, 299-319.
- Fankhauser, S. (1995), *Valuing Climate Change - The Economics of the Greenhouse*, 1 edn, EarthScan, London.
- Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI); and World Resources Institute (WRI). 2000. Gridded Population of the World (GPW), Version 2. Palisades, NY: CIESIN, Columbia University. Available at <http://sedac.ciesin.columbia.edu/plue/gpw>.
- Davies, J.L., 1980. Geographical Variation in Coastal Development London: Longman Group Ltd. 212 p.
- Dobson, J. E., E. A. Bright, P. R. Coleman, R. C. Durfee, and B. A. Worley, 2000. A Global Poulation Database for Estimating Population at Risk. *Photogrammetric Engineering & Remote Sensing* 66(7).
- Gregory, J.M., Huybrechts, P. and Raper, S.C.B., 2004. Threatened loss of the Greenland ice-sheet. *Nature*, 428, 616.
- Hoozemans, F. M. J., Marchand, M., & Pennekamp, H. A. (1993), *A Global Vulnerability Analysis: Vulnerability Assessment for Population, Coastal Wetlands and Rice Production and a Global Scale (second, revised edition)*, Delft Hydraulics, Delft.
- IMAGE Team (2002), *The IMAGE 2.2 implementation of the SRES scenarios*, RIVM CD-ROM Publication 481508018, RIVM, Bilthoven.
- IPCC CZMS (1990), *Strategies for Adaption to Sea Level Rise*, Intergovernmental Panel on Climate Change/Ministry of Transport and Public Works, The Hague.
- IPCC CZMS (1991), *Common Methodology for Assessing Vulnerability to Sea-Level Rise* Ministry of Transport, Public Works and Water Management, The Hague.
- LandScan 2003 Global Population Database. Oakridge, TN: Oak Ridge National Laboratory. Available at <http://www.ornl.gov/gist/>
- Mercer, J. H. (1978), 'West Antarctic Ice Sheet and CO₂ Greenhouse Effect: A Threat of Disaster', *Nature*, 271, 321-325.
- Nakicenovic, N. and Swart, R. (eds.) (2001), *Emissions Scenarios 2000 – Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.
- Nicholls, R. J. (1995) Coastal Megacities and Climate Change, *Geojournal* , 37/3 pp369 - 379
- Nicholls, R.J. 2004. Coastal flooding and wetland loss in the 21st Century: Changes under the SRES climate and socio-economic scenarios. *Global Environmental Change*, 14, 69-86.
- Nicholls, R. J. and Leatherman, S. P. (1995a), 'The Implications of Accelerated Sea-Level Rise for Developing Countries: A Discussion', *Journal of Coastal Research*, 14, 303-323.
- Nicholls, R. J. & Leatherman, S. P. (1995b), "Global Sea-level Rise," in *When Climate Changes: Potential Impact and Implications*, K. M. Strzepek & J. B. Smith, eds. (eds.), Cambridge University Press, Cambridge.

- Oppenheimer, M. (1998), 'Global Warming and the Stability of the West Antarctic Ice Sheet', *Nature*, **393**, 325-332.
- Oppenheimer, M. and Alley, R. B. (2004), 'The west antarctic ice sheet and long term climate policy', *Climatic Change*, **64**, 1-10.
- Small, C. & Nicholls, R.J. 2003, A Global Analysis of Human Settlement in Coastal Zones, *Journal of Coastal Research*, **19(3)**, 584-599.
- Schneider, S.H. and R.S. Chen (1980), 'Carbon Dioxide Flooding: Physical Factors and Climatic Impact', *Annual Review of Energy*, **5**, 107-140.
- Titus et al., 1991
- Titus, J.G. and V. Narayanan (1996), 'The Risk of Sea Level Rise', *Climatic Change*, **33**, 151-212.
- Tol, R. S. J. (2002a), 'Estimates of the Damage Costs of Climate Change - Part 1: Benchmark Estimates', *Environmental and Resource Economics*, **21**, 47-73.
- Tol, R. S. J. (2002b), 'Estimates of the Damage Costs of Climate Change - Part II: Dynamic Estimates', *Environmental and Resource Economics*, **21**, 135-160.
- Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of FUND*, Research Unit Sustainability and Global Change FNU-48, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg (submitted to *Mitigation and Adaptation Strategies for Global Change*).
- Tol, R.S.J. et al (2005) Adaptation To Five Metres Of Sea Level Rise *Journal of Risk Analysis*, in review.
- Vaughan, D. G. and Spouge, J. R. (2002), 'Risk estimation of collapse of the West Antarctic Sheet', *Climatic Change* (52), 65-91.
- Yohe, G. W., Neumann, J. E., and Ameden, H. (1995), 'Assessing the Economic Cost of Greenhouse-Induced Sea Level Rise: Methods and Applications in Support of a National Survey', *Journal of Environmental Economics and Management*, **29**, S-78-S-97.
- Yohe, G. W., Neumann, J. E., Marshall, P., and Ameden, H. (1996), 'The Economics Costs of Sea Level Rise on US Coastal Properties', *Climatic Change*, **32**, 387-410.

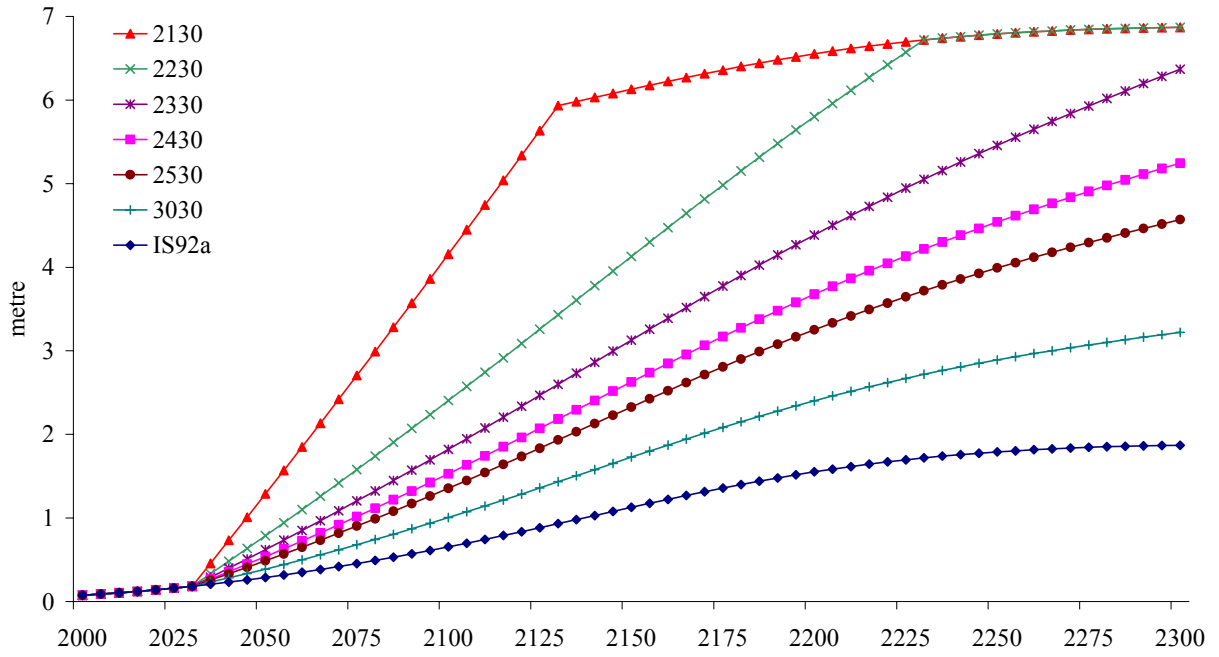


Figure 1. The global-mean sea-level rise scenarios used in the analysis, including the baseline IS92a scenario without any significant contribution from Antarctica.

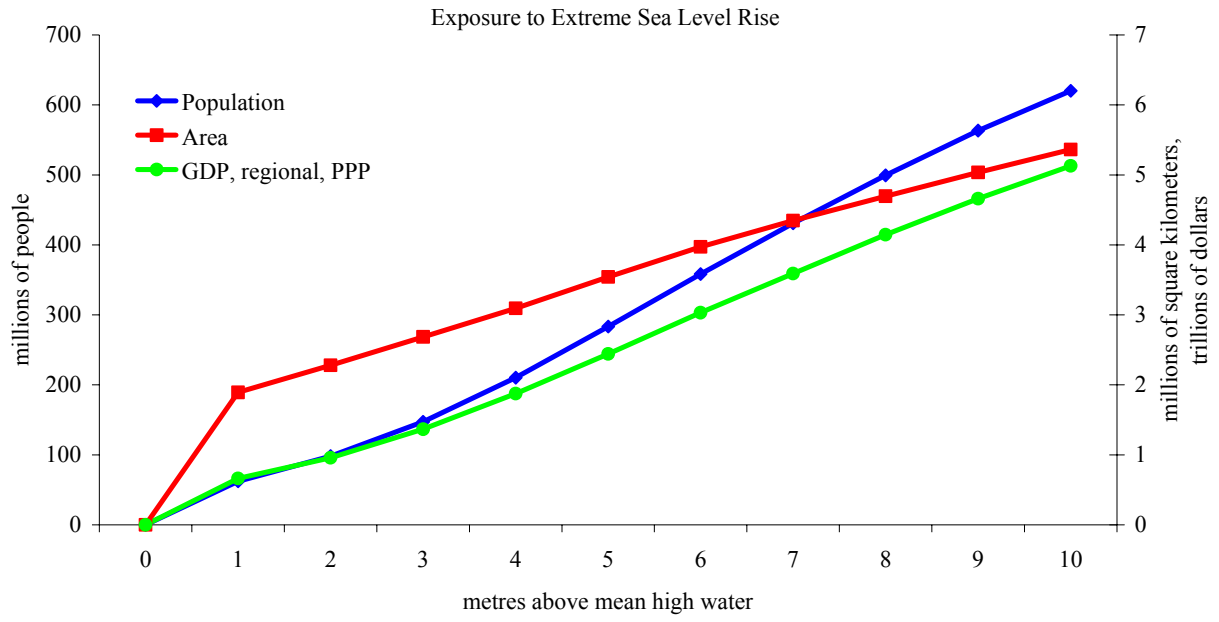


Figure 2. Distribution of population, land area and GDP as a function of elevation in 1995.

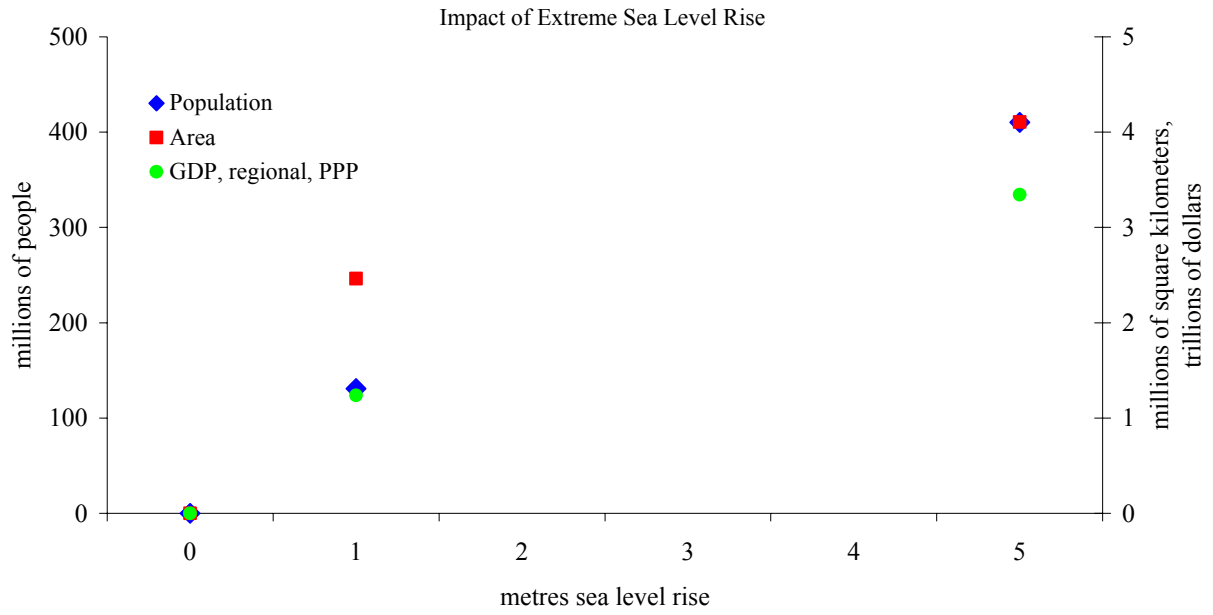


Figure 3. The exposure of population and total income as a function of sea-level rise.

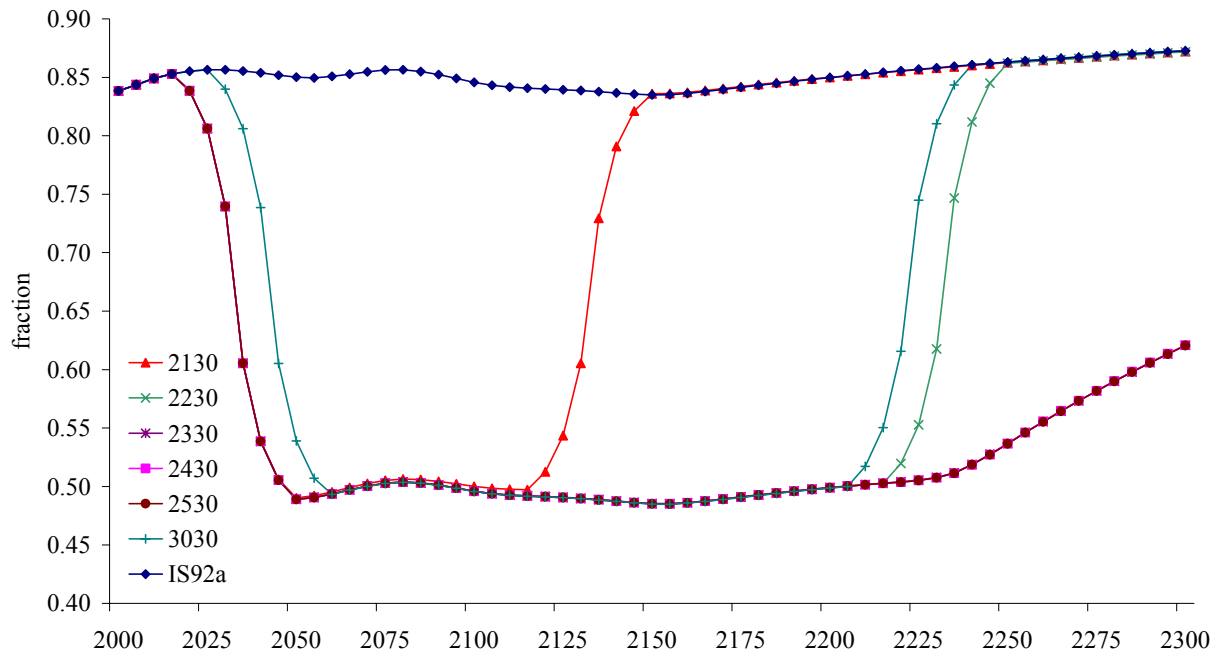


Figure 4. The fraction of coastal protection on threatened coasts at the global scale as a function of time and WAIS scenario.

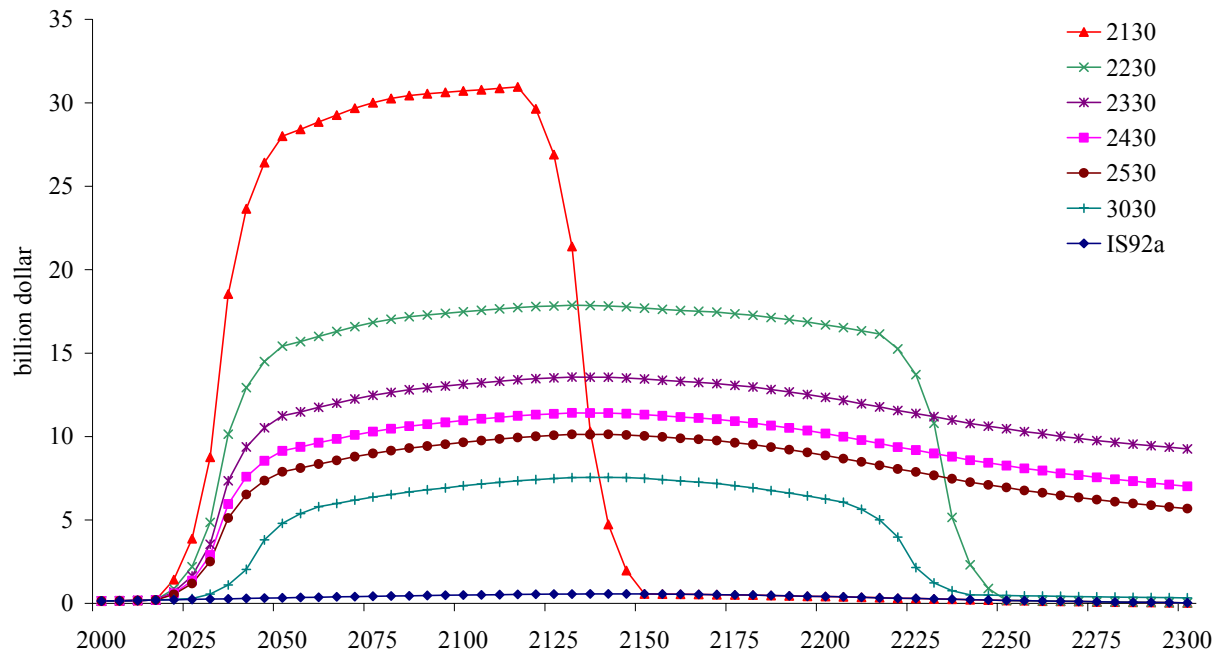


Figure 5. The global costs of coastal protection as a function of time and WAIS scenario.

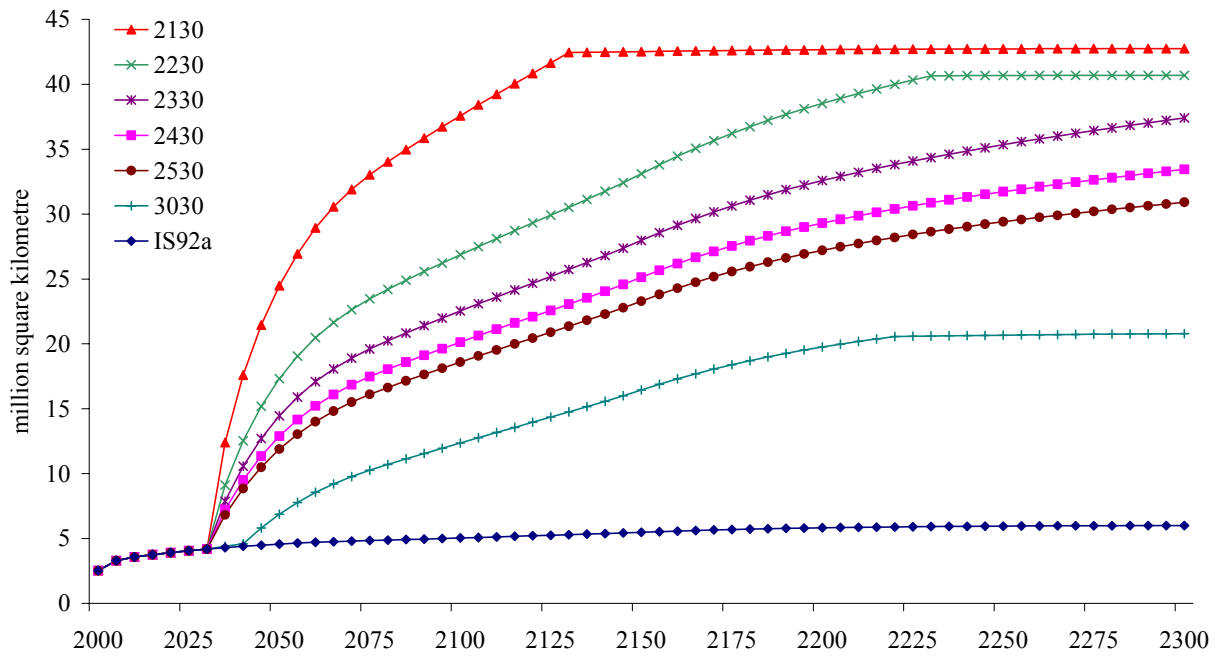


Figure 6. The global cumulative dryland loss as a function of time and WAIS scenario.

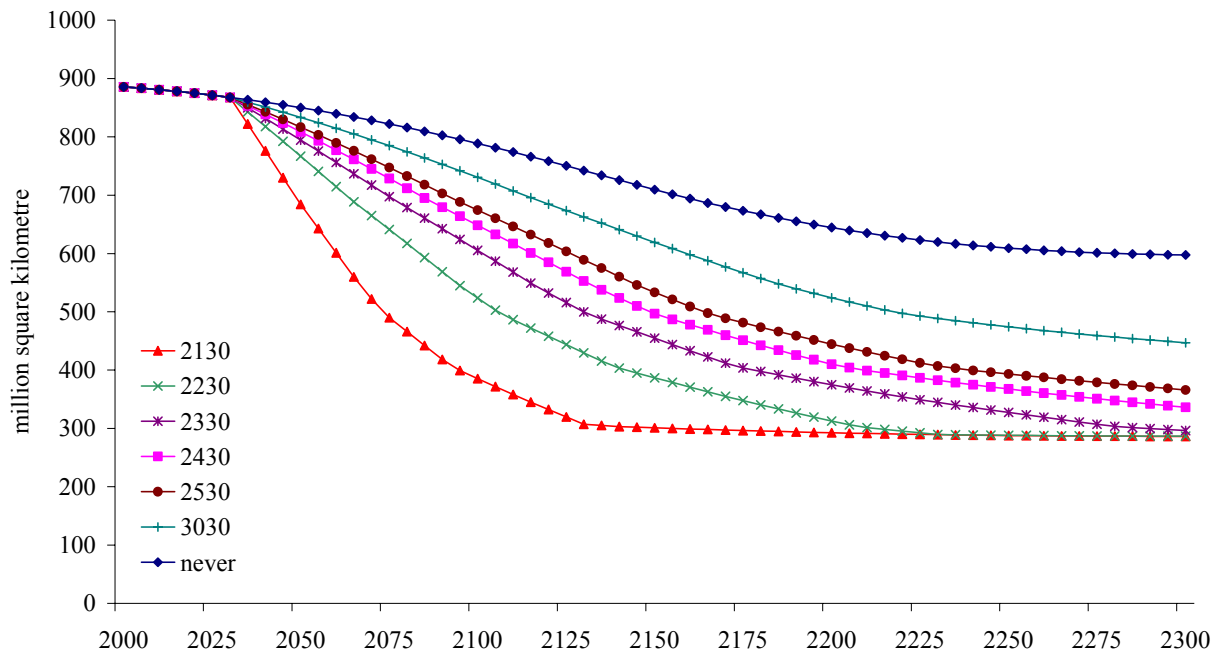


Figure 7. The global wetland area as a function of time and WAIS scenario.