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This work was prepared for the Stern Review on the Economics of Climate Change

Global and regional exposure to large rises in sea-level: a sensitivity analysis

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Summary

This report examines the implications of large rises in sea level, both over the 21st century and beyond.

Using GIS methods, an exposure analysis assesses the land area, existing population and existing economic activity situated within 10-m of present sea levels – these areas are not threatened within the 21st century, but looking further into the future these areas may be threatened if deglaciation of Greenland and the West Antarctic Ice Sheet occurs. The results emphasise the high impact potential of any rise in sea level. Regionally, most threatened land is in North America and Central Asia, with much being relatively unpopulated Arctic coastlines. In terms of population, East and South Asia dominate due to the their large populated delta areas. In terms of economic activity, East Asia, Europe and North America dominate, although this distribution is most likely to change during the 21st century.

Using the FUND model, an impact assessment is also conducted over the 21st century for rises in sea level of up to 2-m/century and a range of socio-economic scenarios. This considers impacts assuming economically-optimum protection responses, so the actual impacts are less than the GIS analysis would suggest, but investment in the protection is required. While the costs of sea-level rise increase due to greater damage and protection costs, an optimum response in a benefit-cost sense remains widespread protection of developed coastal areas, as identified in earlier analyses. The socio-economic scenarios are also important in terms of influencing these costs. In terms of the four components of costs considered here, protection seems to dominate, with substantial costs from wetland loss under some scenarios. The regional distribution of costs shows a few regions experience most of the costs, especially South Asia, South America, North America, Europe, East Asia and Central America. However, there are some important limitations which suggest that protection may not be as widespread as suggested in the FUND analysis. Nonetheless, this analysis suggests that protection is much more likely and rational than is widely assumed, even with a large rise in sea level.

In conclusion, this analysis confirms the significant exposure that exists to sea-level rise, but stresses that human responses including protection are rational even under large changes. Assuming widespread protection, investment is diverted from other uses. Much research remains to refine our understanding of these important issues.

1. Introduction

Human-induced sea-level rise due to human-induced climate change has caused concern for coastal areas since the issue emerged more than 20 years ago. Rapid sea-level rise (>1-m/century) raise most concern as it is commonly felt that this would overwhelm the capacity of coastal societies to respond and lead to large losses and a widespread forced coastal retreat. Less appreciated is the so-called ‘commitment to sea-level rise’ whereby even if the climate is stabilised, sea levels continue to rise for many centuries due to the long timescales of the oceans and the large ice sheets (Nicholls et al., 2006a; Nicholls and Lowe, 2006).

This paper provides evidence on the consequences of large rises in sea level over the 21st Century and in the longer-term due to climate change based on two complimentary methodologies (Nicholls et al., 2006a):

(1) An exposure analysis for land areas within 10-m of present sea level; and

(2) An impact analysis using an integrated assessment model (FUND: The Climate Framework for Uncertainty, Negotiation and Distribution) for large rises in sea level in the range of 0.5 to 2 metres over the 21st Century

The exposure analysis combines data from a variety of sources to estimate the land area, population and economic activity that might directly be affected by sea-level rise. The results give a rough estimate of the magnitude of the problem. The second part of the paper presents results from a modelling exercise that looks at the impacts from sea-level rise, including the potential for protection to avoid damages. The model calculates the welfare loss due to rising sea-levels for a number of socio-economic scenarios, assumes some very basic adaptation of humans to sea-level rise and aggregates damages for a number of assumed damage types.

Each method has its limitations, mainly due to the availability of appropriate data. Combining the two is useful, since they differ in their limitations and some of them can be overcome by looking at both results. The exposure analysis operates on a more detailed geographical data than the modelling exercise and provides an indication of possible impacts based on today’s socio-economic situation under a wide range of sea-level rise scenarios[1], up to 10 m in this paper. The FUND model on the other hand takes socio-economic changes over time into account and has a more refined impact module that attempts to calculate the complete welfare loss due to sea-level rise.

[1] Although note the limitation that this is assuming a uniform global sea-level rise (see Nicholls et al., 2006a).

2. Exposure Analysis

2.1 Introduction

The analysis conducts a first-order analysis of exposure given large possible rises in sea level of up to 10 m above present sea level. By exposure, we examine the potential impacts taking no account of possible human adaptation against these changes. As such these are worst case impacts for the selected socio-economic situation (the world in 1995). For scenarios of 1-m, 5-m and 10-m above present high water, land areas, resident population and GDP are estimated using available global data sets at the national scale, following similar though improved methods compared to Nicholls et al. (2006c). These are then aggregated to the Stern Regions (as defined in Warren et al., 2006).

The rise in sea level considered here might seem large, but it is quite plausible if we consider long timescales (beyond the 21st Century) and the commitment to sea-level rise (Nicholls et al., 2006a; Nicholls and Lowe, 2006).

The results have the following limitations which are worth noting:

- They only consider one socio-economic scenario and take no account of likely changes as socio-economic scenarios after 2100 become increasingly problematic.
- They take no account of non-climate changes in sea level, or possible patterns of sea-level rise. In the first case, this is not possible unless a specific timescale is defined, while in the second case, this remains poorly understood. For more specific analysis and questions, these factors need to be considered.

2.2 Data sources

The exposure analysis was based on a series of global datasets on elevation, population, tidal range, national boundaries and GDP/capita. These data sources are now discussed in turn.

2.2.1 Population data

The Gridded Population of the World, version 3 (GPW3) (CIESIN and CIAT, 2004). This 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 30 arc-seconds (roughly 1 km at the equator). The strength of this dataset is the emphasis on the collection of high quality input data rather than modelling distributions (Nelson and Balk, 2003).

2.2.2 Elevation data

The elevation dataset that was employed is the Global Land One-Kilometre Base Elevation (GLOBE) digital elevation model (DEM) ('GLOBE,' 1999). The GLOBE DEM is a global data set covering 180^o West to 180^o East longitude and 90^o North to 90^o South latitude. The horizontal grid spacing is 30 arc-seconds (0.008333 degrees) in latitude and longitude. The horizontal coordinate system is seconds of latitude and longitude referenced to World Geodetic System 84 (WGS84) and the vertical units represent elevation in meters above Mean Sea Level (Hastings and Dunbar, 1999). The GLOBE digital elevation model is one of the most thoroughly designed, reviewed, and documented global digital elevation datasets to date.

2.2.3 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 LOICZ typology dataset (Maxwell and Buddemeier, 2002). Tidal range is presented as five classes (see Table 1), which were interpreted as average tidal range values. High water was derived as half the tidal range.

Tidal range class	**Tidal range value**
1	tideless
2	<2 meter
3	2 - 4 meter
4	5 - 8 meter
5	>8 meter

Table 1: LOICZ tidal range classes and corresponding values

2.2.4 National boundaries

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

2.2.5 GDP/capita

A national dataset on GDP/capita from the World Resources Institute (http://earthtrends.wri.org/) was used to estimate GDP. This includes estimates based on market exchange rates (MER) and purchasing power parity (PPP). MER gives a better estimate of economic power, while PPP gives a better estimate of economic welfare.

2.3 Data processing and analysis

The population and land areas were derived directly from the datasets above. 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. Data overlays employing zonal statistical functions were used in the context of the spatial analysis that was performed in a series of steps. First the population living within the elevation zone up to 10-m above mean sea level was estimated by overlaying the population and elevation data. Then potential impacts, defined relative to high water, were considered in two steps. In the first step average tidal range values were estimated for all coastal administrative units by averaging the tidal range values of the cells falling within the respective administrative unit. 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 for a 10-m scenario of sea-level rise. In this step, low-lying inland areas and water bodies were masked out. Finally, resident coastal population counts for the areas lost were estimated. This estimation was performed by overlaying the GPW3 dataset, calculating the population cells lying within the lost areas and summing up the population-counts values of the respective cells.

The two GDP estimates are simply based on the product of the people counts and the GDP/capita data.

Due to the nature of the datasets, a number of uncertainties exist. These uncertainties include input data quality, error propagation, matching of data layer boundaries, variable resolutions and data resampling performed during overlays. In the present analysis, an effort was made to address the latter three factors. This was done by improving the definition of the geographical extent (boundaries) of the input data layers and by taking into account the resampling performed during overlay operations which affects the output of zonal functions.

Results are sensitive to the methodology that is used (analysis extent, basic unit of reference etc) for the calculations and further research is required in order to assess the effects of these factors on the final outputs. However these results constitute an improvement to previous analyses.

There seems to be a tendency to slightly underestimate area counts as the overlay criteria were more restrictive than in previous analyses. However, this method should have kept standard errors at lower levels than in previous analyses.

2.3 Exposure Analysis Results

Figure 1 and Table 2 show key aspects of the global exposure to sea-level rise as a simple function of elevation above high water. This includes the land area, the population, and their total income (measured at MER and at PPP). Given the uncertainties in these global datasets, as well as the limitations already outlined, it is important not to over-interpret the results, and they should only be considered indicative (Small and Nicholls, 2003). The distributions all increase more rapidly from 0-m to 1-m and then appear roughly linear to 10-m elevation. This suggests that more land and people (and hence GDP) are concentrated in the most low-lying areas. Taking 10-m elevation, 5.2 x 10^6 km^2, and nearly 400 x 10^6 people are estimated to be exposed. Economic exposure is less when measured in MER than in PPP, indicating that a substantial part of the exposure is in developing countries.

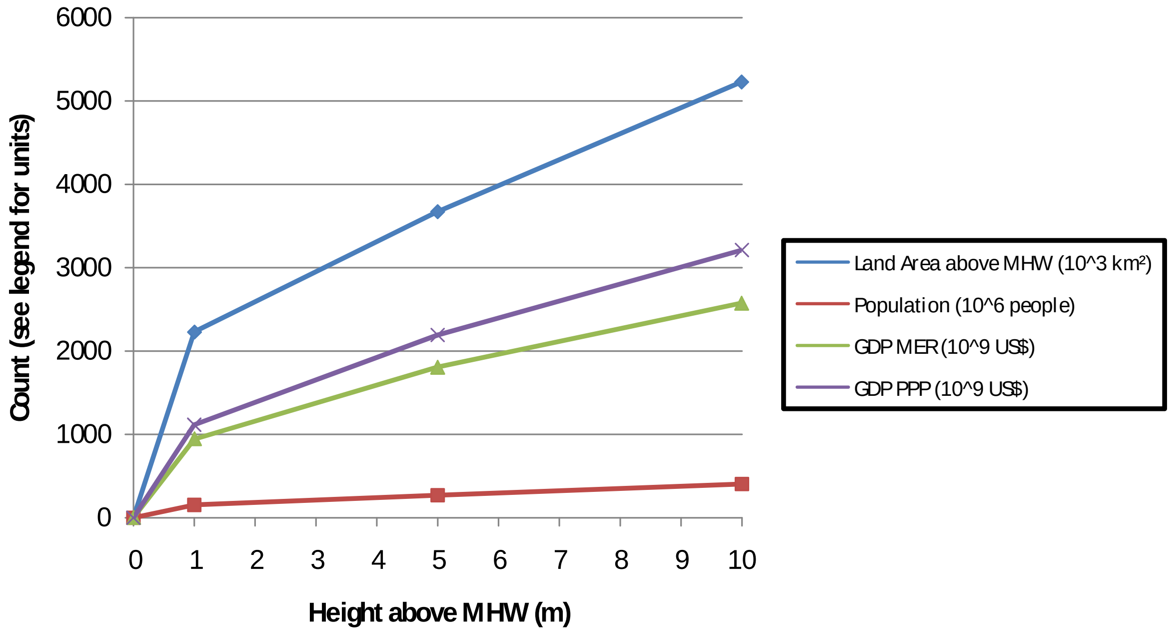


Figure 1: Global exposure of land, people and income up to 10-m above mean high water

Height above MHW (m)	Land Area above MHW (10^3 km^2)	Population (10^6 people)	GDP MER (10^9 US$)	GDP PPP (10^9 US$)
1	2225.6	146	944	1119
5	3670.8	268	1802	2194
10	5227.9	397	2570	3210

Table 2: Global exposure estimates

Table 3 disaggregates the exposure results into the Stern Review regions following Warren et al (2006). Due to the strong vulnerability of small island states to sea-level rise, exposure results are shown for island sub-regions in Table 4.

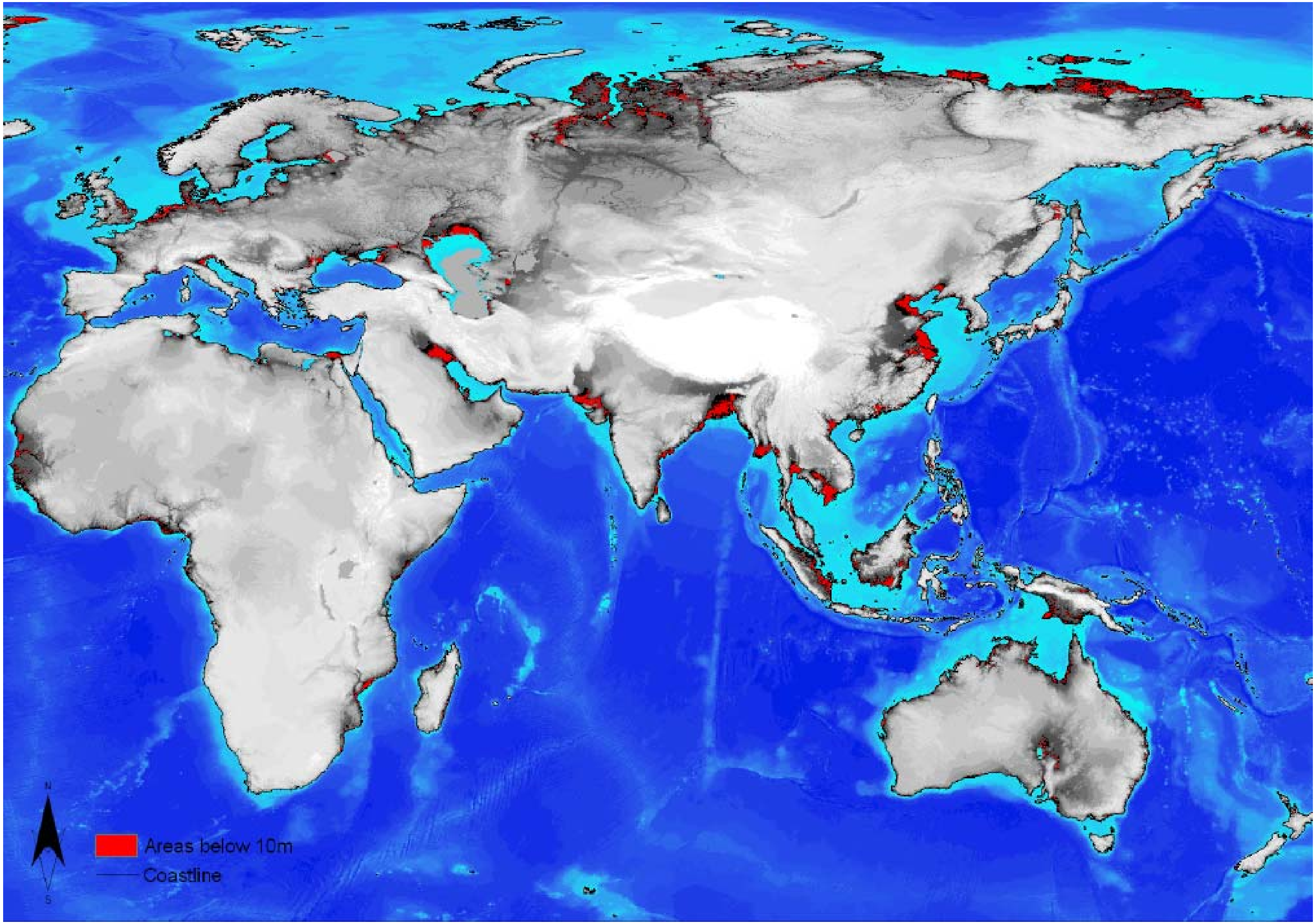
Figure 4 presents relative distribution of exposed land area within 10 m of present sea-levels by the Stern Review regions. It is based on present distribution.

Stern Review region	Exposure by factor and elevation above MHW											
	Threatened land area (10^3 km^2)			Population (millions)			GDP MER (US$ billions)			GDP PPP US$ billions)		
	1m	5m	10m	1m	5m	10m	1m	5m	10m	1m	5m	10m
Australasia	135.4	197.9	267.4	2.2	2.9	3.8	37.9	50.6	67.1	43.9	58.3	77.1
Central America	62.5	140.7	203.2	1.7	4.3	7.1	5.1	12.4	19.5	12.9	31.7	50.9
Central Asia	314.4	658.2	1112.9	0.8	2.1	3.8	1.7	4.4	8.2	5.3	13.6	25.7
East Asia	140.1	249.2	357.2	46.1	92.2	135.3	382.6	731.0	1022.6	352.7	695.0	1004.0
Europe	139.0	229.5	330.9	13.6	21.4	29.7	305.2	469.5	634.8	304.2	469.2	639.4
North Africa	50.1	69.6	103.5	3.1	6.6	12.1	3.6	7.3	13.8	12.3	25.6	47.8
North America	639.5	1000.3	1335.2	4.0	13.8	21.6	102.5	357.5	561.3	139.9	490.0	769.5
South America	254.4	367.8	473.2	8.2	12.7	17.6	34.0	58.1	83.2	53.5	91.7	132.0
South Asia	404.1	603.6	812.4	59.5	102.6	150.9	59.5	89.4	125.5	175.1	281.8	404.4
Southern Africa	39.8	68.8	103.1	2.5	3.7	5.3	0.8	1.5	2.5	3.1	5.0	8.0
West Africa	27.8	44.2	64.2	2.3	3.3	4.9	1.4	1.9	2.7	3.6	4.9	7.2
West Asia	16.3	37.2	59.4	1.1	2.6	4.4	9.3	18.5	28.9	12.9	26.6	43.8
GLOBAL TOTAL	2225.6	3670.8	5227.9	145.2	268.2	396.5	944	1802	2570	1119	2194	3210

Table 3: Regional Exposure Results

Stern Review sub-region	Exposure by factor and elevation above MHW											
	Threatened land area (10^3 km^2)			Population (millions)			GDP MER (US$ billions)			GDP PPP US$ billions)		
	1m	5m	10m	1m	5m	10m	1m	5m	10m	1m	5m	10m
Indian Ocean Islands	0.2	0.2	0.2	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.3
Pacific islands	7.8	9.6	11.3	0.2	0.2	0.3	0.6	0.7	0.8	1.4	1.6	1.7
Caribbean	18.5	40.5	53.2	0.5	1.5	2.6	1.7	4.1	6.0	3.4	8.4	12.9

Table 4: Island Sub-Region Results. In Table 3, these sub-regions are included in South Asia, Australasia and Central America, respectively.



N
S
Areas below 10m
Coastline

Figure 2: Land areas in Europe, Africa and Asia below 10-m elevation (above mean high water).

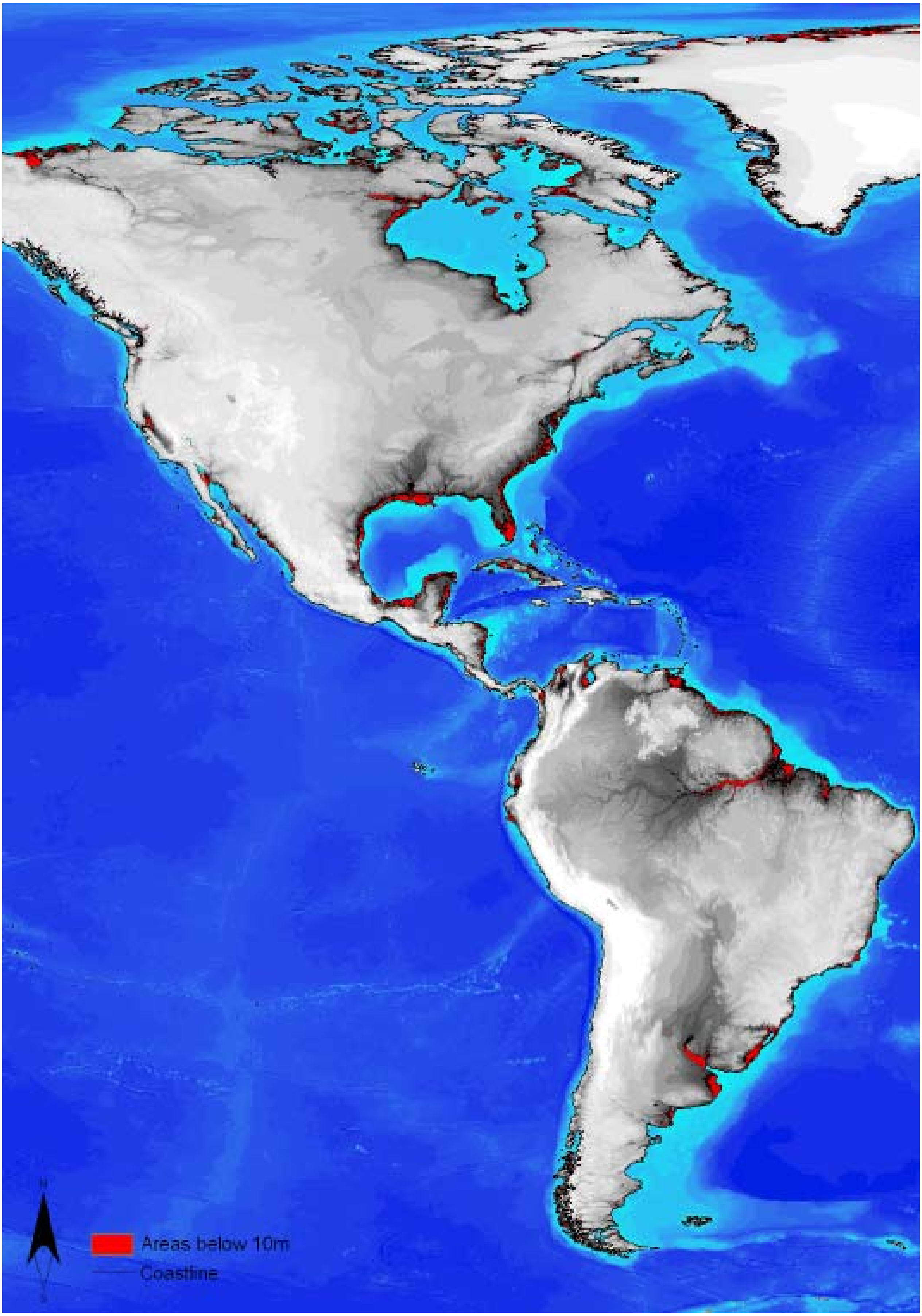


Figure 3: Land areas Americas below 10-m elevation (above mean high water)

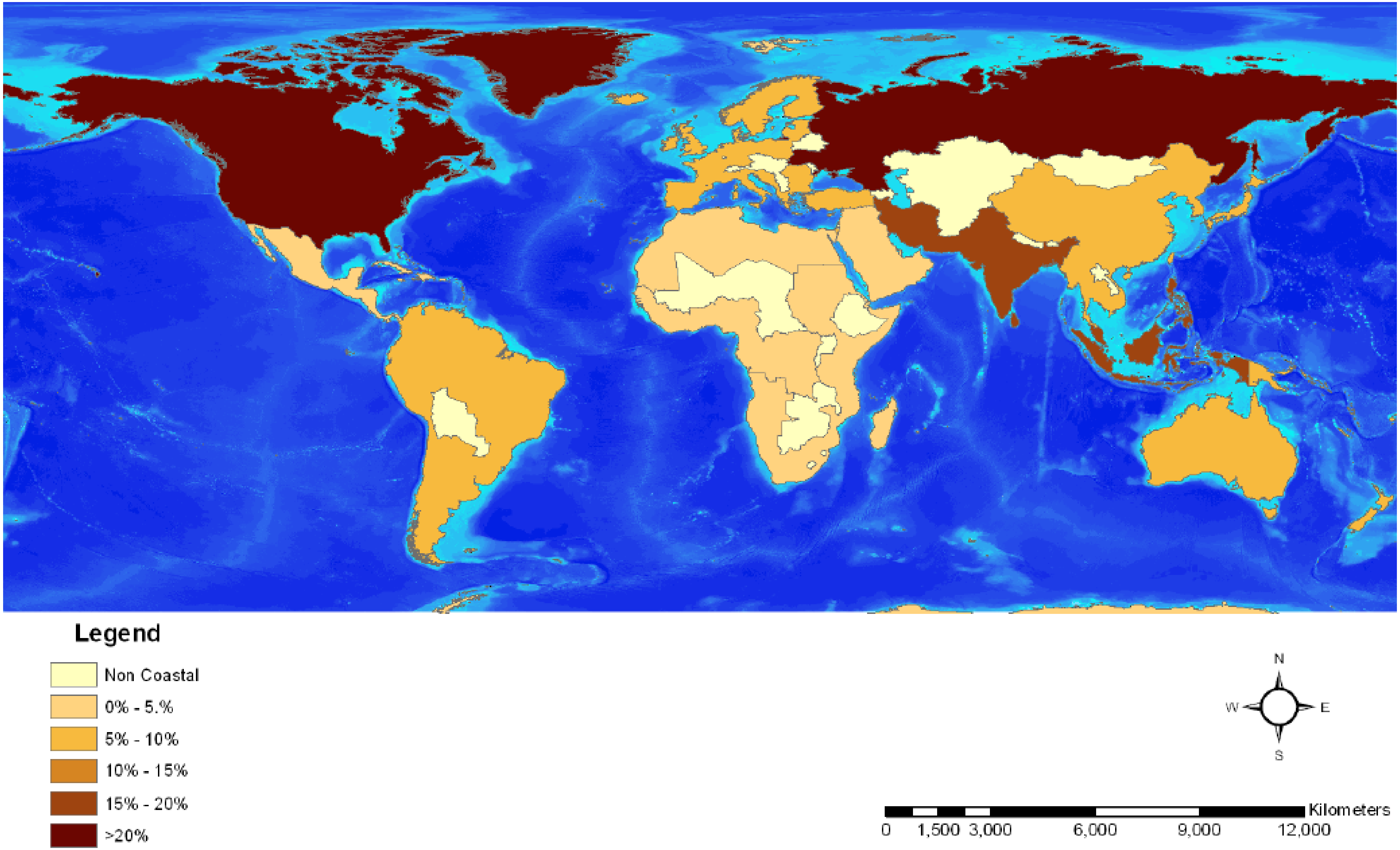


Figure 4: Relative distribution of exposed land area within 10 m of present sea-levels, by Stern Review regions, based on present distribution

Figure 2 and 3 show examples of the land areas below 10-m elevation: much of the threatened area is concentrated in discrete locations such as large deltas in Asia, or the lowlands around the North Sea. Figure 5 to 8 show the regional distribution of land area, population, GDP (MER) and GDP (PPP) below 10-m elevation. In terms of land area, the three most exposed regions are North America (25%), Central Asia (21%) and South Asia (16%). (Figures give percentage of the global exposure). For Central Asia and North America, this includes significant areas around the Arctic Ocean, so while large land areas are exposed, they have limited population or economic activity. South Asia in contrast has large areas in densely populated deltas exposed (Figure 2). In terms of population South Asia and East Asia stand out, with 38% and 34% of the global exposure, respectively. In terms of GDP (MER) East Asia (40%), Europe (25%) and North America (22%) are most important regionally. Considering GDP (PPP), changes the relevant percentages and ranking to East Asia (31%), North America (24%) and Europe (20%).

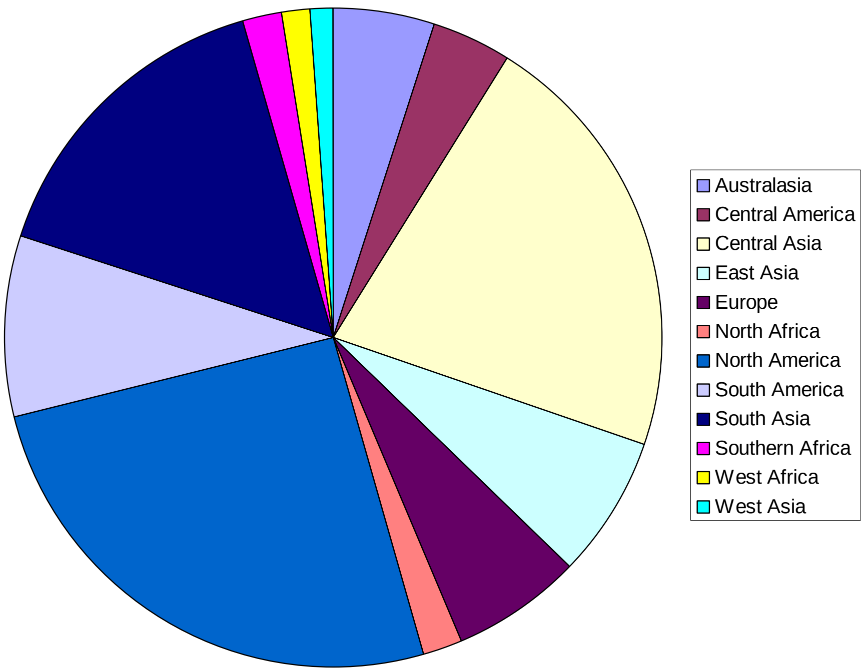


Figure 5: Exposed land area by Stern Region below 10 m

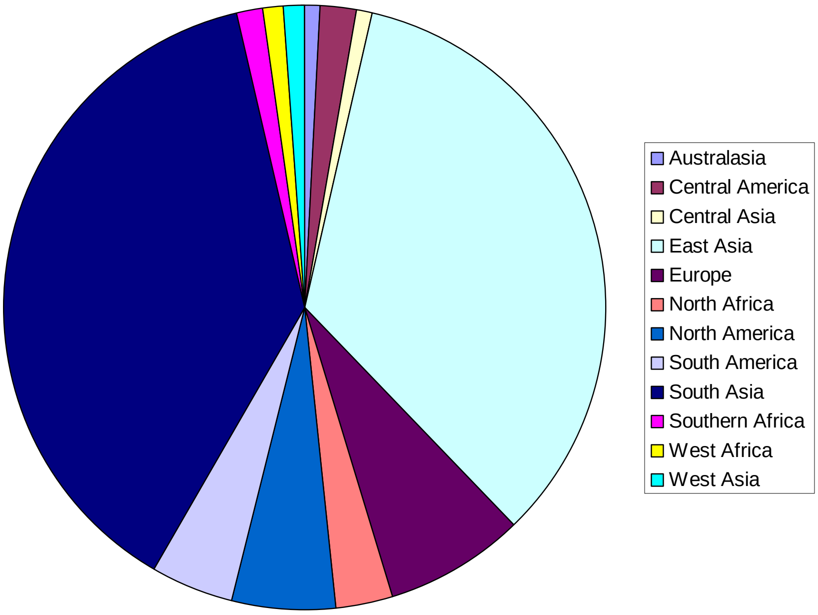


Figure 6: Exposed population by Stern Region below 10 m

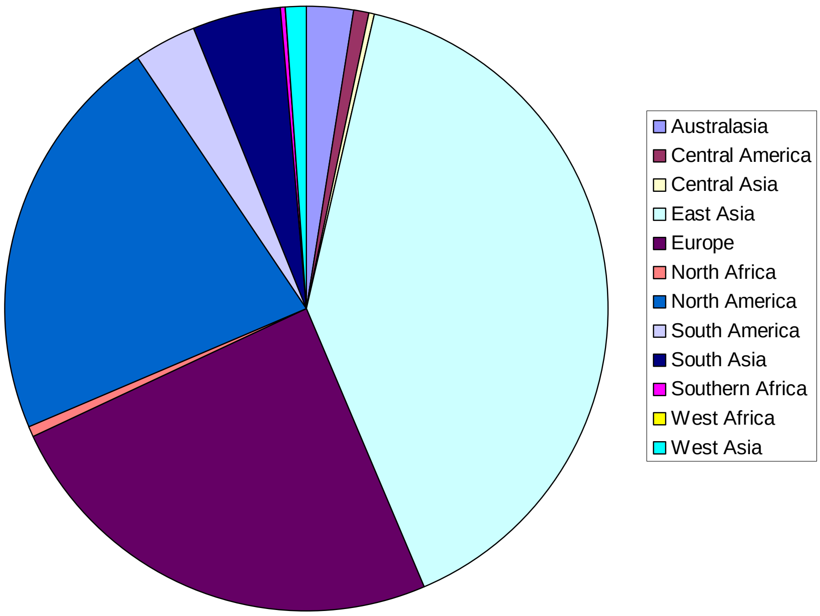


Figure 7: Exposed GDP (MER) by Stern Region below 10 m

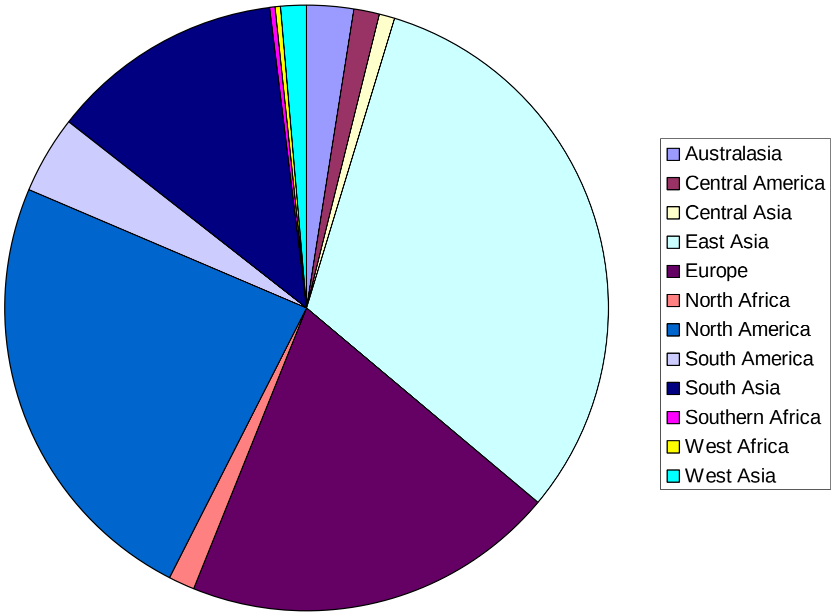


Figure 8: Exposed GDP (PPP) by Stern Region below 10 m

3. Impact Analysis

3.1 FUND Model

The Coastal Module of FUND 2.8n is used to calculate damages caused by various scenarios of sea-level rise over the next century (see Figure 9). This section will give a brief outline of the model components relevant to the calculation of sea-level rise damages. More details of the FUND coastal module can be found in Tol (2006) and Nicholls, Tol et al. (2006b).

The model is driven by exogenous scenarios of population and GDP growth on a per country scale. Five distinct scenarios are evaluated for this study: the SRES scenarios A1, A2, B1 and B2 and a control scenario of constant population and GDP at 1995 levels over the 21st century (termed C1995).

Sea-level rise is specified as a global exogenous scenario. Three distinct scenarios are examined: a rise of 0.5-m, 1.0-m and 2.0-m above today's (2005) sea levels in the year 2100[2]. These correspond to rates of 0.5m per 95 years, 1.0m per 95 years and 2.0m per 95 years, respectively. For the sake of simplicity, sea-level rise for the time steps between 2005 and 2100 is a linear interpolation.

[2] This is consistent with the maximum global scenario of sea-level rise considered plausible by Arnell et al (2005).

Damages of rising sea levels are assumed to have four damage cost components: (1) the value of dryland lost, (2) the value of wetland lost, (3) the cost of building protection against rising sea levels and (4) the costs of displaced people that are forced to leave their original place of settlement due to dryland loss (Figure 9). FUND determines the optimum amount of protection (in benefit-cost terms) based on the socio-economic situation and the magnitude of sea-level rise, and the necessary protection costs. Unprotected dryland is assumed to be lost, while wetland loss is also influenced by the amount of protection: more protection leads to greater wetland loss via coastal squeeze. The number of people displaced is a simple function of dryland loss.

The area of dryland loss is assumed to be a linear function of sea-level rise and protection level. The value of lost dryland is assumed to be linear in income density ($\$/km^2$).

Wetland value is assumed to be logistic in per capita income, with a correction for wetland scarcity, and a cap:

$$V_{t,r} = \alpha \frac{y_{t,r}/30,000}{1+y_{t,r}/30,000} \max\left(2, 1-\sigma+\sigma\frac{L_{\max,r}}{L_{\max,r}-L_{t,r}}\right) \quad (1)$$

where V is wetland value; y is per capita income; L is the wetland lost to date; L_{max} is a parameter, given the maximum amount of wetland that can be lost to sea-level rise; α is a parameter such that the average value for the OECD is \$5 million per square kilometre; and σ=0.05 is a parameter.

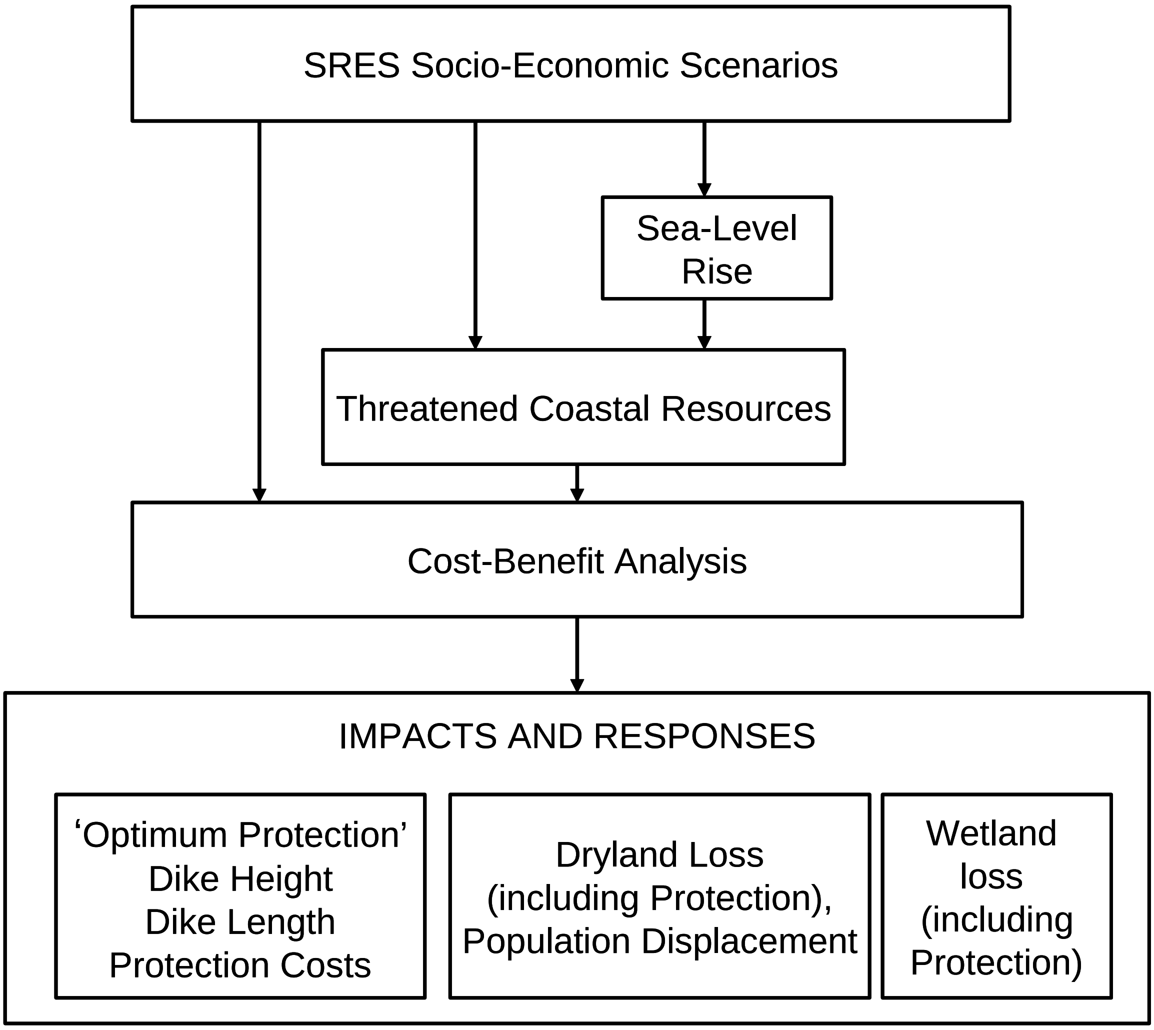


Figure 9: A flow chart summarising the operation of the FUND module for coastal areas

The number of people forced to migrate from a country due to sea-level rise is a function of the average population density in the country and the area of dry land lost. The costs of people displaced is three times average per capita income.

Following the method of Nicholls, Tol et al. (2006b), average annual protection costs are assumed to be a bilinear function of the rate of sea-level rise as well as the proportion of the coast that is protected. This is a first step to overcoming the linear assumptions of the FUND model. The costs increase by an order of magnitude if sea-level rise is faster than 1 cm per year (i.e., protection costs are much higher for the 1-m and 2-m rise scenarios than the 0.5-m scenarios). The level of protection is based on a cost-benefit analysis that compares the costs of protection (the actual construction of the protection and the value of the wetland lost due to the protection) with the benefits, i.e. the avoided dry land loss.

The damage costs presented in this report are total damage costs for the period 2080-2089. All costs are discounted to their 2005 value using the declining discount rate scheme prescribed in the UK Greenbook (H.M. Treasury, 2003). All damage figures are given in 1995 US dollars.

For a more complete discussion of sea-level rise in the context of climate change, see Nicholls and Tol (2006) and Nicholls, Tol et al. (2006c).

3.2 Impact Analysis Results

Results from the model runs can be analyzed along various dimensions. We will look first at the results under different socio-economic scenarios, then disaggregate the four damage cost components, and finally regionally disaggregate the results. The analysis concludes with a look at scenarios without protection, which can be related to analyses of exposure.

3.2.1 Total damage costs by socio-economic and sea-level rise scenarios

While the choice of socio-economic scenario has a significant influence on the damage costs from sea-level rise for the time period analysed for this study, the damage costs vary more over the choice of sea-level rise scenario (Figure 10).

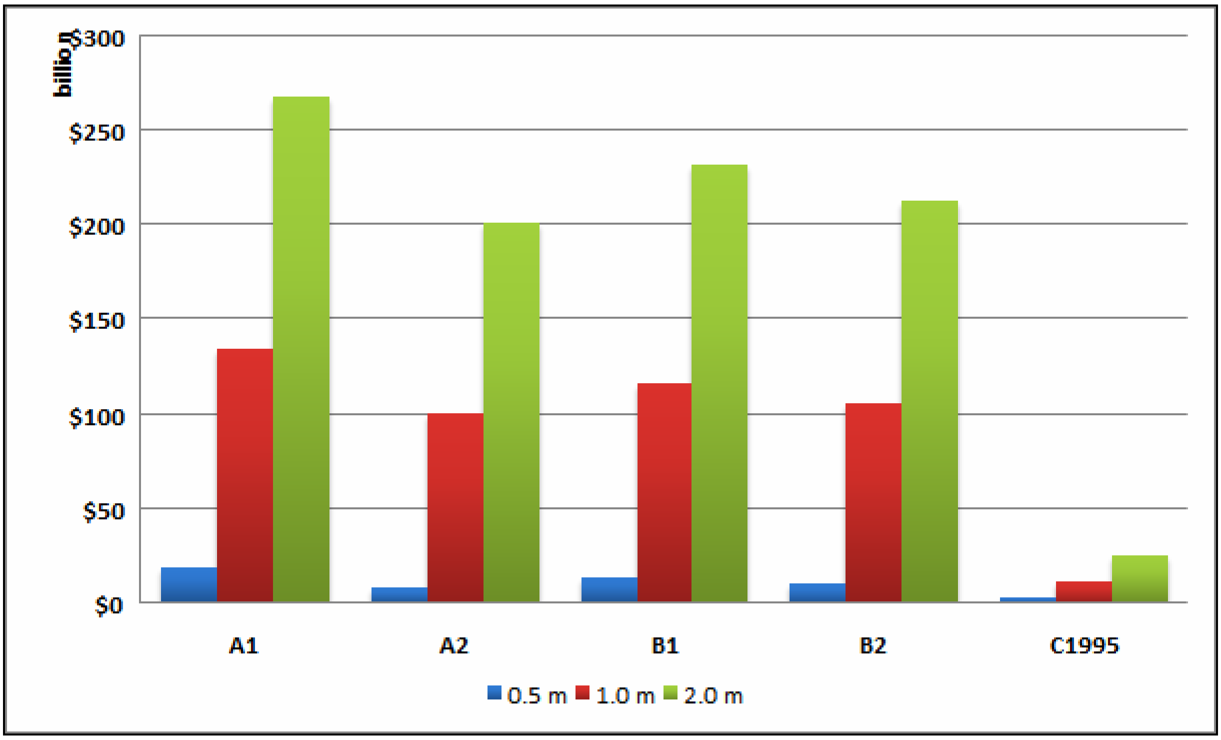


Figure 10: Total damage costs due to sea-level rise in the period 2080-2089 for 0.5m, 1m and 2m sea-level rise in 2100 and for the five socio-economic scenarios with protection.

The damage costs for a 1m rise are between 7 and almost 12 times as high as the damage costs for the 0.5m sea-level rise, depending on the scenario (except for the 1995 control scenario, where the jump is much smaller, but with 4.2 still significant). The jump from 1m to 2m is a lot smaller in magnitude, between 1.9 and 2 times the damage cost of the 1m sea-level rise scenario. There is a significant change in assumptions between the scenario with 0.5m rise and 1m rise that explains much of the difference in the magnitude of increase of damage costs with respect to sea-level rise. Protection costs are assumed to be ten times higher if the rate of sea-level rise is greater than 0.01m per year. This is the case for both the 1m and 2m scenarios, whereas the 0.5m scenario protection costs are much smaller. While the increase in damage costs from the 1m to 2m sea-level rise scenario is almost linear (i.e., a factor of two) over all socio-economic scenarios, the choice of socio-economic scenario has a more significant role to play in the step between the 0.5m and 1m sea-level rise scenario. In some cases the increase of the total damage is higher than the assumed tenfold increase in protection costs (e.g. scenario A2), while in others, the increase in total damage does not follow the increase in assumed protection costs as strongly (e.g. scenario A1).

While the damages from sea-level rise are substantial, they are small compared to the total economy, provided that coastal protection is built. This also holds for the 2m scenario. Note that the global total of Figure 2 hides considerable differences between countries. This issue is discussed in more detail at the end of this report.

In order to understand the reasons for the differences between the scenarios, a closer look at the four damage cost components is needed.

3.2.2 Disaggregating damage costs by socio-economic and sea-level rise scenarios

Figure 11 shows the damage cost components as calculated by FUND and their share of the total damage cost for the 0.5m sea-level rise scenario under the assumption that dikes are built, i.e. that people attempt to protect against rising sea levels following current practise against coastal flooding in much of the world (e.g., East Asia and Europe). The results changes dramatically when it is assumed that people do not protect, a scenario that is analysed later.

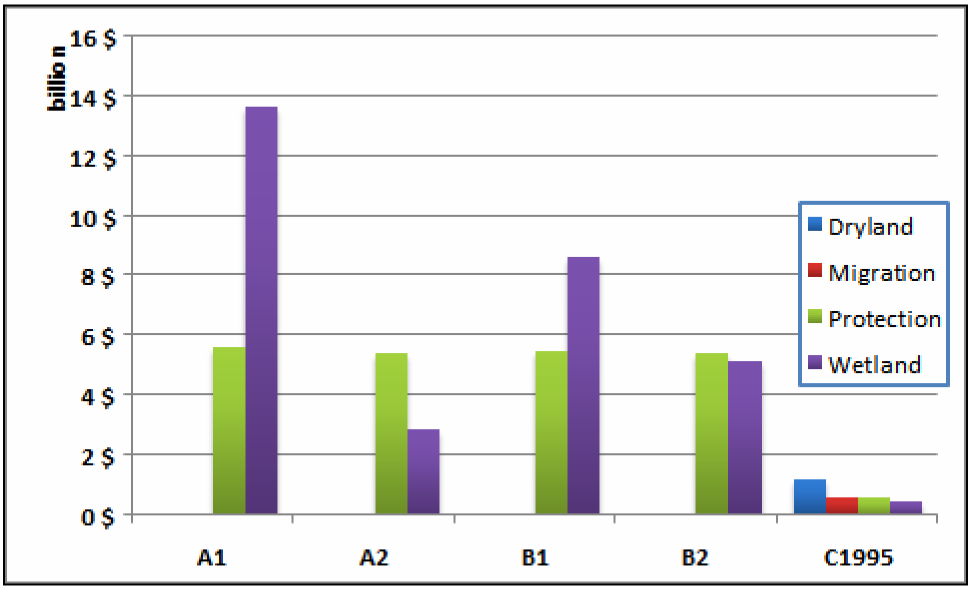


Figure 11: Damage costs of sea-level rise over the four damage cost components in the period 2080-2089 for 0.5m sea-level rise in 2100 with protection. Note that full protection (i.e., no dryland loss and hence no migration) is assumed under A1, A2, B1 and B2.

Ignoring the control scenario for a moment, three conclusions can easily be drawn. First, damage costs from dryland loss and migration are almost entirely avoided, irrespective of the socio-economic scenario selected. This underlines the significance of protection (and adaptation in general). Second, protection costs are not affected by the choice of socio-economic scenario and constitute a significant, and sometimes the most significant, portion of the total damage cost. Third, damage costs from wetland loss are highly sensitive to the socio-economic scenario, with a difference of factor 4.5 between the lowest (A2) and highest (A1) scenario. Since wetland damage costs are a significant share of the total damage for the 0.5m sea-level rise scenario, it is interesting to look at the drivers for the differences in wetland costs.

Two variables influence the wetland costs depicted in Figure 11: the area of wetland lost and the per capita income as shown in Equation (1). The differences in damage costs between the scenarios are almost exclusively due to the latter factor: the differences in per capita income in the socio-economic scenarios. The higher the per capita income, the higher wetland is valued. It is the higher valuation that explains the difference between the scenarios, not a difference in wetland area lost due to sea-level rise, which are very similar between the socio-economic scenarios, for the same sea-level rise scenario.

Looking at the control scenario C1995 reveals the importance of economic growth with relation to the adaptation capability. The costs of building dikes are much more significant in terms of total share of income when GDP is held constant at 1995 levels, which leads to a much lower protection levels and therefore higher damage costs from dryland loss and migration.[3]

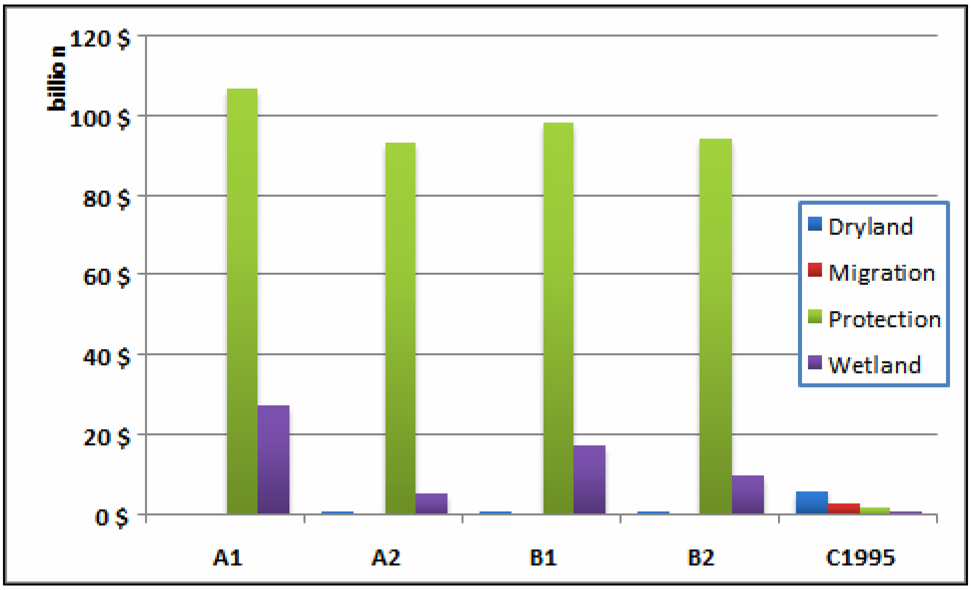


Figure 12: Damage costs of sea-level rise over the four damage cost components in the period 2080-2089 for 1m sea-level rise in 2100 with protection

Figure 12 presents the disaggregation into damage components for the 1m sea-level rise scenario. Protection costs now dominate the total costs for all four SRES scenarios. This is not surprising, given the assumption that protection costs increase by an order of magnitude in this scenario due to the bilinear protection cost calculation. The variation between total costs for protection between the scenarios follow the same pattern that wetland costs show: higher per capita income leads to a higher valuation of dryland, so that more protection is built in the scenarios with high per capita income. While the step from 0.5m to 1m sea-level rise changed the distribution of costs between the four components significantly, the step to the 2m scenario has no such surprises. As can be seen in Figure 13, all costs roughly double compared to the 1m scenario.

[3] Note also that while it is interesting to look at the different distribution of damage costs between the four damage components in the control scenario, one has to take the absolute magnitude of damage of the control scenario with care. The costs for the control scenario are discounted using the Greenbook discounting scheme, which of course assumes economic growth, which is not present in the control scenario.

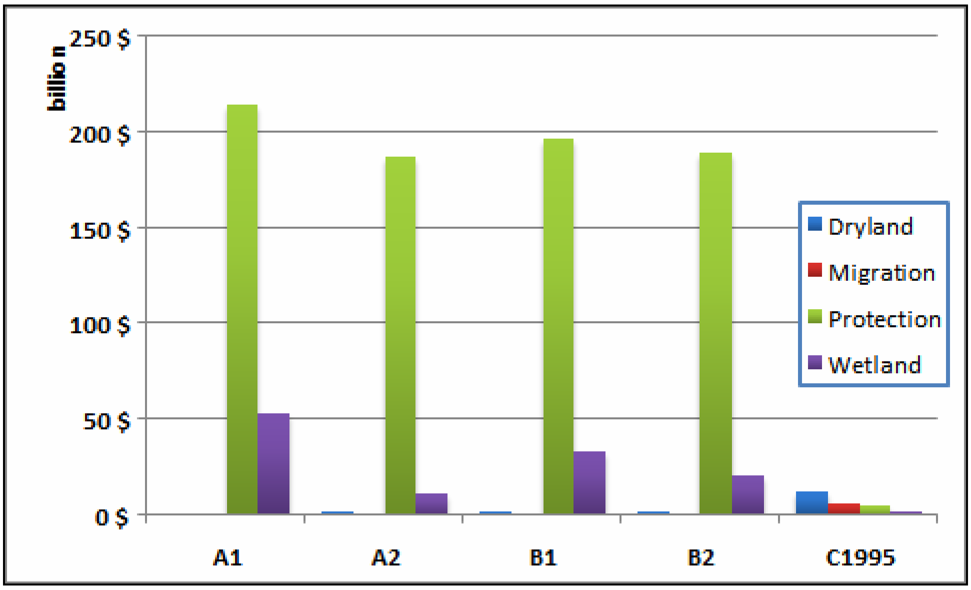


Figure 13: Damage costs of sea-level rise over the four damage cost components in the period 2080-2089 for 2m sea-level rise in 2100 with protection

3.2.3 Regional Distribution of Damage Costs

Sea-level rise damages are not evenly distributed over the world. Figure 14 compares the two scenarios that show the largest difference in total damage cost due to sea-level rise across the Stern Regions. While the distribution of damage costs are not the same for the two scenarios, the same Stern regions bear the majority of damage costs in both scenarios. This should not be a surprise as relative exposure to sea-level rise is the main variable that drives relative damages and for example, East Asia and South Asia have extensive highly populated coastal lowlands irrespective of the scenario considered.

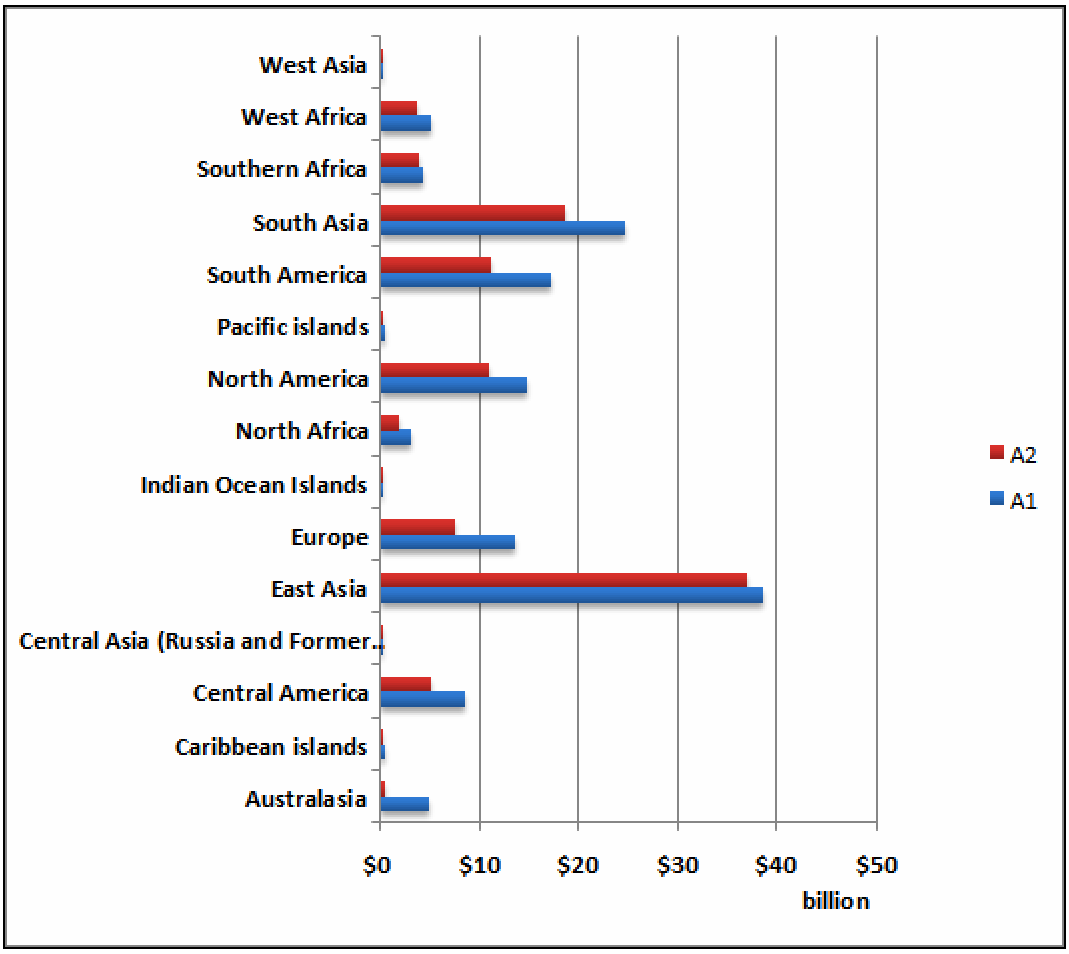


Figure 14: The damage costs of sea-level rise by Stern region in the period 2080-2089 for 1m sea-level rise in 2100 for scenario A1 (highest costs) and A2 (lowest costs) with protection

The three regions that are widely thought to be the most vulnerable to sea-level rise, i.e. the Pacific, Indian Ocean and Caribbean islands bear only a tiny share of the total global damage. At the same time these damage costs for the small island states are enormous in relation to the size of their economy (Nicholls and Tol, 2006). Together with deltaic areas, they will find it hardest to raise the finances necessary to implement protection.

3.2.4 Protection Analysis

The level of protection, that is the length of coastline that is protected using dikes, is normally determined endogenously by a cost-benefit analysis in FUND. Another set of runs where no protection against sea-level rise is allowed were also conducted (for the first time in a FUND analysis). Comparing these two sets of runs with and without protection is insightful for two reasons. First, it shows the huge benefits of protection to sea-level rise in terms of damages avoided. Second, there might be countries that don't have the means to protect their coastline up to the optimal level that would follow from the cost-benefit analysis. This is especially relevant for large rises in sea level as considered in this analysis (Nicholls et al., 2006b).

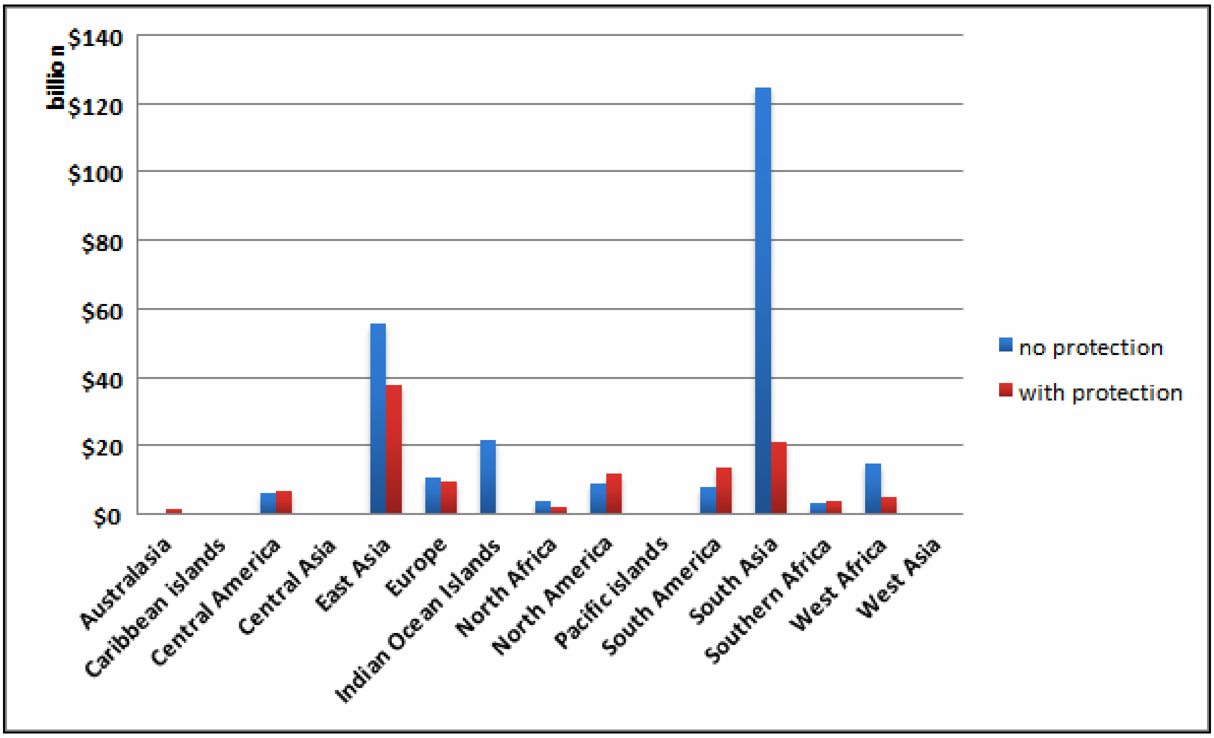


Figure 15: Damage costs due to sea-level rise in the period 2080-2089 for 1m sea-level rise in 2100 for scenario B1

Figure 15 clearly shows the importance of protection for some regions. South Asia is hit by damage costs 5.8 times higher for a no protection scenario compared to a protection scenario. West Africa and West Asia have damage costs in the range of 2.9-3.3 times higher for the no protection scenario. East Asia, Europe and North Africa avoid between 1.1 and 1.5 times higher damage costs with protection. Other regions have lower total damage costs for the no protection scenario than for the scenario that uses a cost benefit analysis to calculate optimal protection. This result is explained with the fact that the cost-benefit analysis on dike building is only approximate and based on myopic assumptions. Particularly, a sharp decline in the economic growth rate in the scenario, but not anticipated by the decision maker, would lead to coastal overprotection. On the other hand, even mild risk aversion would lead to higher dikes than recommended by a cost-benefit analysis. Note that, globally aggregated, avoided impacts outweigh the costs of coastal protection.

The results for the Indian Ocean Islands are regarded as unreliable for this no protection scenario. The Maldives are estimated to be completely inundated in 2085 for the 1-m rise scenario, which raises the value of its dryland for the time step 2080-4 to very large values. This cannot be regarded as a satisfactory valuation from an economic point of view: Such non-marginal damages are outside of the realm of economic valuation. The Maldives disappear much earlier for the 2m sea-level rise scenarios without protection. In those cases, the disappearance of the Maldives do not influence damage cost calculations for the time period 2080-2089, since there is no additional damage happening in that time period anymore.

Disaggregating by damage cost components for some of the region with the largest damage costs shows that lost dryland and resulting migration are the main contributors to damage costs for these regions when they don't protect their coasts (Figure 16). Hence, this analysis well illustrates the enormous benefits of increased protection in terms of damages avoided (cf. Nicholls and Tol, 2006).

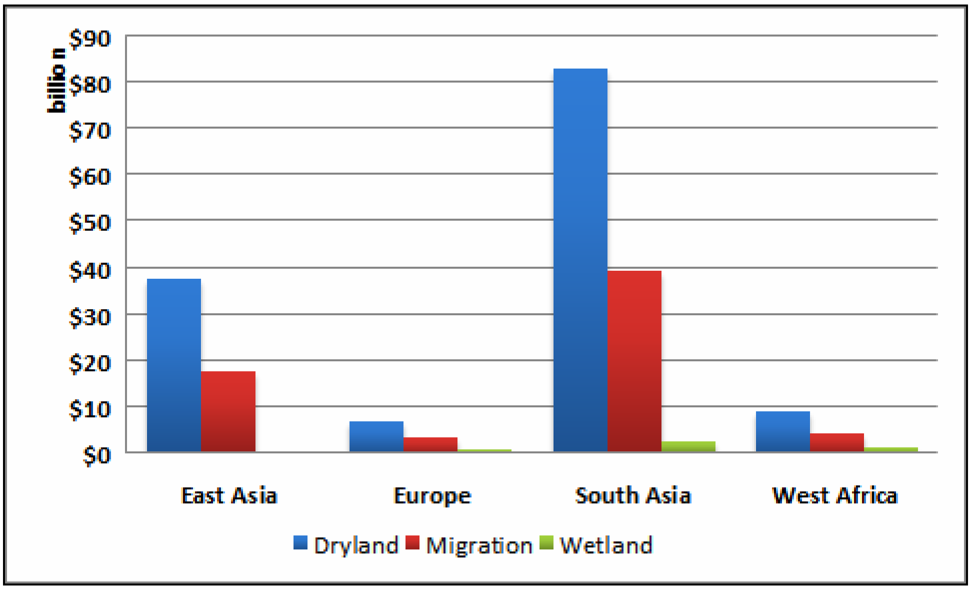


Figure 16: Damage costs of sea-level rise in the period 2080-2089 for 1m sea-level rise in 2100 for scenario B1 without adaptation (hence protection costs are by definition zero).

3.3 Discussion

This analysis with FUND suggests that if sea-level rise was up to 2-m per century, while the costs of sea-level rise increase due to greater damage and protection costs, an optimum response in a benefit-cost sense remains widespread protection of developed coastal areas, as identified in earlier analyses (Nicholls and Tol, 2006; Nicholls et al., 2006b). The socio-economic scenarios are also important in terms of driving these costs. In terms of the four components of costs considered here, protection seems to dominate, with substantial costs from wetland loss under some scenarios. The regional distribution of costs shows a few regions experience most of the costs, especially South Asia, South America, North America, Europe, East Asia and Central America. Under a scenario of no protection, the costs of sea-level rise increase dramatically due to land loss and population displacement: this scenario shows the significant benefits of the protection response in reducing the overall costs of sea-level rise.

While the FUND analysis suggests widespread protection, earlier analysis shows that the actual adaptation response to sea-level rise is more complex than the benefit-cost approach used here (Nicholls et al., 2006a). There are several factors to consider. Firstly, the SRES socio-economic scenarios are quite optimistic about future economic growth: lower growth may lead to lower damages in monetary terms, but it will also lead to less protection. Secondly, the benefit-cost approach implies a proactive approach to the protection, while historical experience shows most protection has been a reaction to actual or near disaster. Therefore, high rates of sea-level rise may lead to many more coastal disasters, even if the ultimate response is better protection. Thirdly, disasters such as Hurricane Katrina could trigger coastal abandonment, and hence have a profound influence on society's future choices concerning coastal protection as the pattern of coastal occupancy might change radically. A cycle of decline in some coastal areas is not inconceivable, especially in future worlds where capital is highly mobile and collective action is weaker. As the issue of sea-level rise is so widely known, disinvestment from coastal areas may even be triggered without disasters: for example, small islands may be highly vulnerable if investors are cautious (cf. Barnett and Adger, 2003; Gibbons and Nicholls, 2006). This raises questions concerning possible thresholds in response to sea-level rise and environmental change, but these issues are poorly understood. For these reasons, protection may not be as widespread as suggested in this analysis, especially for the largest scenario of 2m/century. However, the FUND analysis shows that protection is much more likely and rational than is widely assumed, even with a large rise in sea level. The common assumption of a widespread retreat from the shore is not inevitable and coastal societies will have much more choice in their response to this issue than is often assumed.

While the no protection scenarios have damages that transcend the marginal valuation framework of economics and therefore have to be examined with care, it is also clear from this analysis that – under the assumption that protection is built – such non-marginal losses of land do not occur and calculation of damage costs is possible.

4. Conclusions

In conclusion, this analysis confirms that there is significant exposure to sea-level rise in coastal areas. While not investigated here, this exposure is almost certain to grow substantially through the 21st century as coastal populations grow and develop. The regional distribution is also likely to change significantly due for example to the significant ongoing economic growth in the coastal regions of China. However, widespread protection against sea-level appears economically rational even under large rises in sea level (2-m/century), which is counter to much ‘conventional’ wisdom on the issue. However, the analysis has important limitations and the questions that are raised such as a cycle of disinvestment and ultimate coastal abandonment due to loss of faith in a coastal location need to be investigated and ultimately included in the analysis. Much research remains to refine our understanding of these important issues.

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