The Economic Impact of Substantial Sea-Level Rise

David Anthoff[1]
Economic and Social Research Institute, Dublin, Ireland
International Max Planck Research School on Earth System Modelling, Hamburg, Germany
Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany

Robert J. Nicholls
School of Civil Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Southampton, UK SO17 1BJ, United Kingdom

Richard S.J. Tol
Economic and Social Research Institute, Dublin, Ireland
Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands

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Abstract

Using the *FUND* model, an impact assessment is conducted over the 21st century for rises in sea level of up to 2-m/century and a range of socio-economic scenarios downscaled to the national level, including the four SRES storylines. This model balances the costs of retreat with the costs of protection, including the effects of coastal squeeze. While the costs of sea-level rise increase with greater rise due to greater damage and protection costs, the model suggests that 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 in *FUND*, protection dominates, with substantial costs from wetland loss under some scenarios. The regional distribution of costs shows that a few regions experience most of the costs, especially East Asia, North America, Europe and South Asia. Importantly, this analysis suggests that protection is much more likely and rational than is widely assumed, even with a large rise in sea level. This is underpinned by the strong economic growth in all the SRES scenarios: without this growth, the benefits of protection are significantly reduced. It should also be noted that some important limitations to the analysis are discussed, which collectively suggest that protection may not be as widespread as suggested in the *FUND* results. Equity weighting allows the damages to be modified to reflect the wealth of those impacted by sea-level rise. Taking these distributional issues into account increases damage estimates by a factor of three, reflecting that the costs of sea-level rise fall disproportionately on poorer developing countries.

Key words: Sea-level rise;Socio-economic scenarios;costs;protection;equity weighting

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[1] Corresponding author. Email: david@anthoff.de, phone: +49 (89) 27374106, postal address: Türkenstr. 21, 80799 München, Germany

Introduction

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) raises 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 (e.g., Overpeck et al., 2006). The IPCC AR4 (IPCC, 2007) suggests that a rise of >1-m/century is unlikely during the 21st Century, although no formal upper bound including contributions from the large ice sheets is provided. Others argue that this remains an important issue for scientific analysis based on simple models (Rahmstorf, 2007), observations (Rahmstorf et al., 2007) and palaeo-analogues (Rohling et al., 2008). Less appreciated is the so-called 'commitment to sea-level rise' whereby even if the climate is stabilized immediately, sea levels continue to rise for many centuries due to the long timescales of the oceans and the large ice sheets (Nicholls and Lowe, 2006, Nicholls et al., 2006).

To date few studies have considered large rises in sea-level rise – the few analyses tend to focus on exposure (i.e. potential impacts) only (Nicholls et al., 2006). This paper also includes a coastal protection response. It builds on the earlier global analysis of Nicholls et al. (2008) and provides evidence on the consequences of large rises in sea level over the 21st Century using the coastal module of an integrated assessment model (*FUND*: The Climate Framework for Uncertainty, Negotiation and Distribution) for scenarios of sea-level rise in the range of 0.5 to 2 meters by 2100 (which are consistent with the extremes analysis of Arnell et al. (2005) and the UKCIP09 sea-level rise scenarios (Lowe et al., 2009). The model calculates the welfare loss due to rising sea levels for a number of socio-economic scenarios, assumes some basic adaptation of humans to sea-level rise (a simple choice between protect and retreat) and aggregates damage costs for a number of damage types.

The results are presented using standard discounting methodology and using equity weights. The use of equity weights in the context of climate change was first suggest by Pearce, Cline et al. (1996) and since then a number of studies have applied equity weights on a regional scale in the context of climate change (Tol et al., 1996, Anthoff et al., 2009, Tol, 1999, Azar and Sterner, 1996, Azar, 1999, Pearce, 2003). This paper is the first to present damage estimates that use equity weights on a *national* basis. Equity weights correspond to the intuition that 'a dollar to a poor person is not the same as a dollar to a rich person'. More formally, the marginal utility of consumption is declining in consumption: a rich person will obtain less utility from an extra dollar available for consumption compared to a poor person. Equity-weighted damage estimates take into account that the same monetary damage to someone who is poor causes greater welfare loss than if that damage had happened to someone who is rich. Using national data instead of regional data for such an exercise is important in order to avoid smoothing of income inequalities by using larger regions to calculate average per capita incomes. Use of equity weights is particular appropriate in the context of sea-level rise, given the huge difference in income of those effected and the difficulties of assessing the true welfare loss in such a situation without using a concept like equity weighting.

Model

The Coastal Module of *FUND* 2.8n is used to calculate damages[2] caused by various scenarios of sea-level rise over the next century (see figure 1). 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. (2008).

The model is driven by exogenous scenarios of population and GDP growth on a per country scale. Five distinct socio-economic scenarios are evaluated for this study: the four well-known SRES scenarios A1, A2, B1 and B2 downscaled from the original source (Nakicenovic and Swart, 2000) and a control scenario of constant population and GDP at 1995 levels[3] 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. 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 treated as a linear interpolation.

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 protection (with dikes) 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 1). *FUND* determines the optimum amount of protection (in benefit-cost terms) based on the socio-economic situation, the expected damage

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[2] In this paper, all the costs of sea-level rise are considered damages, including protection costs.

[3] 1995 is the base year in FUND.

of sea-level rise if no protection existed, 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. Wetland loss due to coastal squeeze is counted as a cost of protection. The number of people displaced is a linear 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:

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

where $V_{t,i}$ is wetland value at time t in country i; 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.

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 cost of people displaced is three times average per capita income (Tol, 1995).

Following the method of Nicholls, Tol et al. (2008), 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 level of protection is based on a cost-benefit analysis. The level of protection is modeled as the share of the coastline which is protected. The cost-benefit equation is

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

where L is the fraction of the coastline to be protected. PC is the net present value of the protection cost if the whole coast is protected, WL is the net present value of wetland lost if the whole coast would be protected and DL is the net present value of dryland lost if no protection would take place.

PC is calculated assuming annual protection costs are constant, which is justified for the following three reasons: Firstly, the coastal protection decision makers anticipate a linear sea-level rise. Secondly, coastal protection entails large infrastructural works, which which have a life of 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 per capita income of the economy, g. The net present costs of protection PC are

$$PC_{t,i} = \sum_{s=t}^{\infty} \left(\frac{1}{1+\rho+g_{t,i}} \right)^{s-t} PC_i^a = \frac{1+\rho+g_{t,i}}{\rho+g_{t,i}} PC_i^a \tag{3}$$

where PC^a is the average annual costs of protection, which is constant.

WL is the net present value of the wetlands lost due to full coastal protection. Land values are assumed to rise at the same pace as per capita income growth. The amount of wetland lost per year is assumed to be constant. The net present costs of wetland loss WL follow from

$$WL_{t,i} = \sum_{s=t}^{\infty} \left(\frac{1+g_{t,i}}{1+\rho+g_{t,i}} \right)^{s-t} W_{t,i} = \frac{1+\rho+g_{t,i}}{\rho} W_{t,i} \tag{4}$$

where $WL_{t,i}$ denotes the value of wetland loss in the year and country the decision is made (see above). $W_{t,i}$ is the use value of the wetlands that would be lost due to full protection in country i at time t.

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 per capita income growth. The amount of dryland lost per year is assumed to be constant. The net present costs of dryland loss DL are

$$DL_{t,i} = \sum_{s=t}^{\infty} \left(\frac{1+g_{t,i}}{1+\rho+g_{t,i}} \right)^{s-t} D_{t,i} = \frac{1+\rho+g_{t,i}}{\rho} D_{t,i} \tag{5}$$

where $DL_{t,i}$ is the value of dryland loss in the year and country the decision is made (see above). $D_{t,i}$ is the use value of the dryland that would be lost if no protection would take place in country i at time t.

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.(2008).

The damage costs presented in this paper are the total damage costs for the period 2005-2100. Two different welfare functions are used to aggregate damages across time and space, depending on whether equity weights are employed or not. Without equity weights, monetary damages for every country are calculated, then discounted per country using a social discount rate with a pure rate of time preference of 1% and then those totals for every country are summed as follows:

$$D = \sum_{i}^{N} \sum_{t=0}^{T} D_{t,i} \left(1 + \rho + \varepsilon g_{t,i}\right)^{-t} \tag{6}$$

where D is total damage from sea-level rise, $D_{t,i}$ is damage in country i at time t, $g_{t,i}$ is the average per capita growth rate of consumption in country i from the start of the time period to time t, N is the number of countries and T is the end of the time period under consideration. ε is a parameter for inequality aversion (set to 1 for this paper) and ρ is the pure rate of time preference (set to 1% for this paper).

Equity weighting follows the reasoning outlined in Anthoff et al. (2009). When equity weights are employed, the equation for the aggregation of damages is derived explicitly from a utilitarian social-welfare function as follows:

$$W = W\left(C_{1,1}, \ldots, C_{N,T}, D_{1,1}, \ldots, D_{N,T}\right) = \sum_{i}^{N} \sum_{t=0}^{T} U\left(C_{t,i}, D_{t,i}\right) P_{t,i} \left(1 + \rho\right)^{-t} \tag{7}$$

where W is welfare, $C_{t,i}$ is average per capita income in country i at time t, $D_{t,i}$ is the damage due to sea-level rise, $P_{t,i}$ is population and $U(.)$ is the utility function. For this paper the usual logarithmic utility function $U(c) = \ln c$ is employed. Such a utility function reflects the intuition that a dollar is worth more to a poor person than to a rich person, i.e. it has a declining marginal utility of consumption.

As a linear approximation, damages from sea-level rise are multiplied with the marginal welfare change of consumption of the country they occur to before they are summed:

$$\sum_{i}^{N} \sum_{t=0}^{T} D_{t,i} \frac{\partial W}{\partial C_{t,i}} \approx \sum_{i}^{N} \sum_{t=0}^{T} D_{t,i} \frac{1}{C_{t,i}} \left(1 + \rho\right)^{-t} \tag{8}$$

This gives the welfare loss from sea-level rise in welfare units. In order to convert back to monetary units, one has to multiply the results with the marginal. We follow Fankhauser et al.

(1997) and normalise with world average per capita income. Conceptually, this normalization corresponds to the distribution of a unit loss of welfare that is optimal from the perspective of a global planner. The damage calculated thus is

$$D_{ew} = \left(\frac{dU}{d\bar{C}_0} \right)^{-1} \sum_i^N \sum_{t=0}^T D_{t,i} \frac{1}{C_{t,i}} (1+\rho)^{-t} = \sum_i^N \frac{\bar{C}_0}{C_{0,i}} \sum_{t=0}^T D_{t,i} \frac{C_{0,i}}{C_{t,i}} (1+\rho)^{-t} \qquad (9)$$

where D_{ew} is the equity-weighted damage and $\bar{C}_0$ is world average per capita income at time 0, in our case in the year 2005. Equation (9) can be approximated as

$$D_{ew} = \sum_i^N \frac{\bar{C}_0}{C_{0,i}} \sum_{t=0}^T D_{t,i} \left(1 + g_{t,i} + \rho\right)^{-t} \qquad (10)$$

where $g_{t,i}$ is the average growth rate of per capita income between year 0 and year *t*. The right most term is thus the neoclassical discount rate of money. The term $\bar{C}_0 / C_{0,i}$ is the equity weight for every country. It can be seen that countries with higher average per capita income then the world average will receive a lower weight and countries with lower per capita income a higher weight, following the logic of equity weighting.

Results

Results from the model runs are analyzed along the following dimensions: (1) global damage costs by scenario; (2) the damage cost components; (3) regional impacts; (4). impacts without protection; and (5) equity-weighted results.

Global damage costs by socio-economic and sea-level rise scenarios

While the choice of socio-economic scenario has an influence on the global 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 2).

The damage costs for a 1m rise are between 4.8 and 5.2 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 increase in costs is only 4 times). The increase in costs from 1m to 2m is only 2.0 times the damage cost of the 1m sea-level rise scenario. The assumed bilinear protection costs between the scenario with 0.5m rise and 1m rise explains these different increases in damage costs with respect to sea-level rise. While the increase in damage costs from the 1m to 2m sea-level rise scenario is almost a factor of two in each of the socio-economic scenarios, the difference between 0.5m and 1m sea-level rise does depend on the socio-economic scenario.

In all cases (except the 1995 control scenario) the increase of the total damage is lower than the assumed tenfold increase in protection costs. The overall difference between the SRES scenarios is very small.

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

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

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

Figure 3 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). Note that the results change dramatically if it is assumed that people do not protect; this scenario is analysed in a later section.

Ignoring the control scenario for a moment, three conclusions can be drawn. First, damage costs from dryland loss and migration are a fraction of the costs of protection in every scenario (dryland costs being about one fifth and migration being one tenth of protection costs). Protection costs on the other hand are the most important component for every scenario. This underlines the significance of protection (and adaptation in general). Second, protection costs are less affected by the choice of socio-economic scenario than dryland loss and migration costs. The biggest difference between scenarios for dryland loss and migration costs is a factor of 1.8, for protection costs it is 1.5. Damage costs from wetland loss are even less sensitive to the choice of scenario, with a maximum difference of factor 1.3. Wetland costs are the second most significant damage component in all scenarios. Third, for every cost component except wetland loss, the highest cost scenario is A2, followed by B2, B1 and A1. For wetland costs, the order is reversed, because wetland cost differences between scenarios are mainly driven by the differences in valuation between socio-economic scenarios: higher per capita income place a higher value on wetland loss and therefore produce higher wetland costs. With the other damage costs, higher per capita income mainly leads to more protection, which explains why the effect of higher per capita income is positive in those cases.

Figure 4 presents the disaggregation into damage components for the 1m sea-level rise scenario. Wetland costs are the only ones that react roughly linearly to the doubling of sea-level rise, they are around two times as high as for the 0.5m sea-level rise in all scenarios. Protection costs increase between 4.2 to 6.6 times compared to the lower sea-level rise scenario, while dryland loss and migration costs increase by an order of magnitude (factors between 10.7 and 11.4) compared to the lower sea-level rise scenario. Due to the increase in adaptation costs (i.e. the bilinear nature of protection costs), adaptation is significantly more costly in the 1m sea-level rise scenario and the cost-benefit analysis finds that the optimal length of coast to protect is lower than in the 0.5m scenario (e.g. it is about 40% lower averaged over time for the A1 scenario, 46% lower for A2, 42% lower for B1 and 45% lower for B2), which leads to a situation where total damage is more evenly divided between the four damage cost components.

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 5, all costs roughly double compared to the 1m scenario. This is not surprising, since the model does not have a change in cost assumptions build into this step.

Regional Distribution of Damage Costs

Sea-level rise damages are not evenly distributed over the world. Figure 6 compares the two scenarios that show the largest difference in total damage cost due to sea-level rise across all regions. While the distribution of damage costs is not the same for the two scenarios, the same countries 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 large, densely-populated coastal lowlands irrespective of the scenario considered.

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.

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*. For the first time with a *FUND* analysis, another set of runs where no protection against sea-level rise is allowed were also conducted. Comparing these two sets of runs with and without protection is insightful for three reasons. First, it shows the huge benefits of protection to sea-level rise in terms of the damages avoided. Second, there might be countries that do not 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., 2008). Third, sea-level rise impacts are often presented without considering coastal protection (e.g., Dasgupta et al., 2009). This allows for a comparison between such studies and *FUND*.

Figure 7 clearly shows the importance of protection, in particular for the 0.5m sea-level rise scenario. Total damages are between 3.4 and 3.7 times higher when no protection is build for that scenario, depending on the socio-economic scenario. For 1m and 2m sea-level rise the damages in the no-protection scenario are only around 1.4 times as high compared to a protection scenario. Since protection costs are assumed to be ten times higher than in the 0.5m case, this is hardly surprising. A look at the control Scenario C1995 is particularly interesting, as population and economic indicators are held constant at 1995 levels, while sea-level rise is assumed to occur. Especially in the two scenarios with the higher protection costs (1m and 2m), the importance of the significant economic development assumed in all the SRES scenarios can be seen. In both cases, effective protection is hardly possible under the assumption of today’s socio-economic situation. The lesson to be learned from this is twofold: (1) protection can significantly lower total damages, but (2) only when economic growth enables this sometimes costly investment in protection to occur. Hence protection and economic growth are coupled, which has often been ignored in earlier analyses where socio-economic conditions are held constant as sea-level rises.

Some of the results for no protection scenarios are peculiar at first sight. For example, 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. After 2085, the value is zero. 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 (2050) for the 2m sea-level rise scenarios without protection, so that the costs of the 2m scenario fall below that of the 1m between 2050 and 2085.

Figure 8 displays the benefit gained from protection for specific countries. It shows that protection is a lot more important for some countries than for others, which reflects differences in the efficacy of coastal protection. In densely populated and rich, dike building has a high return in that a small expense prevents substantial damage. If people are dispersed and poor, the pay-off to coastal protection is much smaller.

Equity weighting

Figure 9 compares damages from sea level that are equity weighted with estimates that are not weighted – or rather, that are weighted with the particular assumption that a dollar to a poor woman equals a dollar to a rich woman. Damages are between 2.9 and 3.2 times higher when equity weights are employed. The equity-weighted results indicate the size of the welfare loss due to sea-level rise when the distribution of income of those damaged is considered. Equity-weighing makes the smallest difference in the B1 scenario, which assumes rapid convergence of per capita income, and the largest difference in the A2 scenario for which income convergence is slower. However, the effect of equity weighing is much smaller than the difference in 2100 income distributions would suggest. This is because, in the first part of the scenario, the income distribution is determined by the 2000 income distribution, which is equal between the scenarios.

Figure 10 disaggregates the results for some example countries. Two forces drive the results. Damages in high income countries, like the United States, are scaled down by a significant proportion, in this case the damage estimates for the United States without equity weights are six times higher than with equity weights. For low income countries, the result of applying equity weights is the opposite: for example, Bangladesh’s damage estimates are 12 times higher with equity weighting compared to unweighted monetary results. Hence, the application of equity weights is not uniform across the world: they will increase damage estimates for countries that have a per capita income below world average and decrease damages for countries with per capita income above world average. Given that more impacts accrue in low income countries, the overall effect of applying equity weights is to increase global damage estimates.

Discussion/Conclusions

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., 2008). This analysis also demonstrates that the benefits of protection increase significantly with time due to the economic growth assumed in the SRES socio-economic scenarios. The different assumptions about population and gross domestic product within the socio-economic scenarios are also important drivers of the value of the exposed assets. This influences the protection versus retreat decision explicit with *FUND* and hence the costs of sea-level rise (cf. Nicholls, 2004)..More attention might be given to this aspect of change in future analyses.

In terms of the four components of costs considered in *FUND*, protection dominates, with substantial costs from wetland loss under some scenarios. The regional distribution of costs shows that 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 greatly due to the increase in 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 in *FUND* (Tol and Fankhauser, 1998, Nicholls and Tol, 2006). Building on these views, there are several factors to consider. Firstly, the aggregated scale of analysis in *FUND* may overestimate the extent of protection as shown by more detailed multi-scale analyses of parts of the UK and Germany (Turner et al., 1995; Sterr, 2008). It is also worth noting that retreat is now being considered more seriously, especially in parts of Europe (Eurosion, 2004, DEFRA, 2004, 2006, Rupp-Armstrong and Nicholls, 2007), driven by multiple goals including maintaining coastal wetlands due to the EU Habitats Directive. However, this is unlikely to change the qualitative conclusion that protection can be justified in more developed locations, even given a large rise in sea level. Secondly, 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 reduce the capacity to protect as shown in these analyses. Strong growth underpins the investment necessary to protect. Thirdly, the benefit-cost approach implies perfect knowledge and 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 more frequent coastal disasters, even if the ultimate response is better protection. Fourthly, even though it is economically rational to protect, there are questions of who pays and who benefits, and in some cases such as islands and deltas the diversion of investment from other uses could overwhelm the capacity of these societies to protect (cf. Fankhauser and Tol, 2005). As the benefit-cost ratio improves with time, it appears that near-term decisions on protection may have important consequences for the long-term direction of the adaptation response to sea-level rise. Fifthly, building on the fourth point, *FUND* assumes that the pattern of coastal development persists and attracts future development. However, major disasters such as the landfall of hurricanes could trigger coastal abandonment[4], 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).

For these above 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 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 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.

The equity-weighted results highlight how important it is to not only look at the absolute magnitude of damage but also who will be affected. The welfare loss of even small damages to poor societies can be enormous. There is no consensus within the economic literature that equity-weighted damages ought to be used when policy instruments like Pigouvian taxes are designed, and hence the results presented here should not be used without further investigation for policy design. But there is little question that as a measure of actual welfare loss happening, equity-weighted results are much more accurate than pure monetary damage estimates. The question of what to do about the discrepancy in severity of impacts to poor and rich people is an ethical one, but in calculating damage estimates these differences should be made explicit to not under- or overstate the true welfare loss that climate change might cause, as we have done with the equity-weighted results in this paper.

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[4] The population of New Orleans peaked before Hurricane Betsy in 1965 and never fully recovered (Grossi and Muir Wood, 2006). Hurricane Katrina in 2005 may mark another long-term decline in the city's population.

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Figures

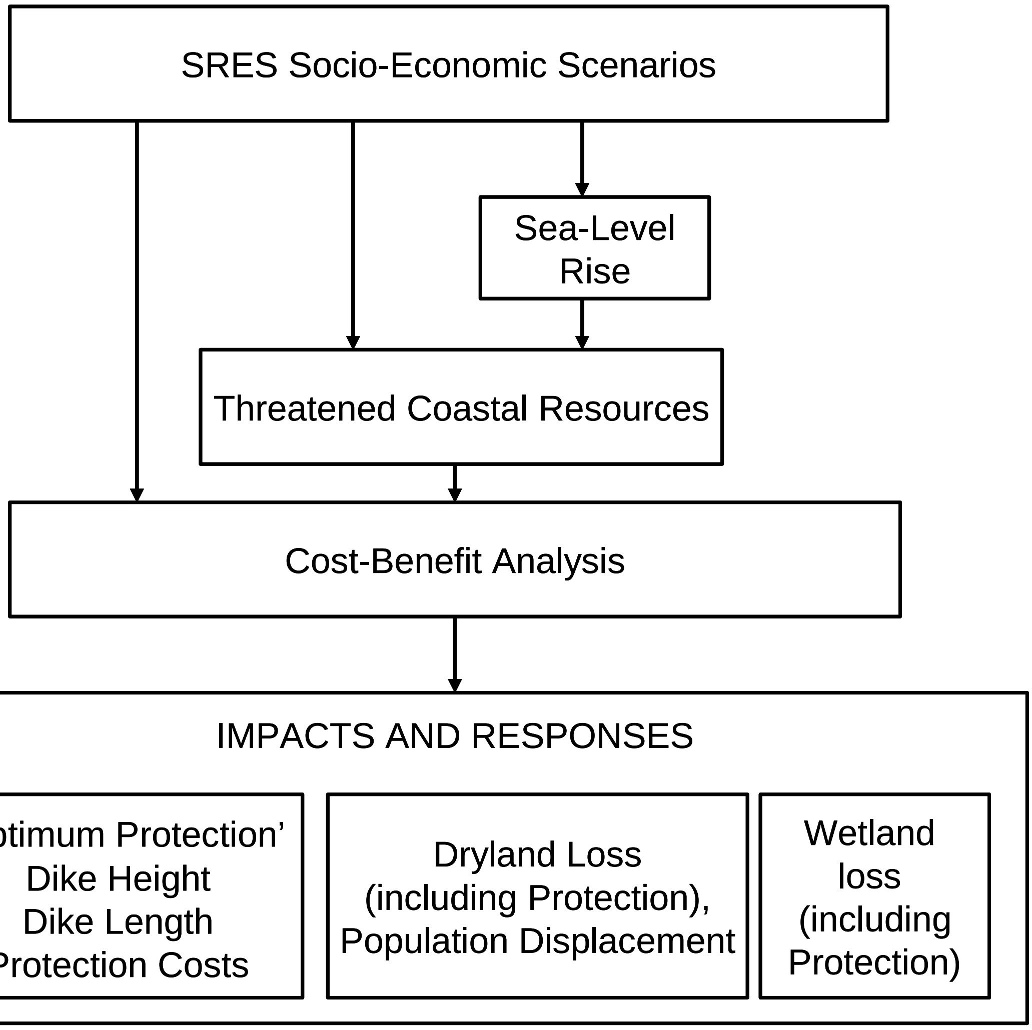

Figure 1: A flow chart summarising the operation of the *FUND* module for coastal areas

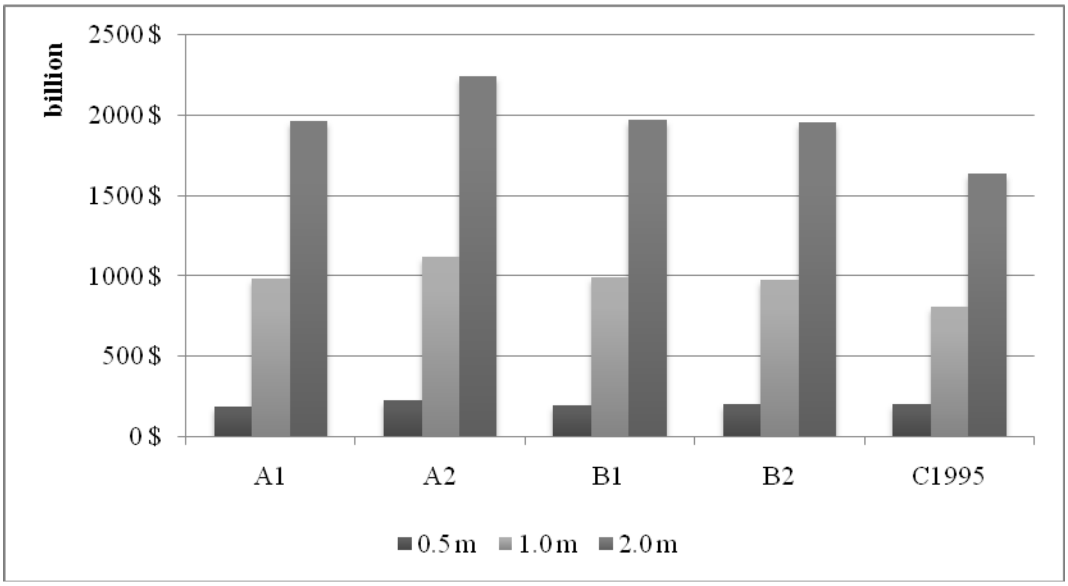

Figure 2: Total damage costs due to sea-level rise for 0.5m, 1m and 2m sea-level rise in 2100 and for the five socio-economic scenarios with protection

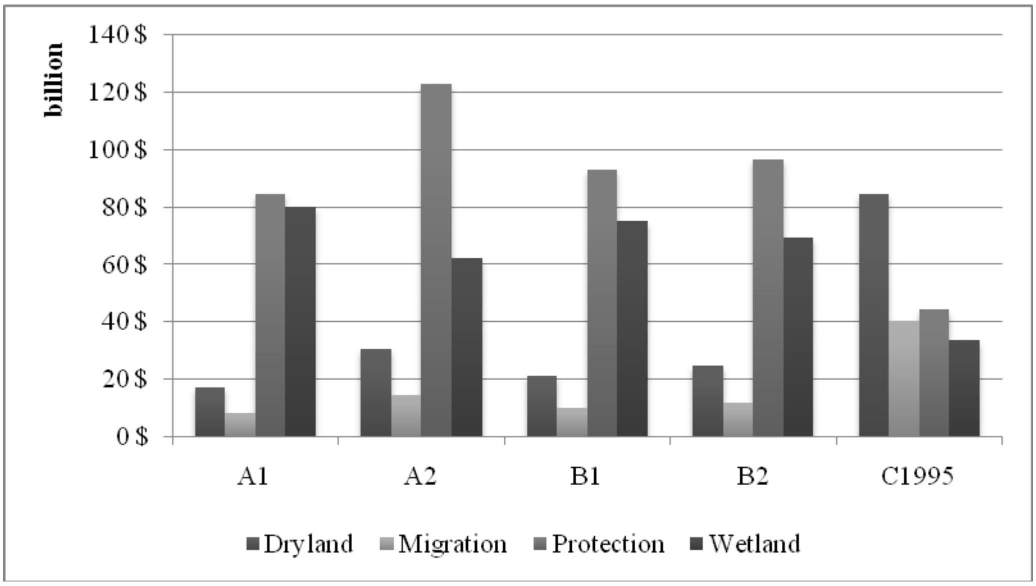

Figure 3: Damage costs of sea-level rise over the four damage cost components for 0.5m sea-level rise in 2100 with protection.

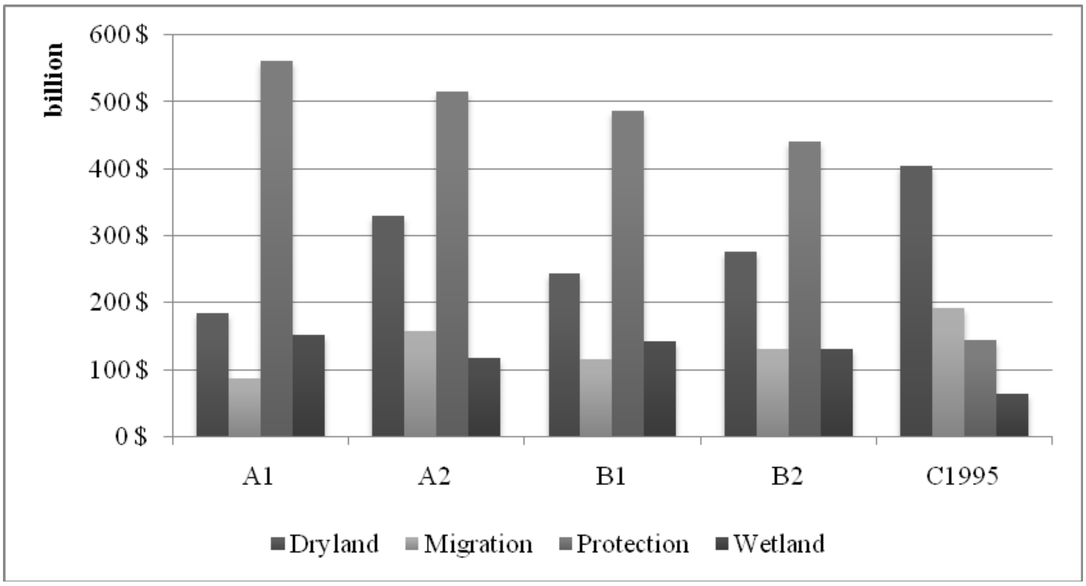

Figure 4: Damage costs of sea-level rise over the four damage cost components for 1m sea-level rise in 2100 with protection

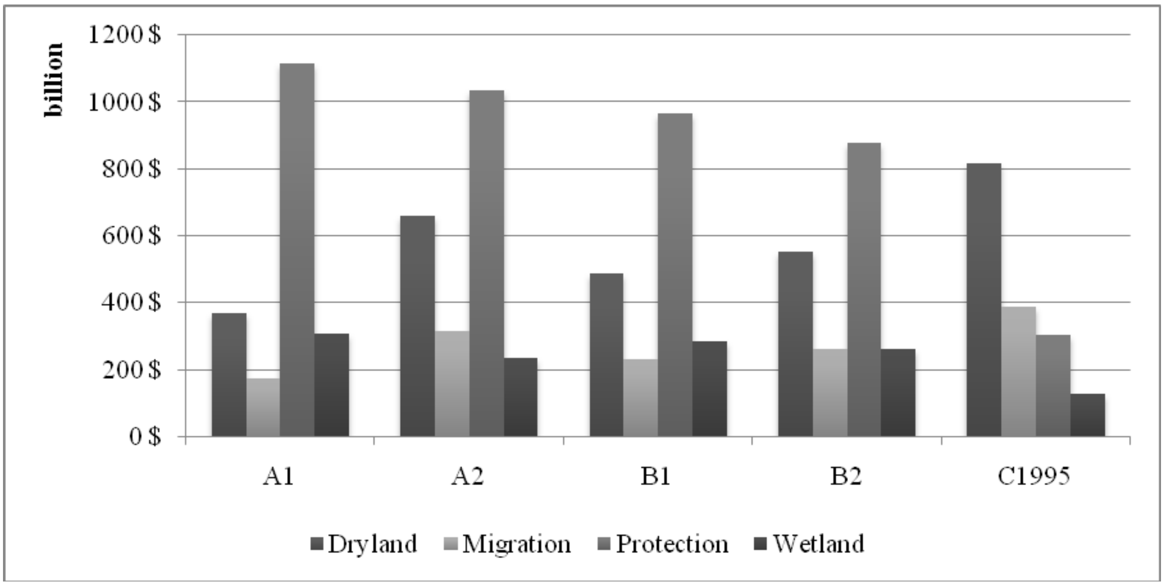

Figure 5: Damage costs of sea-level rise over the four damage cost components for 2m sea-level rise in 2100 with protection

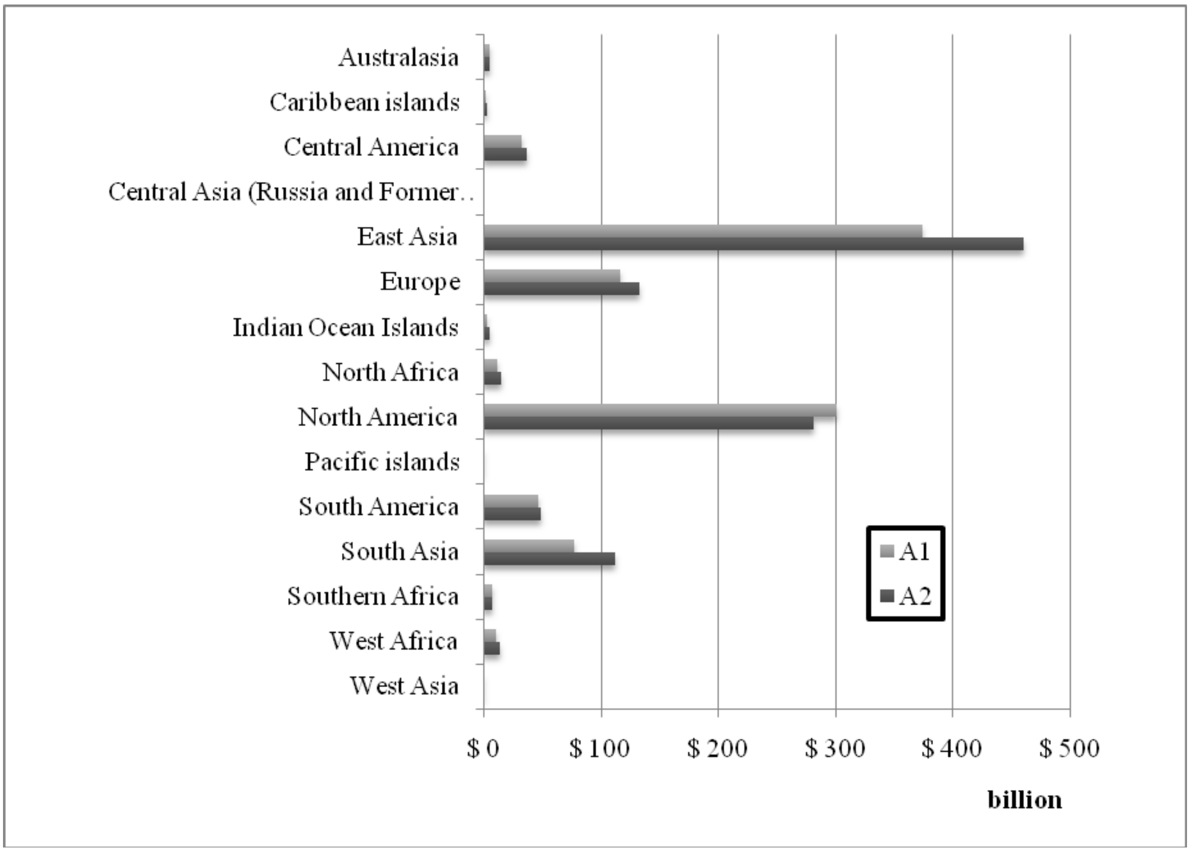

Figure 6: Damage costs of sea-level rise by region for 1m sea-level rise in 2100 for scenario A1 (highest costs) and A2 (lowest costs) with protection

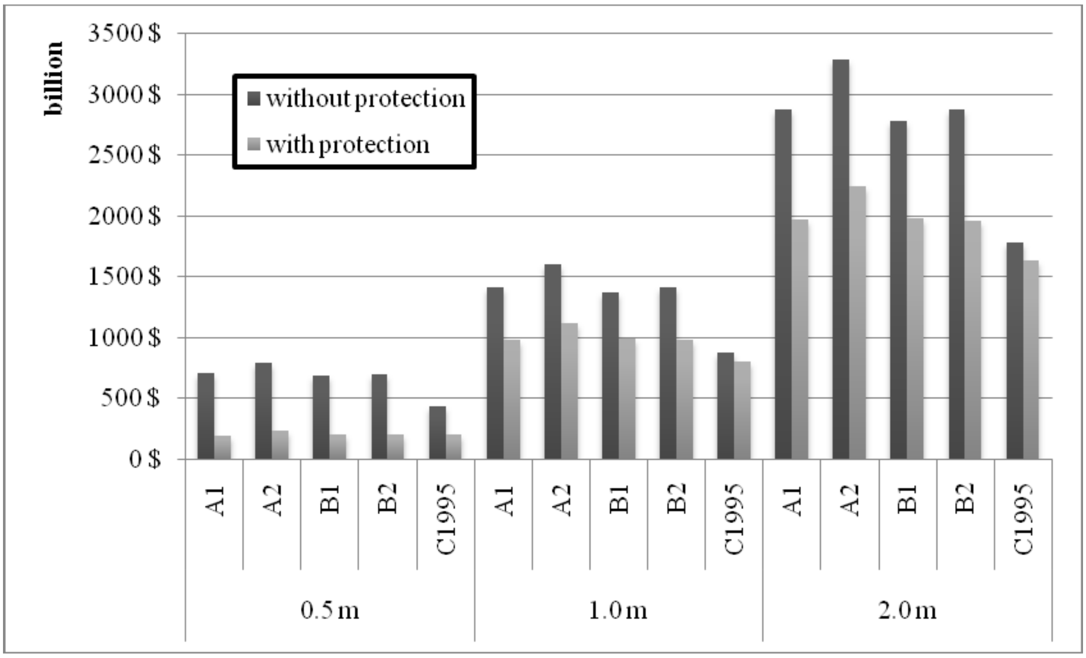

Figure 7: Damage costs due to sea-level rise with and without protection in the year 2100

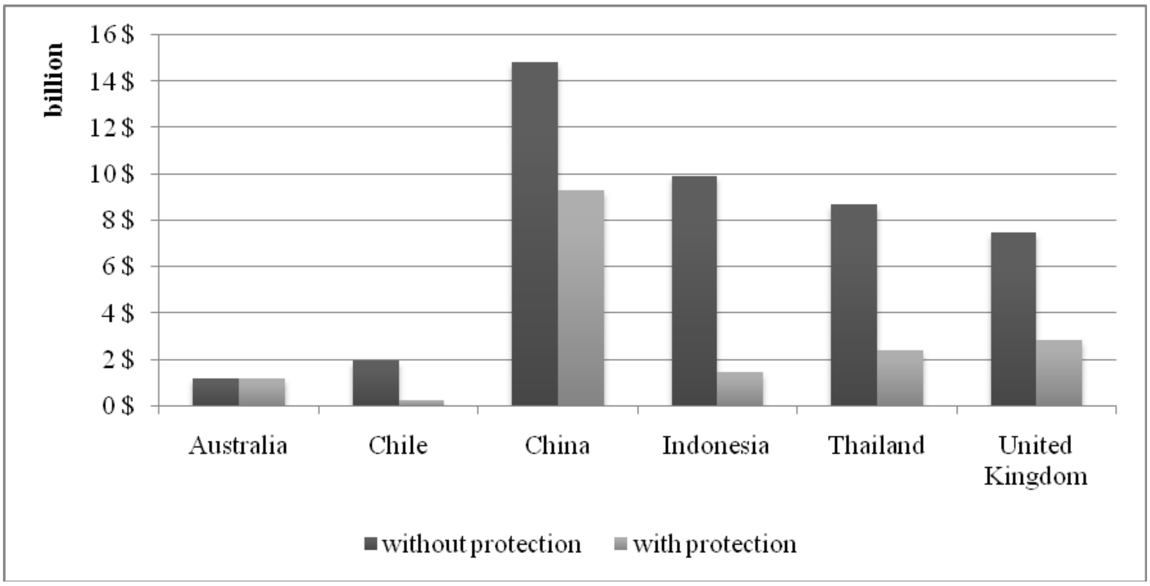

Figure 8: Damage costs of sea-level rise for 0.5m sea-level rise in 2100 for scenario A1 with and without protection for selected countries.

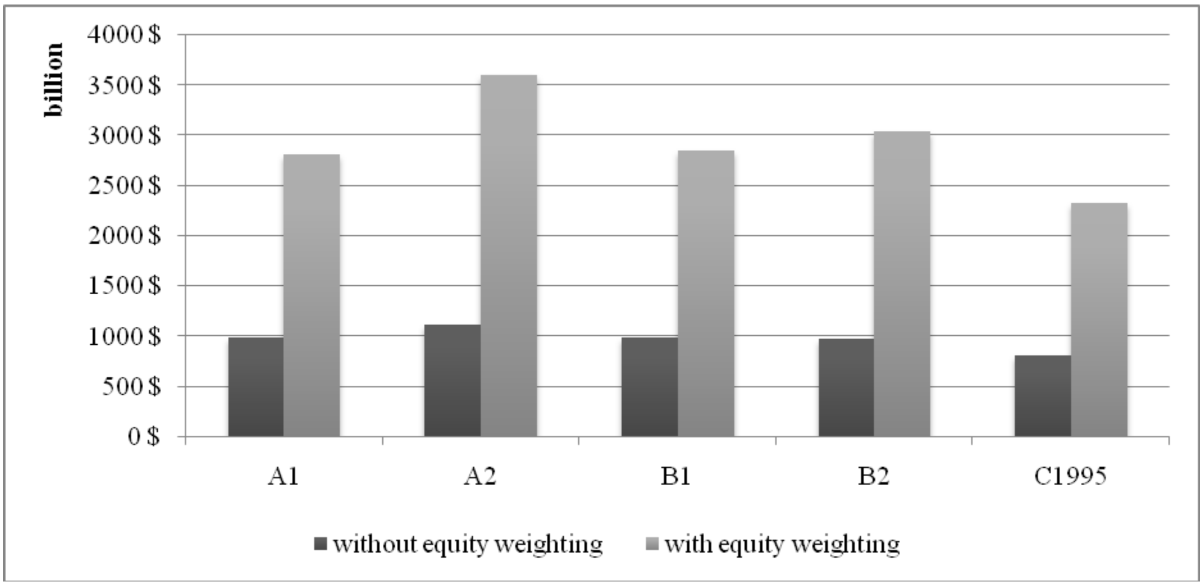

Figure 9: Equity-weighted damage costs of sea-level rise for 1m sea-level rise in 2100 with protection.

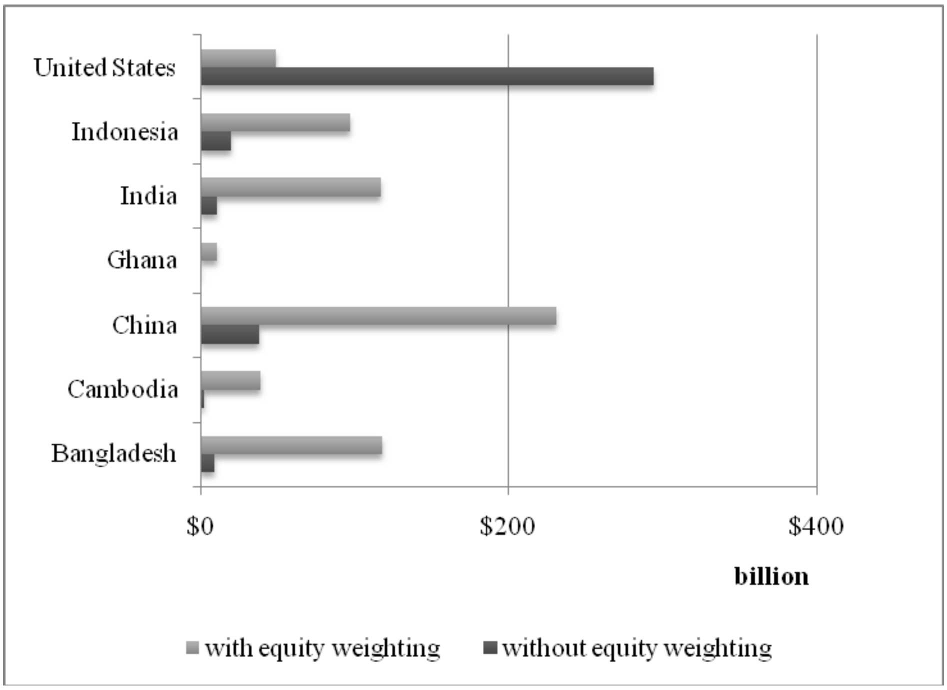

Figure 10: Damage costs of sea-level rise for 1m sea-level rise in 2100 for scenario B1 with protection for selected countries.

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