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The Impacts of Passing Climate Change Tipping Points: A CGE assessment of rapid sea-level rise

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Abstract

The overall impact of sea-level rise (SLR) is one of the reasons of concern related to climate change. SLR could exceed one metre by the end of the century, which would have serious direct impacts on economic activities located near the coastline (e.g. tourist resorts, industries such as refineries, and harbours), and indirect impacts further inland.

This article estimates the potential impact of SLR on the European economy. The study takes account of damage estimates for land loss, migration and sea floods taken from the DIVA model. The overall general equilibrium economic effects are estimated used the GEM-E3 model. Different levels of SLR are considered.

Our study compares three main SLR scenarios. The first, A1B climate scenario, is in line with the IPCC 4AR upper-range value of SLR (0.6 metres rise by 2100), the second, 'Rahmstorf', with post-IPCC research suggesting higher SLR (1.4 metres rise by 2100) and lastly a '2 metres' SLR by 2100. The damages for the whole EU rise from 0.15% of welfare (A1B scenario) to 0.9% ('Rahmstorf') to 1.76% ('2 metres'). Naturally, the losses for specific countries vary greatly.

The study concludes that there is a significant risk of economic damage of these magnitudes, which are somewhat higher than earlier studies. This is due to a wider range of damage impacts being considered. Furthermore, the study notes that further damages beyond those included are possible, such as damages to the water table, to the coastal ecosystem and indirect effects on economic value. As such even these higher damage estimates can be considered conservative figures.

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1 Introduction

Coastal regions provide important services and functions for the economy. The prospect of a changing sea level has significant implications for most countries and, in particular, many major cities around the world (Nicholls et al., 2007). An estimated 6% of world GDP is produced in coastal regions within 5 metres of the current sea level (Dasgupta et al., 2009).

There is considerable uncertainty over the amount of sea-level rise (SLR) that should be expected as a result of climate change. Estimates for this century range from a few decimetres to multi-metre rises (see Section 2 for more details).

This paper estimates the economic impacts of SLR under different scenarios. In addition to the cost from land loss (as was considered in e.g. Bosello, 2011), wider costs from migration and sea floods will also be accounted for. For most countries, these additional costs constitute greater potential damage than that from land loss.

The paper is structured as follows. Section 2 outlines the literature on SLR, firstly looking at the scientific estimates of how much SLR could be expected, and secondly, looking at the economic estimates of the consequent damage from SLR. Section 3 describes the methodology explaining the data and model employed and the scenarios implemented. Section 4 gives the results and Section 5 concludes and suggests future directions for research.

2 Literature review

2.1 Ice Sheet Collapse and Sea-level Rise

At the time of writing the Fourth Assessment Report, the only figures on SLR that the IPCC team was prepared to publish were a prediction of a rise of between 18 cm and 59 cm by the last decade of the 21st century (IPCC, 2007). However, this modest prediction came with a vital qualification: that the figure excludes the possibility of "future rapid dynamical changes in ice flow".

The report discusses the threat of ice-sheet collapse and the consequences for SLR. The specific ice sheets that are considered relatively vulnerable to melting are the Greenland and the West Antarctic Ice Sheets (GIS and WAIS), which together could cause a SLR of around

12 m (Meehl et al., 2007).[3] Although the IPCC authors were well-aware of the possibility of these ice sheets collapsing, they felt unable to place numerical values on the probabilities due to limitations of the existing research.

Sea levels of this amount are estimated to have occurred around the last interglacial stage, 125,000 years ago. As the polar temperatures were around 3ºC to 5ºC warmer than today, it is suggested that this serves as a partial analogue for a 1ºC to 2ºC global warming scenario. Kopp et al. (2009) conclude that it is likely that global sea level during this period peaked at more than 8 m higher than today's level. SLR of this extent is likely to have required major melting of both the GIS and the WAIS.

Subsequent research has developed quantitative predictions for SLR. Velicogna (2009) uses data from the Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission to show that the rate of ice loss is increasing from both the GIS and WAIS. The Copenhagen Diagnosis (2009) reports that satellites show great global average sea-level rise (3.4 mm/yr over the past 15 years) to be 80% above the IPCC's 2007 predictions. This acceleration in SLR is consistent with a doubling in contribution from melting of glaciers, ice caps and the GIS and WAIS. This scenario is generally corroborated by Grinsted et al. (2010). These studies suggest that currently observed melting rates lead one to expect some contribution to SLR from melting ice sheets.[4]

There is an additional line of argument suggesting that SLR could be much faster than even this increased prediction. Essentially, the question is how quickly the process could accelerate. Hansen (2007) describes it this way: "Ice sheet disintegration, unlike ice sheet growth, is a wet process that can proceed rapidly. Multiple positive feedbacks accelerate the process once it is underway."[5] To emphasise the importance of acceleration, the paper muses that if SLR doubles every decade, then a 1 cm SLR from 2005 to 2015 grows to a cumulative total of 5 m SLR by 2100. Though the numbers in this example are expositional, rather than predictive, the concept is important: SLR is likely to be an accelerating process, rather than a linear process.

[3] If both the Greenland Ice Sheet and the *whole* of the Antarctic Ice Sheet were to melt, they "hold enough ice to raise sea level by about 64 metres" (Bentley et al., 2007:101), however the bulk of the Antarctic Ice Sheet is not considered vulnerable to collapse.
[4] Indeed, SLR in PAGE09 has been calibrated to Grinsted et al. (2010).
[5] Rapid melting has occurred in the past, such as the rapid deglaciation 14,600 years ago known as meltwater pulse 1A, which saw a 20-metre rise in less than 500 years (Weaver et al., 2003). Though clearly, the ice sheets prior to this event were considerably larger than those that exist today.

Though the dangers of ice sheet collapse are one of the most significant potential consequences of climate change, precise quantification has proved challenging due to "insufficient data and a limited ability to model the underlying process" (Kriegler et al., 2009). Nevertheless, two studies have used expert elicitation to extract the best available estimates of the likelihood of ice-sheet collapse. Firstly, Kriegler et al. (2009) asked experts to assess, *inter alia*, the likelihood of passing a tipping point, by 2200, where (i) the GIS would begin to move to "an alternative state that is largely ice-free" and (ii) the WAIS would disintegrate towards a state where "West Antarctica becomes an archipelago". To be clear, the experts were not (necessarily) asserting that such events would be complete by 2200, but just that a tipping point would have been reached, which would make the event unstoppable. Under a fairly high emission scenario, which causes a rise in temperature of between 4ºC and 8ºC by 2200 (which is close to the A1B scenario in the standard PAGE09 model), experts believed that tipping points for both ice sheets could well occur. The aggregation of probability intervals ranges from approximately 55 to 100% chance of hitting a tipping point for the GIS by 2200. The range was lower for the WAIS with the aggregation of probability intervals ranging from approximately 20 to 98% chance of disintegration by 2200.

The second expert elicitation study, Lenton et al. (2008), also *inter alia* investigates tipping points, and elicits estimates of the time frames that could be involved. According to the study, an increase in global temperature of 1ºC to 2ºC is likely to be sufficient to cause significant melting of the GIS. Full melting would take at least 300 years, which would cause a maximum of 7 m of SLR.[6] The WAIS is estimated to require 3ºC to 5ºC of warming to collapse, which would also take at least 300 years and cause around 5 m of SLR.

A key difference between the GIS and the WAIS is that the GIS is grounded above sea level. By contrast, most of the bedrock of the WAIS is below sea level. The physical geography of the ice sheet raises the possibility (first suggested by Mercer 1968, 1978) that the ice could slide into the sea and float away (Oppenheimer and Alley, 2004). Once underway, this disintegration mechanism could be faster than the melting that might occur with the GIS. Note that there is no requirement that the floating ice melts for the SLR to occur and it is thought that the ice can move faster than it can melt (ATLANTIS Project, 2004). For this reason, it is suggested (ibid.; Lenton et al., 2008) that rapid SLR is more likely to come from the WAIS than the GIS, despite the higher global temperature required to start the process.

Though ice sheets would be the main source of large SLR, contributions to SLR also come from thermal expansion of the oceans and the melting of glaciers and ice caps. The IPCC gives estimates for SLR from these non-ice sheet sources for the end of the 21st century for the A1B scenario of between 0.19 and 0.43 m of SLR (Meehl et al., 2007). The Delta Committee report (2008) estimates of non-ice sheet SLR for 2200. The method employed is to extrapolate the A1FI scenario values for 2100 based on an assumed simple relation with air temperature. The estimates for non-ice sheet SLR range from 0.4 to 2.1 m. Note however that the A1FI scenario assumes more fossil-fuel intensive development, and consequently, makes these extrapolations somewhat higher than those that would be found using the A1B scenario assumed in the standard PAGE09 model. Nevertheless, SLR from non-ice sheet sources could be as much as 2 m.

To conclude, the worst case scenarios for the collapse of both the GIS and WAIS would involve a 12 metre SLR in 300 years. Taken with some additional SLR from other sources (receding glaciers, sea expansion, etc) of up to 2 m,[7] average SLR could reach 14 m by this time. This figure is used as a guide for the upper percentile values for SLR in the adjustments to the model as explained below.

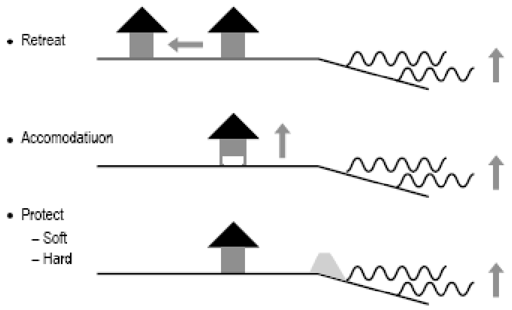
2.2 Estimates of Sea-level Rise Damage

The economic impact of SLR is contingent on the appropriate response for each section of coast line. This section first outlines the options available, before giving some more specific examples of the types of issues that would arise in the face of rising sea levels. Lastly, the literature that addresses the macro-impacts of SLR is surveyed.

The three broad responses to SLR are retreat, accommodation and protection, as summarised in the following diagram:

[6] The study notes that some GIS models show multiple equilibria. Therefore, whilst full melting, which would cause 7 m of SLR, is possible, other lesser degrees of melting are also believed to be possible. Therefore, the study puts the consequence of the melting of the GIS at between 2 and 7 m.

[7] Note that the non-ice sheet SLR was calculated for 2200, not 2300. The decision to limit ourselves to this value is because it is unclear how valid it would be to extrapolate further.



Source: Van Koningsveld et al. (2008)

Each category of response has different economic implications (see Nicholls et al., 2010, for more details). Retreat would involve affected populations migrating from coastal regions. Public policy could be used to restrict coastal development. Accommodation involves various measures to minimise the impact from SLR. For example, coastal homes raised on pilings will suffer less damage from flooding. Accommodation would also involve setting up early warning and evacuation systems, again to minimise the impact on the coastal population. The third response is protection, which involves strategies such as nourishing beaches and building seawalls.

To understand the implications for any particular region of SLR, it is useful to take an example regional impact study. Heberger et al. (2011) analyses key categories of infrastructure in California, which are located in coastal zones. For example, some emergency and healthcare facilities would have to be relocated. They also note that many sites containing hazardous materials are located in coastal zones, estimating that 330 such facilities in California would be at risk from a 100-year flood event if sea-levels rose by 1.4 metres. They also identify 28 wastewater treatment plants, which could be at risk from SLR. The consequences of inundation from floods could damage pumps and other equipment, and lead to untreated sewage discharges. Another category for concern is power plants; they identify 30 coastal power plants that would be at risk under the 1.4 metre SLR scenario. The more detailed studies, such as this one for California (e.g. see Delta Committee, 2008, concerning the Netherlands), remind us that though looking at the GDP provides the best broad summary, each individual stretch of coastline is going to have specific issues to cope with in the face of rising sea levels.

Turning to the macro-impact estimates, Nicholls et al. (2008) makes an estimate of the economic damage that would result from SLR. The paper considers the possibility of the collapse of the WAIS over various time frames, the earliest of which would be total collapse by 2130, which would result in a total of 6 m of SLR. The model allows for coastal land to either be defended (if the benefits of doing so outweigh the costs) or abandoned (if not). This work utilises the DIVA model (as does this paper, see below).

For comparison, two other studies give further indications of potential impacts from large SLR. Dasgupta et al. (2009) calculates the percentage of GDP and population that would be impacted by a 1, 2, 3, 4 and 5 m SLR in 84 developing countries. The estimates are shown in Table 1.

Table 1: Impacted GDP and population from 1, 2, 3, 4 and 5 m of sea-level rise

	1 m	2 m	3 m	4 m	5 m
Impacted GDP	1.30%	2.12%	3.21%	4.67%	6.05%
Impacted population	1.28%	2.03%	3.01%	4.16%	5.57%

Source: Dasgupta et al. (2009)

McGranahan et al. (2007) looks specifically at the case of a 10-metre SLR. Among other results, the study estimates that 10% of the world's population would be impacted by such a rise.

3 Methodology

3.1 Data for SLR and its economic impacts

The input data is taken from the DIVA model (McFadden et al. 2007; Vafeidis et al. 2008). The DIVA model is an integrated model that can assess the consequences of SLR. Data for SLR is provided from the UK Met Office Hadley Centre and the multi-model climate experiment from the European Commission ENSEMBLES project is used. The model is well-established, having been widely used for peer-reviewed publications (including for an earlier estimates of SLR damages for Europe: Ciscar et al., 2011, Bosello et al., 2011).

The model estimates the main coastal impacts from climate change, in particular, land loss due to submergence and erosion, wetland loss, and number of people flooded. In model also produces estimates of the associated economic damages due to land loss, migration and sea floods.

3.2 GEM-E3 Europe model

This section explains briefly the features of the GEM-E3 model and how it has been used to assess the general equilibrium effects of climate change in Europe. Particular attention is paid to the way the damages in each sector have been integrated into the CGE model. The European version of the General Equilibrium Model for Energy-Economy-Environment interactions (GEM-E3) is a multi-country, multi-sector computable general equilibrium model of the EU linking the EU member states economies through endogenous bilateral trade (Van Regemorter 2005; E3MLAB 2010). The GEM-E3 database is mainly based on the input-output tables, national account statistics and energy balances from EUROSTAT.

GEM-E3 covers the interactions between the economy, the energy system and the environment at country and EU level. It allows the evaluation of the welfare and distributional effects of various environmental policy scenarios, and exogenous shocks such as climate change. The output of GEM-E3 includes projections of input-output tables, employment, capital flows, government revenues, household consumption and welfare, energy use, and anthropogenic emissions, among other variables.

The model computes simultaneously the equilibrium prices of goods, services, labour, and capital. The model considers the following economic agents: households, firms, government and foreign sector. The Government behaviour is exogenous in GEM-E3. Under general equilibrium the supply in any market equals the demand and all agents maximize their objective function (benefits for firms and welfare for households) given the corresponding budget restrictions. The European model has eighteen productive sectors, with more resolution in the energy and energy-intensive sectors.

The economic agents (firms and consumers) optimise their objective, subject to various constraints, and determine the supply or demand of capital, energy, environment, labour and other goods. The firms' production uses capital, labour, energy (i.e. electricity and fuels) and intermediate consumption of goods from other branches. For each region, a representative consumer allocates his total expected income between consumption of goods and services, savings and leisure. The demand of goods by the consumers, the firms (for intermediate consumption and investment) and the public sector constitutes the total domestic demand. This total demand is allocated between domestic goods and imported goods, depending on the relative prices[8].

3.3 Modelling the impacts of SLR

The scenarios entered into the dynamic European GEM-E3 model are based on projections for SLR from the DIVA model. The DIVA model is run in a recursive dynamic fashion, solving every five years between 2005 and 2100. Each scenario has a SLR trajectory, with an

[8] The CGE model follows the Armington assumption (Armington, 1969).

associated damage profile. These scenarios are consistent with the literature outlined above (Section 2).

The three scenarios run are (i) the A1Bi scenario, (ii) the Rahmstorf scenario and (iii) the 2-metre scenario. The A1Bi scenario is consistent with the A1B IMAGE scenario, which was chosen over the IPCC A1B as it provides a pattern of SLR. This scenario assumes a warming of 2.4 degrees C by the 2050s and 3.8 degrees C by the 2090s. Sea level rises by 0.6 metres by 2100. The Rahmstorf scenario uses the post-IPCC AR4 work on SLR projections, as presented in Rahmstorf (2007). In this scenario, sea level is projected to rise by 1.4 metres by 2100. The third scenario is called the 2-metre scenario, as this is the SLR by 2100.

The economic module of DIVA computes the costs associated with the following impact categories: migration, sea floods, land losses and wetland losses. The main DIVA market damage components are migration costs and sea flood costs. Wetland losses have not been considered in this assessment, being a non-market impact.

The damages have been implemented in GEM-E3 in a similar way to that of the PESETA project (Ciscar et al., 2011). Sea floods have been interpreted in GEM-E3 as capital losses to the whole economy, affecting the aggregate production function sector-wise. Land losses have been also implemented as capital losses[9]. Migration costs are interpreted as additional 'obliged' consumption, thus reducing welfare.

The DIVA model can simulate the costs both with and without public adaptation. Dike buildings and beach nourishment are the adaptation measures considered. In this application it is assumed that public adaptation measures are not implemented. Therefore the estimated economic impacts would occur without protecting against climate change. That non-adaptation analysis allows identifying at first the most vulnerable European regions to climate change so that insights on the prioritization of adaptation funds can be derived.

4 Results

The results are presented in terms of welfare change, measured as change in equivalent variation. This gives the best overall estimate of the consequences from SLR.

[9] It is assumed that 40% of the sea floods and land losses computed in the DIVA model are market losses.

Table 2 shows the change in equivalent variation results for the EU as a whole under the 3 scenarios at different time periods, from 2030 to 2090. One notes that under the A1B scenario, additional welfare loss due to SLR is estimated to be 0.15% in 2090.

Table 2: Equivalent Variation by time, scenario for whole EU (% loss of welfare)

		2030	*2050*	*2070*	*2080*	*2090*
A1B_AVG	EU	-0.011	-0.043	-0.087	-0.113	-0.147
RAHM	EU	-0.014	-0.064	-0.267	-0.534	-0.902
HIGH	EU	-0.058	-0.425	-1.117	-1.508	-1.757

Damages are higher under the Rahmstorf scenario, rising to 0.90% of welfare. Larger damage is observed for the 2 metre SLR scenario, with more than one percent rise by 2070, rising to 1.76% by 2090.

Comparing the damage values with the associated SLR, the results suggest that marginal damages *rise* at higher sea levels. This can be seen because 0.6 metres of SLR causes 0.147%, 1.4 metres causes 0.9% and 2.0 metres causes 1.76%.[10]

As noted, the above table shows aggregates for the EU as a whole. Table 3 disaggregates the damages to show percentages for each country. One can begin to see that certain countries are more affected, whilst others are barely impacted at all.

[10] The best-fitting power curve through the 3 data points is 0.43X^2.1. Though clearly the very small number of data points makes any estimate very approximate, it nevertheless suggests that the exponent could be greater than 1.

Table 3: Equivalent Variation by country under the 3 scenario (% welfare loss)

	A1B_AVG	RAHM	HIGH
AT	-0.05	-0.05	-0.08
BE	-0.49	-2.09	-6.68
BG	-0.03	-0.05	-0.08
CZ	-0.04	-0.04	-0.05
DE	-0.09	-0.55	-1.13
DK	-0.35	-3.17	-8.95
EE	-0.10	-0.79	-1.48
EL	-0.11	-0.51	-0.74
ES	-0.09	-0.50	-0.82
EU	-0.15	-0.90	-1.76
FI	-0.07	-1.09	-3.35
FR	-0.15	-1.66	-2.18
HU	-0.05	-0.05	-0.06
IE	-0.24	-1.27	-1.55
IT	-0.10	-0.35	-0.75
LT	-0.14	-1.73	-1.94
LV	-0.12	-3.30	-3.64
NL	-0.40	-1.23	-3.38
PL	-0.12	-0.40	-0.50
PT	-0.26	-1.75	-2.51
RO	-0.06	-0.29	-0.53
SE	-0.08	-1.61	-2.62
SI	-0.05	-0.25	-0.28
SK	-0.07	-0.07	-0.09
UK	-0.17	-0.85	-1.80

Obvious candidates for near-unaffected countries are inland countries, such as Austria or the Czech Republic. Other countries are simply less-reliant, economically, on their coastline than the average, such as Poland. The most heavily affected country in the 2 metre scenario is Denmark, which would suffer a 9.0% loss of welfare. Other heavily affected countries under this scenario are Belgium (6.7% loss), Latvia (3.6%), the Netherlands (3.4%) and Finland (3.4).

5 Conclusion

This paper has extended earlier analysis of damage from sea-level rise by incorporating further categories of damage. Beyond the damage from land loss, the costs of migration and sea floods are also considered. The paper also extends earlier analysis by investigating the potential damage from SLR of up to 2 metres.

The findings suggest that welfare losses for the EU by the 2090s would range from 0.15% of GDP for a 0.6 metre SLR, to 0.90% for a 1.4 metre rise and 1.76% for a 2 metre rise. It should be emphasised that these are aggregate estimates for the EU as a whole. The countries with the largest percentage damages being felt by Denmark, Belgium, Latvia, the Netherlands and Finland. All these countries are estimated to suffer more than a 3% loss of welfare. Clearly, within countries local coastal regions affected suffer the majority of such damages.

It is noted that these damages are higher than in some previous studies, due to the wider ranges of damage impacts being considered.

Lastly, it should be noted that, though this study has included a wider range of damages than some previous studies, this does not necessarily mean that *all* possible damages have been accounted for. For example, damage to the water table could necessitate expensive engineering solutions and/or additional migration. The impact that SLR will have on coastal ecosystems may not have been fully accounted for, especially if it turns out that there are consequences for inland ecosystems. At this time, it is probably not possible to accurately estimate either the risk or the cost of these and other more speculative possibilities. Nevertheless, it is worth keeping in mind that radical changes, especially with very high SLR, could result in as-yet-unanticipated consequences.

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