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The economic impact of extreme sea-level rise: Ice sheet vulnerability and the social cost of carbon dioxide☆

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ABSTRACT

The possibility of extreme sea-level rise is one of the commonly cited reasons for concern about climate change. Major increases in sea level would likely be driven by the melting or collapse of major ice sheets. This possibility has implications for the social cost of carbon dioxide, which is a key policy value as well as a useful summary measure of damage caused by greenhouse gas emissions.

This paper extends earlier work on the importance of low-probability, high-impact events for the social cost of carbon dioxide to incorporate the possibility of extreme sea-level rise.

To estimate its impact, an integrated assessment model is used, which allows a probabilistic assessment of climate change damages based on the linkages between the economic and climate systems. In the model, the generic discontinuity damage is replaced with the possibility of large-scale damage from factors that are taken to be correlated with temperature rise and, crucially for this paper, explicit consideration of extreme sea-level rise.

Estimates of the amount of increase in the social cost of carbon dioxide that can be expected from incorporating extreme sea-level rise show that the increase is significant, though not especially large in percentage terms.

The paper contributes to the literature of how to represent uncertain climate impacts in integrated assessment models and the associated estimation of the social cost of carbon dioxide.

1. Introduction

Sea-level rise and its consequences are of great concern for climate change impact assessment. The response of ice sheets to climate change is perhaps the key factor determining whether extreme sea-level rise will occur, and as such is receiving growing attention in the literature. Typically, integrated assessment models do not explicitly incorporate the extent of sea-level rise that would occur were there to be a major melting or collapse of major ice sheets.

Among integrated assessment models, the standard PAGE09 model indirectly includes the possibility of major ice sheet melting or collapse as one of the potential sources of extensive costs due to discontinuity damages. This damage category is intended to account for the impacts of catastrophic events, which might have high economic consequences. As suggested by Weitzman (2010), an alternative method of incorporating catastrophic events into integrated assessment models is to introduce fat tails to the probability distribution functions of relevant parameters. Such tails allow for the possibility that the physical consequences of greenhouse gases and/or the consequent economic damages might be very high.

The approach of adding tails to the probability distribution functions, in place of discontinuity damages, is taken in Pycroft et al. (2011). In that paper, the physical consequences of greenhouse gases are adjusted by incorporating the possibility of high climate sensitivity and, hence, high temperature rise from a given level of greenhouse gases emissions (in line with what is discussed in Weitzman, 2010). In the model used, PAGE09, this has a small effect on sea-level rise, as higher temperatures cause somewhat higher sea level. However, the possibility of extreme sea-level rise is not explicitly incorporated.

One major challenge to the incorporation of relatively rapid ice sheet melting or collapse is the difficulty in quantifying its likelihood. This is due *inter alia* to challenges in modelling the underlying processes (Kriegler et al., 2009). Nevertheless, current

☆ The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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literature does allow estimations to be made of the progress of sea-level rise were there to be an increased contribution from ice sheets.

In order to explicitly model the extreme sea-level rise that would result from ice-sheet collapse, adjustments are needed to both the physical behavioural aspects of the model and the economic consequences. On the physical side, this involves parameterising an appropriate rate of sea-level rise to reflect increases in dynamic ice flow from ice sheets. On the economic side, the consequent sea-level rise induced damage function has also to be appropriately adjusted. The model can then be run so as to estimate the impact this has on the social cost of carbon dioxide, which is chosen as the preferred summary impact measure.

The article is organised as follows: Section 2 introduces and discusses the scientific and economic literature on extreme sea-level rise. Section 3 gives an overview of the PAGE09 integrated assessment model, and explains how both sea-level rise and sea-level rise damages are modelled in the standard version. The adjustments made to standard PAGE09 for this paper, firstly to reflect low-probability, high-impact events related to temperature, and secondly to incorporate extreme sea-level rise, are described in Section 4. Results are presented and commented upon in Section 5, while Section 6 concludes.

2. Literature review

2.1. Ice sheet collapse and sea-level rise

The uncertainty surrounding the expected sea-level rise caused by climate change derives from two sources. Firstly, the uncertainty around the anticipated temperature rise, which itself is dependent on the actions of human society. Secondly, how sea level will respond to the temperature is uncertain, in particular the response of ice sheets. Estimates are made based on the past relationship between sea level and temperature, and through analysing the current structure and behaviour of potential sources of sea-level rise, including ice sheets. One particular challenge in making such estimates is that the speed of temperature change anticipated in the near future has no close analogue in the past. Therefore, the precise likelihood of changes, such as accelerated ice discharge from the Greenland and West Antarctic has "largely defied quantification due to insufficient data, and a limited ability to model the underlying processes" (Kriegler et al., 2009).

For example, the Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC, 2007), predicted sea-level rise of between 0.18 and 0.59 m by the 2090s, however this figure excludes any contribution from "future rapid dynamical changes in ice flow". The Report discussed the threat of increased ice discharge, especially from the Greenland and West Antarctic ice sheets (which together have sufficient ice to cause a sea-level rise of around 12 m), but did not place probabilistic estimates of consequent sea-level rise based on the existing research (Meehl et al., 2007).

There is considerably uncertainty as to how ice sheets would reduce their mass (*e.g.* see Ganopolski and Robinson, 2011, concerning the Greenland ice sheet; Hansen, 2007, offers more general thoughts on the collapse or melting of ice sheets). Though there is already evidence that ice sheets are losing mass faster than IPCC 4AR predictions. 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 Greenland and West Antarctic ice sheets. The Copenhagen Diagnosis (2011) reports that satellites show the rate of global average sea-level rise (3.4 mm/year over the past 15 years) to be 80% above the IPCC's 2007 predictions.

More recent studies have made sea-level rise predictions inclusive of accelerated ice discharge. Pfeffer et al. (2008) estimate the maximum ice discharge based on geographic constraints on ice flow. They find that a 2-m rise by 2100 is "physically possible". However, they suggest that the much lower figure of 0.8 m appears more likely.

Using a different methodology, Vermeer and Rahmstorf (2009) propose a simple semi-empirical relationship between changes in sea level and global mean temperature. The method gives a range for sea-level rise in 2100 relative to 1990 of between 75 and 190 cm, depending *inter alia* on the emission scenario considered.

Also using a semi-empirical approach, Grinsted et al. (2010) suggest a linear response relationship between global mean temperature and sea level. The parameter values are calibrated against historical temperature and sea level records to arrive at estimates for the four parameters of the relationship. For the A1B emissions scenario, using their preferred parameter estimates, the resulting sea-level rise prediction is 0.9–1.3. Indeed, the relationship between global mean temperature and sea-level rise put forward in this paper has been used for the sea-level rise in the standard PAGE09 model. As such, the equations used to describe the relationship (adapted appropriately) are explained in Section 3.1.

In a commentary article, Lowe and Gregory (2010) review the literature and ultimately concur with the notion that sea-level rise is "almost certain" to be below 2 m in 2100, and indeed, that it could be considerably lower. They note that for sea-level rise to significantly exceed 1 m, a considerable increase in the contribution from ice sheets would be required.

Other literature suggests that multi-metre sea-level rise is ultimately likely with global warming, driven by partial or complete collapse or melting of the Greenland and West Antarctic ice sheets (see Kopp et al., 2009; Lenton et al., 2008; Kriegler et al., 2009). However these studies focus on long-term changes without specifying a clear time dimension.

The message from these studies for our purposes is, firstly, that sea-level rise in excess of 1 m by 2100 would require a significant increase in ice flow dynamics, and secondly, that sea-level rise in excess of 2 m by 2100 is considered highly unlikely. For this reason, the sea-level rise parameters in our model have been adjusted to ensure a 90% confidence interval of between 1 and 2 m for the standard global temperature parameters. The parameters that define the relationship are used for all the years for which the PAGE09 model solves leading up to and including 2100 and continuing until 2200 (see Section 3).

2.2. Estimates of sea-level rise damage

For the purposes of this research, we are mostly concerned with global estimates of sea-level rise damages. Nevertheless, it is worth briefly mentioning that studies undertaken at the regional and local scale suggest that such impacts could be significant. For example, a study of infrastructure in California's coastal zones (Heberger et al., 2011) details the numbers of schools, wastewater treatment plants, power plant, sites containing hazardous materials and other key facilities that would be at risk were sea-level to rise substantially. This and other regional studies (for example, see Van Koningsveld et al., 2008, for the Netherlands; Breil et al., 2005, for the city of Venice; Smith and Lazo, 2001, summarise many country- and sub-country-level studies from all continents) are suggestive of what the macro-level damages estimated might mean on a micro-scale.

There are two studies that offer a broad order of magnitude of the damage from multi-metre sea-level rise. The first study is Dasgupta et al. (2009), which uses satellite data of land usage to calculate the percentage of GDP and population that would be