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PERSPECTIVE

Greenland plays a large role in the gloomy picture painted of probable future sea-level rise

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Goelzer *et al* (2012) paint a portentous picture of what is likely to happen to the global sea-level over the next 1000 years. This worrying assessment is based on our current best understanding of how the world's giant ice sheets of Greenland and Antarctica, as well as a quarter of a million smaller glacial ice masses, and the ocean collectively respond to ongoing climate change. Theirs is a state of the science study that integrates these key contributors of sea-level change based on the latest models and current understanding, and an integrated Earth systems modelling approach termed LOVECLIM. As they point out in their study, only a handful of global climate models to date—i.e. models that are used to make predictions of future climate change—incorporate dynamically (fully) coupled ice-sheet models.

According to the scenarios presented by Goelzer *et al* (2012), we could see between 2.1 and 6.8 m of global sea-level rise by 3000 AD, compared with 'just' 1.1 m if the atmosphere is stabilised at 2000 CO_2 levels. Much, up to some 4 m, of this contribution comes from increased melting and mass loss of the Greenland ice sheet, which is several times more sensitive than the Antarctic ice sheet to warming temperatures in these simulations. Interestingly, dynamical ice mass losses through iceberg calving become increasingly less significant for Greenland as the ice sheet retreats further inland during the 1000 yr runs (Sole *et al* 2008). The latest modelling studies show that around a half, perhaps more, of the recent Greenland mass losses (Barletta *et al* 2012, Rignot *et al* 2011) are already through increased melt and runoff (Hanna *et al* 2008, 2012, van den Broeke *et al* 2009); note also the recent (summer 2012) record surface melting of the Greenland ice sheet (Nghiem *et al* 2012) caused by atmospheric forcing (Overland *et al* 2012) and the potential of such events to impact on ice flow (Bartholomew *et al* 2011). By contrast, the greatest sea-level rise reported for Antarctica by 3000 AD is no more than 94 cm; Antarctica remains relatively insensitive for future sea-level rise given a temperature increase of no more than 5–6 °C (quite a lot) above present levels. Oceanic thermal expansion and, especially, glacier melt seem very much second-order effects, compared with the Greenland sea-level contribution, for the next millennium.

As expected, there are considerable differences between the outcomes of the model experiments depending on the time and level at which greenhouse gas emissions are stabilised. I am not quite sure why they 'prefer' the model version which reaches stabilisation at 2000 greenhouse gas levels since those levels have since been significantly exceeded and show no signs of tailing off yet—quite the reverse. According to the famous Keeling *et al* dataset from Mauna Loa in Hawaii, atmospheric CO_2 levels at about 369 parts per million by volume of the global atmosphere in 2000 have since risen to about 392 ppmv in 2012, and this increase shows no signs of abating. Realistically, it's going to be at least another decade or two (or longer) before we can effectively even begin to stabilise atmospheric greenhouse gas levels, assuming the political will is there: which at the moment it is not. Of course this does not commit us to the other three more extreme experimental results (from greenhouse gas stabilization at 2100) reported in the study but we are heading dangerously in that direction. In effect the simulations are sensitivity studies, which may be largely unrealistic but are still useful as a kind of guide to what might happen under future climate change.

Naturally, many uncertainties remain, especially concerning how ice-sheet motion ('dynamics') is represented in the models (e.g. the absence of so-called 'higher order physics' including longitudinal (push–pull) stresses which can rapidly transfer peripheral ice velocity perturbations inland (Price *et al* 2011)). Furthermore, the atmospheric model used in LOVECLIM is very coarse at 5.625° latitude/longitude resolution. There appears to be a cancelling out of errors in LOVECLIM, where its climate sensitivity seems quite low (in comparison with other models) but the simulated enhanced high-latitude warming—often termed Arctic amplification and evident in observed climate data for the last 30 years—is quite high. It would be good to include precipitation as well as temperature changes when modelling the future response of glaciers, even though the former is likely to be less important. I do not agree that uncertainties in climate sensitivity can be adequately accounted for by varying boundary and initial conditions in ensembles of models, as all of the model simulations may be systematically biased due to some physical effect that is improperly considered—or unrepresented—by all of the models, but this is a widely used technique and probably the best that can be done here.

Despite these caveats, Goelzer *et al*'s (2012) results will undoubtedly prove useful for the Intergovernmental Panel on Climate Change (IPCC)'s upcoming Fifth Assessment Report due to be released in 2014. The key challenge remains to further improve the individual components of the Earth system model, especially those concerning ice-sheet dynamics.

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