Sea level rise

How much will global sea levels rise this century? **Jonathan Gregory**, lead author of the chapters covering past and future sea level rise in the Intergovernmental Panel on Climate Change Fourth Assessment Report, highlights the uncertainties and explains that the budget doesn't yet balance.

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Sea level rise is an important consequence of climate change because of its impacts on coastal populations and ecosystems. The UN's Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) stated that, 'Many millions more people are projected to be flooded every year due to sea level rise by the 2080s. Those densely populated and low-lying areas where adaptive capacity is relatively low, and which already face other challenges such as tropical storms or local coastal subsidence, are especially at risk.'

The physical science basis for predicting sea level change is an interesting subject because it involves many effects and some unanswered questions. But in the face of an urgent practical need to assess the impacts, the incomplete state of scientific knowledge can be a frustrating obstacle.

This is not a new puzzle; it has been called the 'enigma' of sea level rise.

When the last ice age peaked 21,000 years ago, global average sea level was about 120m lower than now. As the meltwater from the massive North American and European ice sheets returned to the ocean, sea level rose at rates of over a metre per century, or 10mm per year (mm/yr). Could the same happen in the future? Not in the same way because those ice sheets no longer exist. However, 125,000 years ago, during the last interglacial (between ice ages) Greenland was 3–5°C warmer than now and its ice sheet was substantially smaller.

Model experiments suggest that there is a threshold of global warming, somewhere in the range 1.9–4.6°C, beyond which the Greenland ice sheet is not viable. This range is similar to the likely warming by the end of the 21st century under one of the IPCC's commonly used future emissions scenarios, A1B, which assumes rapid economic growth, population peaking mid-century and energy demands met by a balance between fossil and non-fossil fuels. If such a warm climate were maintained, the ice sheet would eventually disappear, raising sea level by 7m.

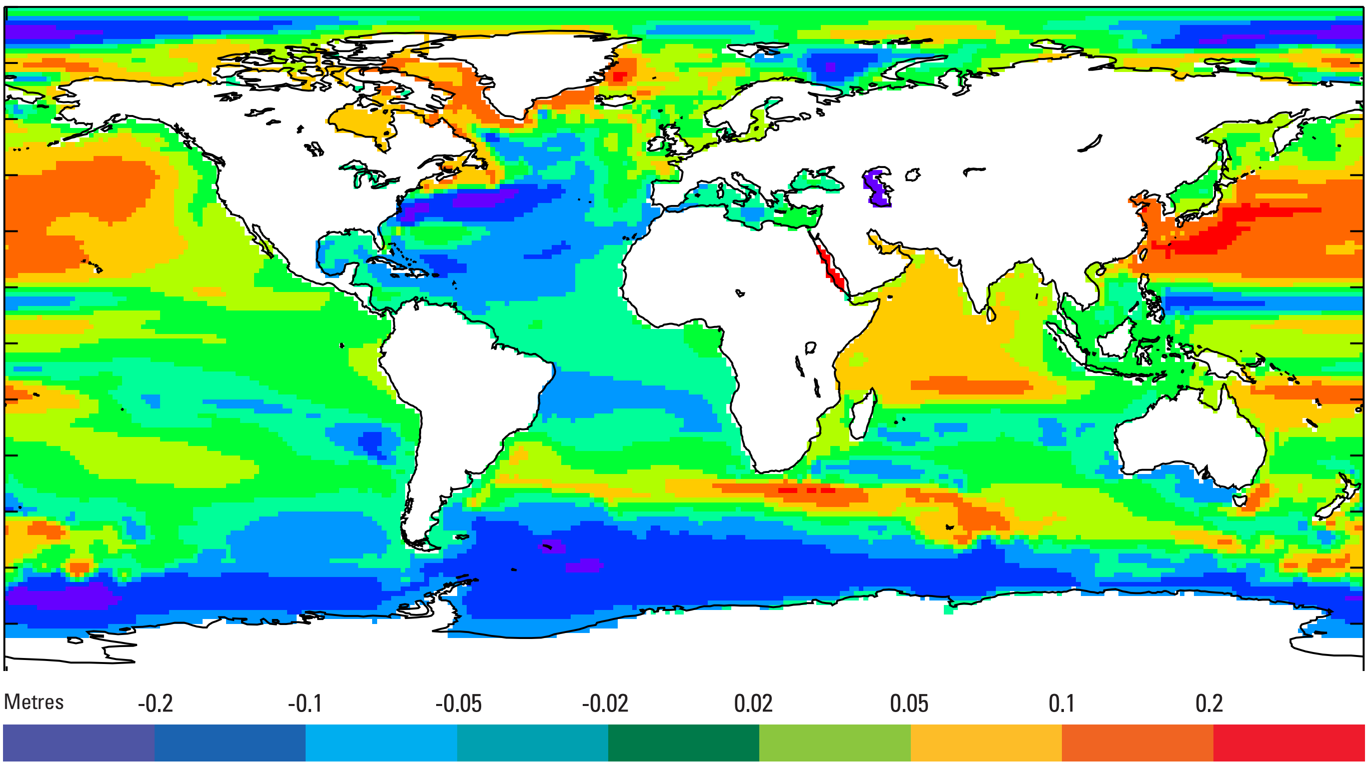
The pressing question is: how quickly could it happen? Current ice-sheet models suggest sea level rise of a few millimetres per year at most.

On average during the last few years, both the Greenland and Antarctic ice sheets have been losing mass. Their combined contribution to sea level rise is 0.1–0.8mm/yr, while the global average rate of rise has been about 3mm/yr. The ice-sheet contribution is hence relatively small at present, but there has been recent acceleration in ice flow speeds, producing increased discharge of ice into the ocean as icebergs. The acceleration could have been caused by recent climate change, through various possible mechanisms, such as ocean warming leading to thinning of ice shelves, and surface melting providing meltwater to lubricate the ice flow. Unfortunately we do not yet have sufficient empirical or theoretical knowledge of the relevant processes to say whether the recent effects are transient variations or the first signs of larger future changes, often labelled ice-sheet collapse.

For other contributions to sea level change, our understanding is better. The main contribution is the thermal expansion of sea water as the ocean warms up. This effect can be calculated from observed changes in ocean temperature, and simulated by the three-dimensional global climate models that are the main tool for making climate predictions.

There is uncertainty in the observational estimate because of the sparse sampling of

Sea level rise relative to the global average for the decades 2080-2099 minus 1980-1999. A negative number means sea level rises less than on average, not that sea level falls. (HadCM3 climate model).



National Snow and Ice Data Center, W. O. Field, B. F. Molnia

The disappearing Muir Glacier, Alaska: 1941 (top) and in 2004. Alaska and parts of Siberia are two of the fastest warming regions on Earth.

large volumes of the deep ocean and remote areas, especially the Southern Ocean, and difficulties with instrumental calibration, but models and observations agree on 1–2mm/yr of thermal expansion in recent years.

Glaciers worldwide have made a larger contribution than the ice sheets recently, despite having only one percent of the total mass of ice on land. This is because they are in warmer climates, making them more sensitive to climate change (see 'A drop in the ocean', this issue). There is uncertainty in their contribution because there is a very large number of glaciers (over 100,000), of which scientists have monitored just a few hundred, and care is needed in treating these as representative. But there is reasonable agreement between observed and simulated changes in global glacier mass balance.

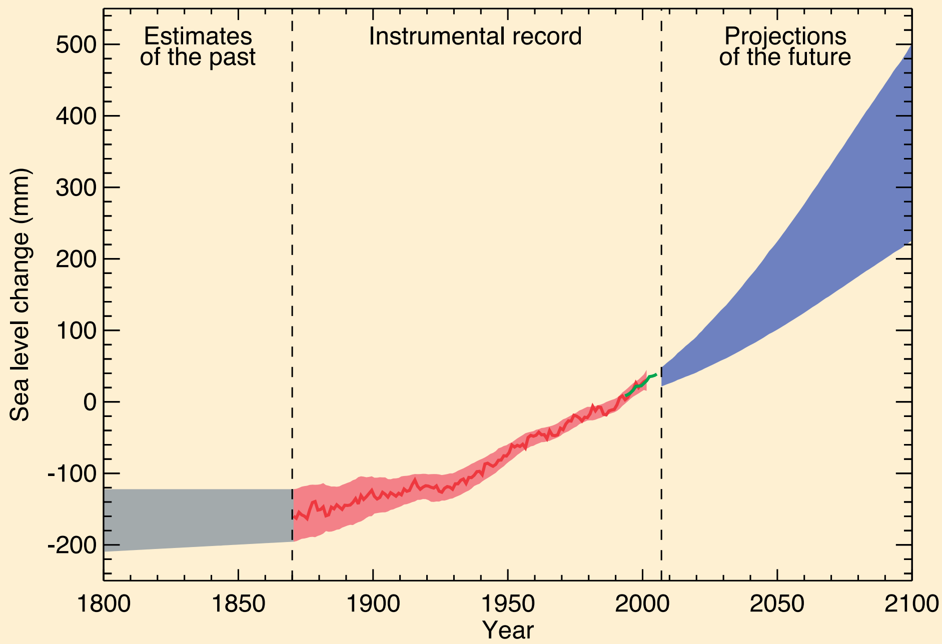
Sea level rise could be substantially larger than the range given.

When we add up the estimated contributions to sea level for recent years (1993–2003), the total agrees with the observed rate of rise within the uncertainties. If we look at a longer period – the last four decades (1961-2003) – both the observed rate of rise, of about 1.8mm/yr, and the sum of contributions from ice sheets, glaciers and thermal expansion are smaller than in recent years, but, crucially, they don't tally.

Smaller thermal expansion and loss of land ice during the longer period is consistent with the cooler average climate of earlier decades. However, for 1961–2003 the best estimate of observed sea level rise is 60 percent larger than the sum of the estimated contributions. This discrepancy indicates a deficiency in our scientific knowledge. It is not specifically a problem with models, because models and observations agree for the main contributions. But, still, the budget is not balanced. To close the budget, one or more of the following must be true: the rate of sea level rise is an overestimate, or one of the terms is underestimated, or there is a missing term. This is not a new puzzle; it has been called the 'enigma' of sea level rise.

Without a closed budget for sea level we cannot satisfactorily account for the increase in rate over recent years. Moreover, the record of 20th century sea level rise indicates large variability in the rate on decadal timescales; the 3mm/yr of recent years is unusually high but not unprecedented. It is therefore unclear if it is a fluctuation or a longer-term acceleration.

Using the same models with which we study the past, we can make projections of sea level change in the future. It is very likely that the rate of sea level rise will be greater in the 21st century than it has been on average in recent decades. For the emissions scenario A1B, the most recent IPCC report gives projections of 0.21–0.48m by the end of the century. Smaller or larger greenhouse gas emissions lead to smaller or larger sea level rise. These latest IPCC projections are quite similar to those of the IPCC Third Assessment Report, but the upper bounds are lower, and the lower bounds higher. This is because better observational datasets have reduced uncertainties in our methodologies. The projections include the effects of future changes in precipitation and melting on ice sheets and the recent acceleration in ice flow, but exclude future rapid accelerations (discussed above) for which we do not



Sea level change from the UN's Intergovernmental Panel on Climate Change Fourth Assessment Report. Future projections relate to emissions scenario A1B: rapid economic growth, population peaking mid-century and energy demands met by a balance between fossil and non-fossil fuels.

have sufficient understanding to make predictions. Therefore sea level rise could be substantially larger than the range given.

As an example, if the contribution of sea level rise from accelerated ice-flow were to grow linearly with global warming, it would add up to 0.2m to sea level this century, but there is no consensus on whether that is an underestimate or an overestimate. The IPCC AR4 stated the problem thus: 'Understanding of these effects is too limited ... to provide a best estimate or an upper bound for sea level rise' – however much the authors would have liked to be able to do that!

Some researchers have suggested that, as an alternative method for projections, we can use the empirical evidence that rate of sea level rise has generally increased during the last century at the same time as global temperature has been rising. Assuming the former is proportional to the latter and using climate model projections of 21st-century warming gives projections of sea level rise of about one metre.

The reason this method gives larger projections is that it implicitly makes an assumption about the discrepancy in the sea level budget for recent decades, namely that this extra contribution will scale up with global temperature. (Note that the missing amount cannot be due to rapid changes in the ice sheets if, as the current assessment suggests, they were not a large contributor in the past few decades.) The IPCC fourth assessment projections, on the other hand, take no account of the discrepancy in the budget. The contrast between the results underlines the need to resolve this problem.

Even if climate change is stabilised… it will take much longer for the sea to reach its final level.

On top of the uncertainty about global average sea level rise comes the issue of its regional pattern. Unfortunately we cannot give confident regional projections because climate models do not agree, except for the conclusion that sea level rise will not be geographically uniform. Some places will see more than average, others less, the spread being tens of percent of the global mean, but the only common feature among all models is smaller sea level rise than average in the Southern Ocean.

The reason for the general disagreement is that the climate models differ in regard to the processes which take up and redistribute heat within the ocean.

One solid qualitative conclusion is that, even if climate change is stabilised in the next century or two, it will take much longer for the sea to reach its final level. It will take many centuries for the deep ocean to catch up with surface warming, but when it does, thermal expansion could generate a one metre or more rise, depending on the level of stabilisation of greenhouse gases.

Despite the controversy over possible rapid changes, the ice sheets have timescales of millennia for full adjustment to climate change, with sea level changes of metres being possible. Policy decisions made in coming decades therefore could have a profound influence for much longer into the future. ✿

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