The Sea-Level Fingerprint of West Antarctic Collapse

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There is widespread concern that the West Antarctic Ice Sheet (WAIS), which is characterized by extensive marine-based sectors (*1*), may be prone to collapse in a warming world. The recent Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (*2*) estimated that this collapse would lead to a sea-level rise of ~5 m. This estimate is derived by converting the total volume of all grounded portions of WAIS into water, filling in any topographic holes associated with marine-based sectors, and spreading the remaining water uniformly (i.e., eustatically) across the oceans (*3*). Although the appropriate effective eustatic value (EEV) for WAIS collapse is uncertain (e.g., will non–marine-based sectors vanish?), we show that, whatever the value, sea-level changes at some coastal sites will be significantly higher (or, less commonly, lower) than the EEV.

The rapid melting of ice sheets and glaciers leads to a sea-level change that departs dramatically from the assumption of a uniform redistribution of meltwater (*4*). An ice sheet exerts a gravitational attraction on the nearby ocean and thus draws water toward it. If the ice sheet melts, this attraction will be reduced, and water will migrate away from the ice sheet. The net effect, despite the increase in the total volume of the oceans after a melting event, is that sea level will actually fall within ~2000 km of the collapsing ice sheet and progressively increase as one moves further from this region. Each ice reservoir will produce a distinct geometry, or fingerprint, of sea-level change.

Although the physics of fingerprinting has been embraced in studies of past sea-level change, it has been largely ignored in discussions of future projections. A widely neglected exception is an analysis by Clark and Lingle (*5*), who were concerned with sea-level changes after a "uniform thinning" of the WAIS. Their fingerprint calculation had its basis in a standard sea-level theory that accounts for load self-attraction (as described above) and the associated elastic deformation of the solid Earth. Their results, reproduced in Fig. 1A, show a zone of sea-level fall close to the WAIS and a maximum rise in the North Pacific. Coastal sites well away from the WAIS have peak values ~5 to 10% higher than the EEV.

The sea-level theory adopted by Clark and Lingle does not allow for shoreline migration, including the inundation and adjustment of regions vacated by grounded, marine-based ice cover, or any feedback onto sea level of Earth rotation changes. We show (Fig. 1B) a projection based on a sea-level theory (*6*) that overcomes these limitations. These results show a highly accentuated sea-level rise in the oceans bordering North America and in the Indian Ocean. Coastal sites in North America would experience a rise ~30% higher than the EEV.

The difference between this and the standard (Clark and Lingle) calculations is shown in Fig. 1C. The far-field geometry of the differential sea-level signal, which includes a roughly uniform rise in combination with a quadrantial form, is diagnostic of the physical mechanisms responsible for the accentuated signal (*1*). In particular, the uniform rise is due to the expulsion of water from the West Antarctic as flooded, marine-based sectors of this region uplift (elastically) in response to the unloading (fig. S1B). The dominant quadrantial signal arises from a feedback associated with Earth rotation (*7*). In particular, the collapse of the WAIS leads to a displacement of the south rotation pole of ~100 m × EEV toward the West Antarctic; this shift drives a sea-level rise in North America and the Indian Ocean and a fall over South America and Asia relative to the EEV (fig. S1, A and C).

These results reinforce serious concerns about the impact on some coastal communities of a future instability in the WAIS. Consider Washington, DC, and the case where we adopt the conventional value of 5 m for the EEV. We predict a sea-level rise 1.3 m higher than the EEV (or 6.3 m total) at this site, an increase above the EEV that is three times greater than predicted using the standard sea-level theory (Fig. 1A). Any robust assessment of the sea-level hazard associated with the loss of major ice reservoirs must, of course, account for other potential sources of meltwater, namely Greenland, the East Antarctic, and mountain glaciers (*8*). Nevertheless, future projections should avoid simple, eustatic estimates and be based on a suitably complete sea-level theory.

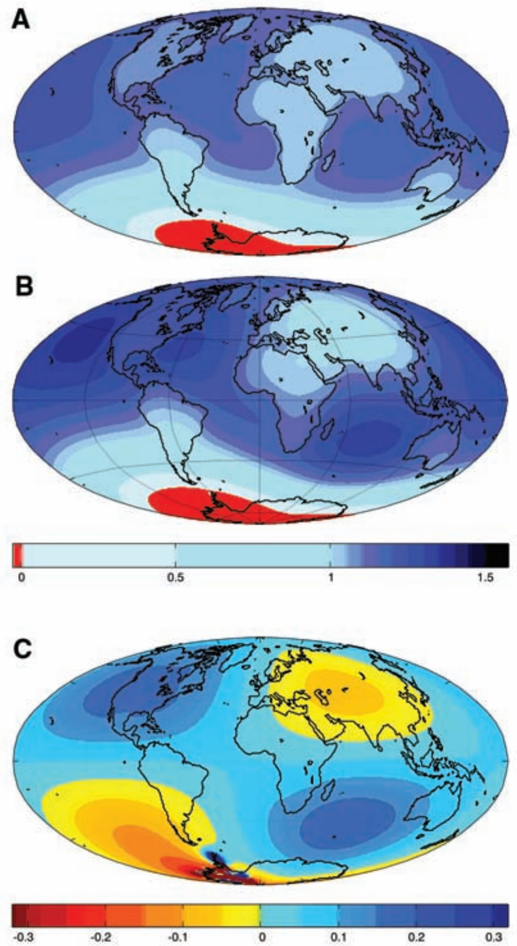

Fig. 1. Sea-level change in response to the collapse of the WAIS computed by using (**A**) a standard sea-level theory (*5*), which assumes a nonrotating Earth, no marine-based ice, and shorelines that remain fixed to the present-day geometry with time, as well as (**B**) a prediction based on a theory (*6*) that overcomes these limitations. Both predictions are normalized by the EEV associated with the ice collapse. In (B), the total volume of the WAIS is used in the calculation, whereas in (A) only an amount of ice with a volume that matches the EEV is removed (because the latter cannot take into account the inundation of marine-based sectors). (**C**) The difference between predictions generated by using the two sea-level theories [(B) minus (A)].

References and Notes

1. Materials and methods are available as supporting material on *Science* Online.
2. IPCC, *Climate Change 2007: The Physical Science Basis* (Cambridge Univ. Press, Cambridge, 2007).
3. J. H. Mercer, *Nature* **271**, 321 (1978).
4. J. X. Mitrovica, M. E. Tamisiea, J. L. Davis, G. A. Milne, *Nature* **409**, 1026 (2001).
5. J. A. Clark, C. S. Lingle, *Nature* **269**, 206 (1977).
6. R. A. Kendall, J. X. Mitrovica, G. A. Milne, *Geophys. J. Int.* **161**, 679 (2005).
7. G. A. Milne, J. X. Mitrovica, *Geophys. J. Int.* **126**, F13 (1996).
8. The sea-level fingerprints associated with these sources will be purely additive, with a weighting reflecting the relative contributions to the total EEV.
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Supporting Online Material
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Materials and Methods
Fig. S1
References

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