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Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet

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Theory has suggested that the West Antarctic Ice Sheet may be inherently unstable. Recent observations lend weight to this hypothesis. We reassess the potential contribution to eustatic and regional sea level from a rapid collapse of the ice sheet and find that previous assessments have substantially overestimated its likely primary contribution. We obtain a value for the global, eustatic sea-level rise contribution of about 3.3 meters, with important regional variations. The maximum increase is concentrated along the Pacific and Atlantic seaboard of the United States, where the value is about 25% greater than the global mean, even for the case of a partial collapse.

Glaciologists have proposed that the marine portion of the West Antarctic Ice Sheet (WAIS) is potentially unstable and that, as a consequence, it may be susceptible to a rapid disintegration as a result of a relatively modest change in climatic boundary conditions (*1*–*4*). There is compelling evidence that the WAIS has undergone partial collapse in the past, possibly as recently as 400 thousand years before the present (kyr B.P.) (*5*, *6*) as a consequence of moderate warming. The proposed instability of the WAIS is a consequence of the marine ice sheet instability (MISI) hypothesis, which has its basis in the idea that removal of fringing ice shelves will result in the rapid and irreversible inland migration of the grounding line where the bedrock is below sea level and slopes downward from the margins toward the interior (*4*, *7*). First suggested in the 1970s, the hypothesis is supported by recent theoretical analysis of grounding line stability (*8*). The WAIS is unique in possessing a large proportion of its mass where these conditions hold (Fig. 1). Collapse is considered to be a low-probability, high-impact event with, for example, a 5% probability of the WAIS contributing 10 mm year^{-1} within 200 years (*9*). Risk and mitigation assessments have, in general, used a single, historic sea-level rise (SLR) value or range resulting from a collapse. The most often quoted range in the literature for a complete collapse of the WAIS is 5 to 6 m with no regional variations (*10*).

The first estimate of the potential eustatic (*11*) SLR from a collapse of the WAIS was about 5 m (*2*) and remains the generally accepted lower value quoted (*12*). As is the case here and in paleoreconstructions (*6*), it was assumed, presumably on the basis of glaciological theory, that ice grounded above sea level would survive, but no details have been provided about how the calculation was made (Fig. 2).

More recently, with the benefit of improved bedrock and surface topography, the total volume of the WAIS, including the Antarctic Peninsula, and ice grounded above sea level was estimated and found to be equivalent to 5 m of eustatic SLR (*13*). This calculation was not, however, attempting to assess the volume of ice that met the MISI hypothesis criteria or any other glaciological or geophysical constraints, such as the response of East Antarctic glaciers or glacio-isostatic adjustment. Previous estimates have not defined the region susceptible to a collapse, the extent of the marine portion of the continent that they assume will contribute, or any assumptions made. The Antarctic Peninsula, for example, is both topographically and glaciologically distinct from the WAIS, lies almost entirely above sea level (Fig. 1 and 2), and was included in the most recent estimate of the sea level equivalent volume of the WAIS (*13*). Further, although much of the WAIS is grounded on bedrock below sea level (BSL), there are extensive areas around the Transantarctic and Ellsworth mountains and the Executive Committee Range that are not and/or that do not have negative bed slopes (i.e., where the bed elevation deepens inland in the opposite direction to ice motion) (Fig. 1 and figs. S1 and S2). Of equal importance is the fact that the impact on SLR of a collapse of the WAIS would not be uniformly distributed across the oceans. Although this was identified at an early stage, the estimation of the regional impact (*14*) assumed a uniform loss across the WAIS and did not include important effects, such as Earth rotational changes (polar wander) and shoreline migration (*15*). Here, we perform a detailed assessment of the potential contribution of the WAIS, taking into account relevant glaciological constraints along with the solid earth and geoid response. To do this, we used recent estimates of the geoid, bedrock, and ice surface elevation, combined with a viscoelastic Earth model, to estimate the regional SLR from a glaciologically consistent collapse of the marine portion of the WAIS. We stress, however, that we are not attempting to assess the validity of the MISI hypothesis, the likely rate of mass loss, or the probability of a complete or partial collapse.

Data sets. We have taken new bedrock elevation data sets for the Amundsen Sea sector of West Antarctica (*16*, *17*) and combined these with an older bed elevation data set for the rest of the continent (*13*), a new ice surface digital elevation model (*18*), and a new geoid derived from Gravity Recovery and Climate Experiment (GRACE) satellite mission data (www.gfz-potsdam.de/pb1/op/grace/results/index_RESULTS.html). We apply these data to two scenarios of steady wasting based on earlier estimates of the rate of wastage of the WAIS (*19*).

To determine the volume of ice resting on bedrock BSL, we merged new bedrock data for the Amundsen Sea Embayment sector with the older BEDMAP data set (*13*). We then identified grid cells that (i) were BSL and (ii) have negative bed slopes. This condition was applied loosely to provide an upper limit for the area susceptible to collapse (*20*). For convenience, this area will henceforth be referred to as the region of interest (ROI). The ROI is shown in Fig. 1 and includes the Antarctic Peninsula, although it is only its most southerly limit and margins that are BSL and nowhere does it satisfy the MISI conditions discussed earlier (Fig. 1).

The volume of ice in the ROI above sea level was summed, excluding floating ice shelves, by using the ice surface digital elevation model with respect to the geoid. We used the EIGEN-GLO4C gravity model, derived from data provided by the GRACE satellite mission, which has a stated accuracy of 0.18 to 0.44 m on the basis of comparison with Global Positioning System data across Europe and North America (www.gfz-potsdam.de/pb1/op/grace/results/index_RESULTS.html). The ice volume above sea level was corrected for the density difference between ice and seawater, assuming a value of 918 kg m^{-3} for the former and 1028 kg m^{-3} for the latter. The same densities were used to calculate the change in volume of submerged ice that is replaced by seawater. An additional term was calculated to take account of the drawdown of newly formed ice margins adjacent to the unstable areas. Where ice has been removed, rather than a nonphysical vertical boundary, the ice surface will, over time, relax to a new equilibrium profile. We estimated the impact of the surface drawdown by imposing a flotation criterion at the new ice margins and then using a thermomechanical ice sheet model to estimate the postcollapse equilibrium profiles, in

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the absence of the collapsed ice (*20*). We also considered the impact of an acceleration in ice motion for the outlet glaciers in East Antarctica that flow into the ice shelves that have been removed (*20*). This defines the total volume of ice in the region that satisfies the MISI conditions plus the response of the extant ice to its removal. Instantaneous melting of the ice satisfying the MISI conditions would produce a eustatic SLR of 2.46 m with an error of 0.2 m resulting from uncertainties in the input data used. Drawdown of extant ice areas is responsible for a subsequent 0.74 m, and a further 0.06 m should be added because of the elastic response of the lithosphere, which gives a total of 3.26 m (table S1). This compares with a value of 4.8 m for the removal of the whole of the WAIS including the Peninsula. We consider two disintegration scenarios based on previous work (*8*, *19*). These scenarios are used solely to calculate the glacial isostatic adjustment and polar wander response. They are not meant to indicate a probable decay behavior, which is likely to be nonlinear and asymptotic. They are equivalent to a eustatic SLR of 6.4 and 1.9 mm year^{-1} and a freshwater flux of 0.07 and 0.02 sverdup, respectively, assuming a linear loss over the time taken for collapse. These values are considerably smaller than, for example, meltwater pulse 1A at around 14 kyr B.P., which was responsible for a ~20-m rise in sea level in ~500 years and which may have partly originated from Antarctica (*21*, *22*). They are also less than the estimate of 10 mm year^{-1} mentioned earlier and derived from a risk assessment study (*9*).

Results. The extant ice and sectors removed are shown in Figs. 1 and 2. After taking into account the drawdown estimate, the volume left is equivalent to 1.8 m eustatic SLR (table S1). This comprises a fairly contiguous and sizable ice cap over the Executive Committee/Flood ranges [Marie Byrd Land Ice Cap (MBLIC) in Fig. 1], which is about 600 km in length and 300 km in width. A smaller (~200 km length) ice cap is centered just east of the Amundsen Sea Embayment. The Antarctic Peninsula makes only a small contribution to eustatic SLR out of a potential total of 24 cm because it is grounded on bedrock substantially above sea level. The other area that lies within the WAIS but which is considered stable is centered over the Ellsworth, Whitmoor, and Thiel mountain ranges and is connected to the East Antarctic Ice Sheet (EAIS) plateau [Ellsworth Mountain Ice Cap (EMIC) in Fig. 1]. The spatial distribution of extant ice is broadly similar to the early reconstruction by Mercer (Fig. 2) but with markedly different estimates of the eustatic SLR (*2*). We believe this discrepancy may be due to the dearth of reliable bed and surface elevation data available at the time of the earlier study (fig. S6). Removal of the sectors in the WAIS that are BSL but with positive bed slopes (i.e., relaxing the MISI condition to cover the entire marine portion) would contribute an additional 49 cm and cannot, therefore, explain the difference (table S1).

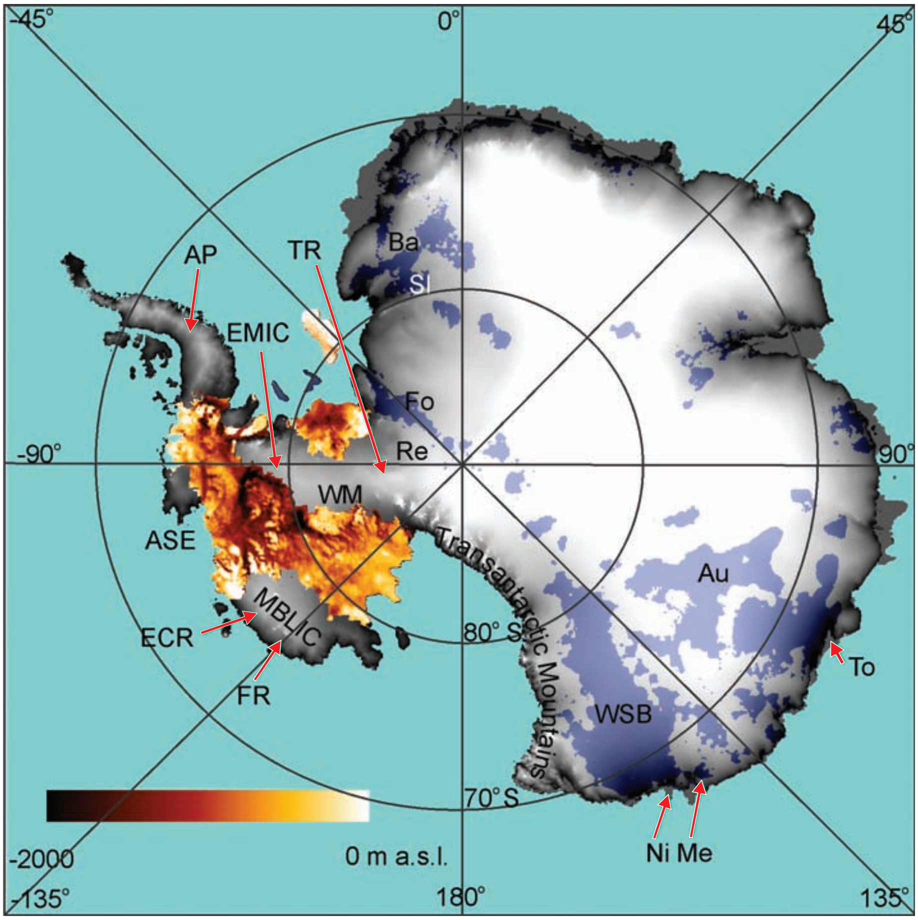

Fig. 1. Antarctic surface topography (gray shading) and bed topography (brown) defining the region of interest. For clarity, the ice shelves in West Antarctica are not shown. Areas more than 200 m BSL in East Antarctica are indicated by blue shading. AP, Antarctic Peninsula; EMIC, Ellsworth Mountain Ice Cap; ECR, Executive Committee Range; MBLIC, Marie Byrd Land Ice Cap; WM, Whitmoor Mountains; TR, Thiel Range; Ba, Bailey Glacier; SL, Slessor Ice Stream; Fo, Foundation Ice Stream; Re, Recovery Glacier; To, Totten Glacier; Au, Aurora Basin; Me, Mertz Glacier; Ni, Ninnis Glacier; WSB, Wilkes Subglacial Basin; FR, Flood Range; a.s.l., above sea level.

Fig. 2. A comparison of the area of ice sheet calculated to survive after a collapse of the WAIS in (**A**) this study and (**B**) the historic study by Mercer (*2*).

Global sea-level changes are not uniform because of regional variations in Earth's gravity field caused by (i) ice mass change in the WAIS, (ii) deformation of solid Earth, and (iii) changes in Earth's rotation vector as a result of mass redistribution. The combination of these effects, all self-consistently included in our solution of the sea-level equation, leads to a complex regional pattern, as already recognized in early studies [e.g., (*23*, *24*)]. We solved the sea-level equation by means of a pseudospectral algorithm (*25*, *26*) for a self-gravitating, spherically

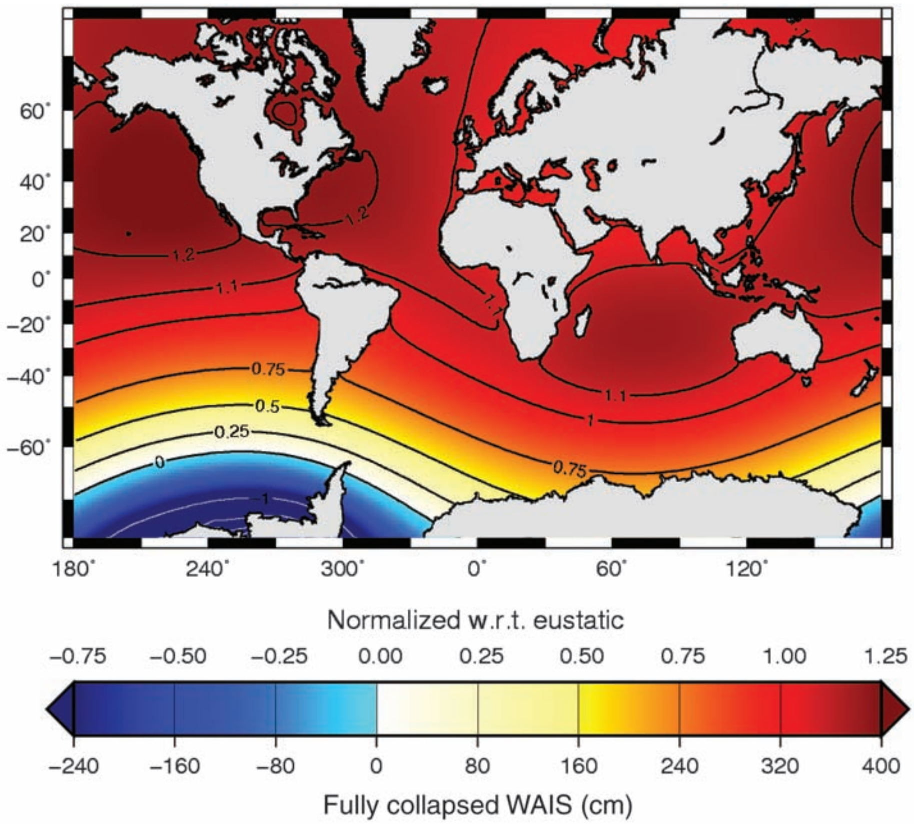

Fig. 3. Regional SLR after instantaneous removal of ice from the ROI, including the effects of self-gravitation, elastic rebound of the lithosphere, and Earth rotation perturbations but excluding the effects of ocean circulation (*29*) and other sources of ocean mass. w.r.t., with respect to.

layered, incompressible, viscoelastic Earth with Maxwell rheology. Our Earth model includes a 100-km-thick elastic lithosphere, a stratified viscoelastic mantle, and an inviscid core, where elastic parameters and densities are average preliminary reference Earth model values (*27*). The effect of WAIS melt on global sea level was computed by taking into account induced variations in ocean-continent geometry (shoreline migration) and perturbations in Earth's rotation vector (polar wander) (*28*). The initial ice load was uniformly distributed over the ROI, and a subsequent ice retreat history was constructed following bedrock elevation curves (at each time, the grounding line is everywhere at the same elevation). We have limited our computations, solely, to the effect of a WAIS collapse. Our sea-level results are, therefore, variations with respect to present-day sea level from this source only.

Figure 3 shows the regional pattern of global sea-level change after complete collapse of the WAIS, considering only the quasi-instantaneous (elastic) response of solid Earth and ignoring ocean circulation effects that are important on a decadal time scale (*29*). In addition, we do not include here mass losses from other sources such as Greenland, glaciers, and ice caps. The peak increase lies in the Indian Ocean and in a latitudinal band centered at ~40°N, along the Pacific and Atlantic coasts of the United States. We provide two scales for sea-level changes: The first is normalized with respect to the eustatic value, and the second, in centimeters, is for the case of complete removal of the ROI. The normalized scale is applicable in the case of partial collapse: for example, in the fast melt scenario (6.4 mm year^{-1}), the maximum SLR at 100 years after present would amount to 81 cm (1.27 times the global eustatic value). The eustatic SLR resulting from the elastic response of the lithosphere within the ROI amounts to about 6 cm (included in the absolute scale in Fig. 3) and subsequently increases because of viscoelastic relaxation up to about 46 cm after 10,000 years (fig. S9).

We conclude that previous estimates of the impact on eustatic SLR of the rapid collapse of the WAIS have been overestimated. Our estimate of the likely limit to the contribution to eustatic SLR for that portion of the WAIS that loosely satisfies the MISI hypothesis conditions is no more than 3.20 m, with the addition of about 6 cm resulting from elastic rebound of the lithosphere. After 10,000 years, viscous glacio-isostatic adjustment and additional inland ice drawdown from the EAIS contribute a further 40 and 20 cm, respectively. Over this time scale, however, other dynamic and surface ice sheet processes may also contribute further mass to the oceans. As noted elsewhere, SLR is not uniformly distributed (*24*), and we find the peak increases lie along the Pacific and Atlantic seaboards of the United States.

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Materials and Methods
Figs. S1 to S9
Table S1
References

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