GEOSCIENCE

# Rapid Sea-Level Rise Soon from West Antarctic Ice Sheet Collapse?

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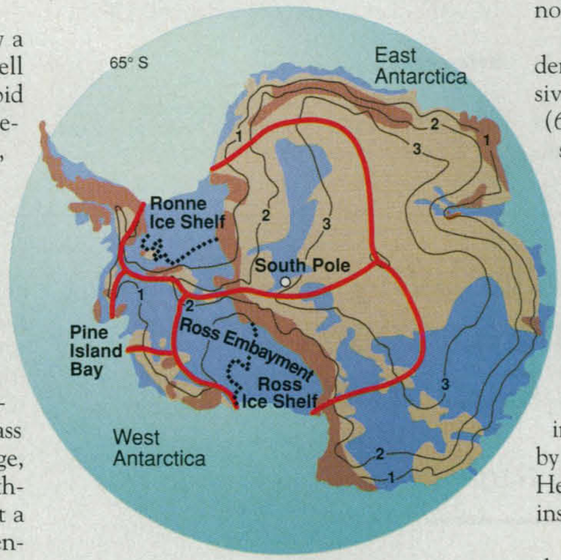
Will worldwide sea level soon rise rapidly because of a shrinkage of the West Antarctic ice sheet (WAIS)? That is a question of widespread interest, great societal import, and considerable controversy. The Intergovernmental Panel on Climate Change (IPCC) Second Scientific Assessment of Climate Change finds that estimating the probability of such an event is not yet possible (*1*). Here I give my perspective of that probability.

Glaciologists generally agree that only a marine ice sheet, one that rests on a bed well below sea level, is likely to undergo rapid change, and they focus on the WAIS because it appears to be the most vulnerable, being open to the ocean on three sides (see figure), and comprises the bulk of the marine ice in Antarctica. Furthermore, it is widely accepted that the WAIS varied in size during the Pleistocene ice ages (the last million years or so). If the entire WAIS were discharged into the ocean, the sea level would rise by 5 or 6 m. The crucial question here, however, is not whether large changes in ice mass can occur, but how likely is it that a large, rapid change, say a doubling of the 20th-century rate to about 4 mm/year (still not a disastrous rate), will occur in the next century or two.

Like other ice sheets, the WAIS is not a single dynamic entity: it comprises three major and several minor drainage systems (see figure) that have separate regimes and are unlikely all to accelerate at once. But as a worst-case scenario, assume that the whole WAIS behaves as a unit. The present-day outflow of ice from the WAIS is equivalent to about 1 mm/year in sea-level rise; that amount is roughly balanced by the withdrawal of water from the ocean to produce snowfall over the ice sheet. Because approximately half of the WAIS is below sea level and consequently already displaces ocean water, the increase in outflow rates needed for a rapid rise in sea level is at least a factor of 6. This large change could come about only from a massive instability. Is there theoretical or observational evidence to suggest the existence of such an instability?

Twenty years ago Weertman (*2*) proposed that a marine ice sheet is inherently unstable. At times of high sea level, as at present, the junction between the grounded ice (ice resting on a solid bed) and the adjacent floating ice shelves (the "grounding line") would retreat unstably into the central interior until all the ice was afloat. The




**Map of Antarctica** showing ice-sheet surface elevations (black contour lines; heights in kilometers), divides between ice-drainage systems (red lines), mountainous regions (brown), sections of the ice sheet where the bed is above (tan) and below (blue) sea level, and the grounding lines (dotted lines) bounding the Ross and Ronne ice shelves.

WAIS owes its existence, in an extension of Weertman's concept (*3*), to "back pressure" from the ice shelves, which restrain the outflow of the grounded inland ice. If the back pressure were diminished or removed (for instance, by rapid ice-shelf thinning), the WAIS would collapse in as little as a century by a catastrophic grounding-line retreat. Sea level would rise half a meter per decade.

But Weertman's analysis was based on a simple model of a marine ice sheet that did not include fast-flowing, wet-based ice streams, which are now known to dominate the grounded ice sheet. The ice streams blend gradually downstream into the ice shelves and respond rapidly to changes at the grounding line. Just how ice streams affect the stability of the WAIS is still uncertain, but recent theoretical treatments tend to support the idea of stability rather than instability, whether or not ice streams are present. For example, Hindmarsh has presented an internally consistent marine ice-sheet model in which the ice-sheet flow is stable and independent of the ice shelf, so long as the ice-sheet slopes are large compared with the ice-shelf slopes, as they are on WAIS ice streams (*4*). Although a definitive model has yet to be produced, it can at least be said that there is no compelling theoretical reason to expect a rapid rise in sea level from the WAIS triggered by ice-shelf thinning. However, a model study of the long-term behavior of the WAIS (*5*) implied a rapid rise about once every 100,000 years; that is, at about the same frequency as interglacial periods, but not in synch with the glacial cycle.

What about the glaciological field evidence? The recently recognized sudden, massive outpourings of icebergs [Heinrich events (*6*)] during the last ice age suggest ice-stream instability in the Northern Hemisphere ice sheets. But in the leading explanation for those events (*7*), acceleration is attributed to transformation of the bed of a potential ice stream from frozen to melting. This process is not applicable to the West Antarctic ice streams because they are already melting at their beds, yet 9 out of 10 exhibit a positive or near-zero "mass balance" (mass in, by snow accumulation, minus mass out, by ice flow). No theoretical model for the Heinrich events that would also imply WAIS instability has been put forward to date.

Of the three main ice-drainage systems in the WAIS, the one that flows into Pine Island Bay (see figure) might be a particularly likely site for accelerated flow because there is no ice shelf to restrain the inflowing ice streams. However, measurements show that this system is not significantly out of mass balance (*8*).

In the heavily studied "Ross Embayment," which includes the Ross Ice Shelf and the ice that flows into it from West Antarctica, several sudden glacial reorganizations have occurred in the last thousand years, as ice streams have stagnated and ice-stream boundaries have undergone lateral jumps of several kilometers (*9*). If the Ross Embayment system were unstable, one might expect a history of large changes in the total outflow of ice into the Ross Ice Shelf. Tracers of the past 1500 years of flow preserved in the Ross Ice Shelf can be compared with the present-day flow of the ice; large surges of the inland ice would be recorded as distortions of the flow tracers. Indeed, one striking deformation of the flow

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tracers has been found: a few hundred years ago there was a large pulse of ice in the southern Ross Embayment, but the flow after that pulse reverted to what it was beforehand (*10*). In fact, the proportion of ice flowing into the Ross Ice Shelf from East and West Antarctica, respectively, has remained approximately constant over the full 1500 years (*11*). This implies that the total outflow in the Ross Embayment has remained relatively unchanged despite the large internal perturbations, which points to a stable, not an unstable, system. Furthermore, glaciological studies of several types have all indicated that there has been no drastic change in the last 30,000 years in the height or flow of the ice sheet within the interior Ross Embayment (*12*). Study of the third major drainage from the WAIS, into the Ronne Ice Shelf, also suggests that there is no gross discordance between the present velocity vectors and flow tracers in the ice shelf, although the evidence is limited (*13*).

In light of the evidence for recent stability, it is difficult to see how climate warming (whether anthropogenic or natural) could trigger a collapse of the WAIS in the next century or two. Ice sheets take thousands of years to respond to changes in surface temperature, because it takes that long for the temperature changes to penetrate close to the bed and only at the bed could increasing temperatures affect the flow rates in any major way. Oceanic warming could cause thinning of the ice shelves, but recent studies with global circulation models have suggested that oceanic warming in the far southern ocean from, say, an enhanced greenhouse effect would be delayed by centuries compared to the rest of the world because of the large-scale sinking of surface waters around Antarctica (*14*). Furthermore, for reasons already cited, it is questionable whether ice-shelf thinning would have any drastic effect on the inland ice. Thus, I believe that a rapid rise in sea level in the next century or two from a West Antarctic cause could only occur if a natural (not induced) collapse of the WAIS is imminent, the chances of which, based on the concept of a randomly timed collapse on the average of once every 100,000 years, are on the order of 0.1%.

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CONDENSED MATTER THEORY

# Superconductivity and Antiferromagnetism in High-$T_c$ Cuprates


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Ten years have passed since the discovery of the high–transition temperature ($T_c$) superconductors. Although there has been no agreement on a complete theory, a consensus has formed that the strong electron repulsion and the quasi–two-dimensional layered nature of these materials are responsible for their anomalous physical properties and high $T_c$. On page 1089 of this issue, Zhang describes a theory that relates one important property of these materials, their superconductivity, with another, the phenomenon of antiferromagnetism.

The repulsive electron interaction in the cuprates tends to increase the spin moments because it reduces the probability of two electrons with opposite spins occupying the same orbital and hence breaks the cancellation of the spin moments. An antiferromagnetic (AF) exchange interaction occurs between these induced spin moments because an electron can hop to the neighboring site without violating Pauli's exclusion principle if the spin there is antiparallel. This virtual process lowers the energy. In high-$T_c$ oxides, the exchange energy $J$ is estimated experimentally to be around 0.15 eV. This large value of $J$ is considered to be responsible for the high $T_c$, and the final theory of high-$T_c$ superconductivity should include an appropriate treatment of this AF interaction. There are two consequences of this interaction: (i) it induces an AF magnetic long-range ordering (Néel state), and (ii) it causes formation of the singlet pair. Zhang proposes an ambitious theory based on SO(5) symmetry that unifies these two aspects (*1*).

A schematic phase diagram of carrier concentration $x$ versus temperature for high-$T_c$ superconductors is shown in the figure. At $x = 0$, there is one electron per copper orbital (half-filled), and band theory predicts the metallic state. However, the strong Coulomb interaction blocks the band motion, and each orbital is occupied by a single localized electron; that is, the system is a Mott insulator. In this Mott insulator, the spins are aligned antiferromagnetically because of the AF interaction mentioned above. This ordering of the spins is destroyed by the doping, and the region of so-called "pseudo gap state" appears, where the pseudo gap is observed well above $T_c$ in nuclear magnetic resonance, neutron scattering, specific heat, photoemission, and infrared optical spectra perpendicular to the plane (*2*).

Here some remarks are in order on the symmetry of the pairing. Let $\psi(\mathbf{r})$ be the spatial wave function for the relative motion of the Cooper pair. The total wave function is the product of the spatial and spin parts. Because of the antisymmetry to the exchange of the two electrons, spin-singlet (-triplet) pairing is accompanied by the even (odd) function for $\psi(\mathbf{r})$. When decomposed into the partial waves, $l = 0$ ($s$ wave), $l = 2$ ($d$ wave), and higher even terms correspond to the spin-singlet pairing, whereas $l = 1$ ($p$ wave), $l = 3$, and higher odd terms correspond to the spin-triplet pairing. In the usual BCS (Bardeen-Cooper-Schrieffer) superconductors, the $s$-wave pairing is a result of the weak attractive force, mediated by means of the electron-phonon interaction. With


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