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Key Points:
- Collapse of the West Antarctic Ice Sheet would change atmospheric circulation over Antarctica
- WAIS collapse warms adjacent areas of East Antarctica and cools coastal Marie Byrd Land
- Ice core data provide supporting evidence for WAIS collapse during the last interglacial period (MIS 5e)

Supporting Information:
- Supporting Information S1

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Influence of West Antarctic Ice Sheet collapse on Antarctic surface climate

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Abstract Climate model simulations are used to examine the impact of a collapse of the West Antarctic Ice Sheet (WAIS) on the surface climate of Antarctica. The lowered topography following WAIS collapse produces anomalous cyclonic circulation with increased flow of warm, maritime air toward the South Pole and cold-air advection from the East Antarctic plateau toward the Ross Sea and Marie Byrd Land, West Antarctica. Relative to the background climate, areas in East Antarctica that are adjacent to the WAIS warm, while substantial cooling (several °C) occurs over parts of West Antarctica. Anomalously low isotope-paleotemperature values at Mount Moulton, West Antarctica, compared with ice core records in East Antarctica, are consistent with collapse of the WAIS during the last interglacial period, Marine Isotope Stage 5e. More definitive evidence might be recoverable from an ice core record at Hercules Dome, East Antarctica, which would experience significant warming and positive oxygen isotope anomalies if the WAIS collapsed.

1. Introduction

It is unknown whether the West Antarctic Ice Sheet (WAIS) collapsed during the last interglacial period, Marine Isotope Stage (MIS) 5e, 130 to 116 ka (thousands of years before present). Eustatic sea level during MIS 5e was 5.5–9 m higher than present [*Kopp et al.*, 2009; *Dutton and Lambeck*, 2012]. The Greenland ice sheet can account for 2 to 4 m [*NEEM Community Members*, 2013; *Stone et al.*, 2013], and glaciers, small ice caps, and ocean thermal expansion <1 m. Full retreat ("collapse") of the WAIS would produce about 3.3 m of sea level rise [*Bamber et al.*, 2009], which could balance the higher estimates for MIS 5e sea level rise, but lower estimates require little Antarctic contribution. Sediment cores from beneath the WAIS [*Scherer et al.*, 1998] provide direct evidence of WAIS collapse in the past but do not sufficiently constrain the timing.

We evaluate whether collapse of the WAIS would have caused regional climate changes sufficiently large to be detectable in ice cores. The idea of using ice core records to determine ice sheet changes has been exploited previously, chiefly under the assumption of a fixed climate, with elevation change expressed through the lapse rate effect on temperature and on isotope ratios in precipitation [*Steig et al.*, 2001; *Bradley et al.*, 2013]. Here we consider changes in regional climate induced by a lowered WAIS topography. We evaluate the influence of WAIS collapse on atmospheric circulation, temperature, and isotope ratios using general circulation model (GCM) experiments at varying levels of complexity and compare the results with ice core records that extend through MIS 5e.

2. Methods

2.1. Climate Model Experiments

We compare GCM control simulations using modern Antarctic topography, with "WAIS collapse" simulations in which the Antarctic topography is reduced. In all experiments, climate boundary conditions (greenhouse gases and orbital configuration) are set to preindustrial values. The surface characteristics (e.g., albedo) are unchanged in all areas between the full modern topography and the altered topography that simulates WAIS collapse. The extent of ice shelves is assumed fixed, and their surfaces are not distinguished from the ice sheet (other than by elevation).

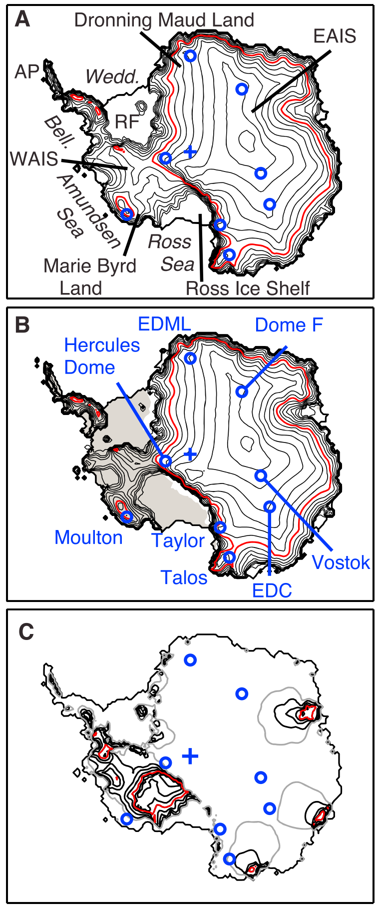

Figure 1. Prescribed Antarctic topography used in the GCM simulations: (a) Modern Antarctic topography, with geographic features. WAIS: West Antarctic Ice Sheet. EAIS: East Antarctic Ice Sheet. RF: Ronne-Filchner Ice Shelf. AP: Antarctic Peninsula. Bell.: Bellinghausen Sea. Wedd.: Weddell Sea. Blue circles: ice-core locations discussed in the text. Blue cross: South Pole. Contours show elevation above sea level; contour interval 250 m. Red contour: 2000 m. (b) WAIS collapse topography for the fully coupled model experiments with CCSM4. For the aquaplanet experiments with GRaM and GFDL-AM2, all of the West Antarctic sector (shaded) is set to zero elevation, and East Antarctic elevations are unchanged. Ice core locations (named) and contours as in Figure 1a. (c) Difference between control (Figure 1a) and WAIS collapse topography (Figure 1b) for the CCSM4 experiments. Red contour = 1000 m elevation change. Contour interval = 250 m. The 100 m elevation change contour is also shown (gray).

We conducted aquaplanet simulations with the Gray Radiation Moist (GRaM) GCM [*Frierson et al.*, 2006] and the Geophysical Fluid Dynamics Laboratory Atmospheric Model 2 (AM2) [*GFDL*, 2004] in which the only topography is a "water mountain" having the shape of Antarctica. Both are coupled to a shallow (2.4 m) slab ocean and have no seasonal cycle. In GRaM, radiative fluxes are functions of temperature alone; there is a convective scheme but no cloud parameterization. In AM2, there are more complete radiation and convection schemes, and cloud and water vapor feedbacks. GRaM was run at T85 (spatial resolution ~1.4°), with 25 vertical levels, and AM2 at 2°×2.5° with 24 levels. In the WAIS collapse simulations with these models, all elevations in West Antarctica were reduced to zero; topographic features such as mountains are not retained. We use the last 5 years of 15 year simulations.

We also conducted simulations with the European Center Hamburg version 4.6 (ECHAM4.6) atmospheric model [*Roeckner et al.*, 1996] at T42 (~2.5°) with 19 vertical levels, coupled to a slab ocean with thermodynamic sea ice. We included the isotope module [*Hoffmann et al.*, 1998] to obtain simulations of oxygen isotope ratios in precipitation. We use the final 30 years of 40 year long simulations. We used global topography, and realistic topographic changes in Antarctica given by the ice sheet model simulations of *Pollard and DeConto* [2009], as shown in Figure 1. Isostatic adjustment to ice thickness changes is accounted for. Topographic features such as Hercules Dome and the mountain ranges of coastal Marie Byrd Land do not change elevation, though moderate (50–100 m) lowering occurs as an artifact of smoothing the high-resolution topography to match the GCM resolution. Elevation changes occur in the major East Antarctic drainage basins, with reductions of more than 100 m extending inland.

Finally, we used the fully coupled ocean-atmosphere GCM, Community Climate System Model version 4 (CCSM4) [*Gent et al.*, 2011], with the same topography as for the ECHAM4.6 experiments, at a land/atmosphere resolution of 1.9° × 2.5° with 26 vertical levels and an ocean resolution of 1°; the sea ice is fully dynamic. The WAIS collapse simulation begins at year 700 of the control simulation and runs for an additional 230 years; the final 30 years of each are used.

2.2. Ice Core Data

The isotope ratio of oxygen ($\delta^{18}O$) in ice is used as a proxy for temperature. Ice core isotope records that include MIS 5e are currently available at six locations in East Antarctica (Figure 1): at Vostok [*Jouzel et al.*, 1993], Taylor Dome [*Steig et al.*, 2000], Dome F [*Watanabe et al.*, 2003], Dome C (European Project for Ice Coring in Antarctica (EPICA) Dome C (EDC)) [*Jouzel et al.*, 2007], EPICA Dronning Maud Land (EDML) [*EPICA Community Members*, 2006], and Talos Dome [*Stenni et al.*, 2011]. Locations are shown in Figure 1, and isotope records in Figure S1 in the supporting information. Hercules Dome in East Antarctica is of interest because it is close to West Antarctica and would have remained at a similar elevation and ice thickness even if WAIS collapsed. Radar profiles indicate that ice from MIS 5e may be recoverable at Hercules Dome [*Jacobel et al.*, 2005].

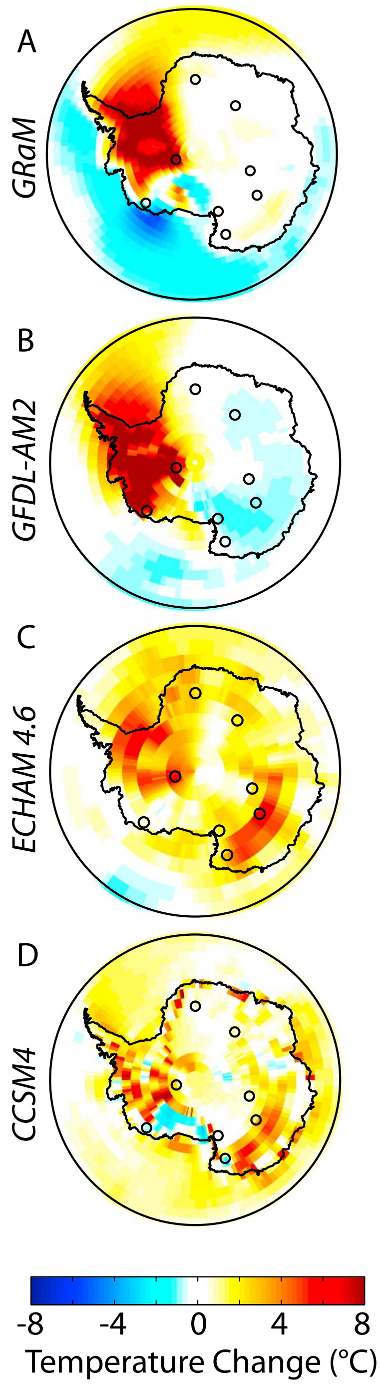

Figure 2. Response of surface temperature to changes in Antarctic topography in GCM experiments (WAIS collapse minus control). (a) GRaM and (b) GFDL-AM2 aquaplanet experiments; all of West Antarctica is removed in the WAIS collapse simulations. (c) ECHAM4.6 with a slab ocean and (d) CCSM4 fully coupled ocean and atmosphere, both with realistic topography. Circles show locations of ice cores discussed in the text.

An isotope record from Mount Moulton is the only currently available West Antarctic record that includes MIS 5e [*Popp*, 2008; *Korotkikh et al.*, 2011]. It was developed from an ice trench in an exposed section(~76°S, 134.7°W, 2820 m above sea level) on the southern shoulder of Mount Moulton, in the Flood Range of coastal Marie Byrd Land, where ice flow brings old ice to the surface. The Mount Moulton record was dated radiometrically by volcanic tephra layers that span the ~600 m long section [*Dunbar et al.*, 2008].

We are interested in differences among the δ^{18}O records during MIS 5e. To minimize artifacts arising from errors in the ice age versus depth relationships, we use the common Antarctic ice core chronology 2012 timescale [*Veres et al.*, 2013; *Bazin et al.*, 2013] and adjust the preliminary timescale [*Popp*, 2008] of the Mount Moulton record by maximizing its correlation with EDC, constrained by tephra layers dated to 10.5±2.5 ka and 135.6±0.9 ka [*Dunbar et al.*, 2008]. The revised Mount Moulton timescale (Figure S2 in the supporting information) is within the combined uncertainties of the radiometric ages and the EDC timescale and is conservative with respect to the comparisons we make; that is, differences would be accentuated if the original timescale were used.

3. Results

Figure 2 shows the surface temperature response of the climate models to the changed Antarctic topography, as compared to the control-run climatology. The largest temperature increases occur in areas with reduced elevation, but there is also substantial warming over areas of East Antarctica where the topography is unchanged. In all experiments, there is warming over parts of the East Antarctic ice sheet adjacent to West Antarctica, including Hercules Dome and coastal Dronning Maud Land (though not generally extending to the EDML ice core site). There is also warming in East Antarctica upslope from areas of reduced topography in the major ice drainage basins. There is significant cooling over parts of the Ross Sea and cooling or no warming in coastal Marie Byrd Land, West Antarctica. Temperature changes off the Antarctic continent vary, but all models show warming over the Ronne-Filchner Ice Shelf and the Atlantic sector of the Southern Ocean. The spatial pattern of the δ^{18}O response, as simulated with the full isotope module in ECHAM4.6, is similar to the temperature response (Figure S3 in the supporting information).

Figure 3 shows the response of the surface wind field and potential temperature (temperature normalized to constant pressure). All models show the same pattern of wind changes, with increased cyclonic flow over areas where the topography is reduced. The potential temperature anomalies closely follow the wind changes; there is greater onshore flow toward areas that warm and greater flow from East Antarctica toward the Ross Sea and Marie Byrd Land, both areas that cool. Changes in the large-scale circumpolar winds are less

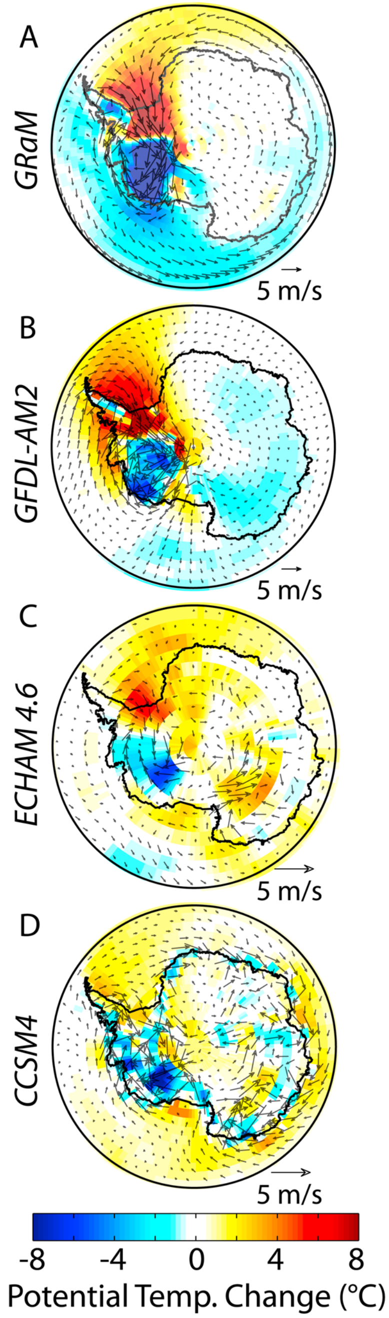

Figure 3. Response of surface wind (arrows) and potential temperature (colored shading). (a) GRaM, (b) GFDL-AM2, (c) ECHAM4.6, and (d) CCSM4. Potential temperature is given by $\theta = T\left(\frac{P_0}{P}\right)^{R/c_P}$ at surface temperature T, surface pressure P, reference pressure P_0 (1000 hPa), gas constant R, and specific heat capacity of air c_P at P_0.

consistent between the models but in all cases are small compared with those over West Antarctica and adjacent areas of East Antarctica.

Figure 4 compares the δ^{18}O record from Mount Moulton with the average of the East Antarctic ice cores (excluding the low-resolution Taylor Dome record), normalized to the peak warmth (maximum δ^{18}O) of the early Holocene. The Mount Moulton record is distinctive in having a smaller maximum in δ^{18}O during MIS 5e than the East Antarctic ice core records. This difference is significant (more than two standard deviations below the mean) for most of MIS 5e.

4. Discussion

4.1. Climate Dynamics

The large-scale wind and temperature changes over West Antarctica can be understood as consequences of relatively simple atmospheric dynamics. The cyclonic circulation anomaly over West Antarctica that occurs when the topography is lowered would be expected from potential vorticity conservation, in that stretching of the air column requires that it spin up in the same direction as the planetary vorticity, i.e., cyclonically. *James* [1988] showed that linear, barotropic dynamics causes an anticyclonic anomaly over topography when an idealized Antarctic-like continent is added in a barotropic model; thus, removal of the topography causes a cyclonic anomaly. *Watterson and James* [1992] found further support for this purely dynamical mechanism in a primitive equation model. *Parish and Cassano* [2003] show that there is little sensitivity of the winds to strong longwave cooling of the continent, implying that the katabatic component of the observed large-scale winds is weak. These considerations explain why all four models show such similar responses to the removal of topography, despite quite different model details.

Adiabatic warming would be expected as a direct response to the thicker atmosphere where the topography is lowered. If warming were strictly adiabatic, there would be no change in potential temperature; hence, a change in potential temperature implies advection. This is clear in the potential temperature fields (Figure 3), indicating that atmospheric circulation changes account for the warming observed over the Ronne-Filchner Ice Shelf and the Atlantic sector of the Southern Ocean, as well as areas of the ice sheet where the topography has not changed, including coastal Dronning Maud Land and in the vicinity of Hercules Dome. Cooling over the Ross sea and coastal areas of Marie Byrd Land reflects advection of cold-air anomalies from the East Antarctic plateau.

The more variable response of the models over the Southern Ocean and most of East Antarctica suggests that the direct effects of WAIS collapse on climate over these regions are small, relative to other processes and feedbacks. In the aquaplanet experiments, large areas over the Southern Ocean cool, while in the fully coupled model results, warming occurs over nearly the entire Southern Ocean. The latter can be attributed to dynamical changes in the ocean due to wind forcing, as has also been observed in a recent WAIS collapse experiment

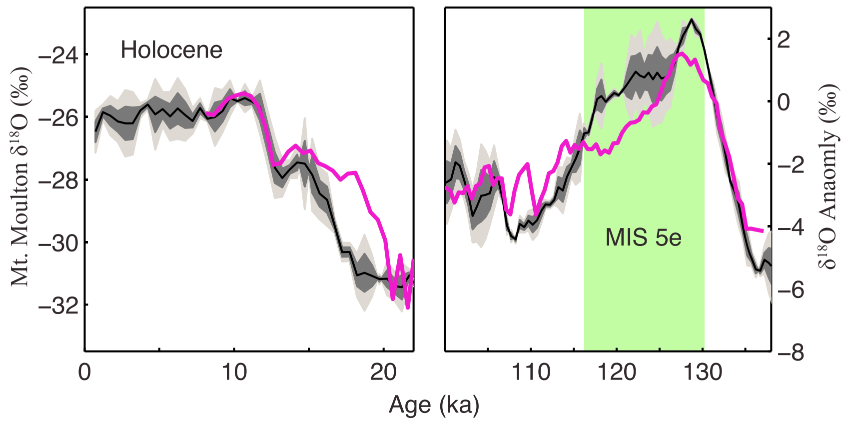

Figure 4. Comparison of East Antarctic ice core and Mount Moulton $\delta^{18}O$ records, relative to the early-Holocene peak value at ~10 ka. The $\delta^{18}O$ anomalies at Mount Moulton during the last interglacial period (green shading: MIS 5e interval) are significantly lower than in the East Antarctic records. Purple line: Mount Moulton $\delta^{18}O$. Black line: average $\delta^{18}O$ anomaly of Talos Dome, EDML, Vostok, Dome Fuji, and EDC records from East Antarctica. Dark gray shading: ± 1 standard deviation (σ) about the East Antarctic mean. Light gray shading: $\pm 2\sigma$. The ice core records are shown individually in Figure S1 in the supporting information.

with a coarse-resolution fully coupled model [*Justino et al.*, 2015], though we note that there is also warming over much of the Southern Ocean in the slab-ocean experiment with ECHAM4.6. Meltwater fluxes—not considered in our experiments—may play a role in the ocean circulation response to a real WAIS collapse [*Holden et al.*, 2010], but this would not alter the fundamental atmospheric response.

Other changes in climate boundary conditions that might be associated with WAIS collapse could influence our results. We assumed that the albedo does not change where the WAIS has been removed; in reality the land ice and ice shelves might be replaced by ocean water that could be free of sea ice in summer. On the other hand, *Otto-Bliesner et al.* [2013] conducted a fully coupled experiment similar to ours (with simpler topography) using CCSM3, in which they replaced WAIS land ice and ice shelves with ocean and used 130 ka boundary conditions. In spite of these differences, their results show the same pattern and magnitude of temperature and winds changes (Figure S4 in the supporting information). We conclude that cooling in the mountains of Marie Byrd Land, relative to the background climate state, and advection of warm anomalies toward adjacent areas of East Antarctica, are fundamental features of the climate response to a collapse of the WAIS.

4.2. Ice Core Interpretation

Our results have important implications for the interpretation of ice core paleotemperature records. *Popp* [2008] presaged our results by suggesting that the comparatively low $\delta^{18}O$ values for MIS 5e (Figure 4) could be explained by altered atmospheric circulation owing to lowered elevations over the WAIS. Our results clearly support this idea. Given a characteristic scaling of $\delta^{18}O$ with temperature of $\sim 0.8^{\circ}/^{\circ}C$ [e.g., *Steig et al.*, 2013], the relatively small $\delta^{18}O$ anomaly at Mount Moulton, 1–2° less than in the East Antarctic ice cores, is in good agreement with the temperature and $\delta^{18}O$ anomalies from the GCM experiments (Figure S3 in the supporting information). The distinctive character of the Mount Moulton isotope record thus supports the idea that WAIS collapsed during MIS 5e. The implication is that the WAIS had already significantly lowered in elevation by ~130 ka, when the Mount Moulton and East Antarctic isotope records begin to diverge (Figure 4).

There are some important caveats. Direct comparison of the model results for surface temperature with ice core $\delta^{18}O$ implicitly assumes a fixed linear relationship. *Masson-Delmotte et al.* [2011] made corrections for moisture source (i.e., sea surface) conditions for the East Antarctic records using deuterium excess measurements and found that the temperature difference between the Holocene and the MIS 5e based on $\delta^{18}O$ alone is overestimated at some locations and underestimated at others. Deuterium excess data are not available for Mount Moulton, and we do not apply such corrections. While our simulations with ECHAM4.6 (Figure S3 in the supporting information) support the use of $\delta^{18}O$ as a temperature proxy, the sensitivity to a variety of potential confounding factors will need to be examined in more detail with additional $\delta^{18}O$-enabled GCM experiments. Another caveat is that the Mount Moulton record has not only relatively low $\delta^{18}O$ values during MIS 5e but also has relatively high $\delta^{18}O$ during the coldest part of the glacial period (~20–40 ka) compared with other records (Figure S1 in the supporting information). Elevated $\delta^{18}O$ at Mount Moulton might be expected if the WAIS were thicker than present, but evidence for a substantially thicker WAIS is equivocal [*Steig et al.*, 2001]. Furthermore, other changes associated with MIS 5e climate that are not considered here, including more modest changes in WAIS short of a full "collapse," may perhaps be sufficient to give rise to the anomalies observed.

Sime et al. [2009] suggested that the varying magnitude of the MIS 5e $\delta^{18}O$ peak in East Antarctic ice cores could be explained by different $\delta^{18}O$/temperature sensitivities, owing to higher MIS 5e temperatures. However, they did not examine the possibility that atmospheric circulation changes associated with reduced topography could explain those differences. In our results with ECHAM4.6, the $\delta^{18}O$ response (Figure S3 in the supporting information) is stronger at Dome C than at Vostok, consistent with the observations, even though the elevation at neither site changes. This is owing to the reduced topography in the major ice drainages in East Antarctica that accompany WAIS collapse (Figure 1). Such results are sensitive to the ice sheet configuration, but it is clear that topography-induced atmospheric circulation changes must be accounted for in the interpretation of ice core records, even where the local topography does not change.

Our results provide guidance on the selection of new ice cores that could be used to obtain more definitive evidence for or against WAIS collapse. One interesting site is Fletcher Promontory, which extends from the WAIS into the Ronne-Filchner Ice Shelf; an ice core record obtained there by the British Antarctic Survey may contain MIS 5e ice. An especially promising location is Hercules Dome, located between the WAIS and the South Pole. Hercules Dome is not likely to have significantly changed in elevation in response to WAIS collapse [*Jacobel et al.*, 2005], but its proximity to the WAIS means that warmer temperatures and elevated $\delta^{18}O$ anomalies at that location may be diagnostic of the changed atmospheric circulation associated with WAIS collapse.

5. Conclusion

Collapse of the West Antarctic Ice Sheet (WAIS) would cause regional changes in atmospheric circulation, with significant anomalies in temperature and isotope ratios in precipitation over adjacent land and ocean areas. Robust responses to WAIS collapse include cooling over the Ross Ice Shelf and Marie Byrd Land and warming over the Ronne-Filchner Ice Shelf, coastal Dronning Maud Land, and at Hercules Dome. Oxygen isotope data from Mount Moulton, West Antarctica, show a significantly smaller difference between the last interglacial and Holocene values than in East Antarctic ice cores. This observation is consistent with the climate model response and thus provides supporting evidence for WAIS collapse during the last interglacial period.

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