AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL068356

Special Section:
WAIS Divide Ice Core Project, high time resolution records of the last 68ka

Key Points:

- The relationship between temperature and accumulation is variable through time for the past 31,000 years in central West Antarctica
- The observed sensitivities of accumulation to a change in temperature are wider than the range of simulated sensitivities
- Model-based projections of increased Antarctic accumulation, and the accompanying sea-level offset, should be treated with caution

Supporting Information:

- Supporting Information S1

Correspondence to:
T. J. Fudge,
tjfudge@uw.edu

Citation:
Fudge, T. J., B. R. Markle, K. M. Cuffey, C. Buizert, K. C. Taylor, E. J. Steig, E. D. Waddington, H. Conway, and M. Koutnik (2016), Variable relationship between accumulation and temperature in West Antarctica for the past 31,000 years, *Geophys. Res. Lett.*, *43*, 3795–3803, doi:10.1002/2016GL068356.

Received 19 FEB 2016
Accepted 27 MAR 2016
Accepted article online 4 APR 2016
Published online 28 APR 2016

Variable relationship between accumulation and temperature in West Antarctica for the past 31,000 years

T. J. Fudge[1], Bradley R. Markle[1], Kurt M. Cuffey[2], Christo Buizert[3], Kendrick C. Taylor[4], Eric J. Steig[1], Edwin D. Waddington[1], Howard Conway[1], and Michelle Koutnik[1]

[1]Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA, [2]Department of Geography, University of California, Berkeley, California, USA, [3]College of Earth Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA, [4]Desert Research Institute, Nevada System of Higher Education, Reno, Nevada, USA

Abstract The Antarctic contribution to sea level is a balance between ice loss along the margin and accumulation in the interior. Accumulation records for the past few decades are noisy and show inconsistent relationships with temperature. We investigate the relationship between accumulation and temperature for the past 31 ka using high-resolution records from the West Antarctic Ice Sheet (WAIS) Divide ice core in West Antarctica. Although the glacial-interglacial increases result in high correlation and moderate sensitivity for the full record, the relationship shows considerable variability through time with high correlation and high sensitivity for the 0–8 ka period but no correlation for the 8–15 ka period. This contrasts with a general circulation model simulation which shows homogeneous sensitivities between temperature and accumulation across the entire time period. These results suggest that variations in atmospheric circulation are an important driver of Antarctic accumulation but they are not adequately captured in model simulations. Model-based projections of future Antarctic accumulation, and its impact on sea level, should be treated with caution.

1. Introduction

Current sea-level rise is primarily driven by two processes: thermal expansion of ocean water and change in mass of glaciers and ice sheets [*Intergovernmental Panel on Climate Change (IPCC)*, 2013]. The mass balance of ice sheets is the difference between the ice that accumulates on the surface and the ice that is lost, either through melt, sublimation, or iceberg calving. For the West and East Antarctic Ice Sheets, mass loss from surface melt is negligible, and we will use the term *accumulation* to mean the net surface mass balance (precipitation minus sublimation). An increase in Antarctic accumulation is expected through the 21st century as warming allows the atmosphere to hold more moisture [*IPCC*, 2013]. However, while the accumulation rate is closely tied to saturation vapor pressure for the high-elevation interior of Antarctica, this is not the case for the coastal and escarpment regions [*Fortuin and Oerlemans*, 1990]. The Antarctic Plateau above 2000 m elevation (Figure 1) accounts for ~60% of the area [*Bamber et al.*, 2009] yet only 20% of the total accumulation [*Monaghan et al.*, 2006]. Therefore, understanding the relationship between temperature and accumulation in the escarpment areas below 2000 m (the edge of East Antarctica and most of West Antarctica) is critical for projecting future Antarctic mass balance and contribution to sea level.

Modern observations of accumulation and temperature in Antarctica have not shown a consistent relationship because of large interannual variability in both parameters [e.g., *Monaghan et al.*, 2006; *Lenaerts et al.*, 2013] and because of limitations in the available reanalysis data [*Nicolas and Bromwich*, 2011b; *Bromwich et al.*, 2011]. In central West Antarctica, which has experienced pronounced recent warming [*Steig et al.*, 2009; *Orsi et al.*, 2012; *Bromwich et al.*, 2013], there has been no discernible increase in accumulation [*Medley et al.*, 2013; *Burgener et al.*, 2013].

Ice cores can be used to extend records of temperature [e.g., *Jouzel et al.*, 1997; *European Project for Ice Coring in Antarctica Community Members*, 2006] and accumulation [*van Ommen et al.*, 2004; *Waddington et al.*, 2005; *Parrenin et al.*, 2007] for centennial to orbital timescales. Past temperatures are commonly derived from water isotopic composition, a proxy for moisture condensation temperature at the site [*Jouzel et al.*, 1997]. Past accumulation rates are more difficult to reconstruct. Independent accumulation estimates can be derived from the depth-age relationship by "destraining" the average layer thicknesses between age markers using

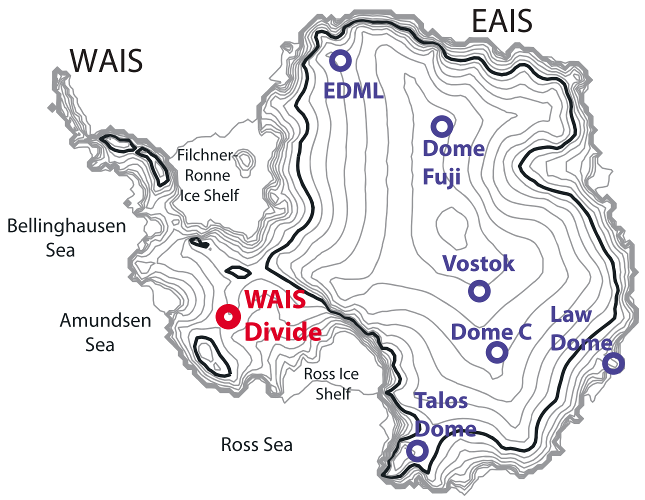

Figure 1. Map of Antarctica. Contour interval is 250 m. The 2000 m contour is the thick black line. Deep ice cores with reliable accumulation records for the past 30 ka from sparse tie points in blue. WAIS Divide, in red, is based on an annual chronology.

an ice-flow model. For this method, the temporal resolution is determined by the frequency of the age markers. When an annual-layer-counted chronology is available, such as for Greenland ice cores, accumulation rates can be reconstructed with high temporal resolution. However, for most East Antarctic ice cores, age markers are spaced thousands of years apart, limiting the inferred accumulation rates to multi-millennial averages.

A common assumption is that the accumulation rate scales with the local temperature, owing to a control by saturation vapor pressure via the Clausius-Clapeyron relationship [*Petit et al*., 1999]. In East Antarctic cores, the sparse age constraints can be combined with the Clausius-Clapeyron relationship to derive continuous accumulation estimates [*Bazin et al*., 2013; *Veres et al*., 2013]. Such accumulation reconstructions are not independent of the temperature reconstructions, which precludes investigating their correlation on millennial and shorter timescales. A recent study [*Frieler et al*., 2015] assessed the multi-millennial relationship between temperature and accumulation at six ice core sites (Figure 1). They showed a consistent ~5%°C^{-1} increase in accumulation across the sites for the glacial-interglacial transition. However, the limitations of the accumulation reconstructions as outlined above prevented analysis at millennial and shorter timescales. The West Antarctic Ice Sheet Divide core (WDC) is unique for Antarctica in having an accumulation-rate history that is derived directly from the annual-layer-counted chronology and not from the water stable-isotope record. Further, the relatively high accumulation and thick ice (~3465 m) at WDC allow information about the past surface temperature history to be preserved in the present temperature profile of the ice sheet [*Cuffey et al*., 1995]. In this work, we analyze the relationship between the accumulation-rate and surface-temperature histories throughout the past 31 ka using the WDC, where the high-resolution data allow for analysis at centennial-to-millennial timescales.

2. Data and Methods

2.1. WDC Site

WDC is located at 1776 m elevation, approximately 24 km from the ice divide between the Ross and Amundsen sectors of WAIS (Figure 1). Central West Antarctica is strongly influenced by storms that penetrate inland from the Amundsen Coast [*Nicolas and Bromwich*, 2011a]. We evaluate how representative WDC is of West Antarctica using the annual-average ERA-interim reanalysis from 1979 to 2015 [*Dee et al*., 2011] which has skill in representing interannual variability in both temperature [*Bromwich et al*., 2013] and accumulation [*Medley et al*., 2013]. The time series of temperature and accumulation of the grid cell closest to WDC have strong positive correlations with West Antarctica as a whole ($r = 0.88$ for temperature and $r = 0.79$ for accumulation, supporting information). While the spatial patterns of temperature and accumulation in West Antarctica are sensitive to the location of the Amundsen Sea Low [*Genthon et al*., 2005], WDC is located near the center of this dipole such that WDC is better correlated with West Antarctica as a whole than with either the base of the Antarctica Peninsula or the western portion of the Ross ice shelf. Thus, WDC is likely to record variations in West Antarctica as a whole. The apparent representativeness of WDC for West Antarctica in the modern climate might not extend into the glacial climate. However, the ice-sheet elevation is unlikely to have changed more than a few hundred meters near the divide during the Last Glacial Maximum [e.g., *Ackert et al*., 2007], and model simulations with increased sea-ice extent show little change in the general pattern of atmospheric circulation [e.g., *Noone and Simmonds*, 2004; *West Antarctic Ice Sheet (WAIS) Divide Project Members*, 2013].

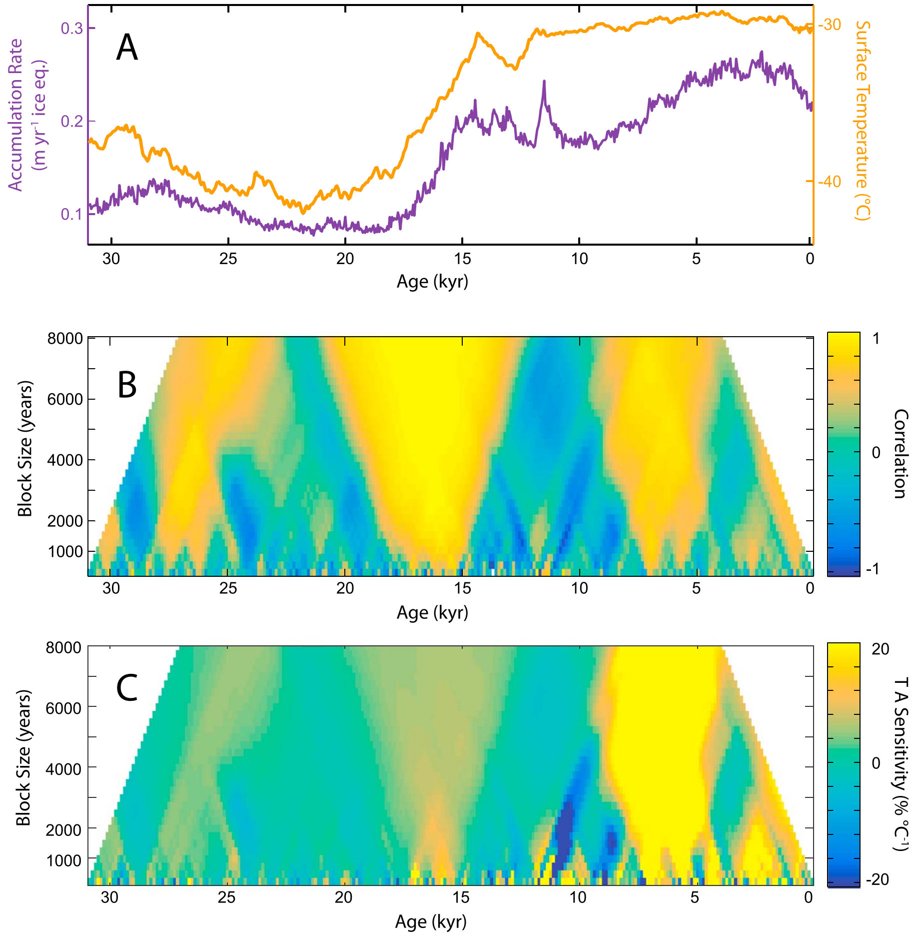

Figure 2. (a) Surface temperature and accumulation histories from WDC. (b) Correlation of the temperature and accumulation records for different block lengths centered at various ages. (c) Temperature and accumulation sensitivity for different block lengths centered at various ages.

2.2. Accumulation History

The WDC accumulation rate (Figure 2a) is reconstructed by correcting the annual-layer thicknesses for flow-induced layer thinning. The WDC timescale (WD2014) is annually resolved to 31 ka and is described in detail in *Sigl et al.* [2015], based on the preliminary timescale in *WAIS Divide Project Members* [2013]. A one-dimensional thermomechanical ice-flow model was used to calculate the thinning that each layer experienced. An important additional constraint on the ice-flow model is the δ^{15}N isotopic ratio of N_2, a proxy for firn thickness [*Sowers et al.*, 1992], which was used with a thermomechanical firn-densification model to estimate past accumulation rates, given the surface-temperature history [*Buizert et al.*, 2015]. Ice-flow model parameters were determined by minimizing the misfit between the modeled and measured borehole temperature profile and between the ice-flow modeled accumulation rate and the firn-densification modeled accumulation rate. Details are given in *Buizert et al.* [2015].

Uncertainty in the inferred accumulation-rate history comes from a variety of sources. Uncertainty in the timescale directly translates into uncertainty in the accumulation history. The WD2014 timescale has uncertainties of only 1% for ages younger than 15 ka and 3% for ages older than 15 ka [*Sigl et al.*, 2015]. A larger source of uncertainty is the amount of thinning due to ice flow that the layers have experienced, which increases with depth (and age) because the thinning is cumulative. We assume that the uncertainty of inferred accumulation rate increases from 0% at the surface, where no thinning has yet occurred, to 25% at 31 ka; the value of 25% is derived from uncertainties in the firn-densification model [*Buizert et al.*, 2015]. Strain increases slowly in the ice sheet and without discontinuities. Thus, the relative uncertainty in reconstructed accumulation rates is much smaller than the absolute values. For example, the accumulation rates at 30 and 31 ka could both be in error by up to 25%, but both would be incorrect by essentially the same amount.

The accumulation-rate history inferred in this way is termed the “ice-core accumulation rate.” It is the amount of ice accumulation at the deposition site, which may be upstream of the drilling site due to ice flow. This must be distinguished from a “climate accumulation rate,” which is the amount of ice accumulation at a fixed location on the ice-sheet surface (e.g., the WDC site). Since there is an accumulation gradient upstream of the WDC site [*Neumann et al*., 2008] and because the core was drilled 24 km from the modern divide, the ice-core and the climate accumulation rates are not the same. We use the advection correction developed by *Steig et al*. [2013] for 9.2 ka to present. The impact of advection for ages older than 9.2 ka cannot be validated against ice-sheet data but is likely small because the horizontal velocities would have been low as the ice originated close to the divide. Therefore, we keep the advection correction constant beyond 9.2 ka. The advection correction is approximately 2% per 1000 years between 0 and 1 ka and decreases to 1% per 1000 years between 8 and 9 ka as the horizontal ice-flow velocity decreases upstream. The advection correction varies smoothly in time and therefore affects the magnitude of accumulation at older ages but not the variability.

2.3. Temperature History

The temperature history (Figure 2a) is derived by combining the WDC water stable-isotope record [*Steig et al*., 2013; *WAIS Divide Project Members*, 2013, 2015] with information from borehole temperatures and nitrogen isotopes. The stable-isotope record provides an initial template which is calibrated to match the measured borehole temperatures, as was done for the interior of the Greenland Ice Sheet [*Cuffey et al*., 1995]. The temperature history is adjusted further using perturbations that simultaneously improve the match to the δ^{15}N firn-thickness proxy and the borehole temperatures. The ice-flow model used in this process is the same as used to determine the accumulation history. Because heat diffuses in an ice sheet, the borehole temperatures contain no information about high-frequency temperature variations. Therefore, in the final optimized temperature reconstruction, the high-frequency information arises entirely from the stable-isotope record whereas the low-frequency information arises from a combination of all three thermometers. No lateral heat-advection correction was made to the surface temperature history because there is no evidence of a strong lateral temperature gradient upstream of the core site [*Dixon*, 2007].

Analysis of firn cores across central West Antarctica indicate that WDC δ^{18}O is a good record of surface temperature, though also influenced by atmospheric circulation, itself related to temperature [*Küttel et al*., 2012; *Steig et al*., 2013]. Thus, a temperature history based on the stable-isotope record should be a good measure of site temperature variability.

2.4. Statistical Tests

To get a general picture of the relationship between temperature and accumulation, we first calculate the correlation for time-block sizes ranging from 250 to 8000 years at time steps of 250 years (Figure 2b). This allows an overview of the relationship through time. Second, we evaluate spectral coherence using the Thomson multitaper technique [*Thomson*, 1982; *Percival and Walden*, 1993] as implemented by P. Huybers (http://www.people.fas.harvard.edu/~phuybers/Mfiles/) to further investigate the relationships for shorter time intervals (Figure 3). The records are averaged to 20 year time steps, though because the surface temperature history has been smoothed such that only multidecadal variations are resolved, we interpret timescales only of 100 years and longer. For the multitaper coherence analysis, we used eight windows as a default and also tested values from 6 to 10; although coherence at specific periods is a weak function of window number, the relationship among the records is consistent across all window choices.

2.5. Climate Model Output

We compare the coherence of the WDC records to results of the Transient Climate Evolution (TraCE) simulation [*Liu et al*., 2009; *He*, 2011], the only continuous GCM simulation through the glacial-interglacial transition. TraCE is a coupled atmosphere-ocean general circulation model simulation from 22 ka to present using the Community Climate Model 3 [*Collins et al*., 2006]. The model resolution is 2.5°. The TraCE simulation includes ice-sheet volume changes based on the ICE-5G reconstruction [*Peltier,* 2004]. In West Antarctica, this results in large and abrupt changes in ice-sheet elevation at WDC that are unlikely to be real [e.g., *Ackert et al*., 2007]. The largest modeled elevation change near WDC occurs at 11.3 ka and introduces large lapse-rate-related

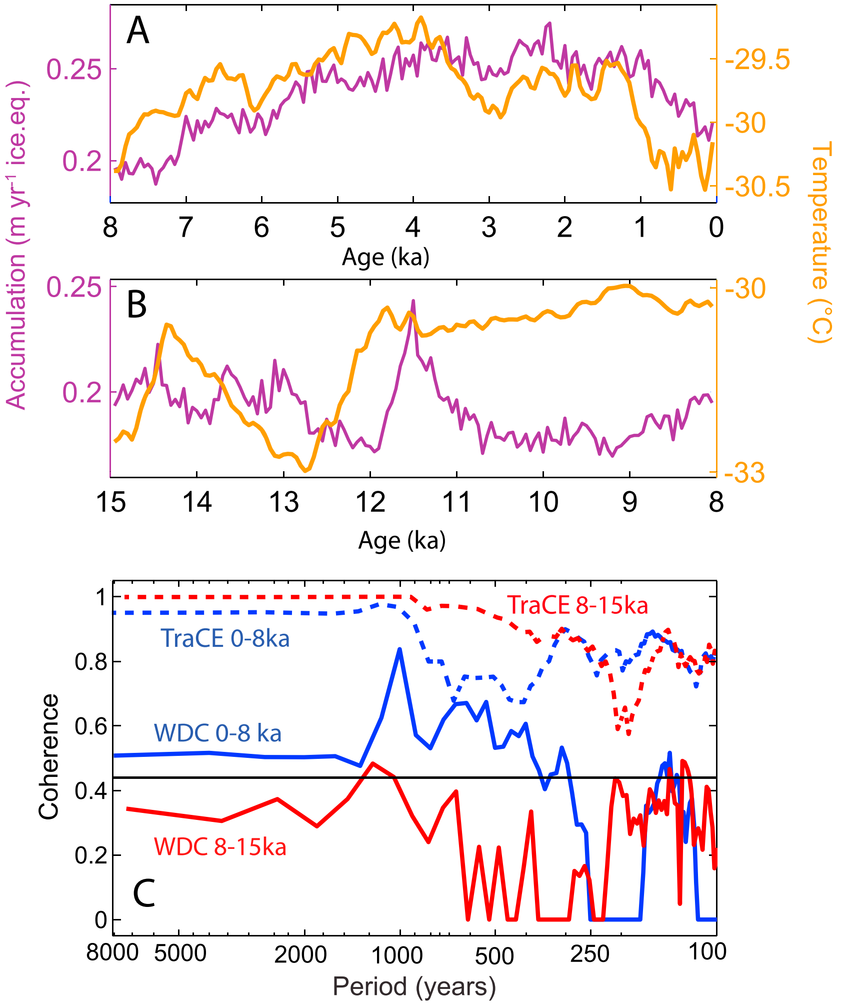

Figure 3. Accumulation and temperature histories from WDC for (a) 0–8 ka and (b) 8–15 ka. (c) Coherence analysis for WDC (solid) and TraCE simulation (dashed). The 95% coherence confidence interval is shown as thin black horizontal line. The records are in phase whenever there is significant coherence, and thus, the phase is not plotted. The TraCE simulation uses a nine grid cell average centered on WDC.

changes in both the temperature and accumulation (Figure S1 in the supporting information). We eliminated the gap in the modeled temperature and accumulation at 11.3 ka by increasing the older temperatures and accumulation rates by the difference between values on either side of elevation change; the results of our analyses (described below) were not significantly affected. We use an average of the nine grid cells (bounding latitude 85°S to 74°S and longitude 118°W to 107°E) surrounding WDC, which yields similar results to using just the grid cell encompassing WDC.

3. Results

The accumulation rate and temperature records for the past 31 ka are shown in Figure 2a. The glacial-interglacial transition dominates both records. Temperatures were ~11°C colder during the Last Glacial Maximum (roughly 24 to 20 ka), and the accumulation decreased to nearly one third of the average Holocene value. Figure 2b shows the sliding-block correlation between both records. The majority of the glacial-interglacial change in both temperature and accumulation occurs in the period from 18 to 15 ka, and we find a strong positive correlation during this period. The sliding-block correlation also illustrates periods when the relationship is more complex. Between 22 and 18 ka, the onset of warming without an increase of accumulation was noted by *WAIS Divide Project Members* [2013]. In contrast, accumulation rates decrease at about 24 ka during the beginning of Antarctic Isotope Maximum 2 when temperatures are rising. The period

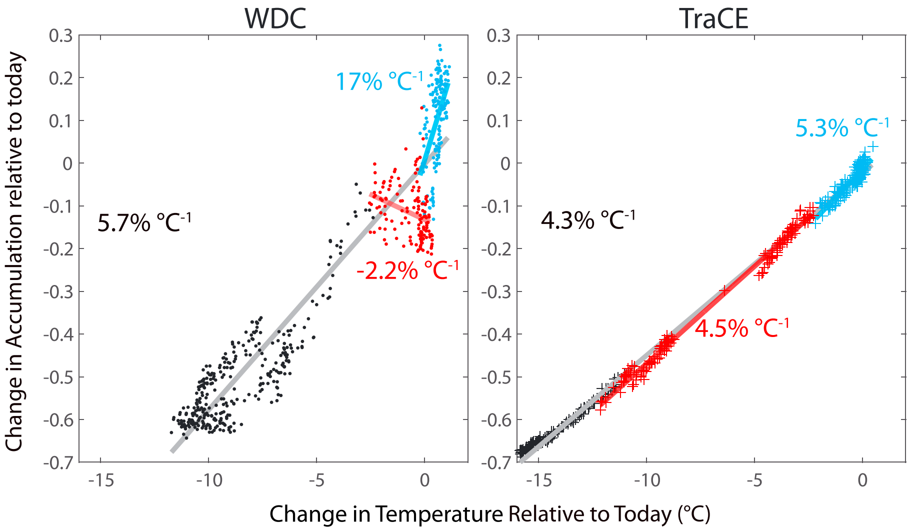

Figure 4. Sensitivity of accumulation to changes in surface temperature. The points from 0 to 8 ka are blue, 8–15 ka are red, and 15–31 ka are black. Gray regression lines are for all data. Blue and red regression lines are for 0–8 ka and 8–15 ka periods only. The gap in the TraCE simulations between −8°C and −4°C is due to a change in modeled elevation of the ice sheet at 11.3 kyr.

8–15 ka is also notable for the lack of correlation between the records whereas the majority of the period from 0 to 8 ka is positively correlated. We will focus further analysis on the two periods from 0 to 8 ka and from 8 to 15 ka because they have smaller uncertainties than periods deeper in the core and because they highlight the variability in the relationship between temperature and accumulation.

The temperature and accumulation histories for the last 8 ka are shown in Figure 3a; this period encompasses the middle-to-late Holocene. The records from 8 to 15 ka are shown in Figure 3b and encompass the end of glacial-interglacial transition and the early Holocene. The coherence of temperature and accumulation (hereafter coherence) is shown in Figure 3c for the two periods. The 0–8 ka period shows significant coherence for timescales greater than 400 years whereas the 8–15 ka period shows no consistently coherent relationship at any timescale. This is somewhat surprising since the 8–15 ka period has larger magnitude variations in both temperature and accumulation than the 0–8 ka period does and thus potentially a larger signal-to-noise ratio. Neither period shows coherence between temperature and accumulation at short (less than 300 years) timescales.

3.1. Comparison With Transient Climate Simulation

The modeled TraCE temperature and accumulation histories (Figure S1) vary substantially from the reconstructed WDC history, which is only partly driven by the large ice-sheet elevation changes imposed in the model simulation. Comparing the model-simulated and WDC-reconstructed time series themselves is thus of limited value. Rather, we compare the coherence to determine if the model is capturing the observed relationship in central West Antarctica.

The coherence of the TraCE temperature and accumulation output is shown in Figure 3c. The TraCE simulation shows significant coherence at all timescales for both the Holocene and glacial termination. The greater coherence at short timescales is expected because the TraCE records are direct model output while the WDC records have uncertainty associated with the proxy reconstructions. The TraCE simulation shows greater coherence than the WDC reconstructions at all timescales and during all periods. For multicentennial timescales, the TraCE simulation finds that the 8–15 ka period is more coherent than 0–8 ka period, in contrast to WDC.

3.2. Magnitude of Temperature and Accumulation Sensitivity

The coherence analysis does not evaluate the relative magnitude of the variations. The 0–8 ka period has a coherent relationship at timescales as short as 400 years, but the magnitude of change in temperature is muted relative to the change in accumulation. Figure 4 shows the change in temperature plotted against the relative change in accumulation; this allows the magnitude of the variations to be compared. We use linear regression to find the sensitivity of accumulation to a change in temperature (hereafter sensitivity). For the record as a whole, the sensitivity is 5.7 ± 1.2%°C^{-1} (2-sigma uncertainty) in agreement with the results by *Frieler et al.* [2015] who found 5.5 ± 1.2%°C^{-1} for WDC. The difference is primarily attributable to the upstream correction used in this study, which was not used by *Frieler et al.* [2015].

The sensitivities for shorter periods deviate considerably from the average for the record as a whole (Figure 4a). The 8–15 ka sensitivity is slightly negative, −2.2 ± 2%°C^{-1}. The 0–8 ka sensitivity is 17%°C^{-1} although the uncertainty in the sensitivity is difficult to determine. Our uncertainty analysis (supporting information) reveals that a wide range of sensitivities are possible with surface temperature histories that can match the borehole temperature profile acceptably; however, the scenarios with low sensitivities also have low correlations as expected if the histories have been perturbed with noise rather than real structure. Thus, we use the 17%°C^{-1} sensitivity from the optimal temperature reconstruction.

The TraCE simulation shows a sensitivity of 4.3%°C^{-1} for the record as a whole, 4.5%°C^{-1} for 8–15 ka and 5.3% °C^{-1} for 0–8 ka. As noted by *Frieler et al.* [2015], the sensitivity for the full record is in approximate agreement with the WDC results. However, the TraCE sensitivities for 0–8 ka and 8–15 ka differ significantly from the WDC results. A potential limitation of the TraCE simulation is the relatively low spatial resolution, so we also compare with a projection for the next two centuries with the Regional Atmospheric Climate Model (RACMO) [*Ligtenberg et al.*, 2013; *Frieler et al.*, 2015], which has a resolution of 55 km (0.5°). The RACMO simulation has a sensitivity of 6%°C^{-1} at WDC, in agreement with WDC multi-millennial sensitivity and the TraCE results but substantially lower than the 0–8 ka WDC sensitivity of 17%°C^{-1}. The RACMO simulation shows more variation in the sensitivities compared to TraCE, but both show a similar pattern of low sensitivity in regions with high accumulation and high sensitivity in the dry East Antarctic interior where accumulation rates are very low. Thus, the difference between the WDC and model-derived sensitivities (TraCE and RACMO) is unlikely to be due to the spatial resolution of the models.

4. Discussion

Model-based projections of future Antarctic accumulation have a continental average sensitivity of approximately 6%°C^{-1} [*Frieler et al.*, 2015]. One climate projection with a regional climate model (RACMO2 [*Ligtenberg et al.*, 2013]) noted that increases in accumulation are driven by increasing temperature and that changes in atmospheric circulation play only a minor role. The sensitivities from modeled simulations described above, the TraCE simulation, and the full 0–31 ka record for WDC (5.7%°C^{-1}) are within the range expected from the Clausius-Clapeyron relationship. However, the sensitivities for the 0–8 ka (17%°C^{-1}) and 8–15 ka (−2%°C^{-1}) periods in WDC are outside the range of sensitivities from the TraCE simulation anywhere on the West and East Antarctic Ice Sheets for the same periods and are not readily explained by simple thermodynamics.

A direct relationship between temperature and accumulation might be expected from the temperature dependence of the saturation vapor pressure. Indeed, the spatial pattern of precipitable water is well described by that of surface temperature [*National Oceanic and Atmospheric Administration*, 2015]. On the global scale, however, the spatial pattern of precipitation rate does not closely mirror the spatial pattern of precipitable water or surface temperature. The spatial pattern of precipitation is strongly controlled by general circulation, synoptic-scale weather events, and local factors such as orography. Thus, changes in the patterns of atmospheric circulation are a likely source for incoherent variability between local temperature and accumulation at the WDC site.

The apparent influence of atmospheric circulation on the temperature-accumulation sensitivity is most pronounced in the WDC histories between 12.7 and 11.3 ka, which includes the onset and termination of the Younger Dryas time period. Despite a 2°C warming between 12.7 and 11.9 ka (Figure 2a), the accumulation decreased a few percent. At 11.9 ka, the warming stopped while the accumulation increased nearly 40% during the next four centuries. The detailed cause of the accumulation increase is not readily apparent. While reduced sea ice is a potential driver to increase the accumulation rate, this should also lead to warming and enriched stable isotopes [*Noone and Simmonds*, 2004; *Küttel et al.*, 2012]. Alternatively, WDC could have experienced an increase in cyclonic-driven precipitation, such as from a strengthening of the Amundsen Sea

Low. A modern analogy may be "atmospheric river" events that affect both West and East Antarctica [*Nicolas and Bromwich*, 2011a; *Noone et al.*, 1999; *Gorodetskaya et al.*, 2014; *Lenaerts et al.*, 2013]. This pattern of circulation is also linked to conditions in the central tropic Pacific through an atmospheric Rossby wave train [*Ding et al.*, 2011]. Because these events originate in the midlatitudes, an increase in accumulation would not necessarily be accompanied by warming and enriched stable isotopes [*Nicolas and Bromwich*, 2011a].

The significant coherence seen at all timescales in the TraCE simulation is an indication that the model may be underestimating the influence of changes in atmospheric circulation and cyclonic activity. As the TraCE simulation finds sensitivities consistent with a suite of general circulation models in the Climate Model Intercomparison Project 5 and with RACMO [*Frieler et al.*, 2015], the discrepancies between the TraCE simulation and the WDC results probably apply to GCM simulations more broadly, including those with higher spatial resolution. While the WDC results support a coherent response of temperature and accumulation at multi-millennial timescales, the timescale of interest for future sea level is centennial. Modern observations have shown that despite rapid warming in central West Antarctica over the past ~60 years [*Steig et al.*, 2009; *Bromwich et al.*, 2013], there has been no discernible increase in accumulation [*Medley et al.*, 2013; *Burgener et al.*, 2013]. In Dronning Maud Land in East Antarctica, a similar disconnect has been observed; large positive accumulation anomalies in 2009 and 2011 are associated with only muted temperature increases [*Lenaerts et al.*, 2013]. Likewise, an East Antarctic core at Law Dome (1400 m elevation) showed a near doubling of accumulation around 7 ka after which the temperature (as measured by stable isotopes) and accumulation varied independently [*van Ommen et al.*, 2004], which was attributed to increased cyclonic activity. Combined, modern climatological observations and available ice-core data from marine-influenced regions of Antarctica suggest that the variability in atmospheric circulation and cyclonic activity is underestimated in climate model projections of future Antarctic accumulation.

5. Conclusion

The unique characteristics of WDC allow the first analysis of the relationship between accumulation and temperature through time at millennial and shorter timescales in Antarctica. While the WDC records are consistent with the multi-millennial (spanning the full deglaciation) average sensitivity of other Antarctic ice cores, the high-resolution and independently derived accumulation and temperature histories reveal considerable variation in their relationship through time. The observed temperature and accumulation histories from WDC are always less coherent than the temperature and accumulation time series from a climate model simulation, suggesting that climate models do not capture the complexity of the atmospheric circulation response. The observations indicate strong coherence and high sensitivity (17%°C^{-1}) for 0–8 ka but no coherence for 8–15 ka. Neither the high sensitivity in the more recent period nor the changing relationship between temperature and accumulation for different time periods would have been expected from model simulations alone. Model-based simulations which indicate an offset to sea-level rise from increased Antarctic accumulation should be treated with caution.

Acknowledgments
This work was supported by U.S. National Science Foundation grants 0944197 (H.C., E.D.W., and T.J.F.), 0944191 (K.C.T.), and 1043518 (C.B.) and a NASA ESS Fellowship (T.J.F.). The authors appreciate the support of the following: WAIS Divide Science Coordination Office, Ice Drilling Design and Operations, National Ice Core Laboratory, Antarctic Support Contractor, and 109th New York Air National Guard. Temperature and accumulation data will be available through National Snow and Ice Data Center.

References

Ackert, R. P., S. Mukhopadhyay, B. R. Parizek, and H. W. Borns (2007), Ice elevation near the West Antarctic Ice Sheet divide during the last glaciations, *Geophys. Res. Lett.*, *34*, L21506, doi:10.1029/2007GL031412.

Bamber, J. L., J. L. Gomez, and J. A. Griggs (2009), A new 1 km digital elevation model of the Antarctic derived from combined satellite radar and laser data—Part 1: Data and methods, *Cryosphere*, *3*, 101–111.

Bazin, L., et al. (2013), An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120–800 ka, *Clim. Past*, *9*, 1715–1731.

Bromwich, D. H., J. P. Nicolas, and A. J. Monaghan (2011), An assessment of precipitation changes over Antarctica and the Southern Ocean since 1989 in contemporary global reanalyses, *J. Clim.*, *24*, 4189–4209.

Bromwich, D. H., J. P. Nicolas, A. J. Monaghan, M. A. Lazzara, L. M. Keller, G. A. Weidner, and A. B. Wilson (2013), Central West Antarctica among the most rapidly warming regions on Earth, *Nat. Geosci.*, *6*, 139–145.

Buizert, C., et al. (2015), The WAIS Divide deep ice core WD2014 chronology—Part 1: Methane synchronization (68–31 ka BP) and the gas age-ice age difference, *Clim. Past*, *11*, 153–173.

Burgener, L., et al. (2013), An observed negative trend in West Antarctic accumulation rates from 1975 to 2010: Evidence from new observed and simulated records, *J. Geophys. Res. Atmos.*, *118*, 4205–4216.

Collins, W. D., et al. (2006), The Community Climate System Model version 3, *J. Clim.*, *19*(11), 2122–2143.

Cuffey, K. M., G. D. Clow, R. B. Alley, M. Stuiver, E. D. Waddington, and R. W. Saltus (1995), Large Arctic temperature change at the Wisconsin-Holocene glacial transition, *Science*, *270*, 455–458.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*, 553–597.

Ding, Q., E. J. Steig, D. S. Battisti, and M. Küttel (2011), Winter warming in West Antarctica caused by central tropical Pacific warming, *Nat. Geosci.*, *4*, 398–403.

Dixon, D. A. (2007), *Antarctic Mean Annual Temperature Map*, Natl. Snow and Ice Data Cent., Boulder, Colo., doi:10.7265/N51C1TTV.

European Project for Ice Coring in Antarctica Community members (2006), One-to-one coupling of glacial climate variability in Greenland and Antarctica, *Nature*, *444*, 195–198.

Fortuin, J. P. F., and J. Oerlemans (1990), Parameterization of the annual surface temperature and mass balance of Antarctica, *Ann. Glaciol.*, *14*, 78–84.

Frieler, K., P. U. Clark, F. He, C. Buizert, R. Reese, S. R. M. Ligtenberg, M. R. van den Broeke, R. Winkelmann, and A. Levermann (2015), Consistent evidence of increasing Antarctic accumulation with warming, *Nat. Clim. Change*, *5*, 348–352.

Genthon, C., S. Kaspari, and P. A. Mayewski (2005), Interannual variability of the surface mass balance of West Antarctica from ITASE cores and ERA40 reanalyses, 1958–2000, *Clim. Dyn.*, *24*, 759–770.

Gorodetskaya, I. V., M. Tsukernik, K. Claes, M. F. Ralph, W. D. Neff, and N. P. M. Van Lipzig (2014), The role of atmospheric rivers in anomalous snow accumulation in East Antarctica, *Geophys. Res. Lett.*, *41*, 6199–6206, doi:10.1002/2014GL060881.

He, F. (2011), Simulating transient climate evolution of the last deglaciation with CCSM3, PhD. Thesis. University of Wisconsin-Madison.

Intergovernmental Panel on Climate Change (IPCC) (2013), Climate change 2013: The physical science basis, in *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K., and New York.

Jouzel, J., et al. (1997), Validity of the temperature reconstruction from water isotopes in ice cores, *J. Geophys. Res.*, *102*, 26,471–26,487, doi:10.1029/97JC01283.

Küttel, M., E. J. Steig, Q. Ding, A. J. Monaghan, and D. S. Battisti (2012), Seasonal climate information preserved in West Antarctic ice core water isotopes: Relationships to temperature, large-scale circulation and sea ice, *Clim. Dyn.*, *39*, 1841–1857.

Lenaerts, J. T. M., E. van Meijaard, M. R. van den Broeke, S. R. M. Ligtenberg, M. Horwath, and E. Isaksson (2013), Recent snowfall anomalies in Dronning Maud Land, East Antarctica, in a historical and future climate perspective, *Geophys. Res. Lett.*, *40*, 2684–2688, doi:10.1002/grl.50559.

Ligtenberg, S. R. M., W. J. van de Berg, M. R. van den Broeke, J. G. L. Rae, and E. van Meijgaard (2013), Future surface mass balance of the Antarctic ice sheet and its influence on sea level change, simulated by a regional atmospheric climate model, *Clim. Dyn.*, *41*, 867–884.

Liu, Z., et al. (2009), Transient simulation of last deglaciation with a new mechanism for Bolling-Allerod warming, *Science*, *325*, 310–314.

Medley, B., et al. (2013), Airborne-radar and ice-core observations of annual snow accumulation over Thwaites Glacier, West Antarctica confirm the spatiotemporal variability of global and regional atmospheric models, *Geophys. Res. Lett.*, *40*, 3649–3654, doi:10.1002/grl.50706.

Monaghan, A. J., D. H. Bromwich, and S.-H. Wang (2006), Recent trends in Antarctic snow accumulation from Polar MM5, *Phil. Trans. R. Soc. A*, *364*, 1683–1708.

National Oceanic and Atmospheric Administration (2015), NCEP/NCAR reanalysis data. [Available at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html.]

Neumann, T. A., H. Conway, S. F. Price, E. D. Waddington, G. A. Catania, and D. L. Morse (2008), Holocene accumulation and ice sheet dynamics in central West Antarctica, *J. Geophys. Res.*, *113*, F02018, doi:10.1029/2007JF000764.

Nicolas, J. P., and D. H. Bromwich (2011a), Climate of West Antarctica and influence of marine are intrusions, *J. Clim.*, *24*, 49–67.

Nicolas, J. P., and D. H. Bromwich (2011b), Precipitation changes in high southern latitudes from global reanalyses: A cautionary tale, *Surv. Geophys.*, *32*, 475–494.

Noone, D., and I. Simmonds (2004), Sea ice control of water isotope transport to Antarctica and implications for ice core interpretation, *J. Geophys. Res.*, *109*, D07105, doi:10.1029/2003JD004228.

Noone, D., J. Turner, and R. Mulvaney (1999), Atmospheric signals and characteristics of accumulation in Dronning Maud Land, Antarctica, *J. Geophys. Res.*, *104*(D16), 19,191–19,211, doi:10.1029/1999JD900376.

Orsi, A. J., B. D. Cornuelle, and J. P. Severinghaus (2012), Little Ice Age cold interval in West Antarctica: Evidence from borehole temperature at the West Antarctic Ice Sheet (WAIS) Divide, *Geophys. Res. Lett.*, *39*, L09710, doi:10.1029/2012GL051260.

Parrenin, F., et al. (2007), 1-D-ice flow modeling at EPICA Dome C and Dome Fuji, East Antarctica, *Clim. Past*, *3*, 243–259.

Peltier, W. R. (2004), Global glacial isostasy and the surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE, *Annu. Rev. Earth Planet. Sci.*, *32*, 111–149.

Percival, D. B., and A. T. Walden (1993), *Spectral analysis for physical applications: Multitaper and conventional univariate techniques*, 583 pp., Cambridge Univ. Press, Cambridge.

Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, *399*, 429–436.

Sigl, M., et al. (2015), The WAIS Divide deep ice core WD2014 chronology—Part 2: Annual-layer counting (0–31 ka BP), *Clim. Past Discuss.*, *11*, 3425–3474.

Sowers, T., M. Bender, D. Raynaud, and Y. S. Korotkevich (1992), δ15N of N2 in air trapped in polar ice: A tracer of gas transport in the firn and a possible constraint on ice age-gas age differences, *J. Geophys. Res.*, *97*, 15,683–15,697, doi:10.1029/92JD01297.

Steig, E. J., D. P. Schneider, S. D. Rutherford, M. E. Mann, J. C. Comiso, and D. T. Shindell (2009), Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year, *Nature*, *457*, 459–463.

Steig, E. J., et al. (2013), Recent climate and ice-sheet changes in West Antarctica compared with the past 2000 years, *Nat. Geosci.*, *6*, 372–375.

Thomson, D. J. (1982), Spectrum estimation and harmonic analysis, *Proc. IEEE*, *70*(9), 1055–1096.

van Ommen, T. D., V. Morgan, and M. A. J. Curran (2004), Deglacial and Holocene changes in accumulation at Law Dome, East Antarctica, *Ann. Glaciol.*, *39*, 359–366.

Veres, D., et al. (2013), The Antarctic ice core chronology (AICC2012): An optimized multi-parameter and multi-site dating approach for the last 120 thousand years, *Clim. Past*, *9*, 1733–1748.

Waddington, E. D., H. Conway, E. J. Steig, R. B. Alley, E. J. Brook, K. C. Taylor, and J. W. C. White (2005), Decoding the dipstick: Thickness of Siple Dome, West Antarctica at the Last Glacial Maximum, *Geology*, *33*, 281–284.

West Antarctic Ice Sheet (WAIS) Divide Project Members (2013), Onset of deglacial warming in West Antarctica driven by local orbital forcing, *Nature*, *500*, 440–444.

West Antarctic Ice Sheet (WAIS) Divide Project Members (2015), Precise interpolar phasing of abrupt climate change during the last Ice Age, *Nature*, *520*, 661–665.