Interhemispheric climate coupling via atmospheric and oceanic teleconnections during abrupt climate change of the last ice age

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Abrupt climate change is a ubiquitous feature of the glacial climate state. Two distinct modes of abrupt, millennial-scale climate variability are commonly distinguished. The first mode is the Dansgaard-Oeschger (DO) cycle, which is most clearly expressed in Greenland ice core $\delta^{18}O$, a proxy for local temperature, with concurrent variations seen in low-latitude hydrology and methane concentrations. The second mode of variability comprises the Heinrich events, identified as layers of ice-rafted debris (IRD) in North-Atlantic sediments that represent periods of extreme cold and iceberg influx in the North-Atlantic. Heinrich events are likewise accompanied by a displacement of the low-latitude rain belts and monsoon systems.

The Atlantic Meridional Overturning Circulation (AMOC) is thought to play a key role in both modes of abrupt climate change [*Henry et al.*, 2016]. The DO cycle consists of an alternating sequence of Greenland cold (stadial) and warm (interstadial) stages, which are linked to switch-like behavior of the AMOC strength and its northward heat flux (with a likely amplification by sea ice cover). Likewise, Heinrich events are accompanied by a strong suppression of the AMOC, probably due to enhanced North-Atlantic stratification by iceberg-delivered freshwater. These oceanic perturbations are all associated with changes to the atmospheric circulation, with the ITCZ and monsoon belts shifting southwards during stadials and northwards during interstadials. It has been theorized that the SH eddy-driven jet and SH westerlies move in parallel with the tropical ITCZ, but evidence for such movement is limited at present.

Antarctic climate is asynchronously coupled to that of the NH [*Blunier and Brook*, 2001], with Antarctica warming during NH cold periods, and cooling during NH warmth. In the thermal bipolar seesaw theory, this pattern is explained as an inter-hemispheric oceanic heat exchange driven by AMOC variations. A recent study from the high-resolution WAIS Divide ice core finds that the Antarctic temperature response lags Greenland climate by about 200 years, consistent with a climatic coupling via ocean currents [*WAIS Divide Project Members*, 2015]. However, it has been shown recently that the thermal bipolar seesaw model breaks down during Heinrich stadials [*Landais et al.*, 2015]. Further, great uncertainty remains regarding the operation of atmospheric teleconnections, and how they impact Antarctic climate. The WAIS Divide Deuterium excess record shows evidence for latitudinal shifts in the moisture source origin synchronous with NH climate and tropical ITCZ movement [*Markle et al.*, in review], but it is unclear at present whether this behavior is unique to the Pacific sector, or applies across the continent.

Here we investigate the interhemispheric climate coupling using high-resolution water isotope records from five Antarctic ice cores (WAIS Divide, Dome Fuji, EPICA Dronning Maud Land, EPICA Dome C, and Talos Dome) that have been synchronized via volcanic matching. As was done for the WAIS Divide site, we stack the individual Antarctic climate events to improve the signal-to-noise ratio. On average the Antarctic climate response to abrupt NH climate change is delayed by approximately 200 years during both DO warming and DO cooling events, in good agreement with earlier results at the WAIS Divide site. However, important differences are observed at the various sites.

Using principal component analysis we show that the Antarctic temperature response can be understood as the superposition of two distinct modes. The first mode is the spatially homogeneous, ocean-driven bipolar seesaw response that lags NH abrupt climate by about 200 years. The second mode is a spatially inhomogeneous, atmospheric mode that is in phase with NH abrupt climate change. The spatial pattern associated with the atmospheric mode resembles modern-day surface temperature variations associated with the Southern Annular Mode (SAM), suggesting it may be linked to latitudinal movement of the SH westerlies and eddy-driven jet. Evidence for migration of the SH westerlies in the Pacific sector was provided by Markle et al. [in review] based on deuterium excess data from the WAIS Divide core core. We provide further evidence for a zonally coherent shift in the winds by repeating the analysis of Markle et al. using deuterium excess records for all five cores.

Last, we show that the Antarctic warming response to NH Heinrich events resembles the aforementioned atmospheric SAM pattern, suggesting part of it can be explained via an extremely southern position of the SH westerlies. However, to explain the full magnitude of Antarctic warming requires a heat pulse from another source; we speculate that this heat may be derived from wind-driven upwelling of relatively warm circumpolar deep water.

Our analysis shows that both atmospheric and oceanic teleconnections couple the climates of both polar regions during the abrupt climate changes of the last ice age. Both modes are needed to explain the observed patterns of Antarctic climate change.

References

Blunier, T., and E. J. Brook (2001), Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, *Science*, *291*(5501), 109-112.

Henry, L. G., J. F. McManus, W. B. Curry, N. L. Roberts, A. M. Piotrowski, and L. D. Keigwin (2016), North Atlantic ocean circulation and abrupt climate change during the last glaciation, *Science*, *353*(6298), 470-474.

Landais, A., et al. (2015), A review of the bipolar see–saw from synchronized and high resolution ice core water stable isotope records from Greenland and East Antarctica, *Quat. Sci. Rev.*, *114*(0), 18-32.

Markle, B. R., et al. (in review), Atmospheric teleconnections between the tropics and high southern latitudes during millennial climate change.

WAIS Divide Project Members (2015), Precise interpolar phasing of abrupt climate change during the last ice age, *Nature*, *520*(7549), 661-665.