Evidence for changes in atmospheric circulation at high southern latitudes, in phase with Dansgaard-Oeschger events

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Millennial-scale variability in the Northern and Southern Hemispheres is widely believed to be linked by changes in the ocean overturning circulation. Perhaps the simplest evidence is the observation that the integral of the Greenland ice core $\delta^{18}O$ time series is highly correlated to Antarctic $\delta^{18}O$ time series (Roe and Steig, 2004). This integral relationship is explained through variations in the net export of heat to the Northern Hemisphere from the Southern Hemisphere via the oceanic overturning circulation. This is the "thermal bipolar seesaw" model (Stocker and Johnson, 2003).

The oceanic bipolar seesaw model explains a number of important features of the paleoclimate record. Yet oceanic processes alone do not account for the full global expression of millennial-scale climate variability. Significant changes in tropical climate also occurred on millennial timescales, and abrupt changes in the tropics are in phase with the abrupt Dansgaard-Oescgher (D-O) warming events recorded in Greenland. The most direct evidence is the in-phase relationship between the global well-mixed methane (CH_4) concentrations, and $\delta^{18}O$ taken from the same Greenland ice cores (e.g. Severinghaus and Brook, 1999).

The link between Greenland D-O events and abrupt changes in the tropics can probably be explained through atmospheric teleconnections that result in a northward shift in the mean latitudinal position of the intertropical convergence zone (ITCZ) when the Northern Hemisphere warms (e.g. Chiang and Bitz, 2005). However, northward ITCZ shifts, if they occurred in phase with abrupt D-O warmings, would also have led to an equatorward shift of the southern high latitude jet (e.g. Ceppi et al., 2013). This would appear in conflict with the observations, since the Antarctic $\delta^{18}O$ records are unambiguously out-of-phase with the D-O warmings. However, results from the transient fully coupled model runs designed to mimic the D-O events suggest that significant ocean circulation changes and atmospheric circulation changes both occurred. Pedro et al. (in prep., 2014) find that the modeled change in Antarctic temperature is consistent with the Antarctic $\delta^{18}O$ data (i.e. gradual warming preceding the D-O event, with cooling beginning shortly after the D-O abrupt warming). There is also an abrupt change in the southern jet, in phase with the D-O warming.

Is there evidence for the high-latitude wind shifts suggested by the models? Results from the new WAIS Divide ice core (Steig et al., 2013; WAIS Divide Project Members, 2013) show that the answer is yes. WAIS Divide has the highest-resolution and best-dated ice core record of $\delta^{18}O$ and CH_4 ever obtained. Because abrupt changes in CH_4 are independently known to occur within just two decades of the D-O events, we can use the CH_4 from WAIS Divide as a precise time marker for abrupt warming in

Greenland, and compare this with other data from the same core. We find that Antarctic temperature (that is, $\delta^{18}O$) maxima occur about 100-200 years later than the abrupt CH_4 increases. This centennial-scale lag is consistent with the interpretation of the Antarctic temperature changes as an oceanic response to the D-O warmings. However, a rapid increase in deuterium excess (d_{excess}) also occurs in WAIS Divide, and this is 100-200 years in advance of the $\delta^{18}O$ maxima; that is, d_{excess} is in phase with CH_4. Deuterium excess is sensitive to sea surface temperature. We show that the d_{excess} signal in the WAIS Divide core is readily explained, both in sign and magnitude, by small (2-3° of latitude) changes in the mean position of the southern high latitude jet. An equatorward shift in the jet results in the average moisture source for Antarctica being shifted further north, towards warmer water, resulting in an increase is d_{excess} in Antarctic precipitation. Equivalently, a shift towards the negative phase of the Southern Annular Mode leads to increased d_{excess}, as shown previously by Schmidt et al. (2008) and as observed in recent ice core data.

The WAIS Divide record supports both the conventional "oceanic bipolar seesaw" model that predicts an out-of-phase relationship between Antarctic and Northern Hemisphere temperature, and the idea that rapid changes in southern high latitude atmospheric circulation should have occurred in phase with D-O events. However, the heat fluxes due to the ocean circulation changes overwhelm those due to atmospheric circulation changes. This is why Antarctic climate – as expressed by temperature sensitive proxies like $\delta^{18}O$, still remains largely out of phase with Northern Hemisphere and tropical climate changes, even though abrupt shifts in atmospheric circulation have occurred that are in-phase with both.