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Key Points:

- Antarctica and Greenland paleo-temperature records associated to DO events are used to construct phase space representations
- The phase space representations' patterns closely resemble the AMOC hysteresis behavior emphasized in numerical simulations
- The resemblance between reconstructed and simulated hysteresis points to a global forcing for DO warmings, linked to the Southern Hemisphere

Supporting Information:

- Supporting Information S1

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North Atlantic Versus Global Control on Dansgaard-Oeschger Events

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Abstract The classic scenario for the generation of Dansgaard-Oeschger (DO) events assumes a link to changes in the Atlantic Meridional Overturning Circulation (AMOC) induced by North Atlantic freshwater perturbations. Recent proxy data emphasize the existence of leads and lags between DO fingerprints in Greenland and Antarctic records, highlighting the potential of a Southern Hemisphere control on these events. Investigating this possibility, we provide a conceptual model resulting from phase space reconstructions based on the northern and southern ice core records. The resulting patterns closely resemble AMOC hysteresis, consistent with a northern abrupt warming linked to gradual global temperature changes. This suggests that rapid DO warmings associated with abrupt AMOC transitions from a relatively weak (cold stadial) state to a stronger (warm interstadial) state can be controlled by global forcing that can be linked to the Southern Hemisphere, rather than by the end of a local temporary forcing in the North Atlantic.

Plain Language Summary The most spectacular abrupt climate changes over the last 120,000 years, known as Dansgaard-Oeschger events, manifest as up to 10 °C warmings developed in just a few decades in the North Atlantic sector, with a clear corresponding footprint on Antarctica. Although it is generally assumed that the main causes of these warmings are linked to changes in the Atlantic Ocean circulation, their triggers are not yet identified. Simulations performed with general circulation models indicate that rapid intensifications of the Atlantic Ocean circulation could be induced by a global temperature forcing linked to the Southern Hemisphere and that their mutual dependence has a specific hysteresis pattern. Here we use temperature paleo-records from Greenland and Antarctica, associated to each DO event, to show that their mutual dependence pattern closely resembles the hysteresis derived through general circulation models. The resemblance suggests that the DO warming events are induced by a global forcing linked to the Southern Hemisphere.

1. Introduction

The identification of abrupt climate events, which marked the last glacial cycle, stimulated paleoclimate investigations and the debate about the potential recurrence of abrupt climate changes in the future. In Greenland ice cores, Dansgaard-Oeschger (DO) events manifest as rapid warmings of 8–16 °C within a few decades (Dansgaard et al., 1993; Oeschger et al., 1984). These are followed by gradual cooling during interstadial conditions and by rapid transitions back to a cold state (stadial). The warming extends across much of the Northern Hemisphere, accompanied by a cooling trend in Antarctica (Buizert et al., 2015; EPICA, 2006; WAIS, 2013).

One leading hypothesis to explain the causes of DO cycles is based on their association with transitions of the Atlantic Meridional Overturning Circulation (AMOC) between weak and strong modes (e.g., Ganopolski & Rahmstorf, 2001a; Manabe & Stouffer, 1988; Stocker & Johnsen, 2003; Zhang et al., 2017). Some models simulate temperature evolutions over Greenland, which are in agreement with observations (Knutti et al., 2004; Liu et al., 2009; Menviel et al., 2014), but they mostly rely on ad hoc North Atlantic imposed freshwater perturbations for transitions between Greenland interstadials and stadials. Alternative mechanisms invoke internal ocean-sea ice instabilities (Timmermann et al., 2003), coupled ocean-ice-sheet variability (Schulz et al., 2002), sea ice in the North Atlantic sector (Li et al., 2005), sea-ice-ice-shelf fluctuations (Petersen et al., 2013), interhemispheric interactions (Banderas et al., 2015), stochastic resonance (Alley et al., 2001; Ganopolski & Rahmstorf, 2001b), internal variability (Ditlevsen et al., 2007; Kwasniok & Lohmann, 2009), or a combination of external forcing and internal variability (Dima & Lohmann, 2009). Despite the significant progress in understanding specific processes associated with abrupt climate changes, the underlying

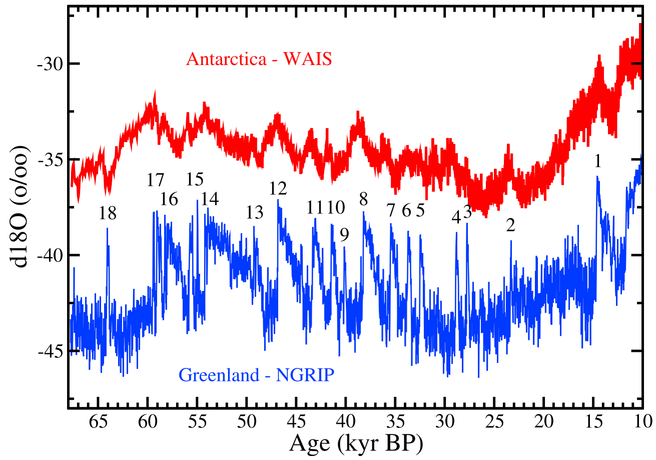

Figure 1. Dansgaard-Oeschger events over the last glacial cycle, represented in Antarctic and Greenland ice cores. West Antarctic ice sheet (WAIS) Divide ice core (red line) and North Greenland Ice Core Project (NGRIP; blue line) δ^{18}O time series on the GICC05 chronology (NGRIP, 2004; WAIS, 2015). The numbers are marking the Dansgaard-Oeschger events.

forcing mechanism for the DO cycles is not fully understood, and the relative roles of changes in the Northern and in the Southern Hemispheres are still under debate. Here we use Greenland and Antarctic isotopic temperature records to build a conceptual model based on phase space reconstructions for the DO events during the last glacial cycle.

The DO cycles manifest differently in Greenland and Antarctic isotopic temperatures (EPICA, 2006; Figure 1). Abrupt Greenland warmings are preceded by a gradual temperature increase in Antarctica. On the other hand, these abrupt warmings precede a reversal to a gradual cooling trend in Antarctica by ~200 years (Buizert et al., 2015; Steig & Alley, 2002; WAIS, 2015).

While temperature signals suggest that the Greenland lead may reflect its influence on the Southern Hemisphere, conceptualized by Stocker and Johnsen (2003) in a linear interhemispheric box model, the lead of Antarctic temperature increase is supported by the lagged linear relationship between Antarctic temperature and the Greenland dust record (Barker & Knorr, 2007). A North-to-South relation is suggested by the so-called freshwater hosing experiments, whereas a South-to-North connection is supported by numerical integrations showing that a Southern Hemisphere gradual temperature increase can cause abrupt warming in the North Atlantic, associated with a rapid transition to a strong AMOC state marked by an overshoot (Knorr & Lohmann, 2003). Similar AMOC dynamics and feedbacks have been identified in response to global temperature changes, which is thought to change synchronously with the Antarctic temperature (Knorr & Lohmann, 2007; Parrenin et al., 2013; Zhang et al., 2017; Figure 2). Although numerical simulations indicate a significant role of global forcing onto AMOC for DO cycles, a clear conceptual approach solely based on paleoclimate data has not been presented yet.

2. Data and Methods

Observational (Curry & Oppo, 1997) and numerical (Ganopolski & Rahmstorf, 2001a; Knutti et al., 2004) studies indicate a strong link between the DO cycles and the AMOC but also between Greenland temperature variations and AMOC changes (Zhang et al., 2017). Consequently, the Greenland isotopic temperature record (NGRIP, 2004) is taken to represent AMOC changes. The synchronized Antarctic isotopic temperature time series, which is linked to atmospheric CO_2 concentration changes at millennial time scales (Ahn & Brook, 2008; Fischer et al., 2010), is assumed to be an indicator of global climate fluctuations (WAIS, 2015). The uncertainty of the temporal synchronization between these two records is less than a century.

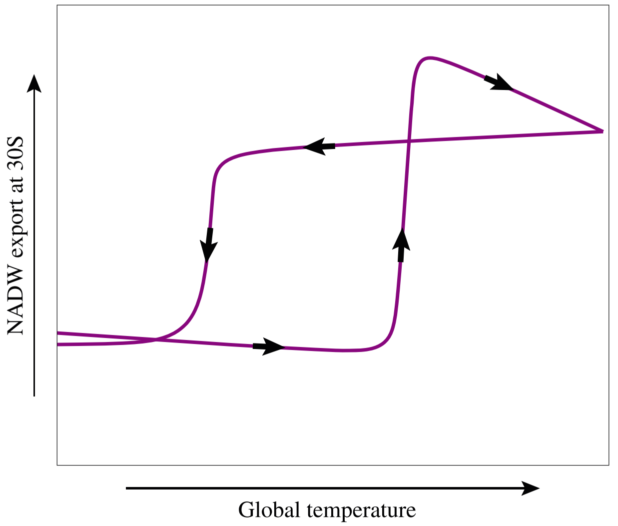

Figure 2. Phase space template. Schematic representation of the hysteresis loop of the thermohaline circulation with respect to slowly varying climate background conditions derived through simulations performed with an ocean general circulation model (Knorr & Lohmann, 2007). A similar diagram was derived in recent numerical simulations in response to atmospheric CO_2 changes (Zhang et al., 2017). NADW= North Atlantic Deep Water.

If the global climate linked to the Southern Hemisphere has a significant influence on the North Atlantic sector through AMOC changes, then the phase space representation based on these two proxy records should resemble the hysteresis template derived through numerical simulations (Figure 2; Knorr & Lohmann, 2007; Zhang et al., 2017). It is characterized by two distinct stable states, rapid transitions between them, AMOC overshoot as part of its resumption and a specific direction in which it is browsed (anticlockwise) as the time passes. This last property reflects the fact that the AMOC resumption/weakening follows an increase/reduction of the forcing, and it is different than the hysteresis property related to freshwater forcing imposed in North Atlantic, in which an increase/decrease of the forcing results in a weakening/strengthening of AMOC.

Here we use the term *overshoot* to refer to that part of the resumption process in which the AMOC intensity exceeds and then rebounds to what is considered to be a strong AMOC quasi-equilibrium state, in the point in which the AMOC strength first overpassed it. Visually, the AMOC overshoot is represented by the triangle located in the upper right part of the hysteresis diagram shown in Figure 1.

In order to construct a phase space representation for each DO cycle, a specific time window was extracted from the West Antarctic ice sheet (WAIS) Divide ice core (WDC) and North Greenland Ice Core Project (NGRIP) isotopic records for each abrupt event. A bidimensional phase space of a DO event results from the representation of the associated NGRIP segment as a function of the corresponding WDC window.

Although the temporal resolution of the data varies with time (between 5 and 60 years), it is quasi-constant for each DO event. The initial data expressed as a function of time were linearly interpolated to equally spaced values (annual means), therefore preserving the initial temporal resolution.

All diagrams are constructed based on a lead of the WDC window over the NGRIP segment. This lead interval is adjusted for each DO event so that the reconstructed phase space reconstruction has maximum resemblance to a hysteresis with two distinct stable states (Figure 2). The adjustment of the lead interval could reflect the dependence of the potential physical mechanisms linking Antarctica with Greenland on the background climate and could compensate for uncertainties of the synchronized chronology. An example for the identification of the optimal lag and a discussion on this approach is presented in supporting information Figure S8.

The simulated hysteresis diagram includes features which are associated to different time scales. The fast transitions and the overshoots are linked to relatively fast variations, whereas the plateau of the stable states are rather linked to longer time scales. Furthermore, high frequency variations, representing noise in the context of this study, could mask the signal of interest here. Consequently, in order to remove the noise represented by high frequency variability, a conventional running mean filter of length N was applied to the phase space representation: the value associated to time t is replaced by the symmetric average of the values corresponding to all time steps contained in the interval $[t-(N-1)/2, t+(N-1)/2]$. The length was chosen according to two criteria: (1) to remove the noise represented by high frequency variability; (2) to preserve all the specific features of the hysteresis diagrams, including the fast AMOC transitions and the overshoot. A filtering example is presented in Figure S9.

3. Phase Space Representations

Four representative phase space reconstructions are shown for DO cycles immediately following Heinrich events (HDO events; Figure 3) and other four for DO cycles which do not immediately follow Heinrich events (non-HDO events; Figure 4), together with the corresponding Antarctic and Greenland isotopic temperature records. The diagrams for DOs 1 to 18 based on WDC and NGRIP records and for DOs 1 to 24 derived from European Project for Ice Coring in Antarctic in the interior of Dronning Maud Land (EDML) and NGRIP (Supporting Information S1) time series are consistent with our hysteresis template.

It is important to note that by decomposing a typical DO event, the specific shape of the hysteresis curve can be tracked back in the properties of the temporal patterns of the Antarctic and Greenland records (e.g., DO8 in Figure 3):

1. the weak AMOC state in the phase space (the lower quasi-horizontal line) could reflect the significant Antarctic warming trend, in association with a weak temperature increase in Greenland;
2. the quasi-vertical transition to the strong AMOC state in the phase space could be due to the abrupt warming observed in Greenland;
3. the phase space AMOC overshoot could reflect the persistent Antarctic temperature increase following the maximum temperature in Greenland and subsequent rebound to the warm state;
4. the graduate cooling during the warm state in the phase space could result from Antarctic significant cooling associated with a reduced Greenland temperature decrease;
5. the fast transition from the strong to weak AMOC state could reflect the abrupt cooling in Greenland at the end of a DO cycle;
6. the asymmetry of the hysteresis diagrams could be induced by the asymmetric trapezoidal temporal shape of DO events; and
7. the lead of Antarctic climate signal over the Greenland isotopic temperature for all DO events could provide the right sense in which the phase space is browsed as time passes.

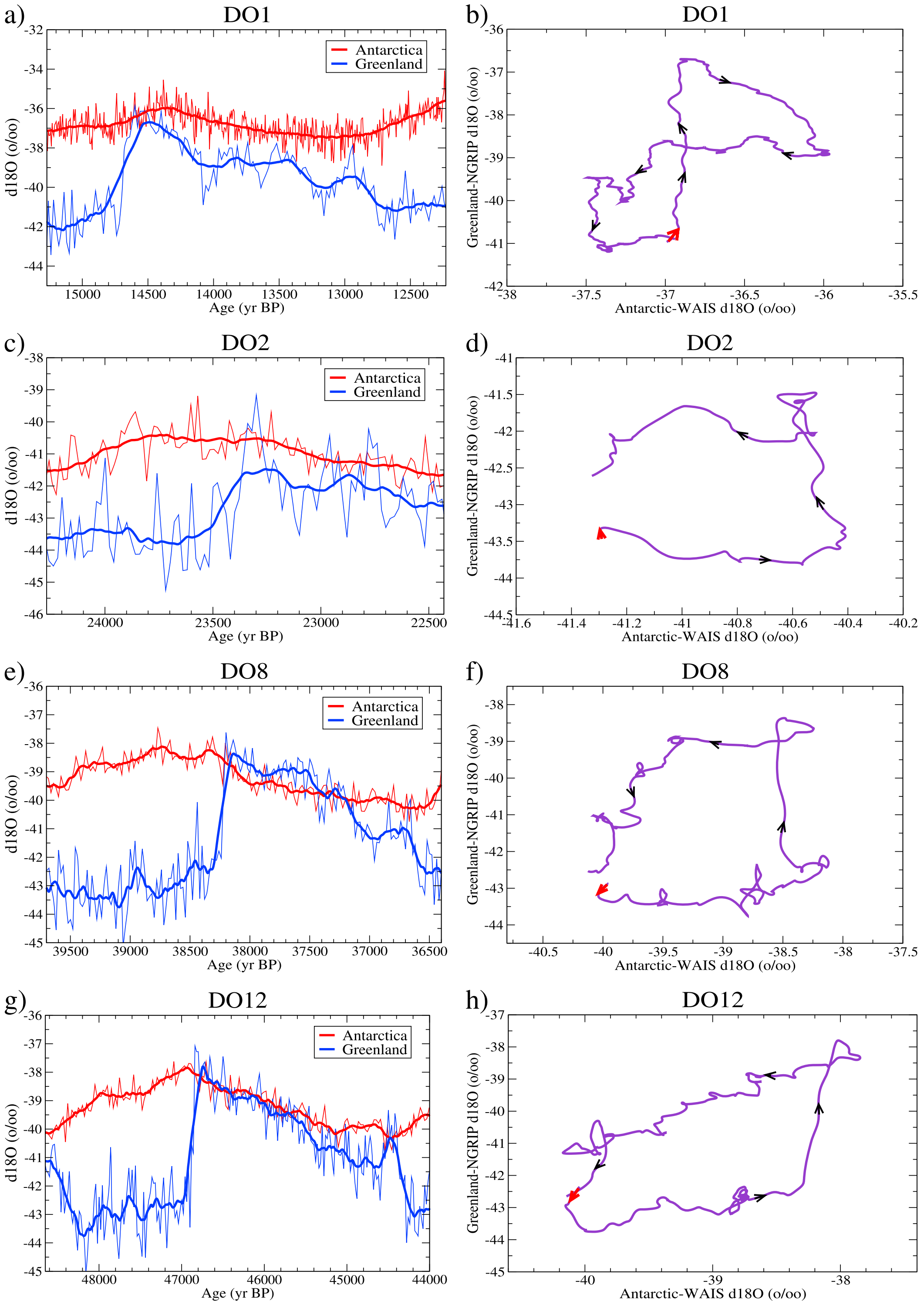

Figure 3. Phase space representations for four Heinrich DO events 1, 2, 8, and 12. Antarctica (red line) and Greenland (blue line) isotopic temperature records associated to the abrupt climate events and the phase space representations constructed based on the two corresponding time series, for DO1 (a and b), DO2 (c and d), DO8 (e and f), and DO12 (g and h). The leads of the WAIS Divide ice core window over the NGRIP segment used to construct these representations are 300, 200, 300, and 350 years, respectively. In the left panels, the unfiltered data are shown with thin lines. The thick lines correspond to running means filtered time series, with lengths of 301 (a), 301 (c), 151 (e), and 201 years (g). The same filters are applied to the corresponding phase space representations shown in the right panels. The red arrows in (b), (d), (f), and (h) indicate where the time starts and, together with the black arrows, indicate the direction of time. WAIS = West Antarctic ice sheet; NGRIP = North Greenland Ice Core Project; DO = Dansgaard-Oeschger.

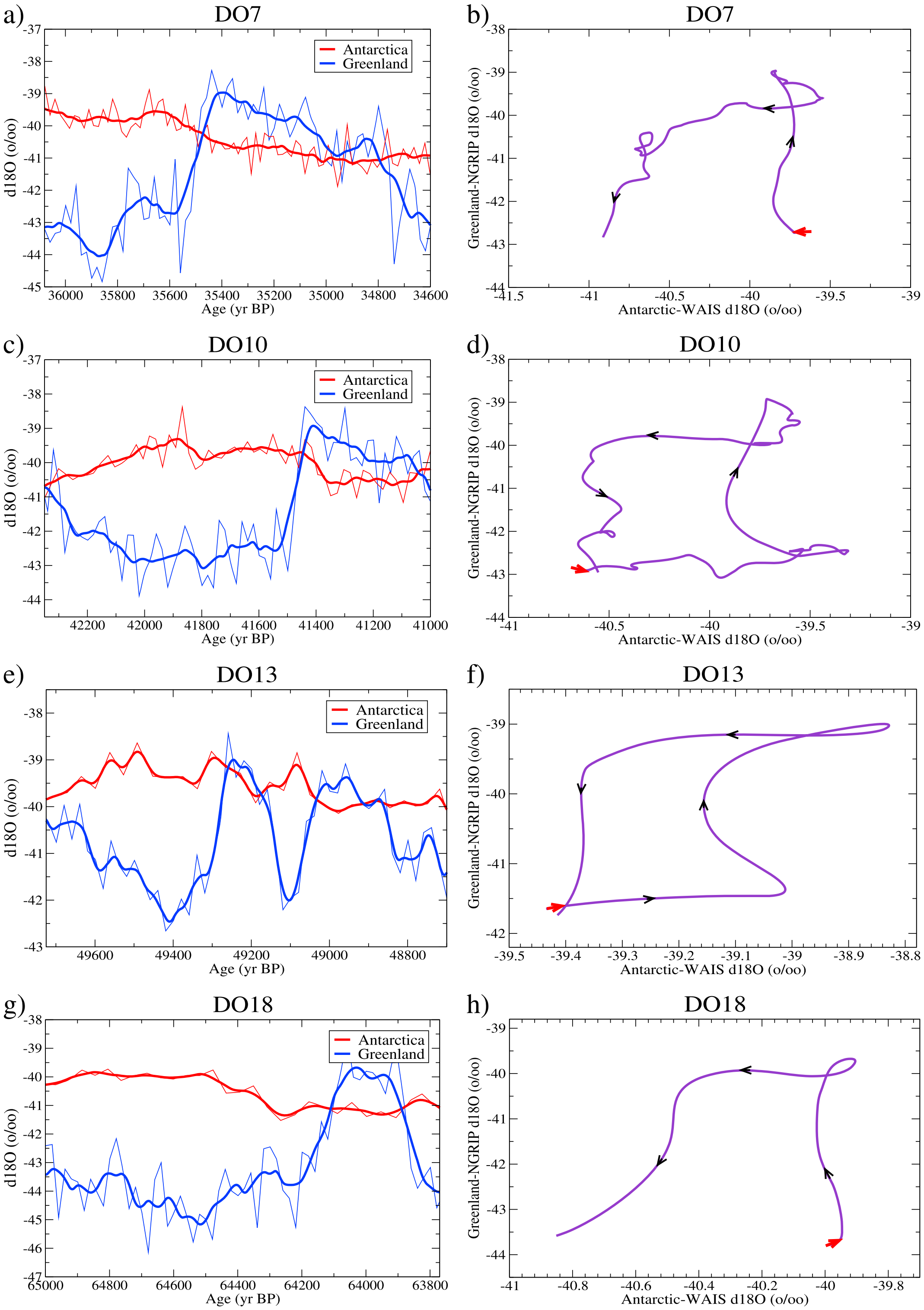

Figure 4. Phase space representations for four non-Heinrich DO events 7, 10, 13, and 18. Antarctica (red line) and Greenland (blue line) isotopic temperature records associated to the abrupt climate events and the phase representations constructed based on the two corresponding time series, for DO7 (a and b), DO10 (c and d), DO13 (e and f), and DO18 (g and h). The leads of the WAIS Divide ice core window over the NGRIP segment used to construct these representations are 200, 300, 250, and 500 years, respectively. In the left panels, the unfiltered data are shown with thin lines. The thick lines correspond to running mean filtered time series, with lengths of 151 (a), 101 (c), 41 (e) and 101 years (g). The same filters are applied to the corresponding phase space representations shown in the right panels. The red arrows in (b), (d), (f), and (h) indicate where the time starts and, together with the black arrows, indicate the direction of time. WAIS = West Antarctic ice sheet; NGRIP = North Greenland Ice Core Project; DO = Dansgaard-Oeschger.

For four HDO events 1, 2, 8, and 12 (Figure 3) and for four non-HDO events 7, 10, 13, and 18 (Figure 4), clear hysteresis shapes are observed in the associated phase spaces, with visible overshoots. Overall, the HDOs are associated with clearer hysteresis shapes than the non-DOs (Figures 3 and 4). In order to test the robustness of these results, this procedure is reapplied and extended to all 24 DO events of the last glacial cycle, based on NGRIP and EDML records, yielding similar results. A detailed analysis of the reconstructed hysteresis diagrams is presented in Supporting Information S1. These results support the idea that the Greenland component associated with rapid climate changes is controlled by a global forcing as documented in Antarctica, which also leads the North Atlantic signal by a few centuries. Our paleoclimate data-based concept is furthermore consistent with the view that the events are generated by an onset of the AMOC.

4. Discussion

Most HDOs and, in general, the longer events are associated with relatively large changes in atmospheric CO_2 concentration (Ahn & Brook, 2014). Therefore, they could rely on interhemispheric interactions in which this greenhouse gas plays a critical role. In a complementary way, some non-HDOs and, in general, the short DOs are not associated with large variations of atmospheric CO_2 concentrations (Ahn & Brook, 2014). Their oscillatory nature could result from bidirectional interhemispheric interactions in which the climatic signal is transferred from south to north through oceanic processes (e.g., Knorr & Lohmann, 2003).

The hysteresis diagram simulated by Knorr and Lohmann (2007) was recently qualitatively reproduced by a comprehensive fully coupled Earth System Model, COSMOS (Zhang et al., 2017). It includes an atmospheric model (ECHAM5), a land surface component (JSBACH32) at a T31 resolution with 19 vertical levels, and an oceanic component (MPI-OM33) with 40 uneven vertical levels coupled to a sea-ice model formulated using viscous-plastic theology. This model was used in simulations over the last millennium, the Miocene warm climate, the Pliocene, the Holocene, and the Last Glacial Maximum. The hysteresis diagram describing AMOC response to varying atmospheric CO_2 concentration, which has a similar pattern with that presented here, includes rapid transitions between two distinct ocean circulation states (Zhang et al., 2017). Such abrupt changes are associated with intermediate ice volume and CO_2 values, but not with conditions corresponding to the Last Glacial Maximum and interglacial periods, for which AMOC is in a monostable regime. Consistent with this, abrupt transitions are not emphasized in simulations of AMOC response to Southern Hemisphere warming for Last Glacial Maximum and preindustrial background conditions, which show a rather linear relationship between these two climate variables (Buizert & Schmittner, 2015). One notes also that CO_2 is a varying factor in the former study but a fixed parameter in the last one.

The main features of each DO in both ensembles of phase space representations are very similar. Therefore, both, the West Antarctica (WAIS-WDC) and the East Antarctica (EDML) records, reflect in a similar manner the Antarctic-Greenland relation at millennial time scale. Although the proxy records from east Antarctica (e.g., EDML) may be influenced more by a global atmospheric forcing, whereas west Antarctic records may reflect more oceanic and sea ice related processes (Stenni et al., 2010; WAIS Divide Project Members, 2013), both show similar hysteresis diagrams. This is consistent with a possible thermal influence of the atmospheric CO_2 on both Antarctic records.

The proxy data suggest a mutual south-to-north connection: whereas the increasing trend of Antarctic temperature leads the Greenland abrupt warmings by a few centuries, the Greenland positive temperature anomalies lead the Antarctic coolings by about two centuries (WAIS, 2015). Together, these two interhemispheric links, associated with positive and negative delayed connections, could represent a negative feedback (Zhang et al., 2017). It could generate an oscillatory climatic signal with a period which is slightly more than double of the combined memory, in the range of the 1,470-year fundamental period which paces the DO events (Rahmstorf, 2003; Schulz, 2002b).

The relatively large amplitudes of the events could result from the AMOC fast transitions, in relation with the flow salinity and with the convection positive feedbacks. However, because the existence of the negative feedback does not rely on the fast transitions, the millennial scale oscillations could manifest also in a linear regime, with relatively small amplitude. This could explain the regular timing of the fundamental millennial cycle through both, glacial and interglacial periods (e.g., Bond et al., 2001; Rahmstorf, 2003).

According to numerical simulations, through modulation of the atmospheric moisture transport across Central America, the global forcing (e.g., atmospheric CO_2 concentration) affects the density of the North Atlantic surface water and could generate the phase changes of the millennial scale oscillations (Zhang et al., 2017). An additional factor which could contribute to the phase changes of the millennial cycle is represented by the North Atlantic component of the global ice volume, which modulates the glacial freshwater fluxes (e.g., from the melting of the Laurentide Ice Sheet) induced by enhanced poleward heat transport due to a strong AMOC. Its effect is likely reflected in the slope of the North Atlantic cooling along the strong AMOC state, which ends with a jump to a weak state (Figure 2). If this forcing is considered, then the interstadial-to-stadial transitions could be related not only to atmospheric moisture transport across Central America but also to North Atlantic ice volume (e.g., Schulz, 2002a). This last factor likely has a comparatively insignificant influence on the stadial-to-interstadial transitions. Consequently, the interhemispheric negative feedback which changes the phases of the millennial oscillations could be reinforced by the freshwater fluxes linked to North Atlantic ice volume only at interstadial-to-stadial transitions. This asymmetric impact of the ice volume on AMOC could explain why the millennial cycle paces only the DO warming phases and why their recurrence time scale is a multiple of the millennial fundamental period (Schulz, 2002b).

5. Conclusions

A previous study showed that, after removing the signal related to the abrupt transitions in Greenland, the residual component matches the Antarctic isotopic temperature with a temporal lag of several hundred years, pointing to a forcing with global influence (Barker & Knorr, 2007). Through a distinct method, our results in combination with numerical simulations indicate that the nonlinear Greenland component associated with rapid climate changes is controlled by a forcing related to the Antarctic climate, which also leads the North Atlantic signal by a few centuries. This suggests that the Greenland fluctuations are linearly and nonlinearly linked to a global forcing associated with Antarctica.

We conclude that our phase space reconstructions based on ice core records suggest that the DO warmings are linked to AMOC fast transitions controlled by global forcing linked to the Southern Hemisphere. They also provide support to the paradigm of nonlinear ocean response to gradual forcing as a cause for abrupt climate changes in the past, which can have analogues with more recent events in the North Atlantic realm (Dima & Lohmann, 2011).

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