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Invited review

A review of the bipolar see–saw from synchronized and high resolution ice core water stable isotope records from Greenland and East Antarctica

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ABSTRACT

Numerous ice core records are now available that cover the Last Glacial cycle both in Greenland and in Antarctica. Recent developments in coherent ice core chronologies now enable us to depict with a precision of a few centuries the relationship between climate records in Greenland and Antarctica over the millennial scale variability of the Last Glacial period. Stacks of Greenland and Antarctic water isotopic records nicely illustrate a seesaw pattern with the abrupt warming in Greenland being concomitant with the beginning of the cooling in Antarctica at the Antarctic Isotopic Maximum (AIM). In addition, from the precise estimate of chronological error bars and additional high resolution measurements performed on the EDC and TALDICE ice cores, we show that the seesaw pattern does not explain the regional variability in Antarctic records with clear two step structures occurring during the warming phase of AIM 8 and 12. Our Antarctic high resolution data also suggest possible teleconnections between changes in low latitude atmospheric circulation and Antarctic without any Greenland temperature fingerprint.

1. Introduction

This introductory section summarizes the history of the identification of the bipolar seesaw pattern from Greenland and Antarctic ice cores (Section 1.1), and the ongoing debate on its causes and mechanisms, combining information from other natural archives, conceptual models, and a hierarchy of climate models (Section 1.2). From these open questions, it motivates the need for improved chronological constraints and high resolution, synchronized climate records documenting the spatial structure of changes in Greenland and Antarctica. The last Section 1.3 finally explains the structure of this manuscript.

1.1. Identification of the bipolar seesaw pattern from Greenland and Antarctic ice cores

Abrupt events punctuating climate variability of the Last Glacial period have been identified worldwide in highly resolved terrestrial, marine and ice core records (Voelker, 2002; Clement and Peterson, 2008). Since the 1960s, successive deep Greenland ice core records have provided continuous and extremely highly detailed records of climate variability, now encompassing the whole Last Glacial period, from 116 000 to 11 700 years ago recorded in GRIP (Dansgaard et al., 1993), GISP2 (Grootes et al., 1993), NorthGRIP (NorthGRIP Comm. Members, 2004) and NEEM ice cores (NEEM Comm. Members, 2013). During this time interval, 25 rapid events, called “Dansgaard-Oeschger events” (hereafter DO events), have been identified in numerous measurements performed along these Greenland ice cores (NorthGRIP

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Community Members, 2004). Greenland abrupt temperature variations are qualitatively recorded at high resolution in water stable isotopes, while their magnitude is estimated using the thermal fractionation of gases inside the firn with an uncertainty of ~2 °C (Severinghaus and Brook, 1999; Kindler et al., 2014). Lasting a few centuries to a few millennia, DO events are characterized by the succession of a cold phase (Greenland Stadial, GS), an abrupt warming of 5–16 °C in a few years or decades, followed by a warm phase (Greenland Interstadial, GI) marked by a gradual cooling before a relatively abrupt cooling into the next GS, taking place within a few centuries. The widespread extent of DO events is reflected in parallel changes in the atmospheric composition (CH_4 concentration, as well as inflexions in the atmospheric $\delta^{18}O$ of O_2, hereafter $\delta^{18}O_{atm}$) (Chappellaz et al., 1993, 2013; Landais et al., 2007). The strong abrupt temperature and CH_4 increases occur in phase, within 10 years (Severinghaus et al., 1998; Rosen et al., 2014). This abrupt variability in the atmospheric composition, being recorded in the air trapped in Greenland and Antarctic ice cores, has provided a critical tool for the transfer of the accurate Greenland age scales based on annual layer counting towards Antarctic ice core chronologies (Blunier et al., 1998; Schüpbach et al., 2011).

Since the 1970s, East Antarctic ice cores have also depicted millennial climate variability during the Last Glacial period, albeit with limitations in temporal resolution emerging from lower accumulation rates, and less accurate chronologies when annual layer counting is not possible. In Antarctic water stable isotope records, this millennial variability is marked by Antarctic Isotopic Maxima (AIM), initially identified in the central East Antarctic plateau as symmetric gradual isotopic enrichment (warming) and depletion (cooling) trends. Using a first synchronization of the Greenland GRIP and GISP2 ice cores with the Antarctic Vostok ice core through the alignment of $\delta^{18}O_{atm}$, Bender et al. (1994a) evidenced a recurrent relationship between Greenland and Antarctic water stable isotope millennial events for the nine longest GS. This Greenland and Antarctica pattern was also shown in parallel by Jouzel et al. (1994). A refined synchronization of Greenland (GRIP, GISP2) and Antarctic (Byrd) ice core records was built by Blunier et al. (1998) and Blunier and Brook (2001) based on the alignment of CH_4 records over the last 90,000 years. 7 main Antarctic warm events were identified (called A events) as Antarctic counterparts of major Greenland DO events. During each of these 7 events, Antarctic temperatures increased gradually during GS, and the end of Antarctic warming coincided with the onset of rapid warming in Greenland.

Using higher resolution data as well as an improved synchronization, it has been further evidenced that each DO event has an Antarctic Isotopic Maximum counterpart (EPICA Comm Members, 2006; Jouzel et al., 2007), except for the first DO event of the Last Glacial period identified in the NorthGRIP ice core, DO25 (Capron et al., 2012). The same bipolar characteristic was also identified at the sub-millennial scale, during GS precursors of DO, or rebound events at the end of GIS, lasting only a few centuries (Capron et al., 2010a), albeit with the restrictions associated with the accuracy of the chronology, a few hundred years at best.

While there is growing evidence for the recurrence of abrupt climate change with similar characteristics during earlier glacial periods from high resolution Antarctic, terrestrial and deep sea records (e.g. McManus et al., 1999; Loulergue et al., 2007; Martrat et al., 2007; Barker et al., 2011; Lambert et al., 2012), we will focus here on the Last Glacial period for which the bipolar structure of events can be accurately characterized from high resolution and well dated records at both poles.

1.2. Causes and mechanisms of the bipolar seesaw

In parallel to ice core records highlighting millennial scale variability during the Last Glacial period, deep-sea sediments from the North Atlantic have revealed the recurrence of iceberg rafted debris in marine cores during GS, associated with iceberg discharges from glacial ice sheets, changes in sea ice extent, surface temperature and salinity, and reorganizations of the thermohaline circulation (e.g. Heinrich, 1988; Bond et al., 1992; Broecker et al., 1992; Grousset et al., 1993; McManus et al., 1998; Labeyrie et al., 1999; Elliott et al., 2002). Six major iceberg discharge episodes were identified as Heinrich events, corresponding to collapses of the Laurentide and/or European ice sheets (see review by Hemming, 2004). A Heinrich stadial was therefore defined as a Greenland cold phase during which a Heinrich event occurred (Barker et al., 2009; Sanchez-Goñi and Harrison, 2010). This feature led to the hypothesis that cold phases during Heinrich events (and, implicitly, all GS) were caused by changes in large scale Atlantic ocean circulation, driven by massive inflows of freshwater linked with glacial ice sheet collapses (e.g. Broecker, 1991; Paillard and Labeyrie, 1994; Ganopolski and Rahmstorf, 2001).

During the last decade, glacial abrupt events have been investigated using coupled ocean-atmosphere models of varying complexity (e.g. Stouffer et al., 2006; Kageyama et al., 2013). Several aspects of the observed patterns can be captured through the response of the Earth system to imposed freshwater perturbations in the North Atlantic (Ganopolski et al., 2001; Liu et al., 2009; Kageyama et al., 2010; Roche et al., 2010), mimicking Heinrich events. Depending on the background state of the climate (glacial or interglacial, orbital context …), of the simulated Atlantic Meridional Oceanic Circulation (AMOC), and the magnitude of the freshwater forcing, these models can produce a complete shutdown of the AMOC (Heinrich-like state) or a reduction of the strength of the AMOC (GS-like state) (e.g. Menviel et al., 2014). In all models, the injection of freshwater robustly produces a significant cooling of the North Atlantic region. The amplitude of the associated temperature change is probably affected by the simulated change in sea-ice extent and feedbacks between sea-ice and temperature that vary in the different models (Kageyama et al., 2013). These hosing experiments also produce an inter-hemispheric seesaw temperature pattern and impacts on the position of the intertropical convergence zone, hereafter ITCZ (e.g. Dahl et al., 2005; Broccoli et al., 2006; Krebs and Timmermann, 2007; Swingedouw et al., 2009) through changes in meridional heat transport. In response to freshwater forcing, climate models simulate a decrease of the NADW (North Atlantic Deep Water) export and a possible increase of the AABW (Antarctic Bottom Water) export in the Southern Ocean (Rind et al., 2001). The alternation between NADW and AABW formation is supported by paleoceanographic deep circulation tracers (e.g. review by Adkins, 2013), as well as by changes in ^{14}C of CO_2 measurements (Broecker, 1998; Anderson et al., 2009). The different models confirm the robustness of the bipolar seesaw signature of the climate response to AMOC weakening with the South Atlantic systematically warming in response to a freshwater discharge applied in the North Atlantic. There are still regional differences in the simulated Southern Ocean response (Clement and Peterson, 2008; Kageyama et al., 2010; Timmermann et al., 2010). Some models simulate a quasi-uniform warming (e.g. Otto-Bliesner and Brady, 2010) while others show contrasted patterns with a West Pacific cooling associated with the Southern Indian Ocean sector warming.

Conceptual models, paleoceanographic data and climate models of varying complexity all converge to show that DO events are associated with changes in AMOC. However, a number of physical