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Invited review

Beyond the bipolar seesaw: Toward a process understanding of interhemispheric coupling

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ABSTRACT

The thermal bipolar ocean seesaw hypothesis was advanced by Stocker and Johnsen (2003) as the 'simplest possible thermodynamic model' to explain the time relationship between Dansgaard–Oeschger (DO) and Antarctic Isotope Maxima (AIM) events. In this review we combine palaeoclimate observations, theory and general circulation model experiments to advance from the conceptual model toward a process understanding of interhemispheric coupling and the forcing of AIM events. We present four main results: (1) Changes in Atlantic heat transport invoked by the thermal seesaw are partially compensated by opposing changes in heat transport by the global atmosphere and Pacific Ocean. This compensation is an integral part of interhemispheric coupling, with a major influence on the global pattern of climate anomalies. (2) We support the role of a heat reservoir in interhemispheric coupling but argue that its location is the global interior ocean to the north of the Antarctic Circumpolar Current (ACC), not the commonly assumed Southern Ocean. (3) Energy budget analysis indicates that the process driving Antarctic warming during AIM events is an increase in poleward atmospheric heat and moisture transport following sea ice retreat and surface warming over the Southern Ocean. (4) The Antarctic sea ice retreat is itself driven by eddy-heat fluxes across the ACC, amplified by sea-ice–albedo feedbacks. The lag of Antarctic warming after AMOC collapse reflects the time required for heat to accumulate in the ocean interior north of the ACC (predominantly the upper 1500 m), before it can be mixed across this dynamic barrier by eddies.

1. Introduction

The thermal bipolar ocean seesaw hypothesis is the prevailing explanation for the coupling of Dansgaard–Oeschger (DO) and Antarctic Isotope Maxima (AIM) events. Stocker and Johnsen (2003) provide the thermodynamic basis for the hypothesis with their suggestion that the temperature anomalies in Greenland and Antarctica during these events could most simply be explained by changes in the rate of cross-equatorial ocean heat transport in the Atlantic, that are modulated at southern high latitudes by a large heat reservoir (commonly assumed to be the Southern Ocean). While the simplicity of the thermal seesaw hypothesis is attractive, the absence of details on the actual physical processes that connect north and south limits its application to the coupled climate system (Wunsch, 2006; Seager and Battisti, 2007; Clement and Peterson, 2008). Indeed, Stocker & Johnsen (2003) did not intend that their conceptual model captured all the relevant physics. The purpose of this review is to explore several key limitations of the thermal seesaw: the means of signal transmission in the Atlantic, the location and means of operation of the heat reservoir, signal propagation across the Antarctic Circumpolar Current and the forcing of Antarctic temperature itself.

The paper is structured as follows: The remainder of Section 1 outlines the development of the thermal seesaw hypothesis and several of its limitations; Section 2 introduces two transient global climate model (GCM) experiments that we use, along with palaeoclimate data, to explore these limitations; Section 3 presents our results on ocean, atmospheric and radiative processes responsible

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for transmission of temperature anomalies between the northern and southern high latitudes; Section 4 describes an energy budget analysis of the specific processes driving Antarctic warming and cooling; Section 5 compares our results to several major predictions and assumption of the thermal seesaw; we conclude in Section 6 with some suggestions on future lines of research that would aid further understanding of the mechanisms involved in interhemispheric coupling and the forcing of AIM events in particular.

1.1. Origin of the thermal seesaw hypothesis

Greenland ice-core records spanning the last glacial period and deglaciation feature abrupt Dansgaard–Oeschger temperature variations of 10–16 °C, between cold (Greenland stadial) and warmer (Greenland interstadial) climate states, see Fig. 1a (Severinghaus et al. 1998; Huber et al. 2006; Kindler et al. 2014). Antarctic ice cores feature smaller and more gradual temperature variation of 1–3 °C amplitude, termed Antarctic Isotope Maxima, see Fig. 1b (EPICA Community Members, 2006; Stenni et al. 2011; Parrenin et al. 2013; WAIS Divide Project Members, 2015). The thermal seesaw concept emerged by heuristically connecting the timing and shape of the DO and AIM events with theory on ocean heat transport and observations of palaeocean circulation (Mix et al. 1986; Crowley, 1992; Stocker and Johnsen, 2003). We briefly review each of these building blocks of the thermal seesaw.

Analysis of the relative timing of the DO and AIM events was made possible by gas-based ice-core synchronisations (Bender et al., 1994), in particular the fast global variations in atmospheric methane that accompany DO transitions (Blunier et al., 1998; Blunier and Brook, 2001). The North Greenland Ice Core Project (NGRIP) and multi-core Antarctic temperature reconstruction shown in Fig. 1 are aligned using this technique. The ice-core data suggest a systematic relationship: Antarctica gradually warms during Greenland stadials (Fig. 1 shading), and gradually cools during Greenland interstadials (Blunier et al., 1998; Blunier and Brook, 2001; EPICA Community Members, 2006; Pedro et al. 2011; WAIS Divide Project Members, 2015). Some internal differences between Antarctic ice-core sites in the structure of AIM events have also been identified (and see Landais et al. 2015; Morgan et al. 2002, and our Section 5).

The principle behind the second building block of the thermal seesaw—net northward heat transport in the Atlantic Ocean—was proposed close to 150 years ago by James Croll.

> "The [Atlantic] currents, which cross the equator are far higher in temperature than their compensating undercurrents; consequently there is constant transference of heat from the southern hemisphere to the northern [Croll, 1870]."

Modern observations and reanalysis data confirm that the Atlantic transports heat northward at all latitudes (Ganachaud and Wunsch, 2000; Trenberth and Caron, 2001; Trenberth and Fasullo, 2017). Today, we associate this northward heat transport (around 1±0.5 PW at the equator) with the warm surface flow and cold deep return flow of the Antarctic Meridional Overturning Circulation (AMOC): warm waters flow northward in the Atlantic surface layers, cool and sink in the polar North Atlantic and then return south, mixing with intermediate depth waters, before returning to the surface either by wind-driven isopycnal upwelling in the Southern Ocean (Toggweiler and Samuels, 1995; Munk and Wunsch, 1998; Marshall and Speer, 2012) or by diapycnal diffusion in the Indo-Pacific basins (Talley, 2013).

The potential for instability of the ocean overturning circulation, with major consequences for the climate system, was first pointed out by Stommel (1961), whose simple density-driven model of overturning circulation suggested that small changes in salt or heat inputs could tip the circulation into an alternative stable regime. Crowley (1992) argued that a collapse of the AMOC would warm

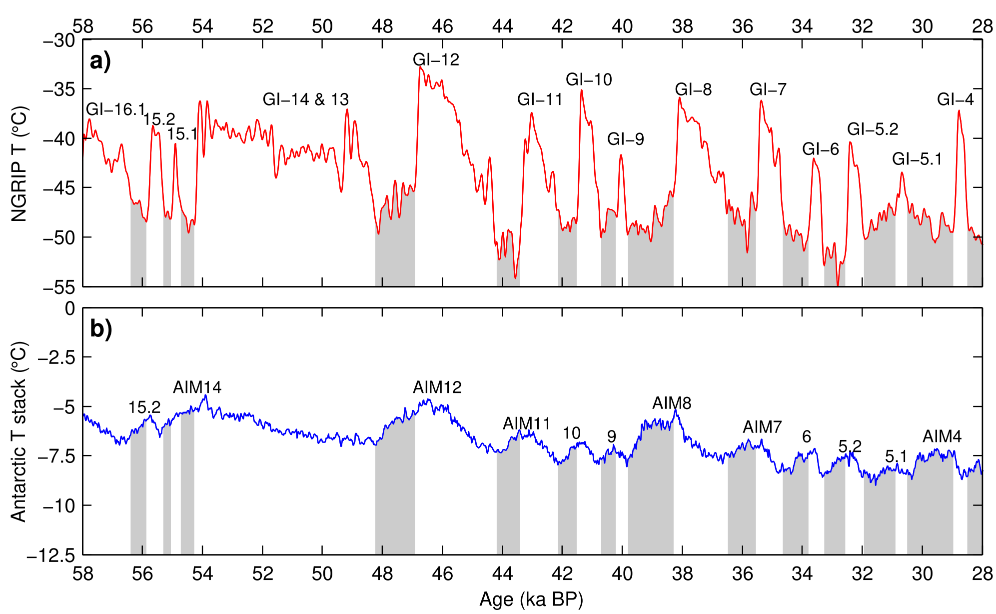

Fig. 1. Temperature reconstructions from Greenland and Antarctic ice cores spanning Marine Isotope Stage 3. a) North Greenland Ice Core Project (NGRIP) temperature reconstruction based on δ^{15}N and δ^{18}O records (North Greenland Ice Core Project members, 2004; Kindler et al., 2014). b) Antarctic Temperature Stack (ATS) based on stacked δ^{18}O and δD records from six Antarctic ice cores: EPICA Dome C, EPICA Dronning Maud Land (EDML), Vostok, Talos Dome, and Dome Fuji as published in (Parrenin et al., 2013), to which we have added data from the WAIS Divide Core (Cuffey et al., 2016). Note how the warming phases of Antarctic Isotope Maxima (AIM) coincide with Greenland stadials (GS; grey shading) and the cooling phase of AIMs coincide with Greenland interstadials (GI). The AIM labelling follows EPICA Community Members (2006) and the GI and GS labeling follows Rasmussen et al. (2014). The time axis is given in thousand of years before 1950 AD, on the Antarctic Ice Core Chronology 2012 (AICC 2012) timescale of Veres et al. (2013). Antarctic temperatures are expressed as an anomaly with respect to the past millennium. Note the much larger temperature variations in Greenland compared to Antarctica and the different ranges of their respective temperature axes.