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Polar synchronization and the synchronized climatic history of Greenland and Antarctica

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ABSTRACT

Stable isotope proxies from ice cores show subtle differences in the climatic fluctuations of the Arctic and Antarctic, and recent analyses have revealed evidence of polar synchronization at the millennial time scale. At this scale, we analogize the polar climates of the last ice ages to two coupled nonlinear oscillators, which adjust their natural rhythms until they synchronize at a common frequency and constant phase shift. Heat and mass transfers across the intervening ocean and atmosphere make the coupling possible. Here we statistically demonstrate the existence of this phenomenon in polar proxy records with methane-matched age models, and quantify their phase relationship. We show that the time series of representative proxy records of the last glaciation recorded in Greenland (GRIP, NGRIP) and Antarctica (Byrd, Dome C) satisfy phase synchronization conditions, independently of age, for periods ranging 1–6 ky, and can be transformed into one another by a $\pi/2$ phase shift, with Antarctica temperature variations leading Greenland's. Based on these results, we use the polar synchronization paradigm to replicate the 800 ky-long, Antarctic, EPICA time series from a theoretical model that extends Greenland's 100 ky-long GRIP record to 800 ky. Statistical analysis of the simulated and actual Antarctic records shows that the procedure is stable to change in adjustable parameters, and requires the coupling between the polar climates to be proportional mainly to the difference in heat storage between the two regions.

1. Introduction

The climate records seen in the polar ice cores can be characterized as nonlinear, complex, oscillating systems, with periods of abrupt warming separated by abrupt cooling. In order to gain a better understanding of the polar climate systems, and possibly even learn to predict the behavior of the polar climates, this paper seeks to propose a stable, reliable, and verifiable conceptual model of the polar climates. For this purpose, we demonstrate the effectiveness of modeling the polar climates as nonlinear oscillators, using the ice volume model (Saltzman, 2002) that represents each polar climate as simple Van der Pol oscillators. These oscillators are coupled and synchronized through the entire duration of the last glaciation.

Synchronization is a basic mechanism of self-organization in complex systems. Its presence in a system can be identified when two nonlinear oscillators (in our case, the polar climates) adjust their initially different natural frequencies to a common frequency with constant relative phase, also known as frequency entrainment and phase locking (Pikovsky et al., 2001). The oscillators must be nonlinear in order to respond to mutual forcing in such a way that their natural frequencies (and phases) are modified by their interaction. Possible evidence of other instances of synchronization within the climate system have been found in non-polar paleoclimate records as well, including the link between North Pacific and North Atlantic deep-water oscillations (Lund and Mix, 1998). Higher frequency examples in recent climate records include the links between the Indian Monsoon and El Nino-Southern Oscillation (ENSO) (Maraun and Kurths, 2005; Tsonis et al., 2007) and the teleconnections between the North Atlantic, the Ethiopian Plateau and the Mediterranean (Feliks et al., 2010), among others. However, at this time, these connections have not been analyzed for their phase and frequency locking, so while they do demonstrate the transfer of energy necessary for synchronization to take place, synchronization itself has not yet been identified.

The possible connections between northern and southern polar temperatures have been identified on multiple occasions, all of which support modeling the polar climates as connected, nonlinear

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oscillators with the potential for synchronization. EPICA Community Members (2006) were first to identify a linear relationship between the stadial intervals at the poles during the MIS3 interval 50 ka–30 ka (1 ka = 1000 years ago) and then suggest that this trend extended to cover the last glaciation. Prior to this, Crowley had put forward the basic bipolar hemispheric seesaw hypothesis (Crowley, 1992; Broecker, 1998) as an explanation of how the abrupt warming episodes in the North Atlantic lead to the beginning of cooling episodes in Antarctica, namely via polar climate communication through meridional (equatorially asymmetric) heat transport and North Atlantic deep water (NADW) production. Blunier et al. (1998) and Blunier and Brook (2001) built on this idea, demonstrating that events in Greenland's climate follow those in Antarctica by about 1–3 ky (1 ky = 1000 years) and that this is due to the ocean controlling the climate at both poles. Hinnov et al. (2002) studied the specific connection between the Byrd and GISP2 records' inter-hemispheric anti-phasing (180° phase shift) of the Dansgaard–Oeschger (DO) oscillations over the 10–90 ka interval. Even more recently, Steig (2006) reported a $\pi/2$ phase shift between the polar climates, seen by analyzing high-resolution records from EDML (Antarctica) and NGRIP (Greenland) cores. Barker et al. (2009) then published data from the South Atlantic which demonstrated the existence of rapid but opposite temperature changes occurring at the same time as those documented in the north and proposed a link between the DO oscillations in the Arctic and the sub-Antarctic temperature variations. In a follow up study, they used Crowley's simple, conceptual bipolar seesaw model to forecast the unknown Greenland record using the 800 ky record of Antarctica (Barker et al., 2011), though the lack of actual Greenland records beyond ~120 ka means that they were unable to validate their results. Finally, in response to this, Rial (2012) proposed the nonlinear phase synchronization of the millennial-scale polar climates fluctuations during the last glaciation as an explanation for the apparent teleconnection between the Polar Regions.

While all the studies mentioned above serve as a basis of justification for this paper, they have all either lacked a statement of quantified statistical significance of the relationship between the two polar regions, only extracted millennial frequency band components using purely linear decomposition techniques, or focused on isolated, short events over the last glacial period. The present study investigates the statistical significance of the presence of polar synchronization over the last glacial period using a data adaptive decomposition technique, surrogate data tests, and long-term methane-matched age models when possible, providing a more complete characterization of the polar connection and behavior of the polar climates as oscillators. Our results will show that the polar behavior is well represented by the polar synchronization model throughout the 800 ky interval of recorded polar climate history. The approach demonstrated in this paper uses the aforementioned, simplified, climate model to closely reproduce the 100 ky Greenland ice core record (GRIP), then extends it a further 700 ky in the past, creating a 800 ky-long simulation of the Greenland δ^{18}O time series. This reconstructed Arctic signal is then numerically transformed into an 800 ky-long simulation of Antarctica's EPICA temperature proxy via the assumption of synchronization. We show that bidirectional, or mutual, phase synchronization affects the millennial cycles but does not appear to affect the long periods dominated by the Milankovitch forcing. A more detailed discussion of the role of nonlinear phase synchronization of the climate system to Milankovitch forcing over the last 5My is the topic of a recent paper by our research group (Rial et al., 2013).

Before exploring the modeling process and our results, though, it is important to emphasize that, throughout this paper, the use of the term synchronization or phase synchronization refers to frequency entrainment and phase lock (i.e. a constant phase difference), and so does not relate to the term *asynchronous* as used by some authors to refer to the polar climate being locked out of phase (Blunier et al., 1998; Stenni et al., 2010). Also, polar synchronization is unrelated to the technique of synchronizing age models using methane records from both Polar Regions (e.g., Blunier and Brook, 2001), though we have indeed made use of the methane-matched age models to compare the phases of Byrd and GRIP and to tune NGRIP and Dome C records to each other (details will be explained later with Fig. 1). This precondition allowed us to analyze phase differences between the two time series assuming the differences in age models to be small and likely irrelevant.

Our paper begins with an outline of the specifics of polar synchronization and describes how to transform one polar climate proxy record into the other in Section 2. Section 3 shows the model simulation of 800 ky of Antarctic climate record through the transformation of Greenland's using both data and the model, as well as discussing model stability under parameter change. Section 4 includes a brief discussion of results, followed by conclusions in Section 5. Details of the mathematical models and statistical data analysis are described in the Appendix.

2. Polar synchronization paradigm

2.1. Polar synchronization

In order to demonstrate the utility of polar synchronization as a model, one must begin with an understanding of synchronization and why it is possible to say that the poles demonstrate its presence. Synchronization itself is a well-established phenomenon, first proposed via Christian Huygens' classic observations of synchronized clocks (Huygens, 1673). Comparing these slightly nonlinear, weakly connected clocks to our more strongly nonlinear, still weakly connected polar climates makes his theory a direct analogy to explain the linked behavior of the polar climates. Huygens stated that two clocks with initially different frequencies (in our case, the poles) hanging from the same beam (connected by oceans and atmosphere) eventually synchronize to a common frequency and phase lock (Pikovsky et al., 2001; Bennett et al., 2002), even with very weak coupling. The phase lock can either be in-phase, anti-phase, or an arbitrary, constant phase. This lock can be observed throughout paleoclimate time series from the polar regions by inducing a constant phase shift of $\pi/2$ to the time series of the most representative abrupt climate events during the last glaciation recorded in Greenland and Antarctica. All millennial scale frequency components in the signal are $\pi/2$ shifted, meaning each of these frequency components is shifted by one-fourth of its period. Thus time series pairs like NGRIP-DomeC or GRIP-Byrd can be formally described as approximate Hilbert transform pairs (Bracewell, 1986; see Appendix A). This process (Figs. 1–3) will be more thoroughly explained in the second part of this section; however, it is important to note this characteristic phase lock here in order to better demonstrate the parallel between Huygens' clocks and our polar climate records.

Unlike the clocks, though, climate oscillators are often highly nonlinear, multidimensional and chaotic, which allows for the presence of many forms of synchrony. For instance, as coupling is increased from zero, nonsynchronous states will undergo phase synchronization (PS), as appears to occur in the polar paleoclimate records. PS does not involve or require amplitude correlation. Other types of oscillations, though, require that the two linked oscillators be systems of identical oscillators, including for what is known as lag and complete synchronization. In identical systems, when coupling is increased beyond what is needed to induce PS, it produces lag synchronization (LS), which appears as