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A minimum thermodynamic model for the bipolar seesaw

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[1] The simplest possible model is proposed to explain a large fraction of the millennial climate variability measured in the isotopic composition of Antarctic ice cores. The model results from the classic bipolar seesaw by coupling it to a heat reservoir. In this "thermal bipolar seesaw" the heat reservoir convolves northern time signals with a characteristic timescale. Applying the model to the data of GRIP and Byrd, we demonstrate that maximum correlation can be obtained using a timescale of about 1000–1500 years. Higher correlations are obtained by first filtering out the long-term variability which is due to astronomical and greenhouse gas forcing and not part of the thermal bipolar seesaw. The model resolves the apparent confusion whether northern and southern climate records are in or out of phase, synchronous, or time lagged. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1635 Global Change: Oceans (4203); 4267 Oceanography: General: Paleoceanography; *KEYWORDS:* bipolar seesaw, synchronization of Antarctic and Greenland ice cores, Dansgaard-Oeschger events, north-south connection

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1. Introduction

[2] Abrupt climate change is one of the rare instances in climate history where the full dynamics of the coupled atmosphere-ocean-sea ice system is manifested [*Alley et al.*, 2003]. Such events thus serve as an important test bed for theories and climate models about how large signals in the climate system are propagated. The best known events of abrupt change are the rapid warmings that are inferred from the stable water isotopes measured in the Greenland ice cores from GRIP and GISP2 [*Dansgaard et al.*, 1993; *Grootes et al.*, 1993]. In total, 24 such events, so-called Dansgaard/Oeschger events, have been found during the last ice age from 14,000 years before present (14 kyr B.P.) back to 110 kyr B.P. The amplitudes of these rapid warmings in Greenland have been estimated using the changes in the stable isotopes of enclosed air to range from 9°C up to 16°C [*Lang et al.*, 1999; *Severinghaus and Brook*, 1999]. Antarctic ice cores, on the other hand, do not show such rapid and large fluctuations, but they exhibit slow millennial-scale warmings and coolings during the last glacial [*Johnsen et al.*, 1972; *Jouzel et al.*, 1987; *Grootes et al.*, 2001]. Climate records derived from Antarctic ice cores thus have a very different temporal characteristic than those obtained from Greenland ice cores.

[3] The purpose of this paper is to present the simplest possible model, a conceptual model, which is able to explain these different characteristics. This purely thermodynamic model is based on earlier ideas of the bipolar seesaw, and enables us to predict a rough estimate of the isotopic record of an ice core in Antarctica when the isotopic record of Greenland is given as an input. This suggests a strong interhemispheric coupling which, we argue, occurs through a combination of the ocean and the atmosphere. This north-south connection is supported by the high values of correlation between the predicted and observed Antarctic records. The predicted isotopic record of Antarctica further suggests that all D/O events in Greenland should be mirrored in Antarctica. However, if they are too weak, or too short, they may not be distinguished from the regional short-term climate signals that also influence the isotopic records.

[4] The most viable mechanism for abrupt climate changes in the North Atlantic region is still associated with reorganizations of the ocean circulation as originally proposed by *Ruddiman and McIntyre* [1981] to interpret the large shifts they found in planktonic foraminifera assemblages in North Atlantic marine sediments during the last deglaciation. *Dansgaard et al.* [1984], *Oeschger et al.* [1984], *Broecker et al.* [1985], and *Broecker and Denton* [1989] also suggested that ocean circulation changes are responsible for the abrupt events they found in the Greenland ice cores and other paleoclimatic archives. The potential climatic significance of ocean circulation changes was already pointed out by *Stommel* [1961] based on a simple model of the density-driven meridional overturning circulation (thermohaline circulation, THC). The THC in the Atlantic transports a substantial amount of heat northward which is responsible for a relatively mild climate in that region [*Ganachaud and Wunsch*, 2000]. A rapid shut-down of this circulation causes a cooling in ocean and atmosphere. This cooling has been simulated using the entire hierarchy of models ranging from climate models of

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reduced complexity to fully coupled three-dimensional AOGCMs [*Maier-Reimer and Mikolajewicz*, 1989; *Stocker et al.*, 1992b; *Rahmstorf and Willebrand*, 1995; *Manabe and Stouffer*, 1997; *Schiller et al.*, 1997; *Ganopolski and Rahmstorf*, 2001; *Rind et al.*, 2001; *Vellinga and Wood*, 2002; *Schmittner et al.*, 2003].

[5] On the basis of these model simulations, a testable prediction about the climate response in regions outside the North Atlantic can be made. *Crowley* [1992] and *Stocker et al.* [1992a, 1992b] suggested that the South Atlantic is cooled by the THC. This is consistent with recent observations showing northward meridional heat transport at 30°S [*Talley*, 2003]. According to this hypothesis, a shut-off of the THC, which triggers a rapid cooling in the north, should produce a warming in the south, because heat is no longer exported northward. This is the basic mechanism behind the bipolar seesaw and would argue for an antiphase relationship between north and south [*Broecker*, 1998; *Stocker*, 1998].

[6] The simple seesaw concept was recently questioned because it does not explain the very different time characteristics, nor does it account for the apparent leads or lags that are suggested by a lag-correlation analysis of the GRIP and the Byrd isotopic temperatures. *Steig and Alley* [2002] present a correlation analysis which shows two maxima, one for in-phase relation with a southern lead by about 1000 to 1600 years, or alternatively an anti-phase relation with a northern lead by 400 to 800 years. *Schmittner et al.* [2003] confirm these findings. The absolute values of the correlations between the high-pass filtered time series are smaller than 0.5, and the two possibilities are statistically indistinguishable. However, they are both inconsistent with the classical bipolar seesaw which postulates anti-phase relation with zero lag. Additional model simulations support the findings of the correlation analysis based on the ice core isotopes and indicate that the northern lead is due to the slow propagation time of signals in the southern ocean, whereas the equally high correlation of in-phase relationship is rather a consequence of the near regularity of Dansgaard/Oeschger events during the last glacial [*Schmittner et al.*, 2003].

[7] Only paleoclimatic data can reveal whether these simplified concepts, at least as zero-order approximations, provide appropriate descriptions of the far-field effects of North Atlantic abrupt climate change. Progress was made by the possibility of synchronizing very distant paleoclimate records. *Bender et al.* [1994] pioneered gas-based synchronization of ice cores. Variations of gases in air are rapidly mixed in the atmosphere and registered on a global scale. By measuring the stable isotope ratio of the oxygen molecule of air, enclosed in the bubbles of Antarctic and Greenland ice, they showed that the relative isotope maxima in Vostok line up with those D/O events that last longer than 2 kyr. They argued for a synchronous, or in-phase, relationship between north and south. A more accurate synchronization is achieved if CH_4 is used as the synchronizing gas. CH_4 shows a sharp peak with almost all D/O events and thus represents a convenient global time marker. *Blunier et al.* [1997, 1998] and *Blunier and Brook* [2001] used CH_4 to synchronize ice core records from Greenland and Antarctica from 10 kyr B.P. to 90 kyr B.P. They found that the warming trends in Antarctica lead the D/O events by about 1000 to 2500 years. When the abrupt warming occurs, a cooling trend sets in. In summary, the ice core synchronizations suggested in-phase or time lag relationships, whereas the bipolar seesaw hypothesis predicts antiphase relation between north and south. Recently, *Clark et al.* [2002] demonstrated using a set of 18 paleoclimatic records covering the last deglaciation from 20 to 10 kyr B.P. that the two leading empirical orthogonal functions explaining the data are the 10,000 year warming trend and an Atlantic dipole (positive in the Atlantic basin of the northern hemisphere, negative in the southern hemisphere). The latter mode is the signature of the bipolar seesaw.

[8] This apparent confusion is compounded by the fact that the best current climate models give conflicting answers regarding Antarctic climate change in response to a shutdown of the Atlantic meridional overturning circulation [*Rind et al.*, 2001; *Stocker*, 2002; *Vellinga and Wood*, 2002]. Here we show that a simple thermodynamic seesaw model can reconcile the ice core synchronization and relax the confusion about in-phase and antiphase. The paper is organized as follows. Section 2 presents the simple thermodynamic model, and tests it on synthetic paleoclimatic data. We then apply the simple model to the stable isotope data from the GRIP and Byrd ice cores in section 3. Discussion and conclusions are given in section 4.

2. Concept of the Bipolar Seesaw: A Revision

[9] The active THC in the Atlantic draws heat from the Southern Ocean [*Crowley*, 1992; *Stocker et al.*, 1992b]. The latter study showed that the sea surface temperature difference between a state with collapsed circulation and a state with an active circulation changes from positive to negative when moving northward across the equator. Using the same model, the important influence of the north-south density difference on the strength of the meridional overturning was demonstrated [*Stocker et al.*, 1992a]. On large spatial scale, a shut down of the THC results in the cooling of the water masses in the north and a warming in the South Atlantic basin. Figure 1 gives an example of simulations using two models of different complexity. A zonally averaged ocean circulation model coupled to an energy balance model of the atmosphere exhibits a clear seesaw (Figure 1a), whereas in a three-dimensional coupled model, the warming pattern is also clear in the south, but in the North Atlantic, the strong cooling is limited to the upper 300 m (Figure 1b). Both models share the result that the temperature response of the bipolar seesaw is weak in the deep ocean, and that most of the changes are confined to the top 1000 m. The reverse process, i.e., the rapid switch on of the Atlantic THC from a collapsed state, should produce similar plots as in Figure 1 but with cooling in the south and warming in the north as recently shown in model simulations [*Weaver et al.*, 2003].

[10] *Broecker* [1998] coined the expression of a “bipolar seesaw”. This hypothesis makes the testable prediction that abrupt coolings in the North Atlantic should leave a clear signal in the South Atlantic and regions influenced by its surface conditions. The requirement to test this hypothesis

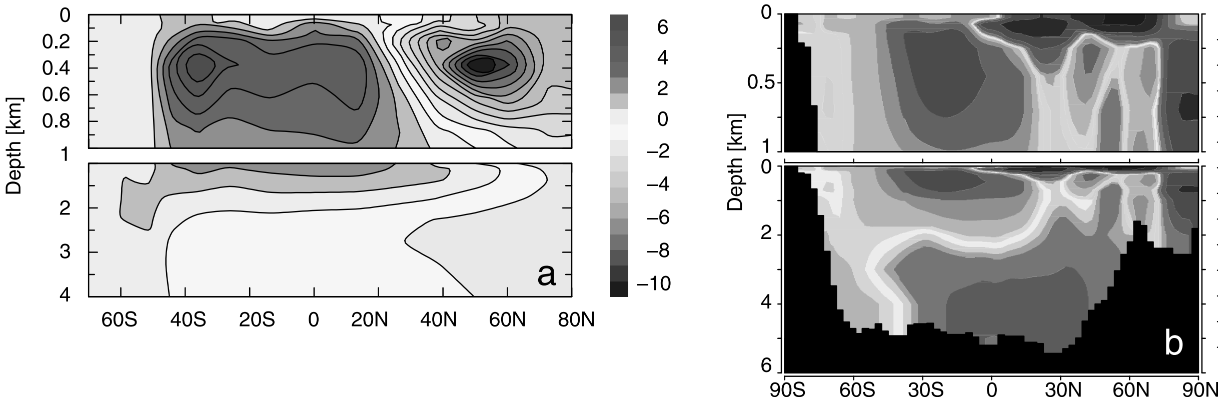

Figure 1. Latitude-depth plots in the Atlantic of the temperature difference between a state of collapsed and one of an active meridional overturning circulation (off minus on). Temperature differences exhibit a bipolar pattern with cold anomalies in the North Atlantic and warm anomalies south of about 10–20°N. (a) Results from the Bern 2d model [*Stocker et al.*, 1992b], (b) and from a three-dimensional coupled model [*Schiller et al.*, 1997]. (Figure 1b supplied by U. Mikolajewicz).

using paleoclimatic data is the construction of absolute timescales for records which are geographically distant from each other. However, timescales need not be absolute; the ice core synchronizations have demonstrated that common timescales, constructed based on varying global properties, are equally suitable.

[11] The original bipolar seesaw (Figure 2, right) implied that changes in the north and south occur at the same time. This requires very fast signal transmission in the ocean. Heating large water bodies requires time due to thermal inertia. A faster response is afforded by wave propagation and the associated vertical displacement of isopycnals. Ocean models show that density anomalies are propagated meridionally by coastal Kelvin waves along the western and eastern basin boundaries. From there, the interior then adjusts in response to westward propagating Rossby waves [*Kawase*, 1987]. Such wave-mediated adjustment processes are fast and occur on timescales of months to a few decades [*Goodman*, 2001]. In the Southern Ocean, the response is slower because of the absence of lateral boundaries which support waves. There, a thermal response is more appropriate. Circulation models suggest that the typical adjustment time of the modern Southern Ocean is on the order of 300 to 500 years [*England*, 1995]. There exists evidence from various paleoceanographic proxy data [*François et al.*, 1997; *Sikes et al.*, 2000; *Goldstein et al.*, 2001; *van Beek et al.*, 2002] and modeling [*Winguth et al.*, 2000; *Meissner et al.*, 2003] that the ventilation in the Southern Ocean was reduced during the last ice age due to increased stratification, and therefore, adjustment times are expected to be longer.

[12] This naturally leads to the following hypothesis: Does the addition of a heat reservoir to the original bipolar seesaw significantly improve the correlation between the isotopic records from Antarctica and Greenland, and if so, what typical timescale of the heat reservoir would be predicted by the correlation analysis? On the basis of Figure 2, we formulate an energy balance of the modified "thermal bipolar seesaw", for which it is assumed that the change in heat storage of a "southern heat reservoir" is proportional to the temperature difference between the reservoir and the southern end of the seesaw,

$$\frac{d\,T_S(t)}{d\,t} = \frac{1}{\tau}[-T_N(t) - T_S(t)]. \quad (1)$$

[13] The temperature anomaly of the heat reservoir is denoted by T_S, τ is the characteristic timescale of the heat reservoir, and T_N denotes the time-dependent temperature anomaly of the northern end of the bipolar seesaw ($-T_N$ is the corresponding temperature anomaly of the southern end communicating with the heat reservoir). Using Laplace transform, one can solve for T_S

$$T_S(t) = -\frac{1}{\tau}\int_0^t \left[T_N(t-t')e^{-t'/\tau}\right]dt' + T_S(0). \quad (2)$$

[14] The reservoir temperature is therefore a convolution of the northern temperature using the timescale τ. There-

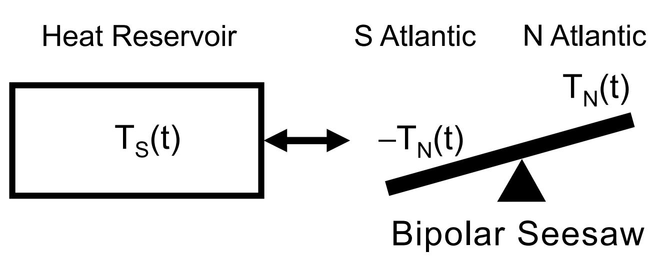

Figure 2. Schematic of the thermal bipolar seesaw model. The original bipolar seesaw is coupled to a heat reservoir possibly representing the Southern Ocean or another slowly responding component of the climate system. The double arrow indicates that in the simple model the heat exchange with the reservoir is parameterized diffusively.

fore, in this simple model, past northern temperature history controls southern temperature with "fading memory". The goal is to estimate the timescale τ from paleoclimatic data and to compare it with estimates of ventilation timescale of the southern ocean.

[15] Equation (2) demonstrates that T_S and T_N will have entirely different time characteristics. Abrupt changes in the north appear damped and integrated in time in the southern reservoir. The model also predicts that the warming events in Antarctica (T_S) should peak at the same time as the corresponding abrupt D/O events in Greenland (T_N). Furthermore, the Antarctic interstadials build up during the preceding Greenland stadials and decay during the associated Greenland interstadials.

[16] In order to test the approach, we now construct for a given time series T_N two predictions of T_S based on equations (1) and (2), respectively. If the temperature of the heat reservoir T_S is not influenced by other processes, we obtain identical time series. However, in reality, these temperatures are strongly influenced by local climate variability. We account for this by adding a red noise signal to T_S, according to

$$T_S^*(t) = T_S(t) + r(t), \quad (3)$$

with a red noise given by

$$r(t) = \alpha[r(t - \Delta t)] + \varepsilon(t), \quad (4)$$

where α is the red noise parameter, and ε is a white noise with given variance, and Δt is the time step used in integrating (1).

[17] The characteristic timescale can be determined from T_S^* by correlating it with T_S, the synthetic record calculated from T_N according to (2). By varying τ in applying (2), we obtain a set of time series T_S. If the hypothesis of the thermal bipolar seesaw is valid, we expect a relative maximum of the correlation Corr(T_S^*, T_S) for the "correct" τ. This is tested for a simple case, in which we generate T_N with amplitudes +1 and −1 representing THC on and off states, which persist for 2000 and 5000 years, respectively. Amplitudes, as well as the on and off times, are subject to small random perturbations (uniformly distributed 0 to 0.3, and 0 to 1000 years, respectively, Figure 3, curve a). From T_N we then generate T_S with $\tau = 1000$ years using either (1) or (2), and add to it red noise with $\alpha = 0.9$. This yields curve c in Figure 3. We now assume that we know only T_N and T_S^*, but not τ. In order to determine τ we calculate Corr(T_S^*, $T_S(\tau)$) using (2) with τ ranging from 100 to 4000 years. This correlation is given in Figure 4, and a relative maximum close to 1000 years (i.e., the "correct" τ) appears. It is obvious that random noise decreases the ability to detect the characteristic time τ. The overall correlation is lower, and the maximum is broader.

[18] It should be emphasized that the concept of the bipolar seesaw is not thought to describe all climate variations for which interhemispheric connections may exist. For example, it is clear that the largest amplitude climate changes, the glaciations and terminations, occurred on much longer timescales than those considered by the thermal bipolar seesaw model. These variations are thought to be a complex combination of solar radiation changes, amplified by changes in greenhouse gases [*Petit et al.*, 1999], changes in seasonality and albedo occurring on Milankovic timescales [*Imbrie et al.*, 1992]. Furthermore, in the simple model only a "generic heat reservoir" with a characteristic timescale is considered. In introducing the simple model, we argued that the heat reservoir could be the glacial Southern Ocean, but the model is obviously too simple to prove this statement. Other processes and climate system components such as e.g., terrestrial ice sheets, could be responsible for the thermal damping of northern temperature variations. Transmitting sea surface temperature signals from the Southern Ocean to the ice sheets in the interior of Antarctica involves many further processes with additional shorter and longer characteristic timescales. This point will be addressed in the discussion.

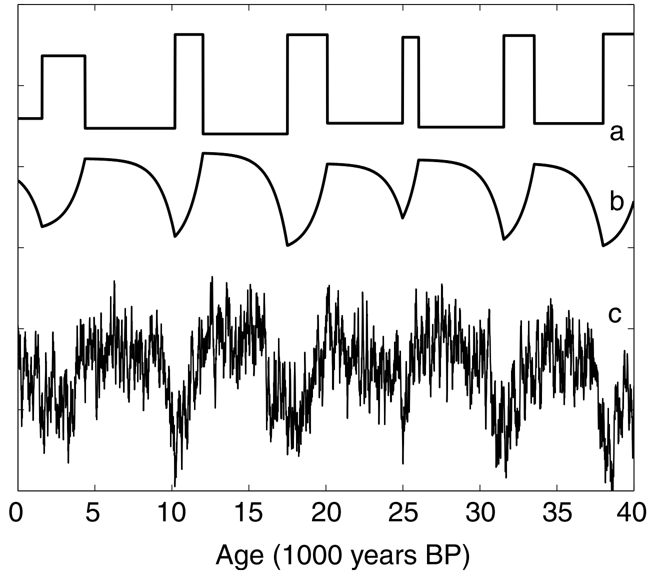

Figure 3. Synthetic paleoclimatic time series to test the thermal bipolar seesaw. On-off signal T_N with approximately 2000 years on (amplitude +1) and 5000 years off (amplitude −1) is shown in curve a. Both times and amplitudes are randomly perturbed. Curve b is the simulated T_S according to equation (2) with a constant $\tau = 1000$ years. Curve c shows $T^*_S = T_S + r(t)$, i.e., red noise of half the variance of T_S added to T_S. The curves are vertically shifted for better visibility.

3. Predicting Byrd From GRIP

[19] We now apply the thermal bipolar seesaw to real data. The goal is to determine how much of the millennial variability in the isotopic record of Byrd (Antarctica) can be explained by convolving the isotopic record of GRIP (Greenland). Two data sets are used [*Johnsen et al.*, 1972; *Dansgaard et al.*, 1993]. First, both GRIP and Byrd isotope data are high-pass filtered with a sharp cutoff period of 8000 years. This is chosen because longer-term variations on the astronomical timescales (Milankovic cycles) should

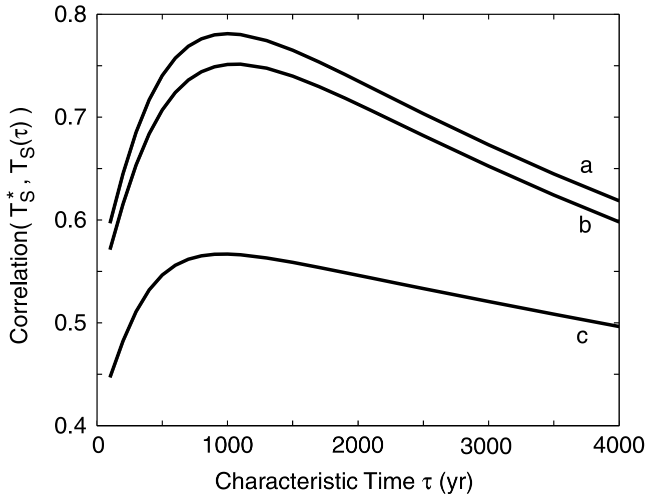

Figure 4. The correlation Corr(T_S^*, $T_S(\tau)$) as a function of varying τ for three cases of red noise added to T_s. The variance of the added red noise is half (curve a), equal (curve b), or twice (curve c) the variance of T_S. In all cases the "correct" τ appears as a relative maximum in the correlation plot demonstrating the ability to reconstruct τ from a noisy time series.

be removed before testing for the bipolar seesaw. Second, we are also testing the hypothesis using unfiltered data of Byrd. For both data sets we focus our analysis on the time span of the last glacial which contains most of the D/O cycles, i.e., between 65 and 25 kyr B.P. The influence of considering the entire last ice age from 88 to 10 kyr B.P., or other intervals is also investigated.

[20] Figure 5 shows the filtered GRIP and Byrd data in the D/O window. A set of convolved GRIP data using (2) with different timescales τ is also shown. These modeled time series are referred to as "modeled Byrd". We note a remarkable agreement between the filtered Byrd and the modeled Byrd, which contains only information of the GRIP high-pass filtered data, when τ = 1120 years (curve c) is selected. For both shorter and longer characteristic timescales τ, the convolution procedure (3) yields time series with lesser agreement with Byrd.

[21] Comparing the modeled record with the data record we suggest that not only the extended interstadials such as 8, 12, 14, and 16/17, together with the preceding stadials have their Antarctic counterparts (A1, A2, A3, and A4), as noted earlier [*Blunier et al.*, 1998]. Rather, almost all of the D/O events in the period from 65 to 25 kyr B.P. can be recognized in the optimal Byrd model, and the smaller excursions are likely the fingerprint of the associated D/O event in the north. The thermal seesaw model suggests that every abrupt warming in T_N generates a relative maximum in T_S, and hence all D/O events are expected to have a counterpart in Antarctica. This would suggest a revised numbering of the Antarctic interstadials (A0, A1, A2, etc.) whereby the number points to the associated D/O event in the Greenland ice cores (0, 1, 2, etc.). However, we prefer to wait for the high-resolution isotope and CH_4 results from the most recent Antarctic ice cores from Dome Concordia, Kohnen Station (both EPICA), Dome Fuji (Japan), and Siple Station (US). If these new, synchronized data confirm the thermal bipolar seesaw, the numbering of the Antarctic interstadials should be revised accordingly.

[22] The characteristic timescale can be determined by plotting the correlation between the Byrd data and the modeled Byrd (convolved GRIP data) as a function of τ. This is shown in Figure 6. The relative maximum is well defined but depends on the length of the record and the data preparation. Filtering and limiting the length to essentially stage 3, both increase the correlation, but the preferred timescale can still be recognized using the original, unfiltered data. The correlation between the Byrd data and the modeled Byrd time series decreases sharply for timescales of less than 500 years, but the reduction of correlation toward longer timescales is weaker. This suggests that a heat reservoir with timescale exceeding 500 years at least, is essential to produce high correlations. It is also visible from Figure 6 that the choice of the window influences the timescale at which maximum correlation is achieved. In most cases the timescale is in the range of about 700 to 1500 years, but for the series of short D/O events 3 to 7

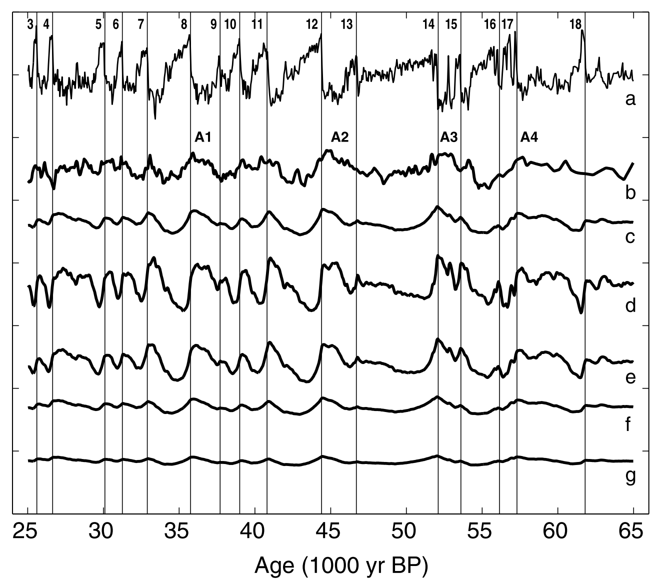

Figure 5. Filtered isotopic data from GRIP (curve a) and Byrd (curve b) using a high-pass filter with a cutoff at 8000 years to remove Milankovic timescales for which the bipolar seesaw does not apply. Modeled time series of Byrd according to equation (2) are given for τ = 1120 years (curve c), for τ = 200 years (curve d), for τ = 500 years (curve e), for τ = 2000 years (curve f), and for τ = 4000 years (curve g), using the filtered GRIP record as input and the characteristic timescale τ. Using the characteristic timescale τ = 1120 years (curve c) yields the highest correlation with the filtered Byrd data (curve b). The other model realizations (curves d–g) with shorter or longer timescales show less agreement with Byrd. The vertical lines mark the Dansgaard/Oeschger events in GRIP. Antarctic warmings in addition to the classic warmings A1 to A4 can be identified.

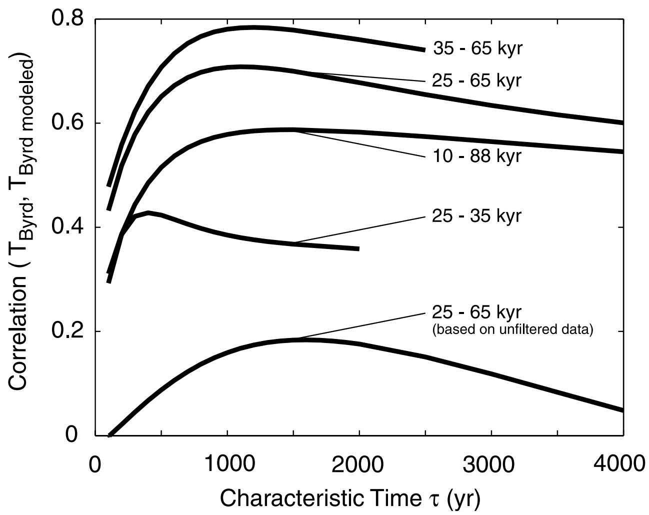

Figure 6. Correlation between the Byrd filtered data and modeled Byrd using different time intervals during the last glacial. The characteristic time at which maximum correlation is found depends on the chosen time window during the glacial. Correlations are much lower if unfiltered data are used, but a relative maximum of τ can still be determined.

from 25 to 35 kyr the highest correlation is obtained at about 500 years.

[23] We note that the proposed simple model is more reasonable than just a lead-lag relationship between the GRIP and the Byrd records. Considering the lag-correlation between the two filtered time series, both *Steig and Alley* [2002] and *Schmittner et al.* [2003] report that for lags between −2 and +2 kyr the absolute values of the lag-correlations are always smaller than 0.5. They find maximum negative correlation (anti-phase) when the north leads the south by about 400 to 800 years. A second positive maximum occurs between 1300 and 1600 years when the south leads the north in phase, as proposed by *Blunier et al.* [1998]. In either case, a direct lead-lag model explains a significantly smaller portion of millennial scale variability in the two ice core records than the thermal bipolar seesaw.

[24] Consistent with the present model is also a direct cross-spectral analysis of the GRIP and Byrd isotope records as shown in Figure 7. The Dansgaard/Oeschger band is clearly visible in the GRIP record as enhanced power between 1500 and 5000 years. On these timescales the phase shift between north and south is around 100°. For a strictly periodic signal T_N with angular frequency ω a phase shift of $\varphi = 180° - \arctan(\omega \cdot \tau)$ is expected based on equation (2). In principle the time constant τ can be estimated from the phase spectrum. However, the wide range of uncertainty in Figure 7 precludes any precise estimation of the time constant τ using spectral methods on the measured data.

[25] It is important to test the bipolar seesaw hypothesis also on other isotope records from the inland of Antarctica. The only currently available record is that from Vostok station which has been synchronized in the interval 10 to 50 kyr B.P. by *Blunier et al.* [1998]. In contrast to the Byrd record, however, the uncertainties are much larger due to lower accumulation rates (and thus increasing the uncertainties in the gas-ice age difference), and the coarser methane data which are the basis of the synchronization. As soon as high-resolution isotopic and methane data measured on ice cores from Dome Concordia, Kohnen Station and Dome Fuji will be available, the synchronization can be performed, and the bipolar seesaw hypothesis can be tested for many more sites. This would establish whether or not the bipolar seesaw captures a pan-Antarctic climate signal.

4. Discussion and Conclusions

[26] We have investigated the possibility that a very simple model can capture the major features of interhemispheric coupling mediated by the Atlantic thermohaline circulation. The classical bipolar seesaw is too simplistic to explain the temperature signals estimated from the isotopic records measured on Greenland and Antarctic ice cores. A simple but essential extension modifies the temporal characteristics of the southern signal: the classic bipolar seesaw is coupled to a southern heat reservoir which dampens and integrates in time the abrupt climate signals that are coming from the North Atlantic.

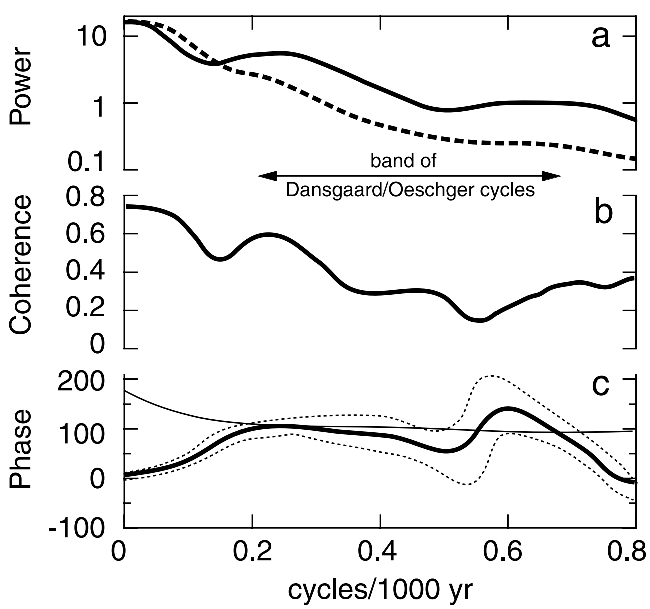

Figure 7. Cross spectra of the time series a and b of Figure 5. (a) Power density of the cross spectra show increased power on timescales from 1500 to 5000 years in the GRIP record (solid line) but not in the Byrd record (dashed line); (b) coherence; (c) the phase shift determined by the cross spectrum is close to 90° to 100° and thus indicative of the bipolar seesaw combined with a characteristic time around 1 kyr or longer. The confidence band of the phase shift is given by the dashed lines; the fine line denotes the phase shift of a strictly periodic signal. The calculations were made by the AnalySeries 1.2 program [*Paillard et al.*, 1996] that employs the Blackman-Tukey method. Here we use 10% lag for the autocovariance series and the Bartlett window.

[27] It is remarkable how much of the variability of the isotopic record in the Antarctic ice cores can be explained by this model. The model demonstrates that not only the prominent D/O events, but also the shorter ones have a counterpart in the Antarctic record. This has been suggested before, but quantitative evidence beyond wiggle matching could not be put forward [*Bender et al.*, 1999].

[28] The thermal bipolar seesaw model allows us to estimate the characteristic timescale on which the thermal damping occurs. Maximum correlation is achieved in the range of 1000 to 1500 years. This timescale is significantly longer than those obtained from ocean circulation models run under modern conditions which give typical adjustment times of the Southern Ocean on the order of 300 to 500 years. Such short timescales are obtained only in the window 25 to 35 kyr B.P. which contains mostly the short D/O events. Because of the weak D/O type signal in this interval of the Byrd record and possible synchronization uncertainties a considerable error margin should be assigned to the derived adjustment times. For the longer windows, which contain the prominent D/O events 8, 12 and 14, the correlation analysis suggests that either the Southern Ocean had a significantly longer adjustment time during the last glacial, or that an additional heat reservoir with a longer timescale might contribute to shaping the north-south correlation such as changes in northern and southern terrestrial ice extent and associated sea level rise.

[29] Independent evidence for longer ventilation times in the Southern Ocean come from both paleoceanographic proxy data and modeling. On the basis of enhanced nitrate depletion south of the modern polar front (~50°S) during the last glacial, *François et al.* [1997] conclude that the stratification in the Southern Ocean was reduced. Synchronzing thephra layers and radiocarbon ages of planktonic and benthic foraminifera, *Sikes et al.* [2000] report significantly older surface and deep reservoir ages in the southwest Pacific during the last glacial and deglaciation. This is consistent with the findings of *Goldstein et al.* [2001] who combined uranium series dating and radiocarbon dates to infer increased ventilation ages in the Southern Ocean. Finally, *van Beek et al.* [2002] use a radiometric method to determine significantly higher surface reservoir ages in the Southern Ocean about 10 kyr ago. Although their samples are from the early Holocene, the study suggests that major changes in surface conditions, circulation and ventilation of the Southern Ocean occurred in the past.

[30] Longer ventilation times of the Southern Ocean during the glacial are also found in ocean models run under glacial conditions. *Winguth et al.* [2000] have combined paleoceanographic proxy data with an inverse model and show that the convection around Antarctica is significantly reduced. This tends to make deeper waters in the Southern Ocean older and, again, points to an increased ventilation time. Using a three-dimensional ocean general circulation model coupled to a surface energy balance model, *Meissner et al.* [2003] have simulated the radiocarbon distribution during the last glacial maximum. They show that the glacial Southern Ocean was dominated by water masses with radiocarbon concentrations typical of today's oldest water masses of the Pacific. This suggests that the characteristic ventilation time of the Southern Ocean at Last Glacial Maximum conditions might well be double than that of today.

[31] An indication for the potential involvement of other slow components in the climate system during the glacial comes from recent findings from a high-resolution ocean record off the Portuguese coast. In this location the bottom waters are of southern origin while the surface properties are influenced by the North Atlantic climate [*Shackleton et al.*, 2000]. The data show that the character of benthic variability is captured by T_S, whereas the planktonic variables exhibit changes reminiscent of T_N. Shackleton and colleagues argued that the timescale of these events is given by the waxing and waning of continental ice sheets. This is supported by recent high-resolution data reconstructing sea level changes during the last glacial which show a striking agreement between the sea level record and Antarctic temperature [*Siddall et al.*, 2003]. This suggests a major role for sea level changes as a global synchronizer, and perhaps even pace maker, of climate signals, although the exact origin of the large changes in sea level remains unknown. Like the bipolar seesaw, these new results challenge the view that the climate changes in Antarctic ice cores are primarily reflecting local or regional climate changes [*Wunsch*, 2003].

[32] Obviously, with our conceptual model we cannot resolve the question which component in the climate system is responsible for the characteristic timescale of order 1000 years that appears in our correlation analysis. These questions will be better addressed when more high-resolution synchronized ice core data are available along with high-resolution marine sediments from the Atlantic and Southern Oceans.

[33] The present concept compares well with model results in which the THC collapses completely in the North Atlantic and therefore heat is accumulated in the South Atlantic as shown in two simulations using comprehensive coupled climate models [*Rind et al.*, 2001; *Vellinga and Wood*, 2002]. However, the transmission of this ocean interior signal to inland Antarctica is still not robustly modeled. The two models reach different conclusions: while both show a warming in the South Atlantic, one has Antarctica warming as well, but the other shows cooling [*Stocker*, 2002]. Admittedly, these model simulations are not yet sufficiently analyzed and compared to each other, particularly with regards to how complete the THC shutdown is. These differences point to little understood atmosphere-ocean interactions in areas of convection and sea ice formation. The influence of interior temperature and water mass changes on sea surface temperature, on ocean-atmosphere heat fluxes, and on the sea ice cover are poorly studied. However, most importantly, one needs to investigate how and what imprint these ocean changes leave in precipitation, isotopes and temperature at coastal and inland stations of Antarctica, from where these paleoclimatic archives are retrieved.

[34] Finally, we note that the thermal bipolar seesaw also resolves some lingering confusion in the paleoclimate community. It shows that signals in the South Atlantic are expected in antiphase with the North Atlantic, and those in

the southern ocean are convolved on a timescale τ on the order of 1000 to 2000 years. For these latter signals the convolution of the GRIP data yields the best correlation with the Byrd data for a time constant of about 1100 years, which is equivalent to a phase delay of some 70 to 80° relative to the South Atlantic signal in the Dansgaard/Oeschger frequency band.

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Correction: A minimum thermodynamic model for the bipolar seesaw

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In our recent paper [*Stocker and Johnsen*, 2003], an exponential factor in equation (2) was inadvertently omitted. The correct equation reads

$$T_S(t) \quad = \quad -\frac{1}{\tau} \cdot \int_0^t T_N(t - t') \cdot e^{-t'/\tau} dt' + T_S(0) \cdot e^{-t/\tau} .$$

Fortunately, none of the results nor figures presented in *Stocker and Johnsen* [2003] change, because in all calculations we used $T_S(0) = 0$, i.e., time series have been normalised.

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