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Comments on 'Coupling of the hemispheres in observations and simulations of glacial climate change' by A. Schmittner, O.A. Saenko, and A.J. Weaver☆

Peter Huybers*

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 54-1724, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA

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Schmittner et al. (2003) argue that during the last glacial period, at millennial timescales, temperature changes in Greenland preceded changes of the opposite sign in Antarctica by 400–500 yr. They provide support for this conclusion by comparing a simple conceptual model with synchronized proxies of polar temperature (Blunier and Brook, 2001). But further analysis of this conceptual model, using the same data, suggests the opposite—that Antarctica leads Greenland. A more conventional cross-spectral analysis of the raw observations also supports the conclusion that Antarctica leads Greenland, and indicates that this relationship applies to the band from 1/7 to $1/2\,\mathrm{kyr}^{-1}$.

The conceptual model states that changes in Antarctic temperatures T_a are negatively proportional to Greenland temperatures T_g,

$$\frac{\partial T_\mathrm{a}}{\partial t} = -sT_\mathrm{g},$$

where s is a constant. Schmittner et al. (2003) visually identify switches in Greenland millennial scale temperature variability, and use their model, referred to as M1, to predict 23% of the Antarctic temperature variance. But in testing the idea that one hemisphere leads another, it is also useful to calculate the relationship between predictions and observations at a range of lags (see Fig. 1). It is found that the most variance is explained, 31%, when changes in Antarctica precede Greenland by 270 yr, thus indicating an Antarctic lead.

For an Antarctic lead scenario, it is more straightforward to predict Greenland temperatures from the Antarctic record. An objective algorithm is used to identify Antarctic temperature excursions exceeding half a standard deviation and then fit a triangular shape to each of these *events*. The configuration of triangles which produces the highest cross-correlation with Antarctic temperatures, after pass-band-filtering between 1/10 to $1\,\mathrm{kyr}^{-1}$, is used to predict Greenland temperatures according to the conceptual model. Except for the lag time between Antarctica and Greenland, all variables are specified by the Antarctic record, giving one degree of freedom in the prediction. More details about the fitting algorithm and this second model, referred to as M2, are given in Huybers (2003); results are shown in Fig. 2a.

The maximum cross-correlation between M2 predictions and Greenland temperatures is 0.73, or half of the variance, when Antarctica leads by 210 yr (see Figs. 1 and 2b). To determine the probability that this correla-

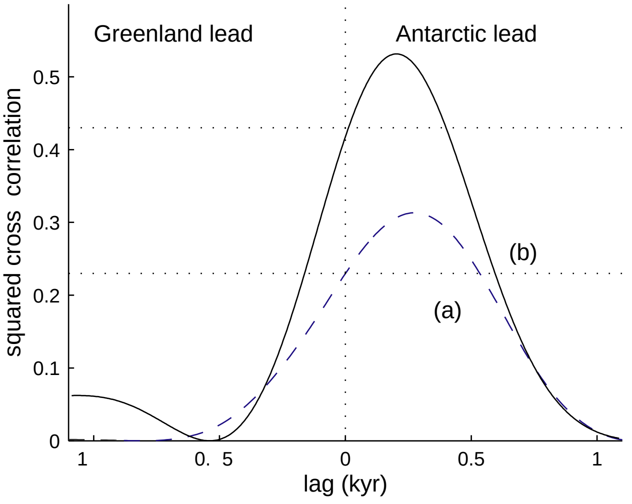

Fig. 1. Squared-cross-correlation as a function of lag between (a) the predictions of M1 and Antarctic temperatures, and (b) M2 predictions and Greenland temperatures. Maximum correlation is achieved when the M1 predictions are made 270 years older and when M2 predictions are made 210 years younger; both indicate an Antarctic lead. See text for a description of the models.

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*Tel.: +1-617-258-6910; fax: +1-617-253-4464.

E-mail address: phuybers@mit.edu (P. Huybers).

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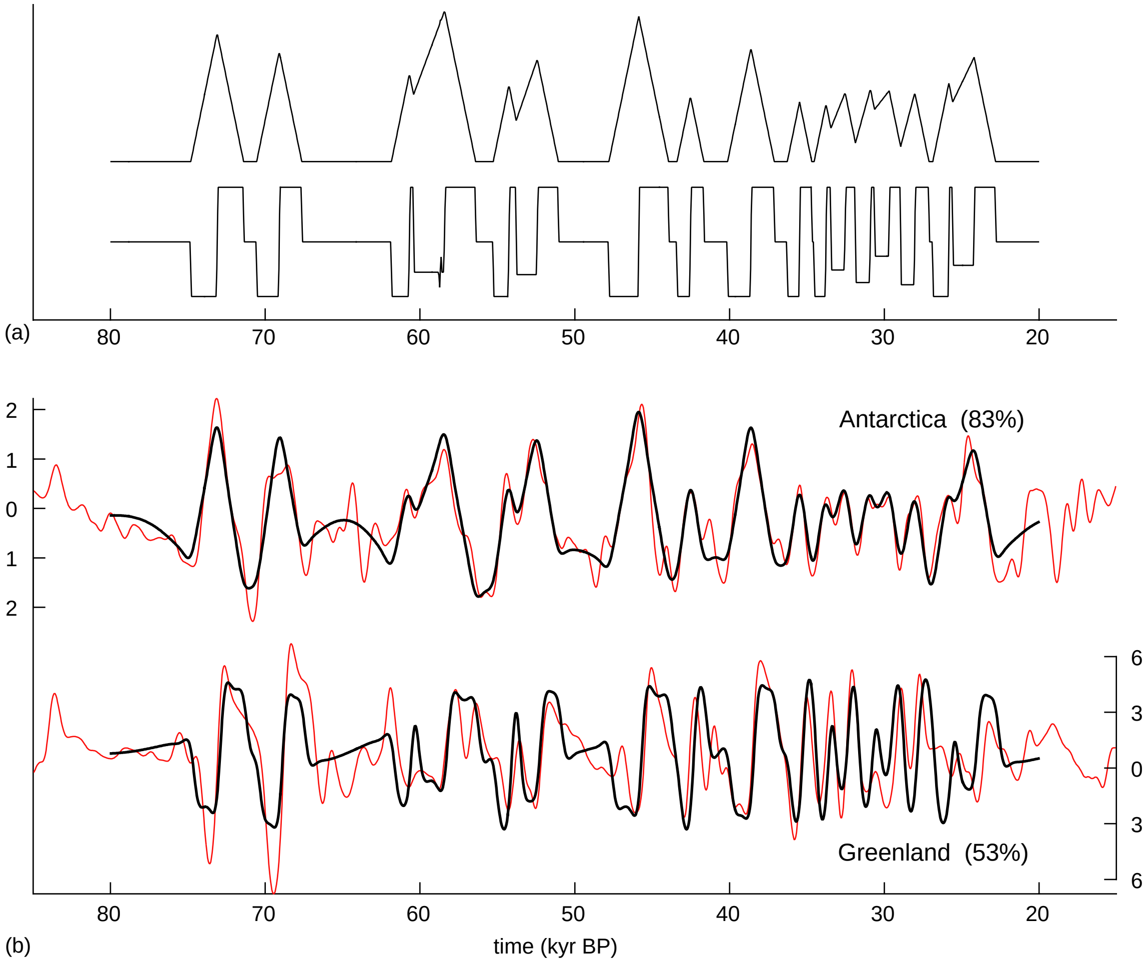

Fig. 2. (a) Fitted Antarctic (top) and predicted Greenland (bottom) temperature variability. (b) Comparison of model (thick lines) and observations (thin lines) after pass-band-filtered between 1/10 and 1 kyr^{-1} and lagging the M2 Greenland predictions by 210 years. The fitted record explains 83% of the observed Antarctic millennial scale variance and predicts 53% of the Greenland variance. Temperature records are plotted in °C according to the scaling given by *Schmittner* et al. (2003). The mean and standard deviation of the model output are adjusted to that of the corresponding observations.

tion arises by chance, a Monte Carlo test is used. The test consists of generating stochastic time-series with a spectral structure similar to that of Antarctic temperatures, fitting the stochastic realizations as described above, and using the fit to predict Greenland temperatures. As observed (Wunsch, 2003), the Antarctic-like signals are modeled as a power law process in which energy diminishes with frequency as f^{-2}. A relatively large lag is permitted, ± 6 kyr, and the maximum absolute correlation is recorded for each of 1000 trials. On average, the Monte Carlo test achieves a correlation of 0.3, while the largest realization is 0.5. Using the observations with M2 gives a significantly larger correlation of 0.7, strongly indicating that inter-polar temperature variability is linked.

The phasing between Antarctica and Greenland, however, is somewhat uncertain due to possible errors in ice-core synchronization. Gas-age ice-age uncertainties are estimated to be ± 100 and ± 200 yr for Greenland and Antarctica, respectively (Blunier and Brook, 2001, supplementary material). Assuming all this uncertainty is systematic and adding variances gives ± 220 yr, or a value roughly equal to the lead estimated from M1 and M2. Therefore, while it is more likely Antarctica leads, synchronous change (i.e. events which start and stop at the same time) or a Greenland lead cannot be ruled out.

A more conventional approach to comparing inter-polar temperature variability is cross-spectral analysis. A multitaper coherence estimate (e.g. Chave et al., 1992) using eight windows (see Fig. 3a and b) agrees with previous estimates (e.g. Hinnov et al., 2002; Wunsch, 2003), but the mean coherence is significantly smaller than the correlation obtained from M2, 0.4 as opposed to 0.7. The difference arises because about 70% of the cross-spectral energy between M2 predictions and Greenland is concentrated in a relatively narrow band between 1/7 and 1/2 kyr^{-1}. Within this band, the

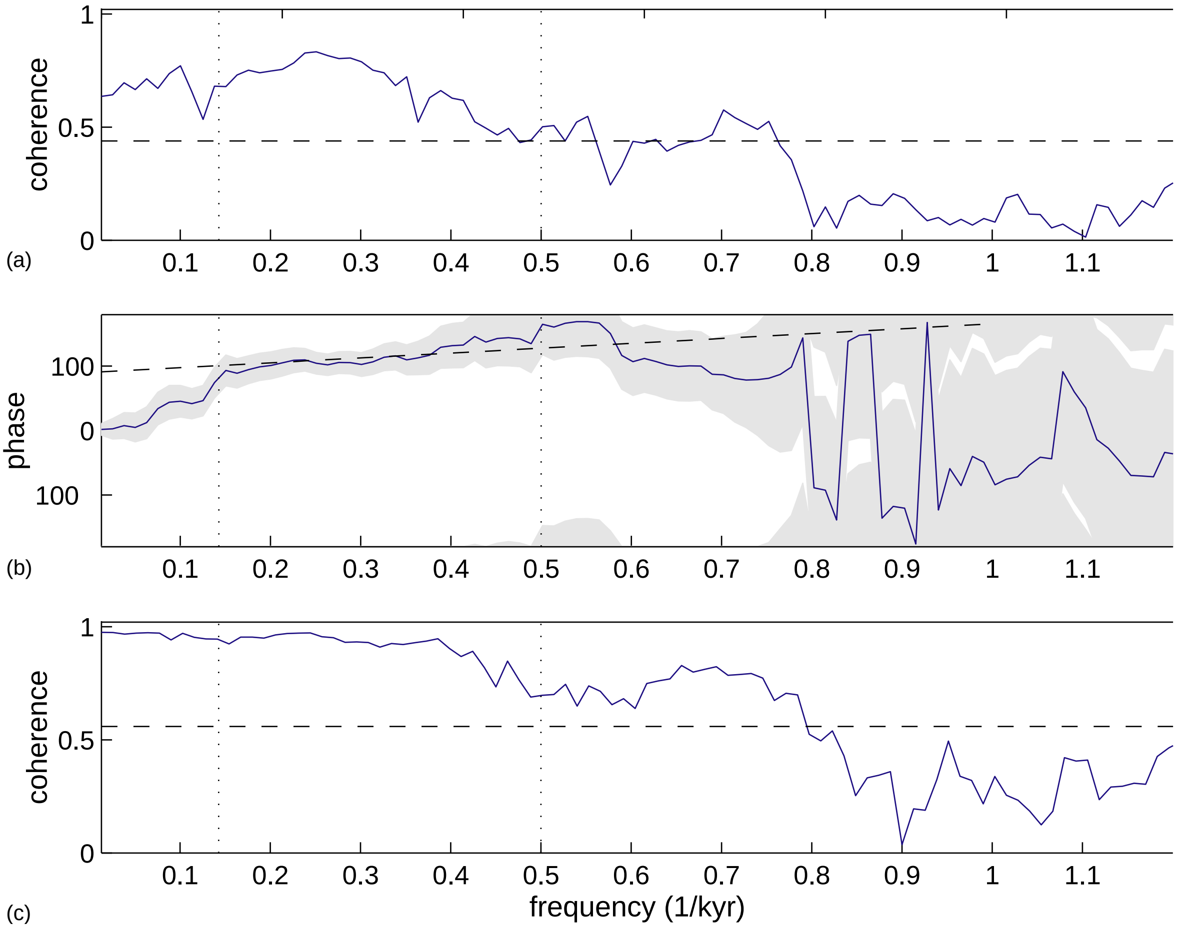

Fig. 3. (a) Coherence between Greenland and Antarctic temperatures over the last 90 kyr, and (b) the relative phase. (c) Coherence between synchronized Greenland and Antarctic methane records. The approximate 95% confidence level for coherence is indicated by a dashed line and the 95% confidence level for phase by shading. The dashed line in (b) indicates the expected phase for an Antarctic lead of 210 years. Estimates are made using the multitaper method with adaptive weighting and eight windows. The vertical dotted lines delineate a band between 1/7 and 1/2 kyr^{-1} containing about 70% of the cross-spectral energy between Greenland temperatures and the M2 predictions.

inter-polar phasing has a trend indicative of Antarctica leading by 210 yr and a mean coherence of 0.7, both consistent with the M2 results. At shorter periods inter-polar temperature coherence diminishes, perhaps indicating a different or diminished linkage at shorter time-scales. Alternatively, errors in inter-polar synchronization could degrade the temperature coherence at higher frequencies. This latter possibility is supported by an analysis of the methane records used in synchronizing the ice-cores (Blunier and Brook, 2001). That is, the methane coherence also begins decreasing near 1/2 kyr^{-1} and is insignificant above 1 kyr^{-1} (see Fig. 3c).

M1, M2, and cross-spectral analysis of the observations, all indicate the most probable scenario is for Antarctic temperature changes to precede shifts of the opposite sign in Greenland temperatures by more than 200 yr. This conclusion is the opposite of that reached by Schmittner et al. (2003). In addition, M2 should be preferred over M1 because it demonstrates greater skill, predicting over 50% of Greenland millennial scale temperature variability. As judged by a Monte Carlo analysis, the M2 result strongly supports the presence of an inter-hemispheric link in the millennial band between 1/7 and 1/2 kyr^{-1}.The presence of a relationship at higher frequencies cannot be excluded.

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Response to the comments by Peter Huybers

Andreas Schmittner[a,*], Oleg A. Saenko[b], Andrew J. Weaver[b]

[a] Institut für Geowissenschaften, Christian-Albrechts-Universität zu Kiel, Olshausenstr. 40, Kiel 24118, Germany
[b] School of Earth and Ocean Sciences, University of Victoria, Canada

Huybers (2003) uses a conceptual model to predict Greenland temperature changes from Antarctic temperatures. He shows that his model has better skill than the model by Schmittner et al. (2003), which was based on predicting Antarctic temperatures from a prescribed Greenland record. He finds the best correlation with observations if his modelled Greenland temperature switches lag the beginning of transitions in Antarctica (AA) by 210 years. From this he concludes that, in contrast to Schmittner et al. (2003), AA leads Greenland. We argue here that a different semantic interpretation of a lag between two time series is the main reason for the opposite conclusions. Both models produce a very similar cross-correlation between AA and Greenland (and very similar to the observations) showing Greenland temperatures preceding changes of the opposite sign in AA by 400–500 years. The conclusion of Schmittner et al. (2003) thus remains valid when the cross-correlation is used as the criterion to establish a lead or lag in two time series.

Schmittner et al. (2003) proposed a physical mechanism for the coupling between Greenland and AA on a time scale of 300–500 years seen in the proxy record. The general idea is that a considerably weakened thermohaline circulation (THC) would transport much less heat from the south to the north, thereby cooling the North Atlantic and Greenland and warming regions around AA. The opposite is true for a stronger THC. They used a coupled GCM to support this hypothesis and to confirm that it takes ~300–500 years for the signal, originating in the North Atlantic and initiated by forcing of reasonable magnitude, to trigger climate changes of opposite sign in AA. They found that the key factor delaying the propagation of the signal from the north to the south for up to several centuries is a slow transition across the strong zonal Antarctic Circumpolar Current. Finally, they used a simple conceptual model which supported their results by explaining the observed cross-correlation with a northern lead model. It is their results from this simple model that are questioned by Huybers (2003). Huybers offers neither a physical mechanism nor GCM-based results to support his results.

Huybers constructs an Antarctic temperature time series by fitting triangles to the observations. Temperatures in Greenland can assume three states in his model (M2). They are zero when AA temperatures are constant, -1 when AA is warming, and 1 when AA is cooling. Our model (M1) assumed only two states in Greenland (-1 and 1) and no fitting to the observations was applied. From these differences it is clear that M2 has an advantage in predicting the continuous record of the observations. Therefore the two models are not directly comparable and the fact that M2 has a greater skill cannot be used to argue against the Greenland lead thesis. Huybers then adds an additional "lead/lag" (referred to as "dt" in the following) such that the switches in Greenland occur only dt years before/after AA started to cool/warm. Such an additional "lead/lag" was not included in the model by Schmittner et al. (2003). Because Huybers varies dt and finds highest correlation of the predicted Greenland temperatures with the observations if Greenland is lagged by d$t = 210$ years, he concludes that Greenland lagged AA. It is important to distinguish this additional "lead/lag" from the lag determined as the extremum in the cross-correlation.

In order to illustrate this difference we show the cross-correlation of both models (for M2 d$t = 210$ years was used) together with the observed record. Both models do

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*Corresponding author. Tel.: +49-431-880-7324; fax: +49-431-880-1457.

E-mail address: andreas@passagen.uni-kiel.de (A. Schmittner).