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Greenland—Antarctic phase relations and millennial time-scale climate fluctuations in the Greenland ice-cores

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Abstract

The Greenland (GRIP/GISP2) and Antarctic (Byrd) ice-cores are examined in the frequency domain, with the data synchronized using common methane variations. Using conventional time-series analysis, a simple picture emerges: there is low-frequency (periods longer than about 10 kyr) coherence between the two records, consistent with a simple time delay, Antarctica leading by 1–2 kyr. Two geographical data points are however, inadequate to infer causality from the south to north time lag. At higher frequencies, in the millennial band, there is no measurable average relationship between the records and they appear to represent different processes, with a regional character. A serious question concerns the extent to which the Greenland cores reflect tracer concentration change without corresponding abrupt climate change. The large, abrupt shifts in ice $\delta^{18}O$ can be rationalized as owing to wind trajectory shifts, perhaps of rather modest size. Many different physical phenomena probably do, however, contribute to the record as a function of time, and time scale.
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1. Introduction

Millennial time-scale signals in ice and seafloor cores have attracted much recent attention because they suggest the possibility of rapid climate change (Clark et al., 1999), with immense societal implications. Furthermore, Bond et al. (2001) have claimed that much of the observed Holocene variability in deep-sea cores is controlled by solar luminosity variations, which if true, is a very important inference about the climate system. There has also been much speculation (e.g., Broecker, 1998; Stocker et al., 2001) about the possibility that the northern and southern hemispheres shift in a "seesaw" pattern.[1]

Blunier et al. (1998) and Blunier and Brook (2001) attempted to find a consistent age model for both Greenland and Antarctic ice-cores under the plausible assumption that atmospheric methane variations should be reflected essentially simultaneously in both locations, because the atmospheric mixing time for methane (CH_4) is about 1 yr or less. The identification of common events in the cores is not straightforward: serious questions exist concerning the relative ages of gases in the ice and gas phases, and the mixing-time argument is only valid if there are no persistently different hemispheric sources. Thus the accuracy of their results remains unclear. It is also true that the resulting time scale is not absolute over the record durations—rather it attempts to minimize the differences in the time scales of the cores. The GISP2 ice-core dating is nearly absolute to about 38 kyr BP, being based upon counting of annual growth lines (Meese et al., 1997), but is modelled prior to that time. At present, however, the Blunier and Brook (2001) age model is probably the best existing representation of the common variability of Greenland and Antarctica, and it is useful to examine, as carefully as one can, the implications of the assumption that there is little remaining error.

2. Data

Fig. 1 is taken from Blunier and Brook (2001) shows their reconstruction, in the lower two curves, of the

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[1] A "seesaw" would conventionally imply a 180° phase relationship. Apparently (T. Stocker, private communication, 2003) such a literal meaning is not necessarily intended in the paleoclimatic context where only a phase shift is meant. Here, I will maintain the conventional usage.

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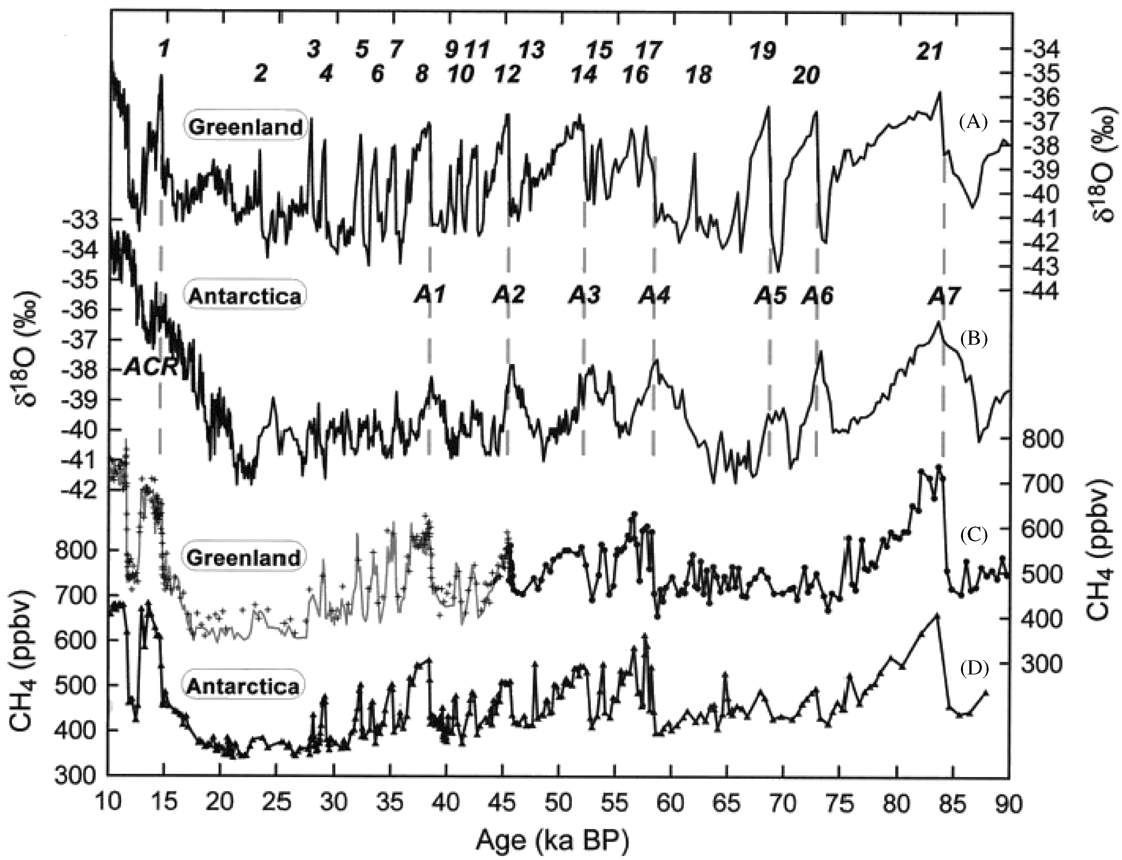

Fig. 1. Taken from Blunier and Brook (2001). Upper curve (A) is the $\delta^{18}O$ in the GISP2 Greenland ice-core; curve (B) is the $\delta^{18}O$ in the Antarctic Byrd core, with time scale adjusted to the GISP2 estimated methane. Curves (C), (D) are the methane data in the cores (for Greenland, data are from both GRIP and GISP2 cores). Dashed vertical lines indicate warm events in the Antarctic core. Numerals at top label Dansgaard–Oeschger events in Greenland. Note that time runs from right-to-left here.

common methane variations in the GISP2 and GRIP ice-cores, with the Byrd Antarctic core. We refer to Blunier et al. (1998) and Blunier and Brook (2001) for a discussion of how the time-scale adjustments were made.

Fig. 1 attaches labels (A1, A2, ...) to various events in the Antarctic core, and their possible association with similar events in the Greenland $\delta^{18}O$ records. Such visual identification and then causal rationalization underlies much of the published discussion of climate change events. A major concern, however, is that two completely unrelated records with a common, rich, spectral structure will *always* display structures which to the eye appear related, but which have no connection. Such discussions often ignore the equally significant failure of records to demonstrate the inferred commonality (e.g., between events A1, A2 in Fig. 1), or Mazaud et al. (2000), or in the detailed event identification, e.g., between Greenland and the Santa Barbara Basin (Hendy et al., 2002, their Fig. 3).

To demonstrate the possibility of false identification, two linear time series, x_t, y_t having identical rules,

$$x_t = ax_{t-1} + e_t^{(1)}, \quad y_t = ay_{t-1} + e_t^{(2)}, \tag{1}$$

were generated using unrelated white noise sequences, $e_t^{(1,2)}$, as shown in Fig. 2. One is tempted to make the connections indicated, e.g., by the line segments. But because the $e_t^{(1,2)}$ were independent the two records are also independent of each other, and the identifications are spurious. (The interval displayed was *not* chosen to be especially troublesome.) By making the two records have identical frequency content, one somewhat emphasizes this tendency, but because climate records in different regions may be driven locally by uncorrelated forces, but obeying identical physics, this situation may be common.[2] As another example, consider the two records in Fig. 3. One might be tempted to make the identifications indicated by the straight lines (or, conceivably, to adjust the age models of the two records, should one be in doubt, to align them). These are real records, but as explained in the caption, they are rigorously unrelated. This problem of false correspond-

[2] Eq. (1) are examples of autoregressive processes of order 1 (written AR(1)). They are the simplest rules for generating rednoise processes, but they can be generalized to arbitrarily high order and written in alternative forms as well.

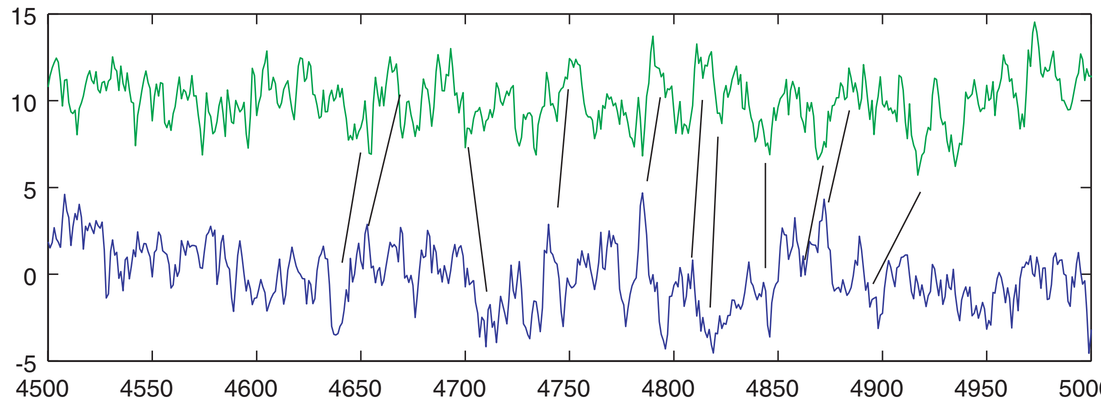

Fig. 2. Possible event identification in two time series. See text for discussion. All units are dimensionless.

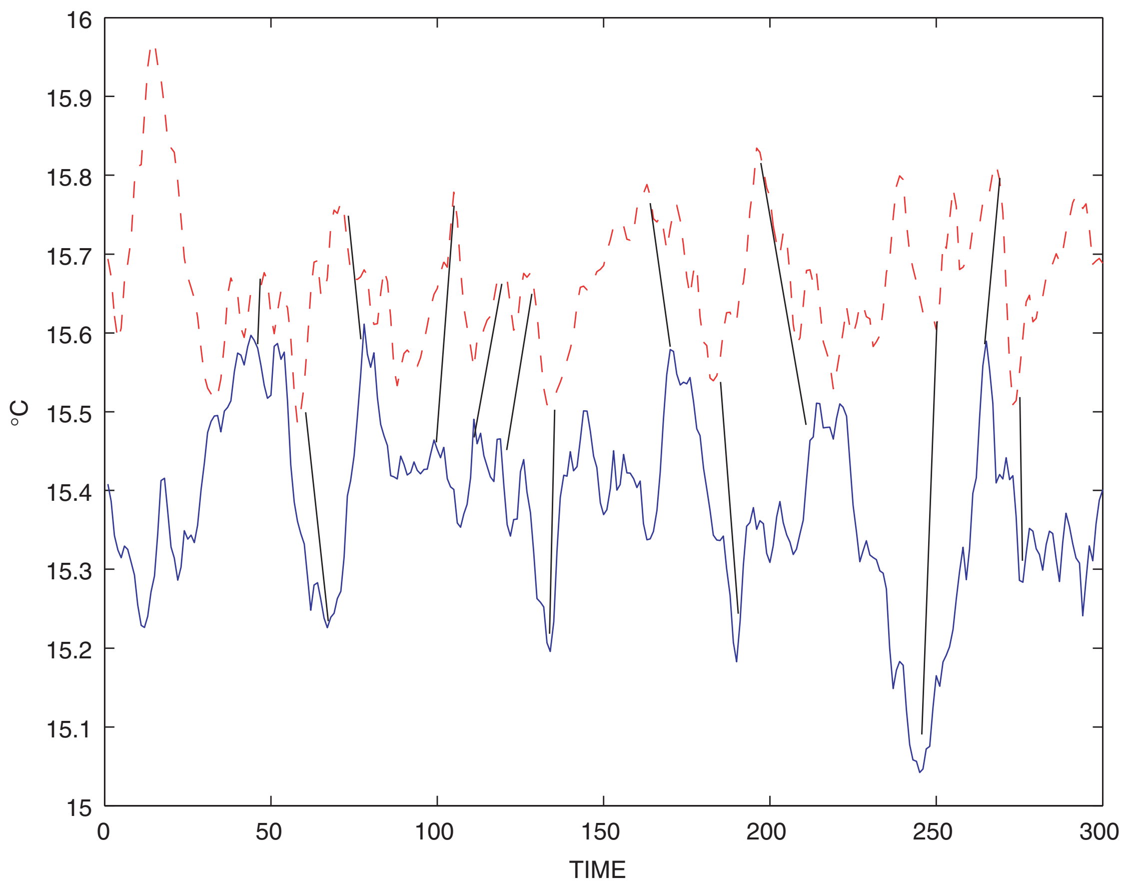

Fig. 3. Two real records, with possible common event identifications indicated by lines. In practice, these are both taken from a temperature record at 574 m at 28°N, 70°W in the North Atlantic. The time increment is 16 min, and the starting times are separated by 33 days so that there is no time overlap between the records. 1°C was added to the red-dashed curve to displace it for visual purposes. The records thus represent internal waves and the particular variations are guaranteed, both in the known physics and through statistical tests, to be unrelated to each other. But the extreme negative events in the blue, solid, curve do appear nonetheless to have counterparts in the red, dashed, curve.

ing structures, with other examples, was discussed in Wunsch (1999) and is sometimes known as the Slutsky–Yule effect. The tendency to see relationships where none may exist is one of the many reasons for development of more objective analysis tools. To begin, Fig. 4 re-displays the separate GISP2 and GRIP-CH_4 records, as adjusted, but with the time reversed to run from left to right to comply with the convention of physics/time-series analysis. The choice is arbitrary but it does permit one, eventually, to connect the records to the modern instrumental ones, as has been done, e.g., with carbon dioxide. The GRIP dates stop at about

-48 kyr and Blunier and Brook (2001) employ a correspondence between GRIP and the GISP2 dates to carry the analysis back before this time. Probably the major source of error is the need to infer the difference in age of gases trapped in the air and in the ice in the Byrd core. For present purposes, we will assume that the structure of this error is not rapidly varying over the record durations, and that the Blunier and Brook (2001) calculations are fundamentally accurate. If, in the future, a major change is made in the ice/gas age model, the conclusions of this paper will have to be revisited.

Measurements made in the GRIP and GISP2 cores have been widely described and discussed; the papers in the special journal issue (*J. Geophysical Research*, C12, November 1997) devoted to the two Greenland ice-cores give a good overview. Many different quantities have been measured, including concentrations of $\delta^{18}O$, deuterium, potassium, etc. We will refer to these, generically, as "tracers," $C(t, \mathbf{r})$, as they are all scalar quantities whose concentrations are determined at least in part by atmospheric advection/diffusion equations of varying complexity, and whose ultimate interpretation must rest upon those equations. $t, \mathbf{r}$ represent true time (only approximately known), and lateral position, respectively. In general, study of the climate record in ice-cores is an inverse problem: that of deducing the atmospheric state from observations of tracer deposition as a function of time. Determining whether there is any direct connection between tracer deposition rates and climate state variables is one of the key problems. Its solution is unlikely to be any simpler than its counterpart in the modern coupled atmosphere/ocean system.

Depending upon the particular property being measured, the data are averages over finite intervals, or point samples. When discretely sampling any continuous record of change, the adequacy of the sampling interval, Δt, or of the averaging, has to be a serious concern. Wunsch and Gunn (2003) discuss general sampling issues in cores and the problem of corruption of low frequency energy by aliases from high frequency. The presence of a remarkable very sharp peak in the spectrum at 1470-yr period in the GISP2 core data was discussed by Wunsch (2000, 2001), who pointed out that if real, it is an extraordinary feature of climate variability, and that a more plausible explanation was that it was a simple alias of the very powerful annual cycle.

Some authors however (e.g., Muller and Macdonald, 2000; Hinnov et al., 2002) confuse the background continuum of energy in the millennial band, with the

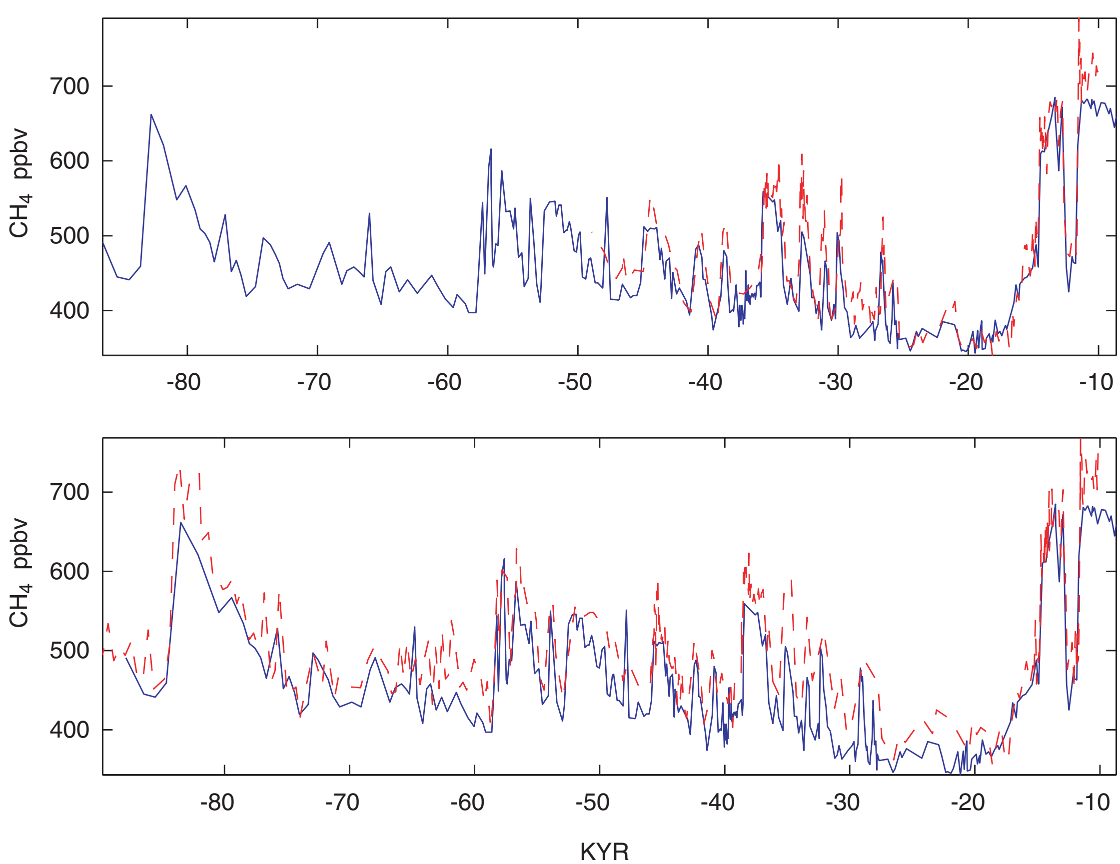

Fig. 4. Byrd (solid-blue) and GRIP (dashed-red) aligned CH_4 records (upper panel), and for the GISP2 core in the lower panel. Note that time here and subsequently, increases to the right.

energy lying in the sharp peak. The peak has less than 3% of the record variance, and its total removal (e.g., Wunsch, 2000, Fig. 2) leaves a record that visually is barely distinguishable from the original one (some of the background energy is inevitably removed too, exaggerating the effect of suppressing the line frequency). The impressive fluctuations visible to the eye in Fig. 4, and other plots here do *not* correspond to the narrow line frequency.

Aliasing, particularly in ice-cores where annual banding and superannual frequency energy is visible, is a troublesome problem. Fortunately (Wunsch and Gunn, 2003) some records are nearly immune to the aliasing problem. Any record in which the power density is as steep as a minus-2 power law,

$$\Phi(s) \propto s^{-q}, \quad q \geqslant 2, \tag{2}$$

aliases sufficiently little energy, that it can be ignored in an exploratory stage. In what follows we will *assume*, therefore, that for any tracer C, discussed here that the spectrum is plausibly as steep as $q = 2$, apart from the existence of the very strong annual cycle. One must, however, always bear in mind that this assumption has been made, and it is unforgiving if false.

In using these records, there are several considerations, including whether to employ primarily the GISP2 or GRIP data and dates, whether to interpolate to a uniform grid, and if so, and what interval, and whether to include, e.g., the interval of the most recent deglaciation. Results shown here prove to be essentially independent, except in comparatively minor details, of any of these assumptions. We will show some results from both cores, but will focus on GISP2.

3. Analysis

Several distinct approaches to analysis of time series exist. In one of them, which has been generally used to discuss inter-record causality, one attempts to visually define "events" in the record, and then to discuss relative starting times and causes, etc. Another approach, through spectral analysis, seeks the average behavior over the record length, broken down not by events, but by frequency bands. Most physical systems display behavior which is a function of frequency—and whose depiction often proves a powerful analysis tool; it is this method we adopt here. (There are equivalent, record-average, time-domain analysis tools. The frequency domain usually proves easier to interpret, but as here, conversion to the time domain is occasionally useful.)

The most powerful time-series analysis methods assume that the records are Gaussian (normal) and statistically stationary. Thus for a Gaussian stationary random process, one can easily show that the record mean and the power spectral density completely define all useful information (they are the first and second moments, and are all that are required for such a process). To the degree that the record is neither Gaussian nor stationary, the mean and spectral density are still extremely useful—but they are no longer *complete* descriptions of the data. Consider an example. Let a record, $x(t)$, have Fourier transform $\hat{x}(s)$, where t is time, and s is circular frequency. The power density spectrum is

$$\Phi(s) \propto \langle \hat{x}(s_1)\hat{x}(s_1)^* \rangle, \tag{3}$$

where $*$ denotes a complex conjugate and the brackets denote the true average value. Then for a Gaussian stationary process, it follows that,

$$\langle \hat{x}(s_1)\hat{x}(s_2)^* \rangle = 0, \quad s_1 \neq s_2. \tag{4}$$

If either, or both, of stationarity or normality are violated, the product in Eq. (4) will no longer necessarily vanish, and (3) will not completely specify $x(t)$; the information in $\langle \hat{x}(s_1)x(s_2)^* \rangle$, $s_1 \neq s_2$ is required too, and one is led to concepts such as the bispectrum which are used to find the missing information. Nonetheless, $\Phi(s)$ remains an important descriptor of the time series, one for which an interpretation can be attempted. A model that claimed skill in calculating climate change could be rejected on the basis that it produced a version of $x(t)$ whose spectral density differed from that of the data in one or more frequency ranges. Such a test is necessary, but not sufficient, as even if the modelled spectral density is acceptable, the model might still be rejected on the more stringent basis that its values of $\langle \hat{x}(s_1)x(s_2)^* \rangle$, $s_1 \neq s_2$ (or equivalent more convenient measures) were not acceptable. In any case, Fourier's theorem remains valid, the frequency representation of $x(t)$ is at a minimum a complete kinematic representation; at best, it is a complete statistical description as well.

Many of the more speculative descriptions of relationships between climate records measured at remote locations depend upon visual identification of intermittent events which are assumed to be identical, often with a postulated significant time-lag between them. Statisticians, of course, advise against choosing, a posteriori, elements of records whose covariance is then proclaimed: such inferences are untestable. Often the assumed relationships are further connected to background levels of the records during the supposed common events. Such a dependence on the background state assumes a strongly non-linear system whose physics is usually only vaguely specified, but whose postulated existence introduces further unconstrained parameters into the estimation problem. The approach taken here is consistent with the experience that linear, record-average, behavior should be described and understood first; one can then move on to much more

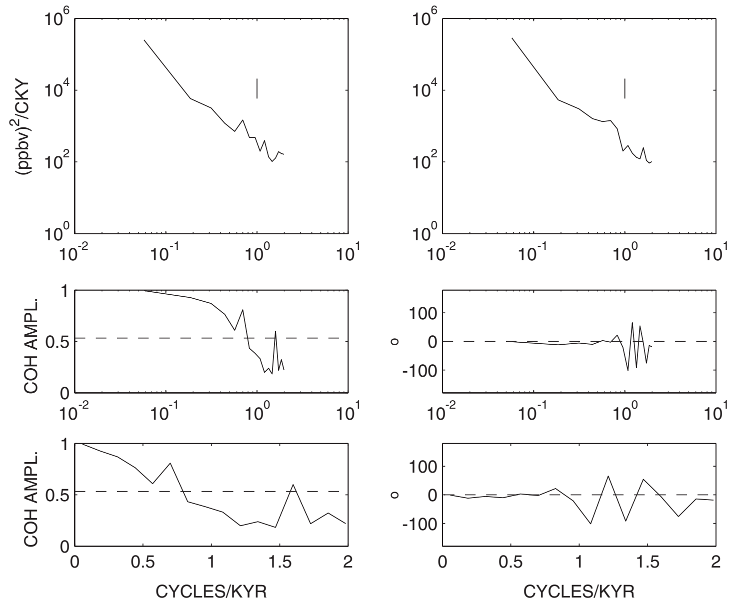

Fig. 5. Upper two panels are the estimated power spectral densities of the methane records at Byrd and GISP2, showing the characteristic rednoise behavior. Lower two panels show the coherence between the two records (magnitude and phase). An approximate level of no significance at 95% confidence is shown (approximately 5% of the values should occur, spuriously above this level, if the records were normally distributed and incoherent). The high coherence confirms the success of the alignment procedure, not its ultimate correctness. Note that the coherence is shown on both logarithmic and linear frequency scales. Here, and in other spectral estimates shown, estimates at adjacent frequencies are nominally independent.

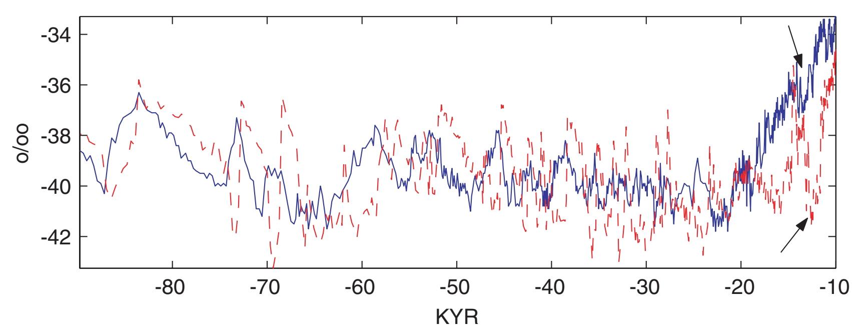

Fig. 6. Measured Byrd (solid-blue) and GISP2 (dashed-red) $\delta^{18}O$ for the methane aligned time scales. Arrows indicate the so-called Antarctic cold reversal (in blue curve), and the Younger Dryas (red curve).

difficult hypotheses of non-stationarity and non-linearity. The end result here is a comparatively simple description.

Fig. 5 displays the spectral density estimates of the interpolated Byrd and GRIP core values for CH_4 (the latter carried back to -90 kyr) as described by Blunier and Brook (2001) using the GISP time scale. Both show the characteristic approximate power-law behavior expected from such records in this frequency band. Also shown are the coherence magnitude and phase. These confirm that the alignment of the age models using the methane records has been successful: there is both coherence above the approximate level-of-no-significance at 95% confidence and with zero phase at periods longer than about 1300 yr. At periods shorter than about 1300 yr, there is no detectable coherence and the relative ages are not determined.

3.1. *Low-frequency oxygen isotope behavior*

We now turn to the oxygen isotope data, $\delta^{18}O$, in the GISP2 and Byrd cores, as depicted in Fig. 6. Some degree of visual resemblance is obvious. The problem is to quantify it. The Antarctic cold reversal and the Younger Dryas are indicated in the figures as events that have sometimes been identified as common to both poles, but with a phase delay (e.g., Blunier et al., 1998). Whether these are indeed related or merely the expected random fluctuations of separate processes is undecidable without more information.

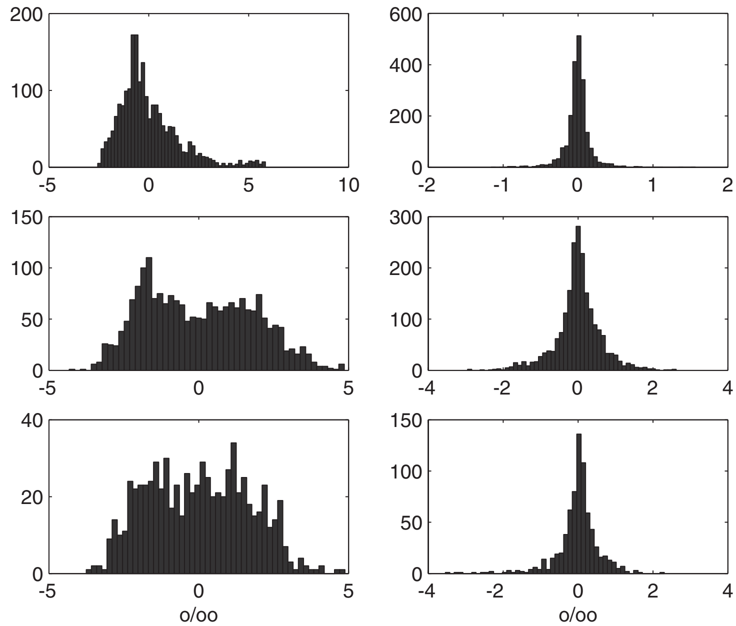

Fig. 7. Left column: frequency functions of occurrences of δ^{18}O in the Byrd (top), GRIP, and GISP2 cores. (Record means were removed first.) Right column is corresponding frequency functions of the numerical time derivatives, $\Delta t d(\delta^{18}\mathrm{O})/\mathrm{d}t$. Byrd distribution is unimodal with a heavy tail. GRIP and GISP2 records display a broad bimodal behavior (more prominent in GRIP). The first derivative removes the bimodality, but leaves the distribution significantly non-Gaussian.

A useful first step in analyzing data is to determine whether the records are approximately Gaussian. Fig. 7 displays for δ^{18}O, the histograms of the three time series, as well as the frequency function of the numerical derivatives of the data. The Greenland and Antarctic records evidently arise from different underlying probability densities (shown readily with quantile–quantile plots, which are not displayed here), and all are non-Gaussian (confirmed with a Kolmogoroff–Smirnov test). Byrd data are unimodal, but with a long tail. The GRIP record is distinctly bimodal, although the peaks are quite broad and the GISP2 record hints at bimodality. The GRIP record is quite striking, displaying not only the visual bimodality, but also, in common with GISP2, the very abrupt transitions between the modes, commonly called Dansgaard–Oeschger events. The bimodality disappears upon time differentiation. Because differentiation is a high-pass filter, the implication is that the bimodality is a phenomenon of the low-frequency elements of the GRIP core, a result confirmed by more elaborate filtering, and a point to which we return later. There are many detailed differences between the GRIP and GISP2 cores—see Johnsen et al. (2001), Hinnov et al. (2002)—but the qualitative behavior described here is independent of which core is used.

The power spectral density and coherence between these records is displayed in Fig. 8. Higher-resolution spectral density estimates are shown in Fig. 9, emphasizing what is only hinted at in the lower-resolution spectra of Fig. 8—that the spectral shape is generally red until about 1/10 cycle/kyr, but becoming nearly white below that. The Byrd and GISP2 records have in detail somewhat different spectral shapes, but both are best characterized as stochastic continuum processes. A slight broad-band energy excess is visible near 1500 yr period in the GISP2 core (Fig. 9), but it does *not* correspond to the very narrow peak of bandwidth of 2-cycles/120,000 yr peak seen in other analyses (the aliasing here would be to a higher frequency, where it is lost in the background noise). No such feature is evident in the GRIP record. This structure is broad band, lying between periods of about 1900 and 1300 yr, and carrying about 5% of the total variance. Whatever its origin, published suggestions that the very slight spectral excess near 1500 yr period in Fig. 9 actually controls the entire millennial frequency band, seem very unlikely. Note also the absence of any significant excess energy here associated with the Milankovitch bands (see Wunsch, 2002b).

In the very lowest resolved frequency bands, the coherence is near unity; the phase shift between them is close to linear with frequency, consistent with what is expected if the two records are simply displaced in time.[3]

[3] If two records $f(t), g(t)$ are related as $f(t) = g(t-a)$, with a constant, the phase shift between them is easily seen to be linear with frequency: $\hat{g}(s) = \exp(2\pi ias)\hat{f}(s)$, where the carets denote the Fourier transforms. The relationship can be restricted, as suggested here, to any finite band of frequencies in the two records.

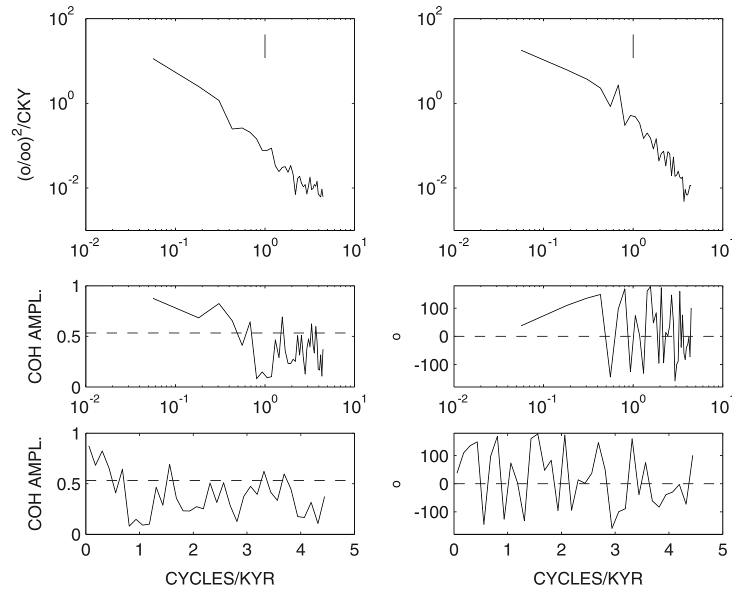

Fig. 8. Power density estimates (top panels) of Byrd (left) and GISP (right) δ^{18}O showing again, a rednoise behavior. Coherence magnitude and phase (lower panels) demonstrate significant low-frequency coherence, and very low coherence at periods shorter than about 2500 yr. Both logarithmic and linear frequency scales are used for displaying coherence. An approximate level-of-no-significance at 95% confidence for coherence amplitude is drawn as a horizontal dashed line.

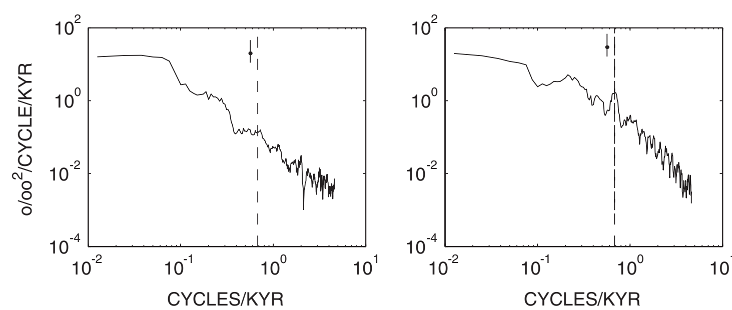

Fig. 9. Multitaper spectral density estimates of the Byrd and GISP δ^{18}O records (another version of top panels of Fig. 8.) The 1470 yr period is indicated on the two estimates. Energy there in the GISP2 record is broad band rather than narrow band in character, and there is no evidence of any sharp peaks. (The predicted alias with the interpolation interval used here is closer to 78 yr period.) No particular evidence appears for any special behavior in the Byrd record near 1500 yr period.

The linearity of the phase shift is obscured by the 360° wrapping in the phase plot and an " unwrapped" phase (Fig. 10) shows the roughly linear trend. This coherence vanishes at periods shorter than about 2500 yr. The conventional levels-of-no-significance and confidence limits displayed here and elsewhere in the literature are only rough guides, as they are based upon the assumption that the underlying time series have Gaussian distributions. Hinnov et al. (2002) discuss the structure of the GISP2-Byrd coherence in the period range of 0.2 to 1 cycles/kyr and argue that the phase is about 90° in two narrow bands around 0.25 and 0.7 cycles/kyr; in general, their result is also consistent with the same linear phase with frequency as seen here.

To study the coherent band, a low-pass filter was applied to the records so that little energy remains at periods shorter than about 2500 yr, and with the result

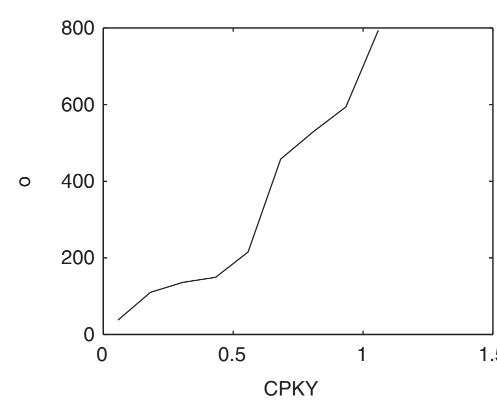

Fig. 10. Phase of the Byrd-GISP2 δ^{18}O coherence between 0 and 1 cycle/kyr, with integer multiples of 360° added to "unwrap" it. The roughly linear relationship is consistent with a pure time delay (which is however, an incomplete description of the behavior).

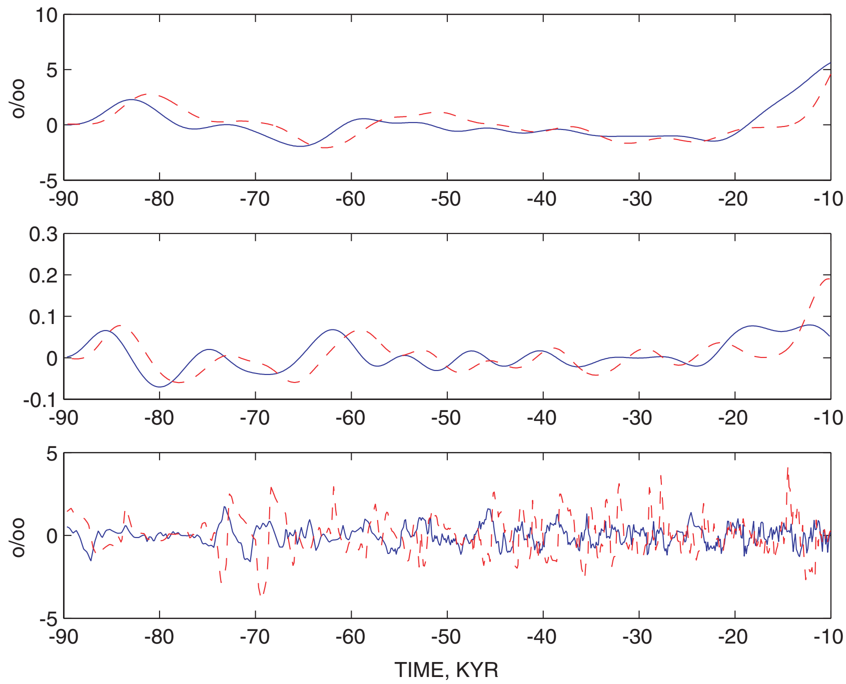

Fig. 11. $\delta^{18}O$ variation at periods longer than about 2500 yr—in the Byrd (solid, blue) and GISP2 (dashed, red) cores (upper panel), and the corresponding time derivatives (middle panel). The visual lead of the Antarctic record relative to the Arctic one is clear (same result applies to the GRIP core). Lower panel is the remaining high-pass energy in the two cores.

visible in Fig. 11. (The red spectrum renders this result insensitive to the choice of cutoff frequency—it is dominated by the very longest periods.) Visually, changes in the Byrd $\delta^{18}O$ uniformly precede those in GRIP, over the entire time span including the deglacial interval. Also displayed is the perhaps more physically meaningful estimate of the numerical time derivatives of the records $(\Delta t d(\delta^{18}O)/dt)$ in which, on average, fluctuations in the grate of change in Byrd precede those in GISP2; the frequency content of the rates of change is clearly higher than for $\delta^{18}O$ itself, as one expects for a broad-band process. A more objective view of these same data is obtained either from the phase information in the low-frequency coherence, or alternatively, in the cross-covariances between filtered the records, as depicted in Fig. 12, and in which the mean temporal lag of Greenland versus Antarctica is 1.4 kyr for $\delta^{18}O$, and 1.8 kyr for the time rates of change. (Slightly shorter time lags are estimated for GRIP.) There does exist some coherent structure with frequency more complex than the simple time delay, but that is a useful zero-order description.

This inference of low-frequency coherence implies a strong relationship between the Antarctic and Greenland records. It is a somewhat different description, however, than, e.g., that inferred by Bender et al. (1999) and others, who point at particular events in both records. Ninneman et al. (1999, their Fig. 3) show deep-sea core $\delta^{13}C$ with low-frequency structures on the 10, 000 yr and longer time scale in the Southern Ocean, consistent with there being a large scale, low-frequency connection between southern and northern latitudes. Shackleton et al. (2000) also noted that benthic $\delta^{18}O$ in an oceanic core near Portugal was visually correlated at these same low frequencies with D/H in an Antarctic (Vostok) core. The result might seem to be consistent also with the inference of Charles et al. (1996) from a deep-sea core off the southern tip of Africa. But their conclusions are based primarily upon visual identification of millennial-scale events in a region notorious in the modern ocean for its extremes of time variability and complex interchanges of water masses from the Southern, Indian, and South Atlantic Oceans.

The conclusion drawn here and in other papers (e.g., as far back at least as Hays et al., 1976) that at low frequencies Antarctic changes on average lead those in Greenland, conflicts directly with that of Alley et al. (2002), who infer a northern hemisphere lead, also using the Blunier and Brook (2001) dates. Their inference is based however, on the identification of record extrema, which as we have seen is problematic, and on the driving of change by insolation variations—which raises many other questions. Cause and effect determination in broad-band processes is not easily accomplished by eye.

The average low-frequency time lead between Byrd and Greenland records, moreover, cannot be used to infer southern hemisphere origination of the change. With only two nearly antipodal data points, inadequate

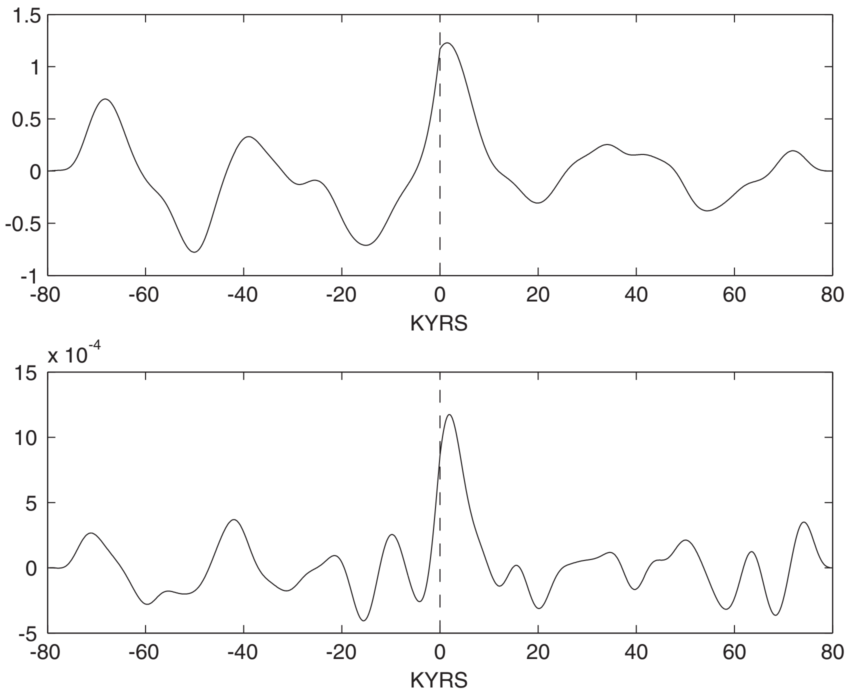

Fig. 12. Cross-covariance (biassed form) of the curves in the upper panel of Fig. 11, and of the middle panel, for the time rate of change of δ^{18}O, demonstrating objectively the time-mean lead of Byrd relative to GRIP.

information is available to detect the global spatial structure (including subtropics, tropics, subpolar, oceanic/land sectors) necessary to distinguish cause from effect.

3.2. Millennial band relationship

Fig. 11 also shows the high-pass Byrd and GISP2 δ^{18}O records, with the low-frequency band energy removed. Both visually, and as depicted quantitatively in the coherence results, there is little or no connection between these records. The logarithmic frequency scale in the coherence amplitude plots (Fig. 8) may give the impression of significant coherence in this band. But the linear frequency-scale plot shows that values occur in isolated fashion above the estimated level-of-no-significance, and with a corresponding highly random phase. For Gaussian processes, about 5% of the values should exceed the 95% level-of-no-significance by happenstance; here about 7% of the millennial band values are above that level, an acceptable deviation. (If the high-frequency coherence of 0.5 taken as an upper bound, then only $0.5^2 \times 100 = 25\%$ of the very small energy level at the highest frequencies would be related in the two-cores—hardly a compelling explanation of their mutual behavior.) With the eye of faith, one can attempt to identify isolated "events" possibly occurring in one or the other record, with differing causal relationships (see, e.g., Fig. 1). But on average, there is no measurable relationship, and one must question whether the event identification is not simply within the range of possibilities that one always has with two noisy records, even if completely unrelated. (Schmittner et al., 2003 suggest a time-average *lead* of about 400 yr by the Greenland core at periods shorter than about 5000 yr. But even if statistically significant, their result accounts for less than 15% of the variance at periods shorter than 5000 yr and does not describe the major variability in this band. No conflict exists between a conclusion that 15% or less of the variance is correlated, and the present inference that most of the variability between Greenland and Antarctica is unrelated. Recall too (Fig. 5), that the methane records become incoherent, even after tuning, at periods shorter than about 1300 yr, leaving the inter-core relationships indeterminate at the shortest periods.)

Errors quoted by Blunier et al. (1998) in their tuning are several hundred years, and may in fact be as large as 1000 yr; it is not clear whether they are random or systematic. Age-model errors could of course, both distort the millennial band spectral densities (e.g., Moore and Thomson, 1991; Wunsch, 2000; Huybers and Wunsch, 2003), and destroy true coherences. Adjustments to the timing of the δ^{18}O data, within these errors, would increase the millennial band coherence (although at the expense of diminishing that of the CH_4 records, unless the δ^{18}O time-scale adjustment can be made independent of the CH_4 time scale, as in ice/gas age variations). One cannot disprove the hypothesis that there is some physically significant millennial band coherence in these records. But there is however, no current evidence that it exists in reality, and its absence is, currently, the simplest working hypothesis.

4. Millennial variability in the Greenland cores

As we have seen, the Byrd and GISP2/GRIP records appear to have very different statistical distributions; there is no measurable high-frequency phase relationship, and nothing resembling a bipolar seesaw. The simplest description would be that at periods shorter than about 10,000 yr, that is in the millennial band, variability as seen in δ^{18}O over Greenland—whatever it represents—is not coupled to that seen in Antarctica. (A very similar conclusion has been drawn independently by Roe and Steig, 2003.) There is no evidence here that the Greenland millennial band δ^{18}O reflects any global phenomenon. Possibly the Byrd core is not representative of the Antarctic as a whole, and ultimately one needs to examine cores from other sectors. But the incoherence with Byrd shows that the millennial band GRIP/GISP2 δ^{18}O variations are not truly global, and the ambiguous outcome of efforts, e.g., to identify even such extreme events as the Younger Dryas in the southern hemisphere, support the inference of the average dominance of primarily local change.

As already noted, the GRIP and GISP2 cores are unusual in their display of rapid shifts, and the bimodal probability density (most conspicuous since $t = -50$ kyr). Bond et al. (2001) have claimed to show that some Holocene features of North Atlantic deep-sea cores, are responding in the millennial band to solar forcing, as measured, especially, by beryllium-10 (^{10}Be) and carbon-14 (^{14}C) data. What happens earlier is not clear. But to the extent that ^{10}Be/^{14}C are coherent with GRIP/-GISP2 δ^{18}O, they are not coherent with the Antarctic record, which has a wholly different character. Thus if solar variability is controlling the Greenland/high latitude North Atlantic millennial variability, it is not controlling that in the Byrd record. Second, the high coherence between a climate proxy (e.g., δ^{18}O) and ^{10}Be/^{14}C, can also be interpreted as implying that these latter tracers are themselves controlled by climate variability and not the reverse. This indeed, is the conclusion of Yiou et al. (1997) and Finkel and Nishiizumi (1997) for ^{10}Be. Atmospheric ^{14}C concentrations are further influenced by ocean reservoir effect changes, again something anticipated to vary with the climate regime. A more general view is that some fraction of the variations in ^{14}C, ^{10}Be represents external, solar-induced forcing, and some fraction represents covariations with the overall climate system, including whatever is externally induced. The scientific problem is to quantify these contributions. But again, one is entitled to the inference that the simplest possible view of the existing data is that Greenland ice-cores reflect primarily local high-frequency climate events of unknown spatial structure. Their temporal structure is now examined in a bit more detail.

4.1. The sharp transitions

Focus now on the high-pass record from the GISP2 core displayed in Fig. 11. The δ^{18}O deposited in Greenland is the record of an atmospheric tracer transported by winds from continental and ocean source regions, along complex time-varying trajectories, to ultimate deposition through precipitation at the core site. Fractionation of the reservoir δ^{18}O values occurs during evaporation, precipitation and mixing along the trajectory, and the ultimate deposition phase. Conventionally (e.g., Jouzel et al., 1997), the δ^{18}O signal is taken to reflect primarily the temperature at the place of deposition, and it is clear that some fraction of the recorded signal does in fact change with local temperature.

Here, however, we wish to propose that much, and perhaps even a dominant, contribution to the recorded signal lies in shifts in wind fields, and the changes necessarily associated with them. Why focus on the windfield? There are several reasons. First, the various ocean circulations (that of mass, heat, freshwater, carbon, etc.) are controlled primarily by the wind (e.g., Wunsch, 2002a; Wunsch and Ferrari, 2003). The wind and its spatial structures are drivers of the entire top-to-bottom circulation, including that part which many authors regard as buoyancy driven. Oceanic response to wind-driving is generally extremely fast and efficient. It has also become clear that the atmosphere is capable of moving into varying states of dominant winds (e.g., the North Atlantic Oscillation (NAO) or its hemispheric counterpart, the Arctic Oscillation (AO)) even in the presence of fixed ocean temperatures.

As an atmospheric tracer, δ^{18}O, is carried to Greenland and Antarctica along complex pathways. Trajectories are perhaps the least stable element of any fluid flow, even simple steady ones (e.g., Ottino, 1989). Newell and Zhu (1994) pointed out that the atmospheric transport of moisture appears primarily in narrow filaments that would be extremely sensitive to shifts in the atmospheric state. If the δ^{18}O measurements do indeed indicate, most of the time, major climate shifts, it would be quite remarkable if the corresponding wind system remained unchanged. A changed wind system would move the source regions for δ^{18}O, both oceanic and land, the trajectories taken to Greenland, and presumably also the surface concentrations of δ^{18}O in the ocean and on land. The least-likely scenario is therefore, that the δ^{18}O record is simply one of temperature change. That temperature is part of it is incontrovertible (Severinghaus et al., 1998; Severinghaus and Brook, 1999), but the fraction, and time scales, corresponding to temperature have to be inferred. (Charles et al., 1994; Jouzel et al., 1997, and references there, discuss elements of the factors governing δ^{18}O.)

We want to explore the hypothesis that some significant fraction of the GISP2 δ^{18}O record consists of fluctuations in the evaporative source region modified by shifted along-track fractionation (see, especially, Charles et al., 1994). The large regional variations in δ^{18}O occurring at the earth's surface today can be seen in Schmidt et al. (1999). Consider two (only) reservoirs as source regions, one in which moisture transported along the track to the core site arrives with concentration $C_1 = -35$, and another in which it arrives at $C_2 = -45$ (the numbers are roughly realistic). Let $x(t)$ be some stochastic time-varying parameter that determines which reservoir dominates the deposition. Let the originating source and trajectory to Greenland be determined by the sign of $x(t)$, $\mathrm{sgn}(x(t))$, so that,

$$C(t) = (C_1 + \xi(t))[1 + \mathrm{sgn}(x(t))] + (C_2 + \eta(t))[1 - \mathrm{sgn}(x(t))]. \quad (5)$$

Here, ξ, η are white noise (purely random) processes of variance 0.03^2 and 0.02^2, respectively, inserted to represent the likelihood that neither the reservoir concentration nor the pathway to deposition would be strictly constant. $x(t)$ is chosen to be a weakly red noise process,

$$x(t) = ax(t-1) + n(t), \quad a = 0.99, \quad (6)$$

with $n(t)$ being unit variance white noise, and depicted in Fig. 13. With $a = 0.99$, $x(t)$ tends to hover around a zero value, moving toward and away in a random walk. By changing a, one can change the probability of being within a distance Δ of $x(t) = 0$, and thus the probability of a transition within time T_c (see Feller, 1957; Vanmarcke, 1983). The role here of $x(t)$ is simply to provide a threshold (arbitrarily taken to be 0—it could be anything) and with an intermittency typical of the simplest of all possible stationary, colored noise, processes.

$x(t)$, $C(t)$ are depicted in Fig. 13 from Eq. (5). The result (middle panel) lacks some of the apparent low-frequency structure of the real record. To mimic its presence, another, unrelated AR(1) process, $z(t)$ was added, to produce $C(t) + z(t)$, plotted in the lowest panel. This structure makes the assumption that the low-frequency behavior of δ^{18}O involves two distinct physical processes: the part generated by the zero crossings of $x(t)$ in $C(t)$, and an unrelated, superimposed random walk. The empirical frequency function for $C(t) + z(t)$ and of its rate of change are displayed in Fig. 14 and should be compared to Fig. 7. One sees in the simulated record a bimodality and a variety of fluctuations at widely varying intervals. By tuning the structure of $x(t)$, one can change this behavior. The point is that the apparently highly structured bimodal time series is produced by a simple (but wholly hypothetical) two-reservoir source hypothesis. A spectral estimate of $C(t)$ (not shown) is also consistent with the red spectrum seen in Fig. 9. The complicated patterns and shifts do not require radical assumptions such as the presence of oscillators and resonances of unknown physics, nor of the shutdown of the North Atlantic meridional heat flux. Attempts at deterministic discussion of $C(t)$ would evidently be quite erroneous. The result does not prove

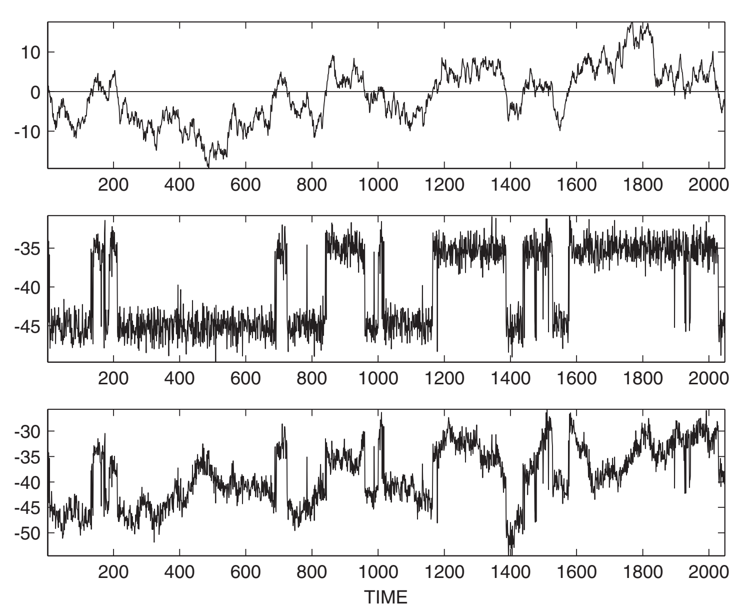

Fig. 13. Top panel shows a rednoise process whose zero crossings are used to trigger a transition of tracer deposition from one reservoir/trajectory to another. Middle panel is the resulting time series of tracer, $C(t)$, and lower panel is $C(t) + z(t)$ where $z(t)$ is a rednoise process uncorrelated with $C(t)$. All units are arbitrary here.

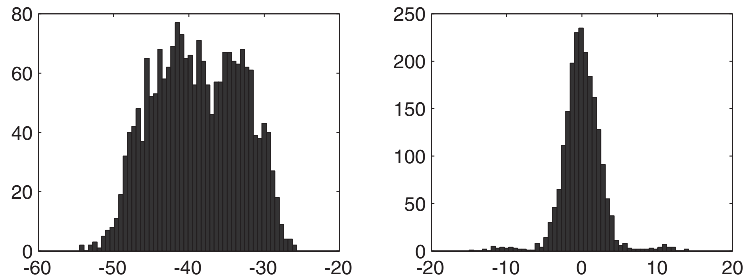

Fig. 14. Histogram of the record in the lower panel of Fig. 13 (left) and of its time derivative (right), showing a strong resemblance to the Greenland core histograms of Fig. 7.

the hypothesis—it merely shows that hypotheses like it *could* be operating to produce at least some of the Greenland δ^{18}O variations. This conclusion is in accord with the inference of Charles et al. (1994). Note that no attempt was made here to tune the various elements of Eq. (5), beyond a rough visual choice of $C_{1,2}$ and the variances of ξ, η.

As in the GRIP/GISP2 data, the bimodality in the frequency function is removed by time-differencing (or, alternatively, by high-pass filtering the time series). The bimodality is created by the low-frequency content of $C(t)$. (Contributions from $z(t)$ are Gaussian.) The power density spectrum of $C(t)$ alone is red (not shown), and almost indistinguishable from that of $C(t) + z(t)$. With real records as in Fig. 11, ordinary filtering cannot separate low-frequency energy present from the superposition of time series analogous to $z(t)$ from that present because of structure in analogues of $C(t)$. Making such a separation in the observations remains an important future direction. (The use of AR(1) time series here is not meant to imply that these are an adequate description of actual climate variability. They provide a qualitative behavior somewhat like what is observed, but the data show that more complicated structures are also present.)

The physics underlying $x(t)$ have not been specified, except to suggest that it could be primarily stochastic. Obvious candidates controlling the wind system include snow cover distributions (e.g., Cohen et al., 2002), growth and ablation of ice sheets (e.g., Wunsch, 2002b), and shifts in sea-surface temperature or sea-ice, or all in concert.

4.2. Discussion

The bimodality of the GRIP/GISP2 δ^{18}O, in this view, then originates in differing wind regimes, which in turn could well affect the oceanic and continental concentrations of δ^{18}O (see Bigg and Rohling, 2000), and which need not necessarily imply massive shifts, e.g., in the North Atlantic meridional heat fluxes (although they would surely be affected to some degree). Little seems known of the ability of the atmosphere to shift wind regimes. On short, modern instrumental, time scales one has the example of the Arctic/North Atlantic Oscillation (AO/NAO); the atmosphere seems capable of moving into varying states of prevailing winds even in the presence of fixed ocean temperatures. How large a wind shift is required is not clear, but it could be rather minor (Newell and Zhu, 1994). One might anticipate a greater tendency to multiple wind regimes in the northern hemisphere as compared to the southern, given the much greater ability there to produce continental ice sheets, to change continental snow cover, and to build significant structures in sea-surface temperature and sea-ice. There is no proof of multiple wind regimes in the northern hemisphere persisting for hundreds to thousands of years, but comparatively slight shifts in the directions of prevailing winds appear capable of changing the deposition of tracers in Greenland at lowest order. In particular, Farrell and Ioannou (2003) show that the position of a turbulent jet can be stable, but, nonetheless, a very sensitive function of boundary conditions (e.g., details of the Laurentide ice sheet). To change the deposition, one in fact would only need a shift in the mean phase of an atmospheric zonal disturbance. A number of papers (e.g., Johnsen et al., 1989; Werner and Heimann, 2002 and references there in) have discussed the various elements affecting the specific concentrations of ^{18}O (and of ^{2}H) deposited in Greenland through time.

On short modern time scales, wind shifts are often correlated with temperature changes (e.g., the NAO). But the relationship is usually imperfect and very complex. Wind shifts as inferred here imply associated changes in local atmospheric temperatures. It remains to deduce the associations.

Extensions of studies of dust deposits in cores, such as that of Biscaye et al. (1997) would be illuminating. These authors conclude, from the physical properties of the dust deposited in the GISP2 core, that during an approximate 3000-yr period about 24,000 yr BP, origin of the Greenland dust remained nearly fixed over east Asia despite major excursions in δ^{18}O during that time. They attribute changes in dust concentration primarily to changes in the atmospheric wind velocities rather than directions. This result is not definitive in terms of the rationalization given here, because the connection between shifts in regions of particulate origin and those of evaporation are unknown, and because the highly "spiky", non-Gaussian, nature of mineral inclusions in ice-cores makes the sampling issues extremely difficult. Nonetheless, extended, detailed analyses of the histories of particle origins would provide at least some constraints on the atmosphere.

In general, the probability that the intriguing GRIP/GISP2 records are generated by single simple causes, such as large-scale temperature changes alone, is very low. One must turn to quantitative estimates of the relative contributions. Before strong conclusions can be drawn about the probability of exciting, abrupt, large-scale North Atlantic sector ocean and climate changes, one must eliminate the reasonable possibility that the record is instead that of unstable atmospheric water vapor trajectories, with perhaps only slight concomitant climate changes. Presumably the Greenland (and Antarctic) millennial variability has a finite geographical extent, which it remains to delineate. The evidence here is that it is not global in extent.

5. Conclusions

Under the assumption of the basic correctness of the Blunier and Brook (2001) methane tuning, we can draw a few specific conclusions:

1. At low frequencies (periods longer than about 10,000 yr), and as suggested many times before, there is significant bipolar coherence, with the Antarctic $\delta^{18}O$ values consistently leading changes in those in Greenland by 1–2 kyr, the value depending upon whether one examines $\delta^{18}O$ or its time rate of change. Time lags of hundreds to one or two thousand years would appear to implicate either slow adjustments in the ocean circulation, or the cryosphere, or both. The result shows that the low-frequency climate system *could* have much more conventional spatial dependencies than some of the complex theories rationalizing "events" would require. These low frequencies thus appear to represent changes that may be truly global in character. On the basis of two geographical points however, inferences of causality should be resisted.
2. At shorter periods—the millennial band—and still assuming the basic validity of the CH_4 time scale, the Greenland and Antarctic records show little or no correspondence: there is no demonstrable coherence and they have markedly different frequency functions. If true coherence exists, its amplitude is below 0.5 with a corresponding common variance of less than 25% of the total energy at high frequencies. The simplest statement is that, *on average*, Byrd and GRIP/GISP2 cores record fundamentally different high-frequency processes, and the changes are not global in the same sense as are the lower frequencies. Apparent correspondences of individual events could be the expected coincidences of noisy time series. Relationships between individual, unique, extreme events could exist, but the burden of proof would be a heavy one. One approach to demonstrating their reality would be by showing their universal appearance in multiple proxies, and the production of a threshold mechanism by which spatial coherence distances would depend upon event amplitude.
3. In neither frequency band is there any evidence of a "bipolar seesaw"—which would be indicated by coherence with phases approaching 180°. Within the high-frequency band, one can visually identify apparent events displaying such behavior, but no such phenomenon exists on average in the record.
4. Both Greenland and Antarctic records exhibit significant non-normal behavior, but in different ways: the Greenland records appear bimodal, and the Antarctic one is unimodal, with a long positive tail, consistent with the statement that they represent different phenomena.
5. Much of the dramatic fluctuations in the Greenland $\delta^{18}O$ record, which have no evident counterpart in Antarctica, can be rationalized through modest shifts in windfield trajectories. The variability seen in Greenland may well have an extensive geographical reach—we only infer that it does not extend to the Byrd sector of Antarctica and in that sense at least, is not global.

Ice-core climate proxies are, fundamentally, records of atmospheric tracer transport deposition. The connections between such records and actual climate state variables (global or local temperature, etc.) are highly problematic and extremely unlikely to be fixed functions of either frequency or location. If one phenomenon likely dominates the millennial band variability of the Greenland ice-core $\delta^{18}O$, it is wind field fluctuations. Such a hypothesis could explain much of the GRIP–GISP2 differences (Johnsen et al., 2001), and any real long-range covariances with other records. Whether the rapid tracer deposition changes also always reflect major climate changes is an open question.

In producing hypothetical mechanisms to rationalize records, some thought should be given to how the hypotheses could be falsified. Here there are several possibilities. (1) If the removal of demonstrable errors in the methane age-adjustments (e.g., because of problems with the ice/gas age difference) produces strong high-frequency $\delta^{18}O$ coherence between poles; (2) if high resolution ocean/atmosphere models cannot generate adequate shifts in $\delta^{18}O$ through pathway and reservoir concentration changes; (3) if the atmosphere cannot sustain wind regimes for long periods despite the memory provided by ice/snow cover and ocean shifts.

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