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L. D. Meeker

Paul Andrew Mayewski
University of Maine - Main, paul.mayewski@maine.edu

Pieter M. Grootes

Richard B. Alley

Gerard C. Bond

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Comment on "On sharp spectral lines in the climate record and the millennial peak" by Carl Wunsch

L. D. Meeker,[1] P. A. Mayewski,[2] Pieter M. Grootes,[3] Richard B. Alley,[4] and Gerard C. Bond[5]

We are writing to comment on *Wunsch* [2000]. We have discussed its content with the author (as noted in the acknowledgements of Wunsch) on a number of occasions throughout the paper's development to its published form. We are concerned that a general reader might gain the impression that we are in agreement with the conclusions of the author, while in fact, we disagree completely. Our reasons for disagreement, which were expressed to the author on several occasions, are based on arguments that do not appear in the paper. The fundamental reasons for our disagreement are summarized below.

Wunsch [2000] is concerned with the origin of a sharp spectral peak at a period of ~1500 years that has been noted in several climate records [e.g., *Mayewski et al.*, 1997; *Grootes and Stuiver*, 1997; *Bond et al.*, 1997]. Figure 1 illustrates one of those series, the record of calcium concentrations from the Greenland Ice Sheet Project 2 (GISP2) ice core [*Mayewski et al.*, 1997] extending from the present (1985) back in time 110,000 years (110 kyr B.P.). Also shown is the band-pass component filtered from the series using a digital filter with central period of 1460 years applied to a uniform 50 year resampling of the series. This component represents 7% of the variance in the resampled calcium series. Figure 1c exhibits a 6000 year segment of the calcium series dated from 30 to 36 kyr B.P. As can be seen, the segment includes a portion of the overall record containing some of the Dansgaard/Oeschsger (D/O) events [*Johnsen et al.*, 1992] for which the 1460 year periodic component oscillates with an amplitude of ~100 ppb. It is this feature of the record which Wunsch believes to be a mathematical artifact due to the aliasing of an annual signal at either a tropical year, 365.2422 days, an anomalistic year, 365.2596 days, or a combination of the two. We do not support this conclusion for both scientific and mathematical reasons.

The mathematical foundation of the author's argument is clear. An oscillation with a period of, for example, a tropical year, when sampled at intervals containing a uniform number of common years (365 days), will appear (aliased) with a period near 1500 common years. Figure 2 illustrates this phenomenon. Figure 2a shows the result of sampling a tropical year periodic oscillation (amplitude of 100 ppb) at a uniform 50 year interval for 6000 years of an artificial record (generated with a step size increment of 0.25 years). (As noted, the calcium band-pass component of Figure 1b is also based on a uniform 50 year resampling of the original GISP2 samples.) The aliasing of the annual oscillation is clear. This, however, represents a point sampling of the record. While once a common protocol for marine sediment cores, point sampling has, in general, been replaced by an alternate process in which the observations represent an average over an interval along the core. This is the sampling protocol underlying the GISP2 and other ice core records. Figures 2b and 2c simulate this averaging process applied to the annual signal that is point sampled in Figure 2a.

Wunsch's assertion of the aliasing effect is apparent. In Figure 2b the uniformly sampled (50 year average) series appears with approximately the same 1500 year periodicity. This confirms the Wunsch's assertion that the averaging acts as an imperfect low-pass filter. However, an average over one (or many) complete annual cycle(s) results in values above the mean of the process, canceling those values below the mean with the final result being an average equal to the mean of the process (plus some noise from partial cycles). Therefore the amplitude of the resampled series is greatly reduced since its divergence from the mean of the annual cycle stems only from the contribution of those portions of the annual cycle not totally contained in the averaging sample intervals. In Figure 2b the reduction in the amplitude of the oscillation is 4 orders of magnitude. The sampling of Figure 2b starts at the mean of the oscillation and induces a periodic result. If sampling starts at a random point in the annual cycle, the sampled series can show a larger peak (Figure 2c), which is still 2 orders of magnitude less than the amplitude of the assumed annual cycle. If the ~1500 year oscillation describing the D/O events is the result of sample-induced aliasing of a tropical (or anomalistic) year forcing, it must come from an annual oscillation with an amplitude exceeding 10,000 ppb. We believe this to be very unlikely. No such levels have been found in any of our Greenland or Antarctic ice cores.

Further demonstration that aliasing is not the cause of the 1460 year signal comes from the sampling method used for GISP2. The original GISP2 record is not uniformly sampled. Although ice samples are essentially uniform in depth, changes in accumulation rate and ice dynamics result, after dating, in unequal samples in time. In the portion of the record shown in Figure 1c the average sample interval is 10.8 years, while individual samples vary from 3.8 to 39.0 years. The GISP2 glaciochemical record is based on an average concentration of the major ions throughout each sample. When the artificial tropical year oscillation is averaged over the actual GISP2 sample intervals (to simulate the GISP2 records), the series shown in Figure 2d results. It is clear that the unequal sampling process does not introduce a significant aliasing effect. Nevertheless, the displayed calcium record contains a definite millennial-scale periodicity that we maintain cannot be a mathematical artifact of the sampling protocol despite its exceptionally sharp spectral peak.

The existence of D/O oscillations in the GISP2 stable isotope series also provides a strong scientific argument against the "alias theory" presented by Wunsch. Owing to gas phase diffusion in the

[1]Climate Change Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA.
[2]Institute for Quaternary and Climate Studies, University of Maine, Orono, Maine, USA.
[3]Laboratory of the Christian Albrechts University Kiel, Kiel, Germany
[4]Earth System Science Center and Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA.
[5]Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA.

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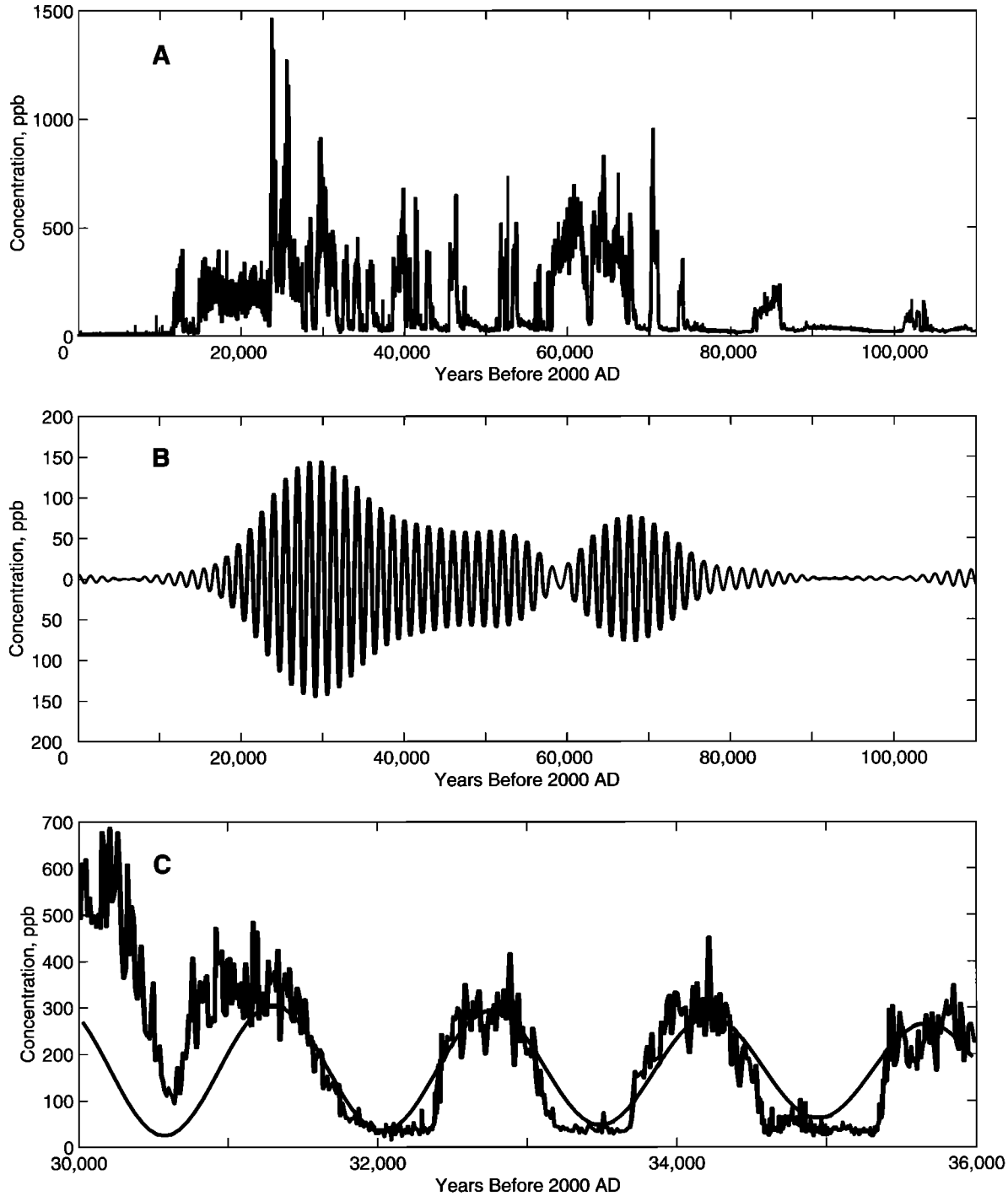

Figure 1. (a) The record of calcium concentrations from the Greenland Ice Sheet Project 2 (GISP2) ice core. (b) Band-pass component filtered from a 50 year resampling of the series of Figure 1a using a digital filter with central period of 1460 years. (c) A 6000 year segment of the calcium series and its band-pass component dated from 30,000 to 36,000 years B.P.

firn layer the seasonal signal is rapidly reduced from >20 to ~2‰. High-resolution isotope sampling of 1 m sections at ~10 samples per annual layer along the core shows the seasonal signal decreasing through the Holocene until it is no longer clearly distinguishable [*Grootes and Stuiver*, 1997, Figure 10c]. This means that diffusion totally eliminates the seasonal signal which is asserted to be the origin of the exceptionally strong ~1500 year spectral peak. The seasonal signal, logically, does not reappear in the deeper glacial ice [*Grootes and Stuiver*, 1997, Figures10d–10f]. Yet in this deep ice, suddenly, Dansgaard/Oeschger cycles of 4–5‰ appear in the isotope series. Since nature itself eliminated the seasonal cycle, we do not see how a seasonal signal of a tropical or anomalistic year's duration could be the origin of the D/O events. Further discussion of the D/O events and their timing by a 1470

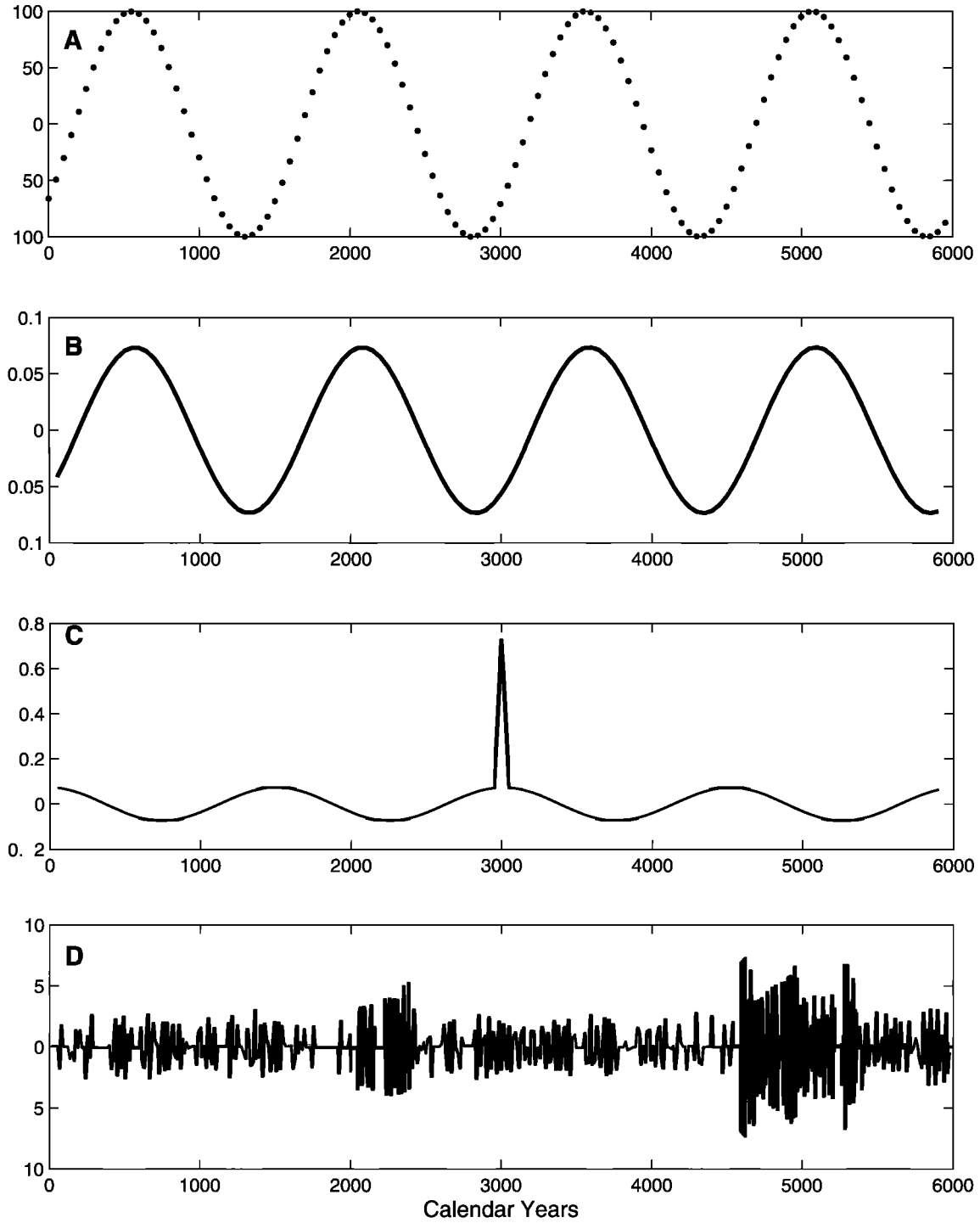

Figure 2. (a) A tropical year periodic oscillation (amplitude of 100 ppb) point sampled at a uniform 50 year interval for 6000 years. (b) The tropical year periodic oscillation of Figure 2a averaged over uniform 50 year samples. (c) The tropical year periodic oscillation of Figure 2a averaged over uniform 50 year samples with random phase. (d) The tropical year periodic oscillation of Figure 2a averaged over the actual GISP2 nonuniform sample intervals.

year cycle in the isotope series is given by M. Schulz (On the 1470-year pacing of Dansgaard–Oeschger warm events, manuscript in preparation, 2000).

There is no doubt that C. Wunsch has raised an interesting issue and provided a necessary warning to those engaged in spectral analysis. Aliasing is always a possibility under a uniform sampling protocol with either point or averaged samples. However, in this instance, we believe that his assertion that the ~1500 periodicity of the climate records is an artifact of the sampling process used on ice and marine sediment cores is not correct and has the potential of diverting scientific attention from an important feature of the Earth's climate history.

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R. B. Alley, Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA.

G. C. Bond, Lamont-Doherty Earth Observatory, Columbia University, Route 9W, Palisades, NY 10964, USA.

P. M. Grootes, Laboratory of the Christian Albrechts University Kiel, 24118 Kiel, Germany.

P. A. Mayewski, Institute for Quaternary and Climate Studies, University of Maine, Orono, ME 04469, USA.

L. D. Meeker, Climate Change Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA. (dave.meeker@grg.sr.unh.edu)

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