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Reply

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I will respond briefly to *Meeker et al.* [this issue] comment on *Wunsch* [2000], without repeating the entire paper. No one should infer from what I wrote that the commenting authors agree with my point of view; the acknowledgment of discussion was not intended to imply consensus.

There are two distinct issues: (1) The conclusion that the sharp peak near a 1470 year period is probably an artifact, in particular, an alias and (2) the most cogent explanation of how the alias is incurred.

It may well be that point 1 remains correct, with my version of point 2 not being so. I am not an expert on the sampling and analysis of ice cores, but after an extended correspondence with several of the present authors, I described what appeared to be the simplest possible explanation.

Conclusion 1 is based on two physical facts which *Meeker et al.* do not address: (1) there are no known pure frequencies in the climate system other than those governed by astronomical forcing (that is, controlled directly by Kepler's gravitational equations of motion), and as I pointed out, the discovery of such a pure frequency independent of external forcing at a period near 1470 years would have implications for the behavior of the coupled atmosphere-ocean system which would be near revolutionary. (How can a complex fluid system maintain such exact memory of a fixed phase over tens of thousands of years?) (2) The apparent pure freuency is nearly perfectly predicted by the very simple formula for the aliasing of the annual cycle when the sampling interval exceeds one half the annual period. Such a precise coincidence, that there is only one pure nonastronomical frequency present in the climate system over the entire spectral range from minutes to 100,000 years and that it "just happens" to appear at the predicted alias period, is at best bizarre. At worst, it would seem to contradict Einstein's claim that nature (God) is not malicious.

The question of whether core sampling and data analysis are adequate to completely suppress the annual cycle is one that I discussed at some length. The zero-order statement is that the modern annual cycle is very large and difficult to wholly remove from data even with completely controlled and accurate time series. The annual midcontinent temperature range today can exceed 50̄C, dwarfing the mean glacial-interglacial temperature change.

Acceptance of the alias hypothesis in no way implies that the Dansgaard-Oeschger events are also an artifact. These latter are a broad-band phenomenon with a character completely different from a pure frequency. One is apples, the other is oranges.

I will not here further defend my explanation of why the alias occurs, but if the authors believe this explanation cannot be the correct one for the presence of the sharp peak, then it becomes important for the core experts to find one because there is then some more subtle and insidious signal processing error present. The only alternative is to find a completely novel fluid physics sustaining a narrow-band, high Q, oscillator in the presence of the immense background shifts taking place in the system over 100,000+ years. What could this physics possibly be? If real, it is surely an "important feature of Earth's climate history," and with implications for the wider system, one should pause to appreciate.

The bandwidth of the observed peak is <2 cycles per 100,000 years, and thus an estimate can made of the required phase stability of a supposed oscillation. Write the periodic component as

$$y(t) = H\cos[2\pi s_a t - \phi(t)], \tag{1}$$

where s_a = 1/1470 yr is the nominal central frequency. Then the instantaneous frequency in (1) is

$$s(t) = \frac{1}{2\pi}\frac{d}{dt}[2\pi s_a t - \phi(t)] = s_a - \frac{1}{2\pi}\frac{d\phi(t)}{dt}. \tag{2}$$

To retain the narrow peak, the frequency modulation by $d\phi/dt$ must therefore be such that

$$\left|\frac{1}{2\pi}\frac{d\phi(t)}{dt}\right| \lesssim \frac{2}{10^5 \text{ years}}, \tag{3}$$

for a phase change of less than $\sim$1.1 æ 10^{-3} deg/yr. This bound would produce a very finely tuned organ pipe!

One can turn the aliasing hypothesis to a positive advantage. Let h be depth in the core and let t be the true time of deposition. Then $h = h_0(t)$ is the rule used by the analyst to produce a uniform timescale. Suppose there are errors in h_0 (t) which should really be some other function, $h = h$ (t) so that there is a difference between the timescale used by the analyst, t', and the true time. Let the difference be approximated as

$$t' - t = \varepsilon t + bt^2 + \ldots \tag{4}$$

It is easy to show that the linear term, εt, would shift the frequency of the aliased peak; from its observed position we find $|\varepsilon| \lesssim 0.03$ or less than a 3%, timing error. Similarly, a bound can be placed on b because finite b broadens the peak. Given the existence of line frequencies in the core record (be they from aliases or from Milankovitch driving), such procedures can be generalized to deduce the nature of age model errors (manuscript in preparation).

References

Meeker, L. D., P. A. Mayewski, P. Grootes, R. B. Alley, and G. C. Bond, Comment on "On sharp spectral lines in the climate record and the millenial peak" by Carl Wunsch, *Paleoceanography*, this issue.

Wunsch, C., On sharp spectral lines in the climate record and the millennial peak, *Paleoceanography*, *15*, 417–424, 2000.

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