# Notes On the Temporal and Spatial Structure of Paleoclimate Time Series *

Preliminary DRAFT Please do not cite

Carl Wunsch

March 1, 2005

**Abstract**

Paleoclimate time series from cores (ice and deepsea) are commonly analyzed with a focus on the presence of (1) supposedly periodic ("cyclic") structures; (2) the assumption that positive and negative extremes with some visual resemblance are necessarily identical events; and (3) comparatively weak elements to the exclusion ofa discussion of the bulk of the record variability. These all represent assumptions about the behavior of climate, rather than deductions from the data. Here it is shown, in the particular context of millennial time scale changes in high resolution cores, that claims of spatially large scale structures obtained by age model matching ("wiggle matching") are equally likely the expected behavior of unrelated records having roughly common spectral structures. Inferences that particular Greenland ice core variability are detectable at hemispheric distances appear to be still undemonstrated and remain assumptions.

## 1 Introduction

A number of themes tend to dominate the discussion of paleoclimate time series.

(1) The search for "cycles", usually implied to be periodic processes. This focus may be a consequence of the pioneering paper of Hays et al. (1976) who showed the existence of spectral peaks in deep-sea cores at the Milankovitch periods. It may also be a consequence of a human need to believe the world is a predictable, readily understood, place and nothing is more predictable or intuitively pleasing than a periodic phenomenon.

(2) The forced alignment of "peaks" in different proxy records. Here "peak" refers not to a spectral peak, but to a local extreme excursion in temporal records. (The process is

*\climatetopics\peakmatching.tex

sometimes known as “wiggle-matching”). One form of alignment occurs in the discussion of Milankovitch forcing, whereby records with poorly constrained age-models are assumed to be displaying common responses to astronomical forcing and are tuned to align similar features. Under some circumstances, such tuning is very sensible. Unhappily, however, it is too easy to generate visually compelling alignments between records known, rigorously, to be completely unrelated. In particular, records with common spectral shapes necessarily have identical numbers of expected zero crossings (and, therefore, maxima and minima) in any given time interval. The eye is an excellent instrument for detecting such structures, and thus tends to produce impressive alignments.

(3) A focus on weak elements of the records, at the expense of the bulk of the variance. This tendency is related to (1). Small, often apparently periodic, structures are the subject of elaborate analyses and models, but even if real, account for a very small fraction of the proxy variability. The remainder, a majority, goes unremarked. A corollary of this focus is the use of sophisticated-seeming analysis tools (e.g., singular spectrum analysis; wavelets) to extract feeble but interesting, structures, when more conventional tools (regression analysis, trend detection, fourier spectral representations) describe dominant features and which are ignored.

At the other analysis extreme, specific events, not susceptible to frequency domain analysis, are identified in one or more records and simply assumed to lie sufficiently far above the noise background to be “obviously” physically the same. Dansgaard-Oeschger events in regions remote from Greenland are prototypical of this form of analysis, but examples directed at e.g., the Younger Dryas, abound. This approach is evidently related to (2).

## 2 Cycles

Figure 1 is taken from Hays et al. (1976). That there are marginally statistically significant spectral peaks in their records near 40, and 20KY and near 100KY seems clear. It is this result that historically led to a fascination with the Milankovitch hypothesis and a search for “cycles.” The surprising inference that such results imply control of climate change by astronomical forcing was discussed by Wunsch (2004). Note, however, that these peaks particularly those near 41KY (obliquity) and near 21KY (precession) periods only describe a fraction of the record variance, . The latter, in particular, seem quite unstable, in the sense of being absent in many other records, and whether they are connected directly to precessional forcing, is the subject of controversy (see Wunsch, 2004; Huybers and Wunsch, 2005).

More will be said about weak spectral peaks later.

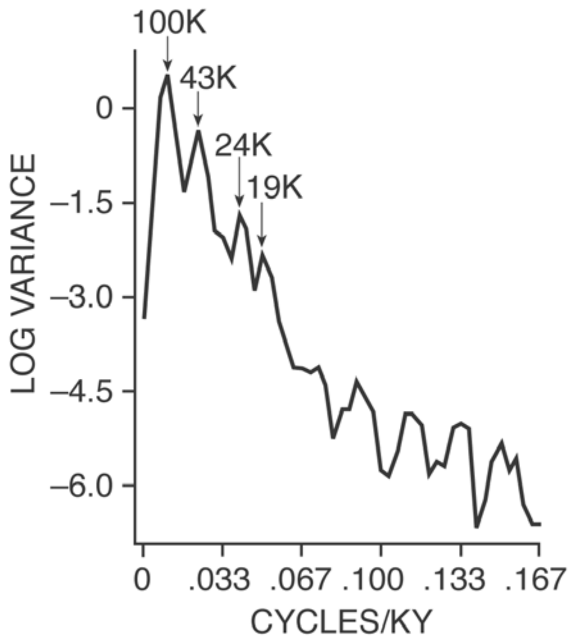


Figure 1: (Re-drawn from Hays et al., 1996) Estimated pectral densityof $\delta^{18}$O from a long-duration deepsea core. The presence of a peak near 41KY period is reasonably clear as is excess energy near 100KY. These and results (see original paper) were an important part of the evidence leading to the conclusion that Milankovitch cycles control climate change, and the search more generally for periodicities in climate. Here the labels (43K, etc.) denote the nominal peak periods in years. Note that the Milankovitch peaks are in general no more conspicuous than the unmarked ones at higher frequency. The logarithmic ordinate means that the 95% confidence interval would be nearly independent of frequency. {hayesetal.tif

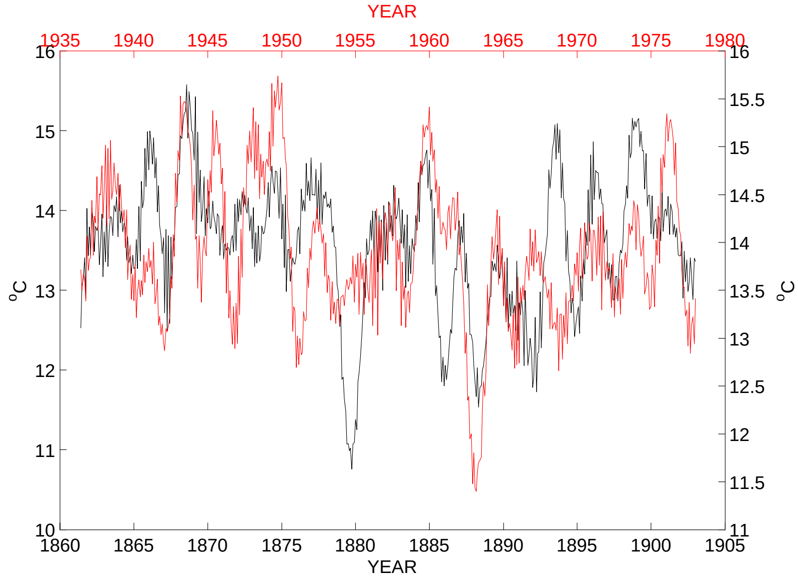


Figure 2: Black curve is the maximum monthly temperature in Oxford England 1861-1903, and the red curve from 1936-1978. The annual cycle was first removed from the entire record, and a three month running average was then formed and plotted, with the two intervals arbitrarily chosen. Although there is a strong visual similarity between the records, with identifiable corresponding peaks and troughs, it is a consequence simply of their common spectral content and hence statistics of zero crossing. The correlation of the two records is 0.4, but is not statistically significant. It could be greatly increased by shifting the relative time bases of the records. For use of the Rice statistics described in the text, one would first remove the record averages. {oxfordmaxtemp

# 3 Spatial Representativity—Wiggle Matching

In any inference about the climate system, the spatial extent of any temporal change must be known. When dealing with paleoclimate, the only realistic possibilities for such inference has lain with the use of multiple cores distributed regionally and globally. The two most prominent issues here include the one already discussed above—what does the particular tracer represent? The second great difficulty lies with the problem of finding an age-model for the proxy—either in an absolute sense, or relative to a reference site, perhaps Greenland. Because of the great difficulties of dating core measurements in the deep-sea (the great majority of the data) resort has commonly been had to tuning the cores, by *assuming* that like-flucutations in diverse cores represent identical physical features, and usually then assumed to be simultaneous.

The major problem in tuning or wiggle-matching is that of "false-positives"—the visual similarity between records that are in truth unrelated. A good deal is known (e.g., Barrow and

Bhavsar, 1987; Newman et al., 1994) about the tendency of the human eye to seek, and often find, patterns in images that are tricks of the human brain. (The classical example is the conviction of a large number of astronomers that they could perceive "canali" or lines, on the Martian surface.) It is for this reason that statisticians over the years have developed techniques for determining significance of patterns independent of the human eye. Such statistical tools must also be used knowledgably, however. Consider Fig. 2, which shows two independent records, but having a sample correlation of 0.4. Indeed there is is a considerable visual similarity between these two sets of observations. If there were any suspected errors in the time bases of these data, one might be strongly tempted to align the maxima and minima, thus driving the correlation coefficient to very impressive values.

In this particular case, there is no time-base uncertainty, and the correlation of 0.4 is not statistically significant, a result that can be determined by using the confidence limits on correlation provided in the statistical literature. The high correlation is an example of what is sometimes known as the Slutsky-Yule effect (e.g., Kendall and Stuart, 1973), that two records with autocorrelation (colored spectra) will tend to show high cross-correlations. (Confidence limit calculations for cross-correlation between such records account for the autocorrelations, and show that the number of independent data involved is far less than the number of data points.)

In Fig. 2, the black curve represents the three-month running average of monthly maximum temperature in Oxford, UK between 1861 and 1903, and the red curve is the same physical variable but between 1936-1978 (the annual cycle having been suppressed). This choice was made because it is a very simple way of obtaining two real physical records with identical spectral densities, but which are truly uncorrelated. The "event" in the black record in 1880 might be identified with the weaker minimum occurring in the red curve just slightly "earlier," and some physical hypothesis for the delay, or for age-model alignment, made.

One way of understanding the tendency to obtain visual correlations is to note that the statistics of record zero crossings (or threshold crossings where the threshold is any temperature value) are dependent upon the low moments of the spectral densities. The probability of extrema (positive or negative) is also closely related to the threshold crossing problem ("Rice statistics"). Cartwright and Longuet-Higgins (1956) is a standard reference, and a summary can be found in Vanmarcke (1983). For zero-mean Gaussian processes, the mean rate of zero crossings (either upward or downward) in a record from which the mean has been removed, depends only upon the first two moments, $\lambda_i$, of the spectral density, $\Phi(\omega)$, with,

$$\lambda_k = \int_{-\infty}^{\infty} |\omega|^k \Phi(\omega)\, d\omega, \quad k = 0, 1, 2, ...., \tag{1}$$ {moments1}

and $\omega$ is the radian frequency. In particular, the expected rate with which the time series crosses zero headed upwards (or downwards) is $\left(1/2\pi\sqrt{\lambda_2/\lambda_0}\right)$. So Gaussian time series with near-identical spectral shapes will have near-identical rates of zero crossings, and of associated positive and negative extremes. One thus expects them to display a great deal of visual similarity even when statistically independent. For non-Gaussian processes (e.g., Larsen et al., 2003) there is a strong tendency for the same result to apply, albeit the quantitative rates of zero-crossing will differ.

The conclusion would be that any two records of the same duration, whether physically related or not, having similar spectral densities will, on average, have the same number of zero crossings, and positive and negative extrema. Thus one *expects* a great deal of visual similarity between such records. One must be wary of records which reflect similar physical situations, but in which there is no plausible relationship between their temporal variations on any particular time scale. An example would be the behavior of mid-latitude weather variations e.g. in mid-continental Asia and mid-continental North America—there may be even be some real (small) correlation among temperature, precipitation etc., but few would claim that aligned maxima or minima demonstrated a causal relationship. Other examples abound: an oceanographic one is the internal wave or mesoscale eddy bands in the ocean at similar latitudes. Whether glacial advance/retreat similarities from distant locations reflect causal relationships or only common underlying physics producing similar patterns of maxima and minima would have to be determined. In any event, in comparing two records and in claiming identity of events, it has to be kept in mind that alignment failures are just as significant, overall, as are their correspondences.

Now consider the problem of the identification of millennial variability in the Greenland ice cores, and the inference that much of it appears also in the Santa Barbara and Cariaco Basin regions, and elsewhere. Peterson et al. (2000) compared Cariaco Basin green-band color ("reflectance") measurements in ODP hole 1002C with the GISP2 $\delta^{18}$O measurements of Stuiver and Grootes (2000), with the two records displayed here in Fig. 3. The Cariaco Basin record was dated with $^{14}$C values, and then visually aligned by Peterson et al. (2000) to the Greenland record. Thus these records have been tuned, and represent the assumption that individual events are both synchronous and identical. It is important to recall that this approach represents an assumption, not an inference from the data.

Visually, there are features in the two records, as adjusted, that are strikingly similar, including the Younger Dryas at about -12KY, and the shifts occuring at about -72, -84KY, (180° out of phase) but many other features appear to be unique to one or the other record (e.g., the Cariaco maxima near -60KY, and one just prior to the YD.) Beyond that, all one can really say

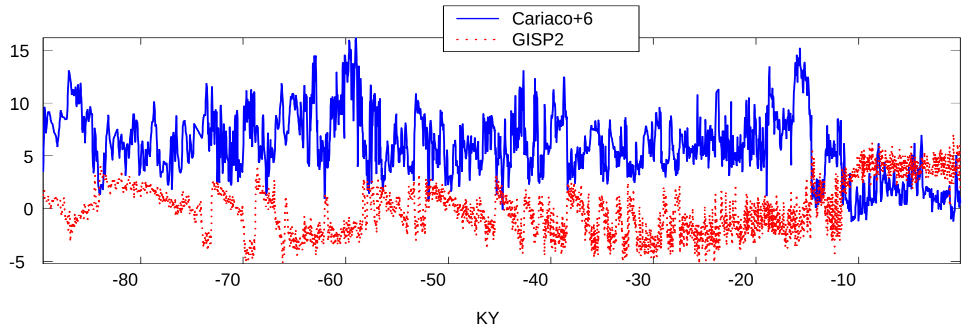


Figure 3: Time series of green-band reflectance in the Cariaco Basin (blue, solid curve) as reported by Peterson et al. (2000) and of $\delta^{18}$O from GISP2 (red-dotted) reported by Stuiver and Grootes (2000). The Cariaco curve has been displaced upward by 6 units. Time runs from left to right. Some features appear common, as one would expect from the manual tuning that was done by Peterson et al. (2000), but some features appearing in one curve do not appear in the other. Whether the similar features are more important to understanding than the dis-similarities is not so clear. Note that the dominant phase between the records is 180° so that fluctuations tend to have the opposite sign. {gisp_cariocot

is that both records exhibit a rich high frequency variability. Altogether, it is not obvious that the records are best described overall as showing similar features. As already noted, of course, one can make the assumption that the high frequency variations are identical, and attempt, within the age uncertainties, to shift the records so that extreme variations coincide. This result is then an assumption.

We seek a more objective measure of the record similarities. Figs. 4, 5 display the power density and coherence between the records (with the negative of the Cariaco record used to render the low frequency phases as 0° rather than 180°). Note that power densities and coherence represent linearizations of the full, general, spectral description of time series. Although there is no particular reason to think that the complete representation is a linear one; experience, however, suggests that beginning with linearization, and then considering possible failures, is the most fruitful way to approach time series analysis.

The power densities are similar, but not identical, and will evidently have qualitatively similar second moments, which determine the zero-crossings. Spectral moments (Eq. 1) have some sensitivity to the high frequency cutoff, as high frequencies are given increasing weight with moment number. If the integrals are stopped at about 1 cycle/100yr, the ratios $\lambda_2/\lambda_0$, which control the zero crossing rates are 3.2, 3.5 respectively for reflectance and $\delta^{18}$O. At the high frequency end, the over-interpolation of the records is likely generating the white noise floor

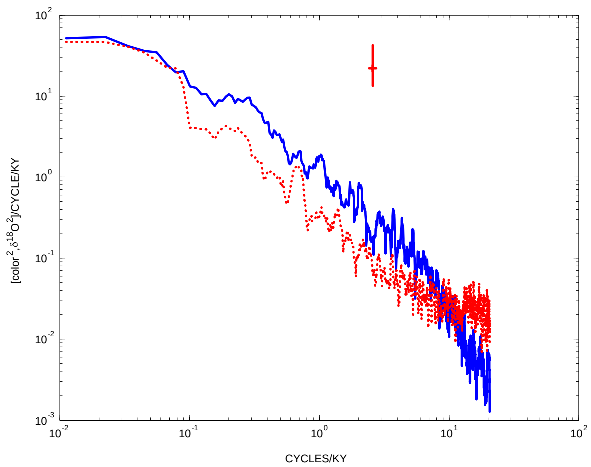


Figure 4: Estimated power density spectra of the Cariaco Basin reflectance data (blue-solid curve), and of the $\delta^{18}$O results (red-dotted curve) of Stuiver and Grootes (2000) as used by Peterson et al. (2000). The spectral shapes are similar but not identical, particularly at high frequencies where the differing original sampling intervals distort the results. The degree of aliasing in these records remains unknown, although Wunsch (2000) has suggested that it is significant in the Greenland core. {gisp_cariocop

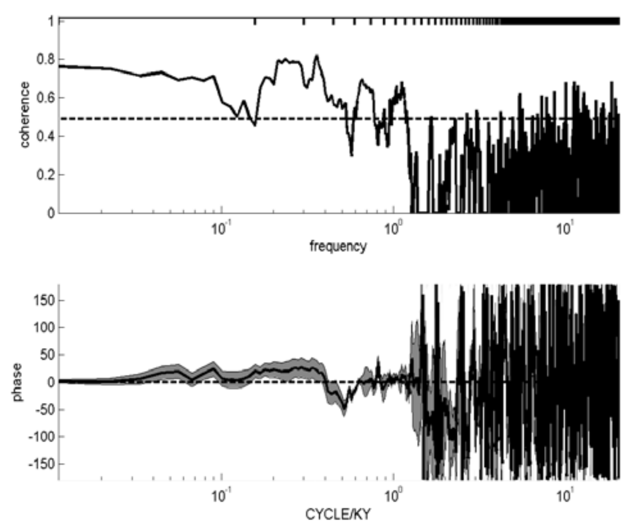


Figure 5: Coherence estimate with a 95% level of no significance for amplitude (upper panel) and with a 95% confidence interval for the phase (lower panel) between the Cariaco Basin reflectance and GISP2 $\delta^{18}$O. Negative of reflectance was used to make the low frequency phase near 0° rather than 180° which causes artificial jumps between ±180°. {gisp_cariococ

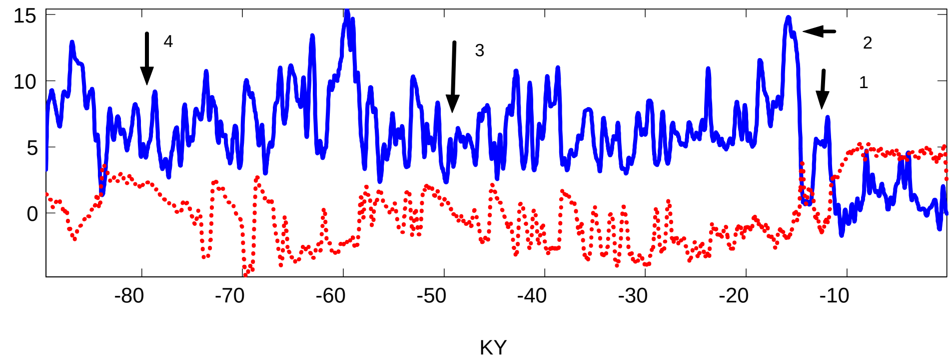


Figure 6: The Cariaco Basin reflectance (+6; solid blue curve) and the GISP2 $\delta^{18}$O (red-dotted) curves in time with almost all energy at periods shorter than about 900 years removed. Arrows denote a few of the features of interst. Number 1 indicates the Younger Dryas; number 2 shows the strong maximum in reflectance just prior to the Younger Dryas, but not so obviously visible in the $\delta^{18}$O curve; numbers 3 and 4 show times when reflectance has a lot of high frequency variability not visible in the Greenland record, and in 4, the local trend in Greenland is absent in the Cariaco Basin record. {gisp_cariacot

seen in Fig. 4. Rates of maximum and minimum appearance per unit time depend upon $\lambda_4$ (Vanmarcke, 1983, Eq. 4.4.7) and which will be even more sensitive to the nature of the high frequency cutoff. The Greenland record does have a weaker variability in the range of about $10^{-1}$ to 10 cycles/KY, possibly a result of the very different underlying physical quantities represented by the two proxies. It is also potentially an artifact of sampling, including the likelihood of aliasing in one or both records (see, e.g., Wunsch and Gunn, 2002).

A high degree of coherence exists at periods longer than about 900 years, and which abruptly disappears at shorter periods. At low frequencies there is a small, but apparently significant, positive phase lag (it is consistent across almost the entire low frequency band), indicating a tendency for changes to appear first in the Greenland record. It is not clear if this result is a consequence of the tuning or not. But the behavior in high and low frequency bands is so strikingly different that one should not discuss them together. This behavior is very similar to that found between Greenland and the Antarctic Byrd core in $\delta^{18}$O (Wunsch, 2003) and which become incoherent at periods shorter than about 2500 years. Having significant coherence extend to higher frequencies between tropics and high northern latitude than between Arctic and Antarctic is consistent with conventional geophysical time series which tend to decorrelate with increasing separation.

The common structure of the two records is perhaps best appreciated by the time series plot

(Fig. 6) with the incoherent short period energy removed. Certain structures stand out as common to the records: most conspicuously the appearance of the Holocene and the Younger Dryas. Certain other structures, e.g. the fluctuation in both at around -38KY and perhaps at -60KY. On the other hand, some structures do not appear in common: the reflectance variations within the Holocene, the large event just preceding the Younger Dryas in the Cariaco Basin, and many of the comparatively rapid changes there. In the period around -80KY the dominant changes appear to be in-phase, rather than 180° out-of-phase as is more characteristic of the records as a whole. Note that in any simple physical system, *coherence implies a strong correspondence in amplitude variation as well as in the phase* (zero crossings or extreme positions). The only simple statement here is that at low frequencies there is significant correlation between the records, but it is a complicated relationship not easily reduced to a statement about variations in one record being recorded one-to-one in the other—not a surpise in such a complex system. Note that a coherence of 0.6 implies that $0.6^2 \approx 0.35$ of the record variance is common. The remaining 65% is not (linearly) related.

The disappearance of any coherence at periods shorter than about 900 years has at least three explanations: (1) Although both records have a physically rich variability, it is primarily regional in character and there is no simple relationship between them. This interpretation would be similar to that describing, e.g., London UK and New York City daily temperature variations. (2) The age-model error has a larger influence on the short-period variations than on the long-period ones (consistent e.g., with the analytical results of Moore and Thomson, 1991, and Wunsch, 2000) and destroys what would otherwise be a strong coherence. The very abrupt nature of the change is somewhat at odds with the simplest such result—one would expect a gradual transition, and the rapid change might be related to the tuning process. (3) Other processes, almost surely present at high frequency in the Cariaco Basin and in Greenland that are incoherent may be masking a true coherence.

Adequate information to distinguish these different interpretations is not available. One can assume the validity of explanation (2) and align the records as Peterson et al. (2000) and many other authors have done. But it is essential to always remember that this is an assumption, not a demonstrated fact. To render it fact (if it is such), one needs much better age control, at least between the records, if not in an absolute sense. Stuiver and Grootes (2000) estimate the GISP2 age model as reaching a 10% error at about 2500m depth (ages about 60KY), increasing beyond that to about 20% at depths of 2500-2800m (ages 110KY). It is not stated how that error is manifested, whether as systematic or random or exactly what it represents. But a 5% error at -20KY, if interepreted as a standard deviation, is a 1000 year expected error—one obviously permitting a significant amout of adjustment in the GISP2 structure. The errors in

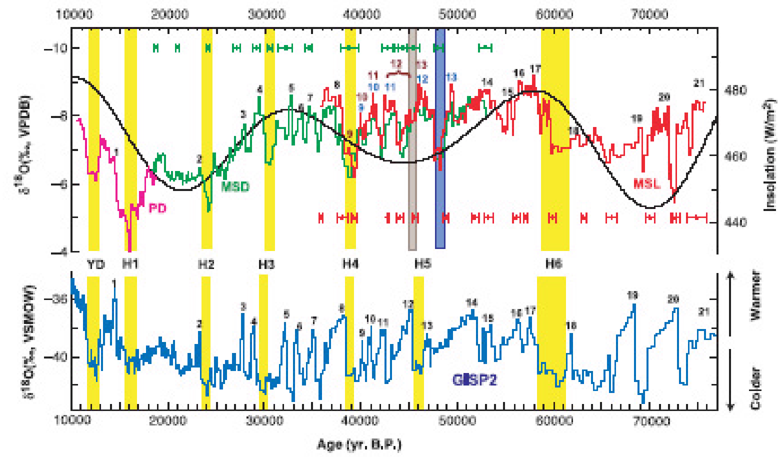


Figure 7: From Wang et al. (2001). Results from Hulu Cave stalagmites. Purple, green, red curves are calcite $\delta^{18}$O in the differing stalagmites. Lowest curve is $\delta^{18}$O from GISP2 (?), with a scale reversed from that of the Cave data. Black curve is 33°N local insolation (!). The Younger Dryas (YD) is shown as are the various Heinrich events as identified by Bond et al. (1993). {hulucave11.jp

the reflectance data $^{14}$C dates are not specified.

The comments made here about the relationship between a remote site and the Greenland ice cores are not confined to the Cariaco Basin. Similar analyses to that of Peterson et al. (2001) have been carried out for the Arabian Sea (Schulz et al., 1998), the Santa Barbara Basin (Hendy et al., 2002), and Hulu Cave near Nanjing, China (Wang et al. 2001) among numerous other locations. Figs. 7, 8 display the Hulu Cave results where the timing is not a serious issue. Fig. 9 shows the visual identification by Alley (2005) of corresponding events in Greenland and in China., The Santa Barbara Basin $\delta^{18}$O record is shown in Fig. 10. It is left to the reader to decide if the records are showing common events or only common characteristic variability..

There seems to be an expectation, often unstated, that as periods of climate fluctuations lengthen, the spatial scale over which they are correlated also grows. This expectation is sometimes justified (the glacial-interglacial fluctuation clearly has a major element correlated globally). Important elements of the climate system exist, however, that at near-zero frequency, retain a zero-order spatial variability. These elements include the ocean/continent distribution, and to very long periods, the ice cap regions, as well as the distribution of mountainous areas. That very low frequency temperature or precipitation patterns in the center of a continent should be strongly correlated with those over the open ocean, or in proximity to a continental ice sheet, is not obvious. (Saharan drought patterns persisting for thousands of years have no obvious relationship to precipitation patterns in nearby Europe.) Fig. 11, from Huybers (2004),

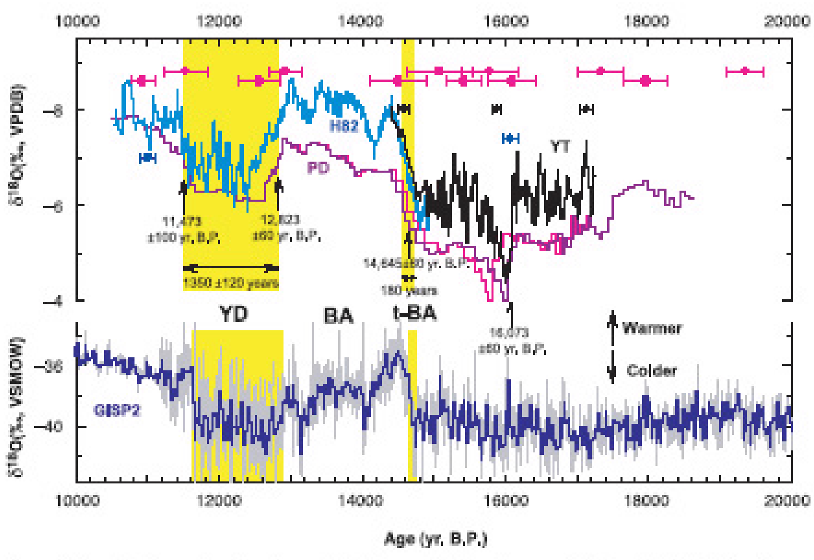


Figure 8: From Wang et al. (2001). $\delta^{18}$O of Hulu cave stalagmites (purple, black, blue) using differing averaging intervals, and the GISP2 record. Time runs from right to left. Yellow bands indicate the Younger Dryas, and the "transition" prior to the Bolling Allerod. Note that these records have been adjusted to show simulateneity of some features. {hulucave21.jp

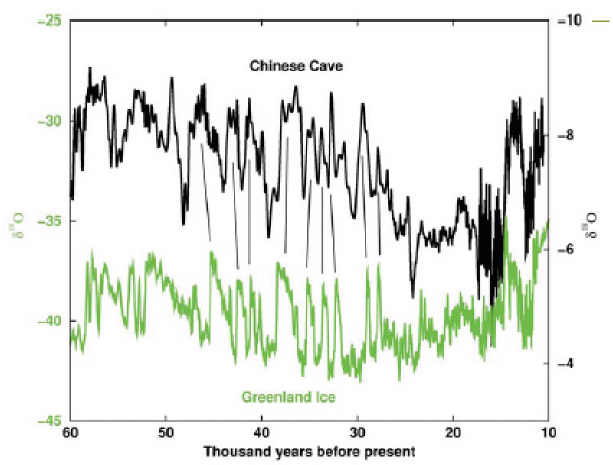


Figure 9: Identification of supposedly corresponding events in the Hulu Cave record and in Greenland ice core (Alley, 2005). Notice, e.g., that the large excursions in the Hulu cave record near -45KY and -30KY have no counterpart in the Greenland record. {alley_hulucav

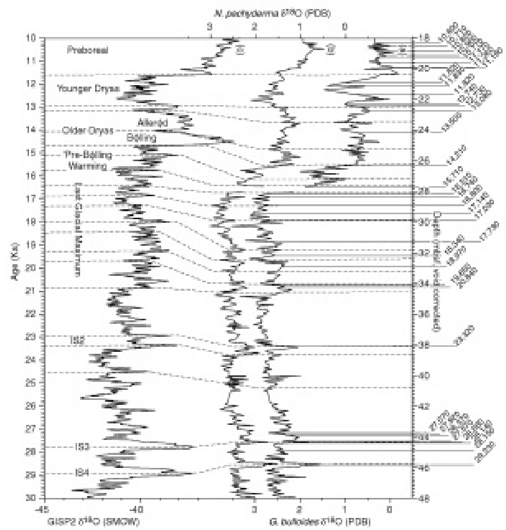


Figure 10: (From Hendy et al., 2002) showing the apparent correspondence between the $\delta^{18}$O record in Santa Barbara Basin and that in the GISP2 record. That an equivalent degree of high frequency variability exists in both records is evident; whether the oscillations actually correspond as the dashed lines indicate, is much less obvious. Note that Hendy et al. (2004) invoke *local* wind and ocean circulation effects to rationalize the Santa Barbara record. {hendyetal1.jp

shows the correlation between central Greenland surface temperature and the rest of the world in the NCAR-NCEP reanalysis out to periods of 50 years. The lower panel shows the same correlation between the Devils Hole site (e.g., Winograd et al., 1992) and the rest of the world. Fifty year periods are a small fraction of the time scales seen in climate fluctuations, but are not entirely irrelevant in a discussion of decadal scale abrupt climate change. The pattern of correlation is quite complex, suggesting that central Greenland temperatures can well be 180° out of phase with not-very-distant regions and that the correlations as expected, weaken with distance. A similar comment can be made about the Devils Hole site, not inconsistent with the regional interpretation placed on it by Herbert et al. (2001), and about the regional Southern California current system invoked by Hendy et al. (2004). Greenland regionality seems to be no less.

## 4 Minor Elements

The intense interest in finding supposed cycles (usually, but not always, implied to be periodicities), has led to many papers attempting to isolate such features in records through power density spectral estimates. Often, these are emphasized by plotting the results on linear scales—

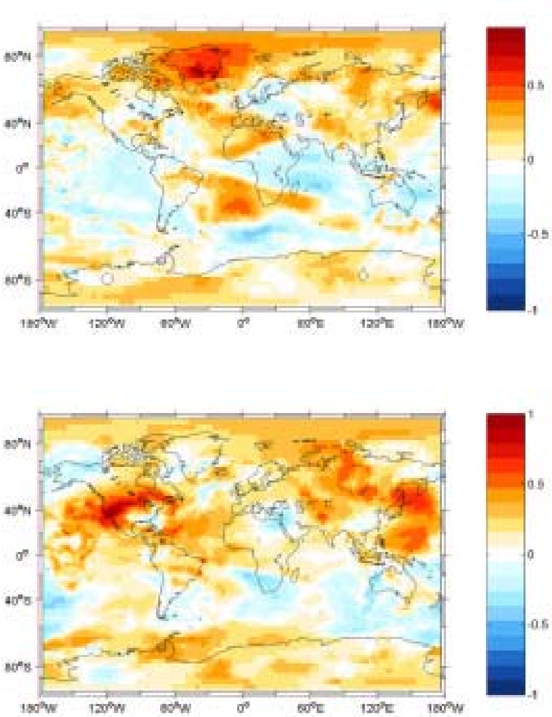


Figure 11: From Huybers (2004). Correlations of surface air temperatures with temperature at the GISP2 site in Greenland (indicated by an x). Also the location of the Byrd site is indicated by a circle in Antarctica, and for Vostok by a diamond. bottom Cross-correlations with the location of Devils Hole in Nevada. Prior to computation both low frequency trends and high frequency (periods shorter than one year) were suppressed. {huyberscorrfi

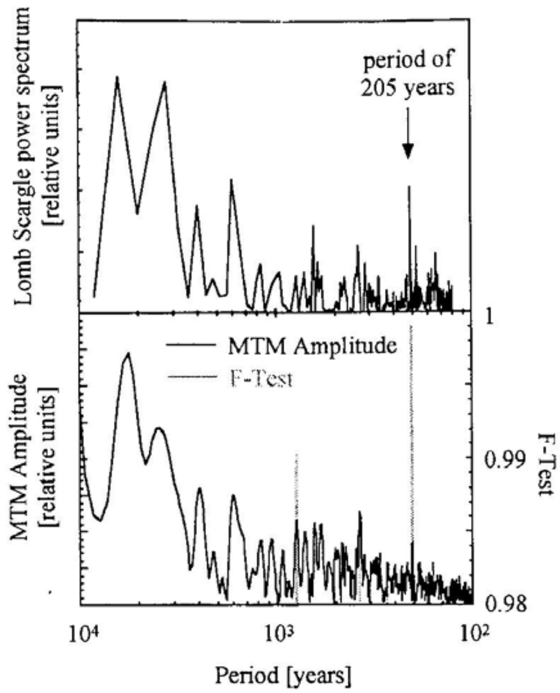


Figure 12: Power density spectrum by least-squares fit (upper panel) to $^{10}$Be data in the GRIP ice core, as taken from Wagner et al. (2001, GRL). Arrow points to an apparent isolated peak at 205 years, and which is labelled the deVries cycle in solar variability. Even if the peak is statistically significant, it appears to contain a very minor fraction of the record variance for the periods shown (much more variability energy would lie at frequencies above the highest one shown here). (The ordinate is interpreted as being a linear scale. Units are not shown.) Lower panel displays an "amplitude spectrum" inferred to be a square root of the spectral density, computed using a multitaper (MTM) method. Although claimed to be significant using an F-test, the putative peak contains even less of the estimated variance (which would require squaring the displayed curve). Note that in his discussion of confidence limits for determining significance of pure frequencies, Thomson (1990; cf. Percival and Walden, 1993, P. 512-513) advises using a very high confidence level, typically $1 - 1/N$ where $N$ is the number of data points, because of the probability of false positives. (For $N = 1000$, one needs significance at 99.9% or better.) Scale plotted in period is inferred to be equivalent to the more conventional one in frequency. {devriescycle.

which tends to emphasize isolated maxima at the expense of weaker, but far more numerous, adjoining values (Wunsch, 2000, Appendix). It is also rare to be informed about the fraction of the record variance being described by the spectral peak.

An example of both of these problems can be seen in Fig. 12, taken from Wagner et al. (2001). A time series of $^{10}$Be in the GRIP icecore was analyzed to produce the peak marked by an arrow in the upper panel of the figure, and supposed to represent the so-called de Vries cycle in solar output. Whether or not such a cycle actually exists is almost beside the point. Although it is not so easy to estimate from the published figure, and much the high frequency energy in this record has been truncated in the display, it would appear that this peak accounts for a minute fraction (perhaps a few percent) of the record variance. Note too that there is no confidence interval, and the peak is actually significantly weaker than other unremarked structures at lower frequency. Exactly why it should be singled out for special comment is obscure, even if it is statistically meaningful, when most of the record variability is evidently described by other frequencies. If the remainder of the record were well-understood, one might sensibly focus on this phenomenon as the next most important feature, but the gross behavior of the $^{10}$Be record, and its relationship to solar insolation is unclear.

Innumerable other such discussions of "cyclicity" in the paleoclimate record exist (e.g., Chapman and Shackleton, 2000), but we will not belabor the point except to say that explicit statements of the fractional variance being discussed would be highly welcome in all such studies.

A parallel development exists in claims that particular "events" in the time domain in various records must correspond. Generally speaking, one needs to first determine the record average behavior before the significance of particular fluctuations can be evaluated. Even then, concrete inferences can be difficult to draw. On a more human time scale, consider two records of sealevel variability at time scales of minutes to hours in gauges sufficiently separated that there is no coherence between them. Suppose a weak tsunami becomes visible in the records, one that is a few standard deviations above the background variability. A claim that the records are showing the same physical phenomenon would normally rest upon (1) a statement that an excursion so far from the background mean based upon the omnipresent stochastic variability is improbable and, (2) a buttressing calculation that the signal travel time is consistent with the expected longwave speed between the two sealevel gauges. Even given (1), it is (2) that would generally be regarded as the absolutely necessary determinant, because *even improbable events must occur* when one has long enough records (e.g., Diaconis and Mosteller, 1989; Seife, 2000).

## 5 Discussion

In a search for the most efficient description of paleoclimate records in ice and other cores, it is important to focus on the major elements. Periodic elements are exceptional, and generally weak. What hard evidence over the last 100KY exists suggests that global scale correlations of climate change occur only at periods exceeding about 1000years. Shorter period, and "abrupt" climate change signals are not demonstrably coherent over thousands of kilometers except by *assumption.* Exceptions do exist—the Younger Dryas signal is convincingly present in many North Atlantic basin-scale records, and perhaps in the southern hemisphere (Denton and Hendy, 1994), but beyond that arguments seem primarily to be about statistically marginal, visually identified "events." None of this disproves the hypothesis of global scale variability on decadal to 1000 year time scales—it merely says that the existing paleoceanographic record does not support it. Categorical assertions that one is dealing with global scale events, particularly with reference to the D-O oscillations (Broecker, 1997), are unsupported.

In a companion manjuscript, it is suggested further, that what large-scale signals do exist on centennial and decadal time scales are most easily explained through shifts in the wind system, leading to changes in tracer deposits. Cores record tracer deposition, by either the atmosphere or ocean or both, and tracer transports are particularly sensitive to minor shifts in trajectory.

*Acknowledgements.*

I had useful comments from P. Huybers and J. Sachs.

## References


Alley, R. B., 2005: Abrupt climate changes, oceans, ice, and us. *Oceanography*, 17, 194-206.

Barrow, J. D. and S. P. Bhavasar, 1987: Filaments: what the astronomer's eye tells the astronomer's brain. *Q. J. Royal Astronom. Soc.*, 28, 109-128.

Cartwright, D. E. and M. S. Longuet-Higgins, 1956: The statistical distributions of the maxima of a random function. *Proc. Roy. Soc., A*, 237, 212-232.

Chapman, M. R. and N. J. Schackleton, 1999: Evidence of 550-year and 1000-year cyclicities in North Atlantic circulation patterns during the Holocene. *The Holocene*, 10, 287-291.

Diaconnis, P. and F. Mosteller, 1989.Methods for studying coincidences. *J. Am. Stat. Assoc.*}, 84, 853-861.

Hays, J. D., J. Imbrie, and N. J. Shackleton, 1976: Variations in the Earth's orbit, pacemake of the ice ages. *Science*, 194, 1121-1132.

Hendy, I. L., J. P. Kennett, E. B. Roark, and B. L. Ingram, 2002: Apparent synchorneity of submillennial scale climate events between Greenland and Santa Barbara Basin, California from 20-10ka. *Quat. Sci. Rev.*, 21, 1167-1184.

Hendy, I. L., T. F. Pedersen, J. P. Kennett and R. Tada, 2004: Intermittent existence of a southern Californian upwelling cell during submillennial climate change of the last 60kyr. *Paleoceanog.*, 19, doi:10.1029/2003PA000965.

Herbert, D. D. J. D. Schuffert, D. Andreasen, et al., 2004: Collapse of the Californai Current during glacial maxima linked to climate change on land. *Science*, 293, 71-76.

Huybers, P. and C. Wunsch, 2005: . Obliquity pacing of the glacial cycles, *Nature*, in press.

Huybers, P., 2004: *The Origins of Ice Ages: Insolation Forcing, Age Models, and Nonlinear Climate Change*. PhD Thesis, MIT, xx p..

Kendall, M. G. and A. Stuart, 1973: *The Advanced Theory of Statistics*, 3rd Ed., Vol. III. Griffin, London, 585 pp.

Larsen, G. C. W. Bierbooms and K. S. Hansen, 2003: *Statistics of Local Extremes*. Riso/-R-1220 (EN) Riso/ National Laboratory, Roskilde, Denmark, 62pp.

Moore, M. I. and P. J. Thomson, 1991: Impact of jittered sampling on conventional spectral estimates. *J. Geophys. Res.*, 96, 18,519-18,526.

Newman, W. I., M. P. Haynes and Y. Terzian, 1994: Redshift data and statistical inference. *Ap. J.*, 431, 147-155.

Percival, D. B. and A. T. Walden, 1993: *Spectral Analysis for Physical Applications. Multitaper and Conventional Univariate Techniques.* Cambridge Un. Press, Cambridge, 583 pp.

Peterson, L. C. G. H. Haug, K. A. Hughen, U. Ro"hl, 2000: Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial. *Science*, 290, 1947-1951.

Seife, C., 2000: CERN's gamble shows perils, rewards of playing the odds. *Science*, 289, 2260-2262.

Stuiver, M. and P. M. Grootes, 2000: GISP2 oxygen isotope ratios. *Quat. Res.*, 53, 277-284.

Thomson, D. T., 1990: Quadratic-inverse spectrum estimates: application to paleoclimatology. *Phil. Trans. Roy. Soc. A*, 332, 599-602.

Vanmarcke, E., 1983: *Random Fields: Analysis and Synthesis.* The MIT Press, Cambridge, 382 pp.

Wagner, G., J. Beer, J. Masarik, R. Muscheler, P. W. Kubik, W. Mende, C. Laj, G. M. Raisbeck and F. Yiou, 2001: Presence of the solar de Vries cycle ( 205 years) during the last ice age. *Geophys. Res. Letts.*, 28, 303-306.

Winograd, I. J., T. B. Coplen, J. M. Landwehr, A. C., Riggs, K. R. Ludwig, B. J. Szabo, P. T. Kolesar, K., M. Revesz, 1992: Continuous 500,000-year climate record from vein calcite in Devils Hole, Nevada. *Science*, 258, 255-260.

Wunsch, C. and D. E. Gunn, 2003: A densely sampled core and climate variable aliasing. *Geo-Mar. Letts.*, 23(1),DOI: 10.1007/s00367-003-0125-22003, .

Wunsch, C., 1999: The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. *Bull. Am. Met. Soc.*, 80, 245-255.

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

Wunsch, C. , 2004: Quantitative estimate of the Milankovitch-forced contribution to observed quaternary climate change. *Quaternary Sci. Rev.*, 23/9-10, 1001-10012.