Bradley, R.S., 2011. High-resolution paleoclimatology. In: M.K. Hughes, T.W. Swetnam and H.F. Diaz (eds). **Dendroclimatology: Progress and Prospects**. Developments in Paleoenvironmental Research 11, Springer, Berlin, 3-15.

1. HIGH-RESOLUTION PALEOCLIMATOLOGY

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Key words: Paleoclimate, Climate dynamics, Proxies, Natural archives

Abstract

High resolution paleoclimatology involves studies of natural archives as proxies for past climate variations at a temporal scale that is comparable to that of instrumental data. In practice, this generally means annually resolved records, from tree rings, ice cores, banded corals, laminated speleothems and varved sediments. New analytical techniques offer many unexplored avenues of research in high resolution paleoclimatology. However, critical issues involving accuracy of the chronology, reproducibility of the record, frequency response to forcing and other factors, and calibration of the proxies remain. Studies of proxies at high resolution provide opportunities to examine the frequency and magnitude of extreme events over time, and their relationships to forcing, and such studies may be of particular relevance to societal concerns.

Introduction

Paleoclimatology uses natural archives to reconstruct climate in the pre-instrumental period. The longest instrumental records are from western Europe and a few these extend back into the early 18th (or even late 17th) century. However, for most regions, continuous instrumental measurements rarely extend beyond the early 19th century, with some remote (desert or polar) regions having barely 50 years of observations (Figure

1). Consequently, our instrumental perspective on climate variability is extremely limited. In particular, it is unlikely that we understand the full spectrum of variability of the most important climate modes (such as ENSO, PDO, NAO etc). High-resolution paleoclimatology addresses this issue by focusing on climate proxies that can be resolved at seasonal to annual resolution. These proxy records may extend back continuously from the present, or provide discrete windows into the past, to shed light on modes of variability in earlier times. By providing data at a resolution comparable to that of the instrumental record, high-resolution paleoclimatology plays an important role in resolving anthropogenic effects on climate. Specifically, it helps to place contemporary climate variability in a long-term perspective (*detection*, in IPCC parlance) and enables climatic changes to be examined in terms of forcing mechanisms (*attribution*). High-resolution paleoclimatology also provides targets (either time series or maps of past climatic conditions) with which models (GCMs or EBMs) can be tested and validated, and it offers the opportunity to explore climate dynamics (modes of variability, abrupt climate changes, climate system feedbacks) over long periods of time. Thus, high-resolution paleoclimatology naturally interfaces with, and complements, the research priorities of the climate dynamics community.

Data sources for high-resolution paleoclimatology

The critical requirements for high-resolution paleoclimatology are that:

1) an accurate chronology can be established; this generally requires replication of the archive being sampled
2) the archive can be sampled in detail, ideally at seasonal to annual resolution, but at least at the resolution of a few years
3) the parameter being measured is reasonably well understood in terms of its relationship to climate (i.e., its mechanistic and seasonal response) so that it can be calibrated in terms of climate, using the instrumental record as a yardstick for interpreting the paleo-record
4) the relationship between the proxy and climate observed today has been similar in the past (the principle of uniformitarianism)
5) the record captures variance of climate over a wide range of frequencies, or at least the window of variance which the proxy does capture is known

In the next section, these issues are examined with reference to the main archives that are available for high-resolution paleoclimatology: tree rings, corals, speleothems, ice cores and varved sediments. This is followed by a discussion of the opportunities and challenges in high-resolution paleoclimatology, with particular reference to dendroclimatology.

Chronology and replication

An accurate timescale is essential in high-resolution paleoclimatology. A chronology is commonly obtained by counting annual increments, using variations in some parameter to mark the passage of time. This might be the cyclical ^{18}O maximum in a coral record, registering the sea-surface temperature minimum over each annual cycle, or the presence of a “clay cap” in varved lacustrine sediments, marking each winter’s sediment layer, or the width of a tree ring between the large, open-walled spring cells which form each year. However, simply counting these recurrent features in a sample (even if counted several times by different analysts) does not guarantee an accurate chronology. The best procedure is to replicate the record using more than one sample (core), to eliminate potential uncertainties due to “missing” layers and to avoid misinterpretation of dubious sections. On this matter, dendroclimatic studies have a clear and unambiguous advantage over most other paleoclimate proxies. Duplicate cores are easily recovered and cross-dating using one or more samples is routinely done. Tree ring chronologies are thus as good as a natural chronometer can be, at least for those regions where there is an annual cycle of temperature or rainfall and trees are selected to record such changes in their growth. However, for those vast areas of equatorial and tropical forests, where trees are not under climatic stress and so do not produce annual rings, establishing a chronology has been far more challenging. Recent analytical improvements using continuous flow isotope mass spectrometry have made feasible the almost continuous sampling of wood, so that annual changes in isotopic properties can be identified, even in wood that appears to be undifferentiated in its growth structure (Poussart et al., 2004; Evans and Schrag, 2004). This opens up the possibility of using trees for paleoclimatic reconstruction in regions that were hitherto unavailable. However, replication of samples from nearby trees is still necessary to reduce chronological uncertainties in these newer records.

In the case of most other high resolution proxies, replication is rarely carried out. This is generally related to the cost of sample recovery (in terms of logistics or time) or because of the analytical expense of duplicating measurements. Most coral records, for example, are based on single transects through one core, though the veracity of the chronology may be reinforced through the measurement of multiple parameters, each of which helps confirm the identification of annual layering in the coral. Similarly, in ice cores, multi-parameter glaciochemical analyses can be especially useful in determining a secure chronology (McConnell et al., 2002a; Souney et al., 2002). In addition, in some locations more than one core may be recovered to provide additional ice for analysis and to help resolve uncertainties in chronology (Thompson, 1992). It may also be possible to identify sulfate peaks in the ice, related to explosive volcanic eruptions of known age. Such chronostratigraphic horizons can be very helpful in confirming an annually counted chronology (Stenni et al., 2002). Varved sediments are sometimes analyzed in multiple cores, but sample preparation (such as impregnation of the sediments with epoxy, thin section preparation etc) is expensive and very time-consuming, so duplication is not commonly done. Where radioactive isotopes from atmospheric nuclear tests in the late 1950s and 1960s can be identified in sediments (and in ice cores) such horizons can be useful time markers. Tephra layers (even finely dispersed crypto-tephra) can be useful in confirming a sedimentary chronology if the tephras can be geochemically fingerprinted to an eruption of known age (e.g. Pilcher et al., 2005). Finally, where annual layer counting is not feasible—as in many speleothems—radioactive isotopes (^{210}Pb, ^{14}C and uranium-series) can be used to obtain mean deposition/accumulation rates, though there may have been variations in those rates between dated levels.

High resolution sampling

Advances in analytical techniques have now made sub-annual sampling and measurements fairly routine in most high-resolution proxies. Whereas tree rings were generally measured in terms of total annual increments, densitometry now enables the measurements of wood density and incremental growth in early and latewood sections of each annual ring. Image analysis provides further options in terms of cell growth parameters (Panyushkina et al., 2003). Isotopic dendroclimatic studies require sub-annual sampling resolution to determine growth increments. In corals, such detailed sampling is now routine; often 10 or more samples will be obtained per annual increment (e.g. Mitsuguchi et al., 1996; Quinn and Sampson, 2002). Stalagmite research has rarely achieved such detail, with sampling intervals (in most studies) of a few years, at best. However, some studies have established chronologies by counting annual layers on polished sections under a microscope, and new analytical approaches (using an electron microprobe, secondary ionization mass spectrometry [SIMS], or excimer laser ablation inductively coupled plasma mass spectrometry [ELA-ICP-MS]) have made it feasible to identify annual layers through seasonal changes in trace elements (such as Mg, Ca, Sr, Ba and U), along multiple transects of a sample (e.g. Fairchild et al., 2001; Desmarchelier et al., 2006). Image analysis of varved sediments (via impregnated thin sections examined under a petrographic or scanning electron microscope) can reveal intra-annual sediment variations that may be associated with seasonal diatom blooms or rainfall events (Dean et al., 1999). In ice cores, it is now possible to make continuous multi-parameter measurements, providing extremely detailed time series (McConnell et al 2002a, b). Thus, in most natural archives available for high-resolution paleoclimatology, detailed measurements can be made to both define annual layers, or growth increments and to characterize changes therein. However, it is not necessarily the case that an annual layer fully represents conditions over the course of a year. Much of the sediment in a varve, for example, may result from brief periods of runoff. Similarly, annual layers in an ice core represent only those days when snowfall occurred. Indeed, they may not even do that, if snow was subsequently lost through sublimation or wind scour. Coral growth increments may result from more continuous growth, and trees may also grow more continuously, at least during the growing season. Speleothems accumulate from water that has percolated through the overlying regolith, and so short-term variations related to individual rainfall episodes are likely to be "smoothed out". Nevertheless, there is some evidence that extreme rainfall episodes can be detected in the carbon isotopes of speleothems in areas where the throughflow of water is rapid (Frappier et al., 2002).

Relationship between natural archive and climate

Extracting a climatic signal from individual archives requires an understanding of the climatic controls on them. Analysis of the temporal relationships between variables may provide a statistical basis for calibration, but a theoretical basis for such a relationship is also required, to direct some light into the statistical black box. This may require *in situ* process-based studies to understand the factors controlling the proxy signal. Even if such studies are short-term, they can provide valuable insights into how climate influences the system being studied, and hence improve our understanding of the paleoclimatic record. For example, studies of meteorological conditions at the ice-coring site on Sajama, Bolivia demonstrated strong seasonality in snow accumulation, with much of the snowfall that accumulated late in the accumulation season being subsequently lost via sublimation (Hardy et al., 2002). Consequently the ice core record is made up of sections of snow that accumulated for (at most) a few months each year, demonstrating that division of such records into 12 monthly increments is not appropriate (cf. Thompson et al., 2000). Similarly, hydrological studies in the Arctic have shown that in some lakes, much of the runoff and associated sediment may be transferred into the lake over the course of only a few weeks. For example, measurements at Sophia Lake (Cornwallis Island, Nunavut, Canada) showed that 80% of the runoff and 88% of the annual sediment flux occurred in the first 33 days of the (1994) melt season (Braun et al., 2000). This sediment was subsequently distributed across the lake floor, forming an annual increment (varve) but the climatic conditions that mobilized the sediment were brief and perhaps unrepresentative of the summer season (and the year as a whole). Other studies of arctic lakes indicate that watersheds containing glaciers provide more continuous runoff and associated sediment flux throughout each summer, and thus provide a better proxy for summer climatic conditions (e.g. Hardy et al., 1996). Thus, understanding the environment from which the proxy archive is extracted is critically important for proper interpretation of the paleoclimate record. Process-based studies (often derided as simply “monitoring”) have also provided insights into climatic controls on corals, showing strong non-linearities at high water temperatures (Lough 2004). *In situ* measurements within caves, aimed at better understanding of paleoclimate records, is now also being carried out (e.g. McDonald et al, 2004; Cruz et al., 2005). By comparison, dendroclimatology is far advanced because ecophysiological studies of tree growth have a long history. Consequently, factors influencing tree growth increments are well understood (cf.. Fritts, 1974; Schweingruber, 1998; Vaganov et al., 2006) providing a very strong foundation for paleoclimatic studies using tree rings.

Uniformitarianism

Perhaps because of the rapidity of recent climate change, many archives are no longer responding to climate in a manner that typifies much of the past. This was first noted by Briffa et al. (1998) who showed that some trees that were formerly strongly influenced by temperature were no longer so influenced, or at least, not to the same extent. Figure 2 shows the geographical distribution of this effect. Briffa et al., (2004) speculate that this might be related to recent increases in ultra-violet radiation resulting from the loss of ozone at high elevations. Others have argued it might reflect the fact that trees in some areas have reached a threshold, perhaps now more affected by drought stress than was formerly the case. Whatever the reason, it raises the question as to whether such conditions might have occurred in the past, and if so, would it be possible to recognize such a "decoupling" of the proxy archive from the ("normal") climate driver. Paleoclimate reconstruction is built on the principle of uniformitarianism, in which the present is assumed to provide a key to the past. If modern conditions (during the calibration period) are not typical of the long-term, this assumption will be invalid. It is thus important to resolve the reasons for such changes and determine if additional parameters (such as cell growth features) might provide clues about when such stresses may have overwhelmed the typical climate response.

On a related point, it is clear that many natural archives are being detrimentally affected by recent changes in climate. Thus, many high elevation ice caps in the tropics have been affected by surface melting and strong sublimation, so that the recent isotopic record has been degraded or even lost entirely (Thompson et al., 2000). Similarly, corals in many areas were greatly affected by exceptionally high sea-surface temperatures associated with the 1997-98 El Niño (Wilkinson et al., 1999). Many century-old *Porites* colonies in the Great Barrier Reef were killed at this time.

Frequency response

High-resolution records may have certain low frequency characteristics that differ from the spectrum of the climatic environment in which they are situated. Such effects may be due to long-term biological growth (in the case of trees, and perhaps corals), compaction (ice, sediments), non-climatic changes in depositional environment (lake sediments, speleothems), etc. This issue is especially important as efforts are made to extend paleoclimatic reconstructions further back in time, to reveal changes in climate over thousands of years. Sediments are certainly affected by compaction, but this can be relatively easily corrected for by examining changes in density. This is also true in ice cores. Diffusion of isotopes within firn leads to a reduction in the amplitude of isotopic values that must also be considered. Deposition rates in speleothems are determined by radiocarbon or uranium series dates, and this is generally sufficient to determine if deposition has been continuous over time. Certainly there are no compression issues to be concerned with, so in that sense speleothems do offer a very good option for identifying low frequency changes in climate. This is illustrated well in the Dongge cave record of Wang et al (2005) (Figure 3) which shows an underlying low frequency decline in monsoon precipitation, related to orbital forcing, on which decadal to centennial-scale variations are superimposed, which appear to be (at least in part) related to variations in solar irradiance.

The issue of determining low frequency changes in climate has been most problematical in dendroclimatology. The biological growth function of trees must first be removed before climatic information can be extracted. In doing so, some low frequency information may be lost. Furthermore, since most tree ring series are short, assembling a composite long time series from many short records, makes it even more problematical to obtain low frequency information over timescales longer than the typical segment length (Cook et al 1995). New approaches to standardization of tree ring series have been developed and these help to preserve more low frequency information than more traditional methods. However, such approaches require very large data sets and so cannot be applied in all cases. Another approach involves combining different proxies, some that may contain more low frequency information with others that capture well higher frequency information, so that together they cover the full spectrum of climate variability (Moberg et al, 2005). This approach has much promise, and further fine-tuning will likely lead to a better understanding of large-scale climate variability over recent millennia.

High resolution proxies: challenges and opportunities

High resolution paleoclimatic records provide unique opportunities to better understand the climate system because they extend the limited sampling interval that is available from short instrumental records. This longer perspective is especially important for studies of rare events, such as explosive volcanic eruptions or the occurrence of extreme climatic conditions, such as droughts or floods. Ice cores reveal (through sulfate and electrical conductivity measurements) that there have been much larger explosive volcanic eruptions in the past than during the period of instrumental records (Zielinski et al., 1994; Castellano et al., 2005), and by identifying these events, it is then possible to explore the relationship between eruption size and location and the subsequent climatic effects (e.g. D'Arrigo & Jacoby, 1999). Many dendroclimatic studies have recognized the connection between explosive eruptions and cold growing season conditions, which sometimes led to frost damage in trees (e.g. LaMarche and Hirschboeck, 1984; Baillie and Munro, 1988; Briffa et al., 1990; D'Arrigo et al., 2001). Proxy records of volcanic forcing also provide a much larger database of eruption events than are available in the instrumental period; by compositing climatic conditions following such events, the signal to noise ratio is increased, giving a clearer view of the climate system response to such events. Thus Fischer et al. (2006) were able to show that summer conditions in Europe have tended to be both cold and dry after major tropical volcanic eruptions, but in winter a positive NAO circulation has generally been established, resulting in mild, wet conditions in northern Europe and well below average precipitation in the Alps and Mediterranean region.

Dendroclimatic research has been especially important in documenting the frequency, geographical extent and severity of past drought episodes as well as periods of unusually high rainfall amounts; such studies have been especially extensive in the United States (e.g. Stahle and Cleaveland, 1992; Hughes and Funkhauser, 1998; Cook et al., 2004). These have shown that there has often been a strong connection between severe droughts in the southwestern United States and the occurrence of La Niña episodes, although the precise geographical pattern of each drought has varied over time (Stahle et al., 2000; Cole et al., 2003). Tree ring research has also been applied to reconstructing modes of circulation in the past, such as the North Atlantic Oscillation (NAO) (Cook et al., 1998; Cullen et al., 2001), Pacific Decadal Oscillation (PDO) (Gedalof and Smith, 2001) and the Atlantic Multidecadal Oscillation (AMO) (Gray et al., 2004). In all of these cases, the paleoclimatic reconstructions have expanded our understanding of the spectrum of variability of these modes of circulation and provided insight into how large-scale teleconnections (and interactions between Atlantic and Pacific-based circulation regimes) may lead to persistent, large amplitude anomalies over North America and other regions.

Great strides have been made in constructing hemispheric and global-scale patterns of past climate variability by combining many different types of high resolution paleoclimatic records, using a variety of statistical methods (Mann et al., 1998, 1999, 2005; Rutherford et al., 2005; Moberg et al., 2005). These studies have demonstrated the importance of volcanic and solar forcing, and of the increasingly dominant effects of anthropogenic forcing over the last 150 years. Nevertheless, such studies largely rely on the most extensive database of paleoclimatic reconstructions that are currently available, which is that provided by dendroclimatology. On the one hand, this is good because the physiological basis for how trees respond to climate is well understood, thanks to decades of careful studies, and tree rings provide the most accurate chronologies available. However, using tree rings in long-term paleoclimate reconstructions is dogged by questions of uniformitarianism (a question not unique to dendroclimatology, of course) but more significantly, by the difficulty of resolving the full spectrum of climate variability from overlapping, relatively short, tree-ring series. Resolving this matter, by obtaining longer records where possible, expanding the tree ring database to improve data density back in time, and by developing new statistical approaches are all necessary to ensure that long-term paleoclimatic reconstructions are as reliable as possible. New isotopic and image analysis techniques applied to tree growth may add further information about past climate variations, in regions formerly off-limits to dendroclimatologists, thereby extending the geographical domain for large-scale climate reconstruction. New proxies, especially from lake sediments and speleothems will likely further supplement this expansion of high resolution records, providing records with more robust low frequency characteristics that can be combined with proxies that are exceptionally good at capturing high frequency climate variability (e.g. Moberg et al., 2005). In this way, the next decade of high resolution paleoclimatology will likely see paleoclimatic reconstructions with far less uncertainty, covering more geographical regions and providing meaningful estimates of climate sensitivity before the Anthropocene.

Acknowledgements

I gratefully acknowledge the support of my research by NOAA (NA050AR4311106), NSF (ATM-0402421) and the Department of Energy (Contract DE-FG02-98ER62604).

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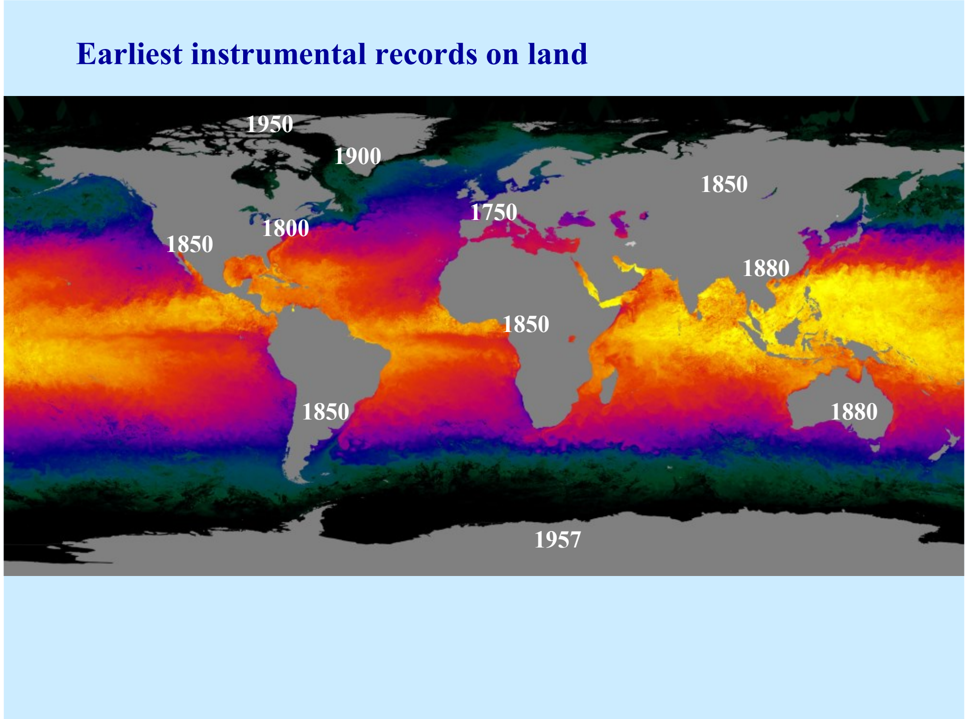

Figure 1. Approximate earliest date of continuous instrumental records, which defines the need for high-resolution proxy-based data prior to these dates.

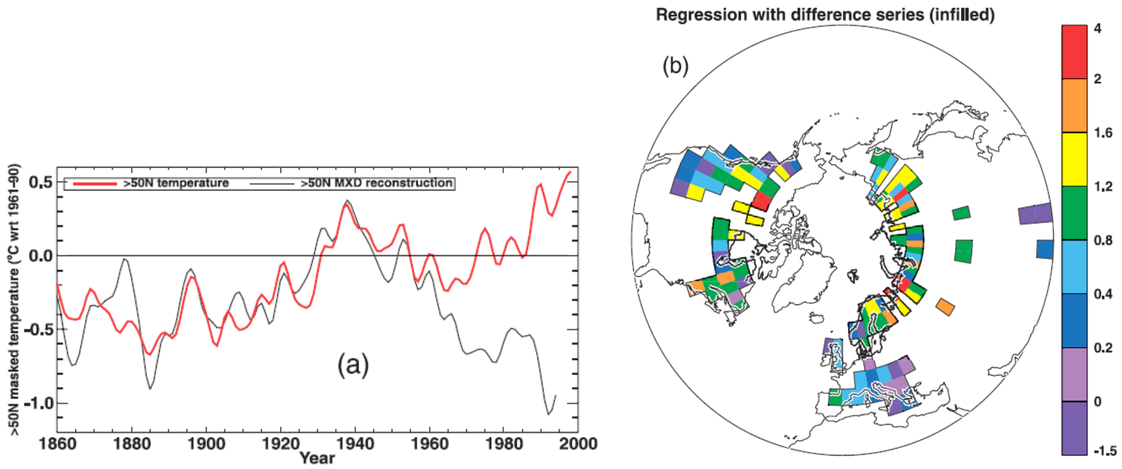

Figure 2. (a) Instrumental temperatures (red, heavier line) and tree-ring density reconstructions of temperature (black, thinner line) averaged over all land grid boxes north of 50ºN, smoothed with a 5-year low-pass filter.

b) map showing where the average temporal pattern of divergence between tree-ring density chronologies and mean warm season temperatures is most apparent. The smoothed difference between the black and red curves in Figure 2a were regressed against the local difference curves produced from the averages of data in each grid box. Where the regression slope coefficients are progressively greater than 1.0 (the yellow, orange and red boxes, which are generally the most northerly locations), the greater is the local difference between density and temperature. In the areas shown blue and light purple (areas further south), the difference is apparent but of lower magnitude. The areas shown as dark purple (basically the most southern regions) do not show the divergence [note change in scale on color bar] (from Briffa et al., 2004). On-line version shows these figures in color.

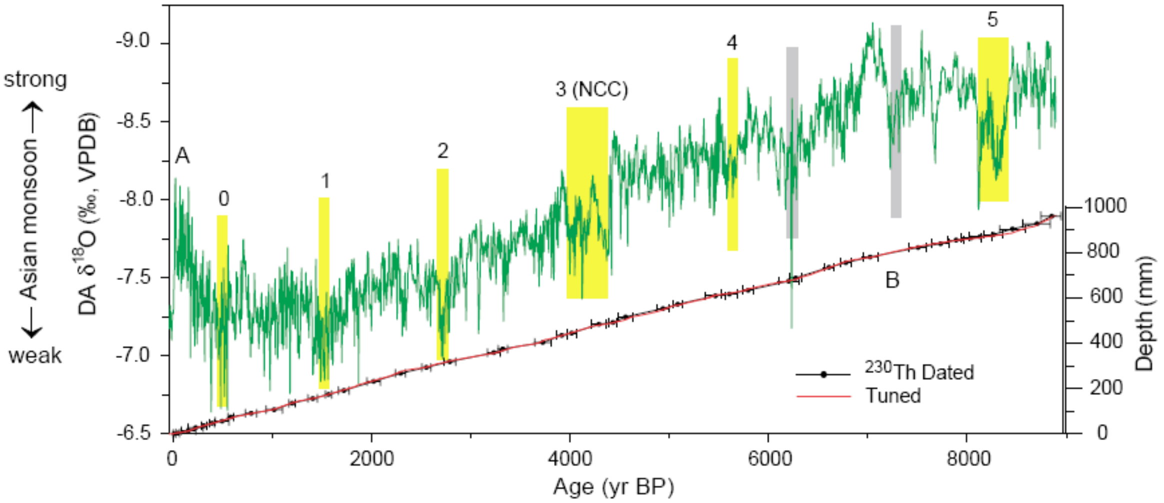

Figure 3. A) δ^{18}O time series of a Dongge Cave (China) stalagmite (thin line). Six vertical shaded bars denote the timing of Bond events 0 to 5 in the North Atlantic. Two vertical gray bars (without numbers) indicate two other notable weak Asian monsoon periods that can be correlated to ice-rafted debris events. Higher frequency variability appears to be related to solar (irradiance) forcing. NCC is the Neolithic Culture of China, which collapsed at the time indicated.

(B) Age-depth relationship. Black error bars show ^{230}Th dates with 2σ errors. Two different age-depth curves are shown, one employing linear interpolation between dated depths and the second slightly modified by tuning to INTCAL98 within the ^{230}Th dating error (from Wang et al., 2005). On-line version shows this figure in color.