Timescales of Climate Change

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Introduction

Climate varies. Although often defined in terms of 'average weather,' or the expected values of statistical parameters over some interval, when looking at climatic time series plotted over any interval (from years to millions of years) for any location (from point to globe), one sees the tremendous variability of the record. Typical values or central tendencies for a climate variable can indeed be observed, as can general ranges of values within which the variable remains. However, most of the time a climate variable (and that part of the climate system it represents) might be described as continuously heading from one level to another, never remaining at a particular value for long. Intervals with low variability are generally the exceptions rather than the rule in climatic time series. Here, 'variance' refers to the statistical quantity (the mean of the squared deviations about the long-term mean); 'variability' refers to the tendency of records to vary; and 'variation' refers to a particular portion or feature of a record or to the time-course of a variable.

Variability of climate occurs across a range of timescales (the focus of this article) and does so in a fashion that exhibits considerable structure. Rather than displaying a simple pattern of variability that increases as a function of time span or record length, as with a system that obeyed simple scaling laws (Kantz and Schreiber, 2004), the climate system has some preferred temporal scales of variability that reflect the nature of the external forcing of the climate system or the internal time constants of the components of the climate system itself (Saltzman, 2002). Although some of these external controls are intrinsically periodic, such as the variations of the Earth's orbital elements (Imbrie et al., 1984), most are not. Similarly, the internally generated variations of climate, including some that might be described as 'cyclical,' are best described as only quasiperiodic.

One approach for characterizing or describing the variability of climate is the variance spectrum, which displays a statistical property, variance, as a function of the period or frequency of the variation. 'Peaks' in such a display point to particular frequencies or timescales at which variability is concentrated. A schematic version of a variance spectrum for the climate system for timescales from a year to a billion years is illustrated later. In addition, evolutionary or 'moving-window' spectral analyses can be used to reveal the changing importance over time of variability on different timescales, and two examples are also described.

Perhaps owing to its heritage in signal processing (Jenkins and Watts, 1968) and to its wide application in developing the astronomical (Milankovitch) theory of climate change, the application of the variance spectrum to illustrate timescales of climate variability naturally directs a user toward the periodic or oscillatory features in a time series. Hence, explanations of those features usually invoke some kind of regular cyclical mechanisms, either external (Sun, Moon, planets) or internal (oscillatory 'climate-modes').

Several factors may predispose researchers to see cycles in time series (in addition to the tendency to see order in apparent chaos). These include the tendency for climate variables to vary between some general limits, and the consequences of applying some common data-analytical methods, such as the variance spectrum or moving-average filters. A few examples discussed later will show how spurious periodicities can arise when characterizing the timescales of climate variability.

An alternative approach for describing the nature of climate variability is to describe the characteristic features or kinds of variations that recur in many climatic time series. There is a relatively small number of kinds or patterns of variation that climatic time series display. These occur across a range of different timescales and can be distinguished by the extent of their influence throughout different levels in the climate-system hierarchy, their predictability, and the extent to which they represent progressive trends, or regular or irregular variations.

Climate Variations

The Hierarchy of Climate System Controls and Responses

Climatic variations occur within a hierarchy of controls and responses, which begin at the highest level with the external controls of climate, proceed through global, hemispheric, continental, and regional scales, and end with the variations of individual climate variables at specific locations at the lowest level (Bartlein, 1997). Responses at any one level of the hierarchy become the controls of variations of the components at lower levels. For example, on timescales of 10^4–10^6 years, ice sheets are dependent variables in the climate system, governed by orbitally controlled variations in insolation. At shorter timescales (10^4–10^3 years), ice sheets act as independent variables that have an important influence on global temperatures and atmospheric circulation. With the exception of the annual cycle, there is a general tendency for the variations of components at higher levels in the hierarchy to exhibit more long-term variability, while those at lower levels experience more short-term variability.

The existence of this hierarchy also has implications for attempts to explain the variations at a particular location. For example, although climatic variations at a location are ultimately governed by global-scale controls, a specific paleoclimatic record is not representative of the general state of the global system. This situation arises because the intermediate controls and responses have the potential of reinforcing, canceling, or even reversing the longer-term global trends. Gradual changes in large-scale controls may sometimes produce abrupt local changes when atmospheric circulation is reorganized. Conversely, abrupt changes in the large-scale circulation may produce warming in some regions and cooling or no change in others, as can be seen in the spatial anomaly patterns of year-to-year variations of climate. Consequently, while it may be difficult or even impossible to ascribe a particular climate variation at a location to a specific configuration of higher-level controls, shorter-term variations at lower levels are strongly conditioned by the particular state of system at higher levels. Therefore, any discussion of the timescales of climatic variability should explicitly acknowledge the spatial scale or extent of the system being discussed.

Some Representative Paleoclimatic Time Series

To illustrate the spectrum and characteristic features of climatic variations across a range of timescales, it will be useful to examine some representative time series. **Figure 1(a)** is a composite global oxygen-isotope record that provides a general description of the global cooling during the Cenozoic that culminated in Quaternary glacial–interglacial variations (Zachos et al., 2001). This record was constructed from a number of individual records, which can be plotted as individual points, but not as time series. In addition to the general trend, individual steps toward colder conditions are evident. **Figure 1(b)** shows another composite record, this time constructed by superimposing or 'stacking' individual records to form a single series (Lisiecki and Raymo, 2005). This shows the periodic variations in global ice volume associated with the Earth's orbital elements, as well as the changes in the relative importance of the variations at different timescales.

Oxygen-isotopic variations from the GISP 2 Greenland ice-core record are shown in **Figure 1(c)** (Stuiver et al., 1997). This series shows the large-amplitude millennial timescale variations known as the Dansgaard–Oeschger cycles that occur throughout most of the record, the Younger Dryas climate reversal (12 800–11 600 years BP, Alley et al., 1993), and the much lower amplitude variability in this record during the Holocene. **Figure 1(d)** shows a speleothem oxygen-isotope record that exhibits the long-term decline in the strength of the East Asian monsoon, along with decadal-to-century variations throughout the Holocene, a pattern typical of many Holocene records (Mayewski et al., 2004). **Figure 1(e)** illustrates a reconstruction of Northern Hemisphere temperature anomalies over the past two millennia (Moberg et al., 2005), along with the observational record of the past century (Hansen et al., 2006). Like other similar reconstructions (Mann and Jones, 2003), this record shows interannual-to-century-scale variations, and the unprecedented increase in temperature over recent decades.

These series do not illustrate the entire range of variations experienced by the climate system over the Quaternary. A network of time series that span the different timescales and levels in the hierarchy would be required, and such a network does not exist. However, this set of series does illustrate the variety of characteristic features in climatic time series that will be discussed further later.

The Spectrum of Climate Variability

There are several ways of schematically illustrating the nature of climate variability (in addition to simply plotting representative series). These include 'powers-of-ten' presentations (Webb, 1989), wherein climatic time series of different duration (e.g., the past 100 000, the past 10 000, the past 1000 years) are plotted and examined; portrayal of the variance spectrum of climatic time series, which reveals the relative importance of variations at different timescales (Mitchell, 1976; Shackleton and Imbrie, 1990); or 'scale diagrams' that indicate the characteristic temporal and spatial scales on which the particular components of climate vary (McDowell et al., 1991). Of these, the variance spectrum has often been used to illustrate the relative importance of climatic variations on different timescales.

The Variance Spectrum

The variance spectrum displays the relative or absolute magnitude of variance in a time series at a particular period or frequency, as a function of that period or frequency (**Figure 2**), and provides a 'frequency domain' summarization of climate variability. Typically, variance spectra are plotted on log scales to accommodate the large range of timescales discussed, and the general tendency is for the total variance of longer-term variations of the climate system (e.g., glacial–interglacial variations) to be orders-of-magnitude larger than shorter-term variations (e.g., interannual variations). Mitchell (1976) drew a schematic variance spectrum for climate-system variations that covered timescales ranging from the age of Earth (geological timescales) down to hours (meteorological timescales). Based on analyses of series that represented parts of this time range (Hays et al., 1976; Kutzbach and Bryson, 1974), as well as considerable intuition, Mitchell's spectrum was innovative in its attempt at presenting a general conceptual model that organized a large body of insight into how the climate system operates. Subsequent workers have progressively refined Mitchell's schematic spectrum (Saltzman, 2002), or developed data-derived spectra for parts of the record (Shackleton and Imbrie, 1990; see also Wunsch, 2003).

Figure 2 is based on Mitchell's spectrum, supplemented by material from the descendent papers. It differs somewhat from Mitchell's in that the spectrum here was drawn to display an overall slope of −2, that is, the 'power-law' spectrum of a simple random walk, in order to depict the long-run 'nonstationarity' of the climate system (Wunsch, 2003). Superimposed on this general background variability, which dominates the spectrum, are 'peaks' that represent the concentrations of variability associated with external drivers or internal autovariations. Some of these, like those associated with the annual cycle, ENSO, and the orbital elements, have underlying physical mechanisms that are truly cyclical (and hence are drawn with sharper peaks), while others, like the Holocene or tectonic 'cycles' do not. These are commonly referred to as 'cycles' but at best are only quasi-, or apparently, periodic. They are drawn here with broader peaks or 'shoulders' in the spectrum.

The first-order pattern on the schematic spectrum is the great increase in variance that occurs with increasing period, with second-order peaks of lower importance superimposed on this overall pattern. Comparisons can be made between the peaks and overall background variance at particular timescales. For example, the variations in global ice volume at a period of 100 ka that characterize the past million years (**Figure 1(b)**) have similar variance as the variations in the general mean state of climate that take place on 5–10 My timescales (**Figure 1(a)**). The tectonic 'cycle' peaks represent climate-system variability on timescales of 400 My ('Wilson cycles' of continental

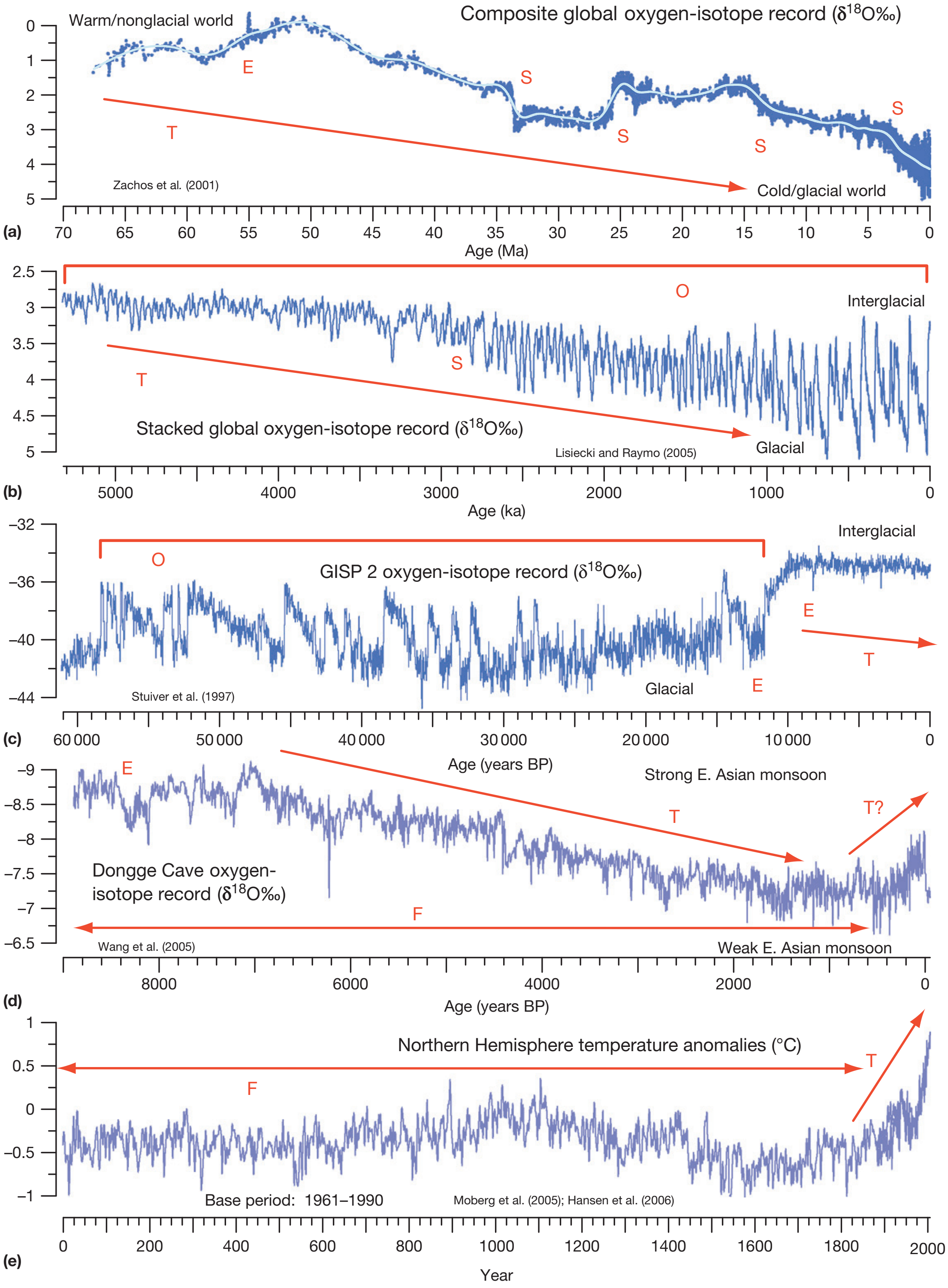

Figure 1 Some representative paleoclimatic time series and examples of typical kinds of climatic variations: (a) composite global oxygen-isotope record for the Cenozoic (Zachos et al., 2001); (b) stacked global oxygen-isotope record (Lisiecki and Raymo, 2005); (c) oxygen-isotopic variations from the GISP 2 Greenland ice-core record (Stuiver et al., 1997); (d) Dongge Cave speleothem oxygen-isotope record (Wang et al., 2005); (e) reconstruction of Northern Hemisphere temperature anomalies over the past two millennia (Moberg et al., 2005), along with the observational record of the past century (Hansen et al., 2006). Typical kinds of climatic variations (**Table 1**) are illustrated as follows: T, trend; S, step; O, oscillation; F, fluctuation; and E, event.

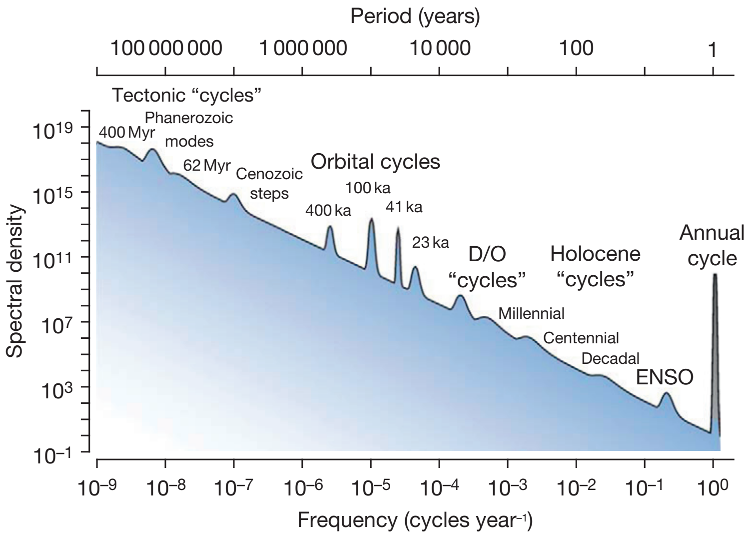

Figure 2 Schematic variance spectrum of climatic variations.

assembly and reassembly; Wilson, 1966), 200 My (variations among Phanerozoic climate modes, Frakes et al., 1992), 62 My (fossil diversity variations; Rhode and Muller, 2005), and steps in the Cenozoic oxygen-isotope record that are approximately 10 My apart (**Figure 1(a)**; Zachos et al., 2001). Orbital cycles include the 400, 100, 41, and 23 (plus 19) ka climate (ice-volume and monsoon-strength) variations related to periodic insolation variations. A broad spectral peak is shown for Dansaard–Oeschger cycles (**Figure 1(c)**), although these variations are not strictly periodic (Alley et al., 2001). Holocene timescale variations are shown schematically as broad peaks corresponding to millennial, centennial, and decadal-scale variability. Although often described as ‘cycles’ (e.g., ‘1500-year Bond cycles,’ see Bond et al., 2001), the periodicity of the variations is not sufficiently regular for them to be considered truly cyclical. Similarly, ENSO-related variations are only quasiperiodic and contribute a broad peak to the variance spectrum, while the truly periodic annual cycle contributes a very narrow peak. (The width of the annual-cycle peak on **Figure 2** is exaggerated for visibility.)

The overall impression from either the schematic spectra, or from the time series themselves, is that (with the exception of the annual cycle) the variations of the climate system are almost completely stochastic. Even the variations arising from external controls that are nearly deterministic (such as the variations of the orbital elements that generate ice-volume variations) or from internal variations with physical generating mechanisms that are oscillatory in nature (such as ENSO) have considerable unpredictable ‘noise’ components. Variability of climate could thus be described as occurring over all timescales, with variability greatly increasing as scale increases, but with concentrations of variance at some preferred timescales.

Changing Variability

A variance spectrum, such as that in **Figure 2**, displays the ‘global’ level of variance at specific periods, and consequently masks the ‘local’ (over time) changes in the importance of variability at particular periods, which is evident in many climatic time series (**Figure 1(b)** and **(c)**). One device for illustrating such changes in variability or in the relative importance of variations on different timescales is the evolutionary spectrum, also known as a moving-window spectrum. Evolutionary spectra constructed using the wavelet procedure (Torrence and Compo, 1998) for the stacked marine oxygen-isotope record (Lisiecki and Raymo, 2005) and the bidecadal GISP 2 oxygen-isotope record (Stuiver et al., 1997) are shown in **Figure 3**. The plots show ‘scaled power’ or variance plotted as a function of period of variation and time.

The evolutionary spectrum for the stacked global oxygen-isotope record clearly shows the increase in importance in 41-ka variations beginning around 2.65 Ma and in 100-ka variations beginning around 1 Ma, but it also shows that variations at these timescales were important during previous times. The 41-ka variations are evident throughout the record and variations at the other orbital periods can be seen to vary in their relative importance. The evolutionary spectrum for the GISP 2 oxygen-isotope data (**Figure 3**) clearly shows the importance of millennial-scale Dansgaard–Oeschger variations prior to the Holocene and also illustrates the changing period of those variations. From the beginning of the record plotted here until around 42 000 years BP, variance is concentrated at periods around 5000 years, and shifts to progressively shorter periods from then until 30 000 years BP. During MIS 2 and during the Holocene, there is little concentration of variance at any period shorter than 5000 years. The high variance at the longest timescales (e.g., 10 000 years and longer), although not demonstrably significant due to record-length constraints, reflects the important underlying signature of orbital-timescale variations in this record.

Changes in the relative importance of variations on different timescales are the rule in climatic time series, appearing in a variety of differing contexts (Overpeck and Webb, 2000). Explanation of the changes in variability of climatic time series presents a potentially greater challenge than explanation of changes in the mean, but must be accepted owing to the great impact climate variability has on human activity.

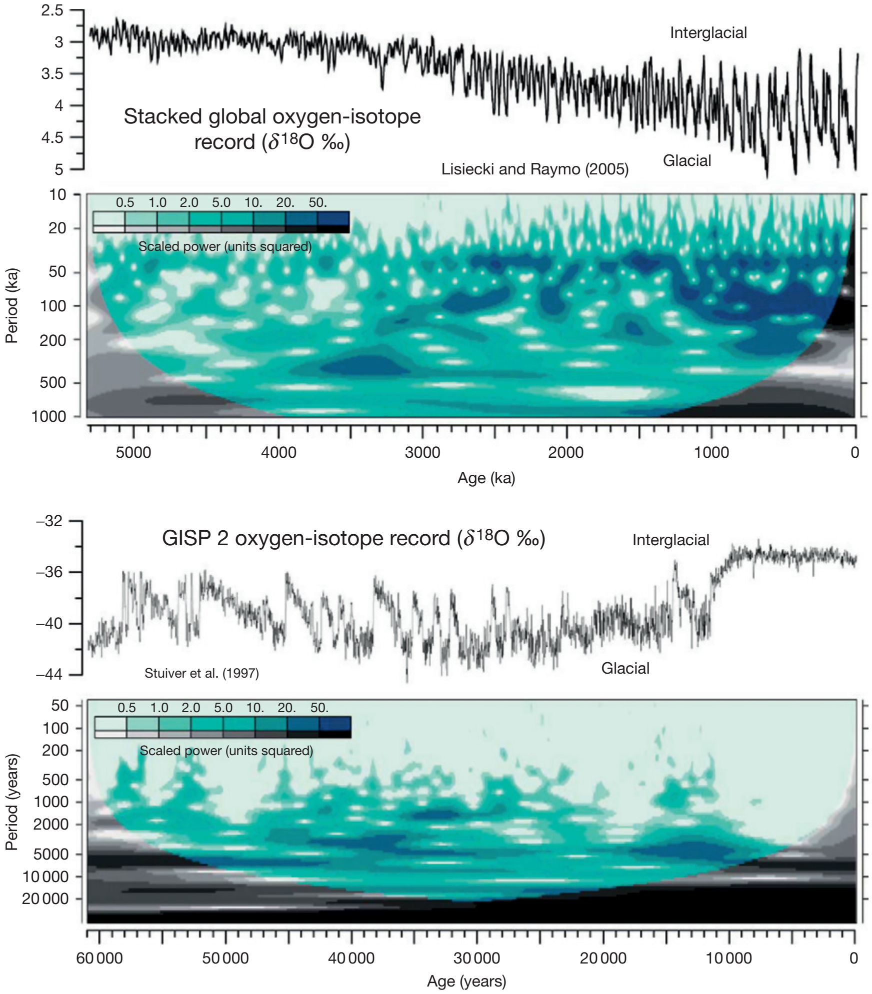

Figure 3 Evolutionary spectra calculated using the wavelet method (Torrence and Compo, 1998; http://atoc.colorado.edu/research/wavelets/) for the stacked global oxygen-isotope record (Lisiecki and Raymo, 2005) and oxygen-isotopic variations from the GISP 2 Greenland ice-core record (Stuiver et al., 1997). Gray areas indicate the regions outside of the 'cone of influence' where record-length considerations make the estimates less robust.

Spurious Periodicity

As mentioned earlier, the use of the variance spectrum to characterize climate variability, when coupled with the general tendency of climatic time series to wander back and forth, naturally directs attention toward explanations of climatic variability that invoke controls or mechanisms that are cyclic in nature. However, it is likely that the nature of the variability plus some commonly applied data-analytical tools yield series that merely appear periodic when they intrinsically are not so.

Figure 4 shows three examples of time series that feature quasiperiodic variations, each generated by filtering or transforming a series of normally distributed random numbers in an intrinsically aperiodic way. In each figure, the random numbers are plotted in gray in the background on an arbitrary scale, and the generated series in black.

Figure 4(a) shows a time series generated by the second-order autoregressive model:

$$z_t = \phi_1 z_{t-1} + \phi_2 z_{t-2} + a_t$$

where $\phi_1 = 1.32$ and $\phi_2 = -0.66$, and a_t is a normally distributed or Gaussian white-noise time series. This is the 'classical' second-order autoregressive or AR(2) model that describes Wolfer's sunspot series (Box and Jenkins, 1976), and autoregressive models have generally found wide application in representing time series with both short- and long-run memory. The resulting series clearly shows a rough 10 time-step oscillation, and further displays a change in amplitude and regularity of this oscillation mid-way through the series, which would probably provoke comment if this were a real paleoclimatic time series.

Figure 4(b) shows a linearly detrended time series, $\tilde{x}_t$, where

$$\tilde{x} = x_t - b_0 - b_1 t$$

and x_t is an integrated autoregressive process

$$x_t = x_{t-1} + y_t$$

$$y_t = \phi_1 y_{t-1} + a_t$$

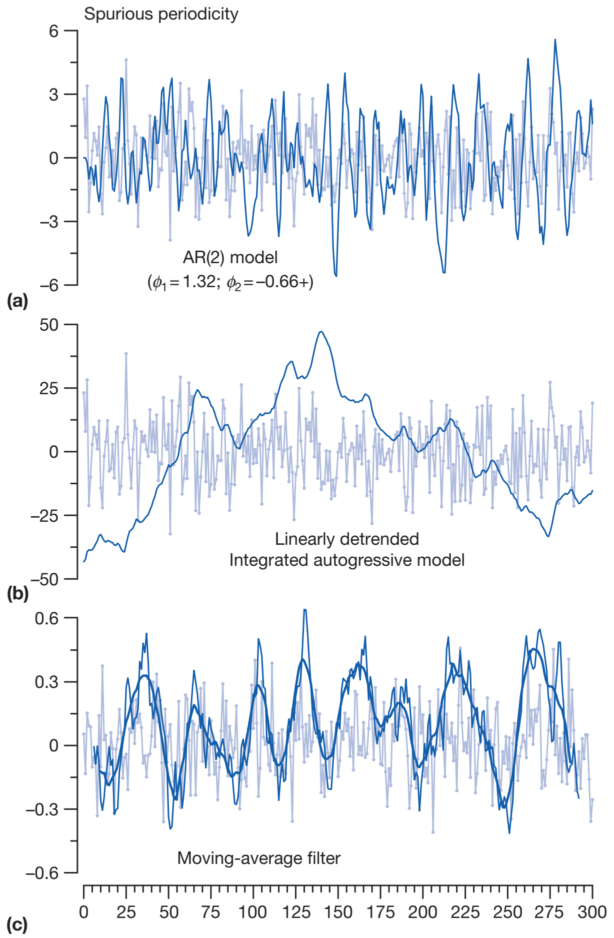

Figure 4 Some illustrations of spurious periodicity. Series plotted in pale blue are the white-noise time series used to generate the simulations in dark blue: (a) a second-order autoregressive process (AR(2)); (b) an improperly detrended integrated autoregressive model; and (c) running mean-filtered white noise (thick blue line represents the output from a 15-term running mean, thin blue line from a 10-term running mean of the data represented by the thick blue line).

with $\phi_1 = 0.8$ and a_t a normally distributed white-noise time series. The series x_t is an example of a 'difference-stationary' time series, or one in which the first differences of the series, $y_t = x_t - x_{t-1}$, are stationary or vary in a stable fashion over time. If treated instead as a 'trend stationary' time series, spurious periodicities can appear in the residual series, $\tilde{x}$, when x_t is linearly detrended (Nelson and Kang, 1981). The example series shows a broad cycle with a wavelength close to the record length and also shows lower-amplitude, higher-frequency variation, with a period around 20 time steps. Again, although generated by an aperiodic process, the resulting series could be viewed as being cyclic in nature. Paleoclimatic time series are frequently detrended as part of preliminary steps in data analysis.

Probably the most frequently applied method for generating apparently periodic variations in a time series when none really exist is illustrated in **Figure 4(c)**, which demonstrates the Slutsky–Yule effect (von Storch and Zwiers, 2001). The dashed line in **Figure 4(c)** is the result of applying a 15-term running mean to a white-noise time series:

$$y^t = \frac{1}{n}\sum_{i=1}^{n} w_i a_{t-i}$$

where $n = 15$, $w_1 = w_2 = \cdots = w_n = 1$, and a_t is the white-noise time series. The solid line is simply the y_t's further smoothed by a 10-term running mean. The resulting series are clearly periodic and would likely be described or explained as 'cyclic' if they were real. Slutsky's theorem (Jenkins and Watts, 1968) shows that by repeated application of summing (as in the running mean) or differencing filters, white noise can be reduced to a sine wave. In practice, smoothing like that done by the running mean can occur naturally in paleoclimatic records that integrate environmental conditions over time, but usually the smoothing occurs during data analysis.

All three series appear periodic yet are generated by relatively simple processes, without invoking any mechanism that could be intrinsically cyclical or periodic in nature. Because there are multiple ways of generating series with apparent periodicity, some of which are related directly to commonly applied data-analysis procedures, a relatively high standard should exist for declaring a particular series as cyclical and searching for explanations within the class of oscillatory or cyclical physical mechanisms.

Characteristic Kinds of Climate Variability

A Taxonomy of Typical Features in Climatic Time Series

An alternative 'time domain' approach for describing the nature of climate variability, other than that provided by the variance spectrum, is to describe the kinds of typical features or characteristic variations that recur in many climate climatic time series across a range a different timescales. There are a relatively small number of different kinds of variations that climatic time series display.

Table 1 gives examples of such typical variations, the levels in the climate system hierarchy that contain the controls of the variation, and those that are involved in the response. The table also indicates the predictability and reversibility of the individual kinds of variations. Climate variations are (a) predictable (P), if the timing and amplitude of the variations can be specified; (b) expectable (E), if either the timing or amplitude can be specified, but not both; or (c) unpredictable (U), if neither the timing nor amplitude of the variation can be specified. Variations are reversible (R), if the climate returns to a previous general mean state following the occurrence of the variation, or not reversible (N), if the climate does not return. The predictability and reversibility has implications for the biotic response to climate variations: Migration is the principal response to predictable and reversible climatic variations, while evolution (and extinction) is that for unpredictable and irreversible variations (Bartlein and Prentice, 1989; and Bennett, 1997). The table also shows the relative importance of trend, systematic (or periodic), and irregular components.

Table 1 Characteristic features or kinds of climatic variations

Kinds of variations	*Examples*	*Levels in hierarchy*[a]		*Predictability/ reversibility*[b]		*Components of temporal variations*[c]		
		Control	*Response*	*Predict.*	*Reverse*	*Trend*	*System.*	*Irreg.*
Trends								
Era-long	Cenozoic global cooling and glacierization	E	G–L	E	N	H	L	L
Glacial–interglacial	Last deglaciation	E,G	H–L	P	R	H	L	L
Multi-millennial	Late Holocene summer cooling in northern mid-latitudes	G–C	R–L	E	R	L	L	H
Century-long	Global warming	G–C	R–L	E	R	L	L	H
Steps								
Inter-epoch	Onset of N. Hemisphere glaciation (~2.65 Ma)	E	G–L	U	N	H	L	L
Millennial	5.5 ka African Monsoon collapse	C	R–L	E	R	H	L	L
Oscillations								
Periodic (orbital)	Ice sheet growth and decay, monsoon strengthening/ weakening	E	G–L	P	R	L	H	L
Changing-periodic (orbital)	Strengthening of 100-ka cycle in past million years	E	G–L	U	N	L	H	L
Quasiperiodic (suborbital)	Dansgaard–Oeschger ‘cycles’ (75–10 ka)	E,G	H–L	E	R	L	M	H
Interannual (10^0–10^1 yrs)	ENSO variations, decadal-scale climate anomalies	H,C	R–L	E	R	L	M	M
Fluctuations								
Holocene (10^3–10^4 years)	Holocene temperature and precipitation variations	G,H	C–L	E	R	M	L	H
Submillennial (10^3–10^4 years)	Medieval warm period/Little Ice Age variations	G–C	R–L	E	R	L	L	H
Interannual (10^0–10^1 years)	Aperiodic interannual climate variations	H,C	R–L	E	R	L	L	H
Events								
Excursions (10^5–10^6 years)	Late Paleocene Thermal Maximum	G	C–L	U	R	H	L	L
Climate reversals (10^2–10^4 years)	Younger Dryas climate reversal (~12.8–11.6 ka)	G–C	R–L	E	R	H	L	L
“Abrupt changes” (10^1–10^2 years)	8.2 ka event	G–C	R–L	E	R	L	L	H
Interannual (10^0–10^1 years)	Pinatubo eruption global cooling	G	R–L	E	R	L	L	H

[a] Levels in climate system hierarchy (E, external; G, global; H, hemispheric; C, continental; R, regional; L, local) controlling (Control) characteristic features of climatic variation or responding (Response) to them.

[b] Predictability (Predict.) and reversibility (Reverse) of characteristic features of climatic variations: P, feature is predictable at the temporal or spatial scale indicated; E, feature is expectable, but not specifically predictable; U, feature is unpredictable.

[c] Relative amplitude (H, high; M, medium; L, low) of components of temporal variations (Trend, Systematic (periodic or otherwise predictable), Irregular).

Trends

Trends are progressive increases or decreases in the levels of a particular climate variable; they appear in paleoclimatic variations on all timescales, but are particularly evident at certain scales. At the longest timescales displayed in Figure 1(a), cooling during the Cenozoic is evident in the general change in oxygen-isotopic ratios toward heavier values (i.e., toward cooler oceans, more ice). This trend is probably driven by the external controls of the climate system, with all the lower levels in the hierarchy responding. The general trend is broken, of course, by local increases in global temperature (as in the Eocene, ~50 Ma), and by locally more rapid decreases, but the overall impression when viewing this series is of a progressive movement toward cooler conditions. The cooling trend is therefore expected once underway (but its particular amplitude is not predictable), nonreversing overall, and dominated by the long-term changes (Table 1). Figure 1(b), oxygen-isotope data for the past 5 My, also shows a generalized trend, which is the same climatic change as the more rapid decrease in global temperatures that is evident in the last part of Series A. On a shorter timescale (Figure 2(c)), the general transition between the Last Glacial Maximum (about 21000 years ago) and the present can be viewed as a trend (predictable and reversible), although broken by the Younger Dryas climate reversal (between 12.8 and 11.6 ka). During the Holocene (Figure 1(d)), many locations in the northern mid-latitudes experienced a cooling trend in summer, or in the northern tropics and subtropics, a reduction in the strength of the monsoon. Finally, during the last century (**Figure 1(d)**), the global mean temperature, as well as that at individual stations, has generally increased.

Steps

Steps are the abrupt (relative to the timescale of variations under consideration) transitions from one level to another, and appear on many different timescales. Notable examples of steps in the representative series include the unpredictable and nonreversing interepoch decreases in global temperature during the Cenozoic (**Figure 1(a)**). Similarly, abrupt steps occur at the beginning and end of the Younger Dryas climate reversal and at the terminations of the 'Dansgaard–Oeschger' cycles during the interval between 60 and 20 ka (**Figure 1(c)**). These steps are expected, but not predictable, and have little irregular variation superimposed on the transition from one level to another.

Oscillations

Oscillations are either periodic or quasiperiodic variations about a stationary or slowly changing level and are one of the more prominent features of paleoclimatic time series. Oscillations dominate the glacial–interglacial variations in global temperature, and the variations in the continent–ocean temperature contrast that govern the monsoons, each generated by the periodic variations of the Earth's orbital elements (**Figure 1(b)**) (Imbrie et al., 1984; Prell and Kutzbach, 1992). Consequently, these variations are highly predictable and systematic. One important characteristic of the oxygen-isotope variations apparent in **Figure 1(b)** is the change in the relative importance of the different periodic components. Prior to 1 Ma, the 41-ka cycle is relatively more important, whereas thereafter, the 100-ka cycle becomes more prominent. These changes in periodicity seem inherently unpredictable and nonreversing. Quasiperiodic variations (i.e., variations that are less regular than the strictly periodic ones of the stacked global record) appear at 'suborbital' timescales, as in the aforementioned Dansgaard–Oeschger cycles. Interannual climate variations such as those constituting the El Niño/Southern Oscillation (ENSO) variations (Diaz and Markgraf, 2000) have also been described as quasiperiodic. Although systematic variation is apparent in these series, they are only expected owing to the absence of strict periodicity.

Fluctuations

Fluctuations are aperiodic variations of climate appearing at all timescales, but they tend to be more evident at shorter timescales. Variations in Northern Hemisphere temperature are dominated by interannual fluctuations, with decadal- and centennial-scale variations of less importance, with the exception of the past century. Fluctuations are expected, but not specifically predictable features in individual time series, and are distinguished from steps by their inherent reversibility.

Events

Events are similar in nature to steps, but are variations that return rapidly (relative to the timescale of variations under consideration) to a previous state, and hence are always reversible and distinct from steps. Examples of events are the late Paleocene Thermal Maximum (the distinct oxygen-isotope peak at 55 Ma visible in **Figure 1(a)**), the Younger Dryas climate reversal, and 8.2-ka 'event' evident in the GISP 2 record (**Figure 1(c)**). What constitutes an event, as opposed to one of many fluctuations in a record is subjective, but generally events are both large and isolated, relative to nearby or background fluctuations.

At any given time or place, the prevailing climate is the product of the superimposition of all these features as they occur across all the different timescales. The efficacy of a particular feature in producing a response in some biotic or abiotic environment that is encoded in the paleoenvironmental record probably depends on the amplitude of the associated climatic variation and its duration, the number of features superimposed, the tendency for a particular variation to be predictable or reversible, and also on the existence of intrinsic thresholds.

Summary

The mean state of climate (or of the climate system) varies considerably, and these variations are expressed across a range of timescales. Moreover, the variability of the mean-state variations also varies over time. Despite this situation, there is considerable structure to the variability of climate. When viewed in the frequency domain, most of the variability of climate is related to the general increase in variance with increasing timescale, but there are several preferred timescales of variability related to the influence of external controls of climate and to internal mechanisms that generate quasi-periodic variations. The preferred timescales or periods related to external controls are those of 10^6 years and longer, which are related to tectonic controls, 10^4–10^6 years related to variations of the Earth's orbit, and the annual cycle, while those related to interval variations occur on interannual-to-millennial scales.

When viewed in the time domain, a small number of characteristic kinds of variation can be seen that recur across the full range of timescales. These typical variations include trends, steps, oscillations, fluctuations and events, and the superimposition of these generate climatic time series that show little stasis, or intervals of low variability over time.

See also: **Glaciation, Causes:** Astronomical Theory of Paleoclimates. **Paleoclimate:** Introduction. **Paleoclimate Modeling:** Quaternary Environments. **Paleoclimate Reconstruction:** Approaches.

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