

Links between the Annual, Milankovitch, and Continuum of Temperature Variability

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Climatic processes are intimately coupled so that understanding variability at any one time-scale requires some understanding of the whole. Spectra of Earth's surface temperature exemplify this interdependence, having a continuum of variability following a power-law scaling¹⁻⁷. But while specific modes of interannual variability are relatively well understood^{8,9}, the general controls on continuum variability are uncertain and usually described as purely stochastic processes¹⁰⁻¹³. Here we show that power-laws scale with the size of annual (1 yr) and Milankovitch period (23,000 and 41,000 yr) cycles. The annual cycle corresponds to scaling at monthly to decadal periods, while millennial and longer periods are tied to the Milankovitch cycles. Thus the annual, Milankovitch, and continuum of temperature variability together represent the response to deterministic insolation forcing. The identification of a deterministic control on the continuum provides insight into the mechanisms governing interannual and longer period climate variability.

Relative to the annual and Milankovitch cycles^{14,15}, the continuum of climate variability has received little attention, but is nonetheless expected to embody a rich set of physics¹². We focus on the continuum of surface temperature variability because of its pertinence to society and because of the relative abundance of records. The continuum can be described using spectral power-laws; $P(f) \sim f^{-\beta}$, where P is spectral energy, f is frequency, and β is the power-law.

Power-laws arise in physical systems as a result of nonlinearities transferring energy between different modes.

Climate variability exists at all time-scales. At interannual and decadal time-scales surface temperatures exhibit a strong land-sea contrast with β averaging one over the oceans and zero over the continents³⁻⁵. At millennial and longer time-scales, icecore and marine paleoclimate records indicate β is closer to two^{1,3,6,7,12}. Thus, long-period temperature variability has a larger β than does short-period variability, with a transition occurring near centennial time-scales. Note that icecore paleodata resolve time-scales both shorter and longer than centennial periods and demonstrate a change in the power-law near centennial periods^{2,3}.

Numerous explanations have been advanced regarding the continuum, including stochastic resonance¹¹, modified random walks¹², and diffusion¹³, but all these models are partial descriptions of the variability. Ultimately, one seeks a physics of climate from which the temperature spectrum can be deduced, something analogous with oceanography's theories for tides¹⁶ and internal waves¹⁷. Further analysis of the continuum is expected to aid in distinguishing the processes which control climate change.

We use Thomson's multitaper method¹⁸ to estimate the surface temperature spectra (see Methods). Surface air temperatures (two-meter values) from the NCEP-NCAR instrumental reanalysis¹⁹ are analyzed from 1948 to 2002 and show, as expected, that β is smaller over land^{4,5}. Not previously documented is that β is also smaller toward high-latitudes. For comparison, the average land-sea contrast in β is 0.2, while the average equator-to-pole difference is one. The average standard error in individual estimates of β is ± 0.16 .

The spatial patterns associated with β and the annual cycle mirror one another (see fig. 1). Zonally, the annual amplitude is smallest at the equator, steeply increases to mid-latitudes, and then more gradually increases toward the poles; β has the opposite pattern. The Southern Hemisphere has a smaller annual amplitude and larger β than the North, presumably because of the greater ocean area. Similarly, the greater marine influence on the western margins of North America and Eurasia leads to a smaller annual amplitude and larger β than in the east.

Tropical ocean surface temperatures generally have a large β and a small annual cycle. That the largest values of β occur in the eastern equatorial Pacific probably owes to the El Niño variability. Note that El Niño does not obey a power-law, but rather increases estimates of β by superimposing energy on the continuum at two to five year periods⁸. The presence of El Niño variability is also why the largest standard errors in β , ± 0.3 , occur in the eastern equatorial Pacific. The relatively large annual cycles in the eastern equatorial Pacific and Atlantic owe to seasonal changes in upwelling²⁰.

The close relationship between the spectral energy at annual periods and the continuum is also evident when spectra are binned and averaged according only to annual period energy (fig. 1e). Bins are designated from minimum to maximum annual energy at intervals of $0.2 \log_{10}(\text{°C}^2/\text{ds})$ and, on average, contain 780 individual spectra. β decreases with the log of the annual period energy, P_1 , as $\beta = -0.26 \log_{10}(P_1) + 0.81$. The cross-correlation between β and $\log_{10}(P_1)$ is -0.98. Although β decreases with increasing P_1 , the average spectral energy between periods of 1.1 and 30 years, \bar{P} , actually increases. For regions having $P_1 > 1$ (i.e. the extra-tropics) interannual and annual period energy are related as $\log_{10}(\bar{P}) = 0.58 \log_{10}(P_1) + 2.05$ with a cross-correlation of 0.99. Thus the three primary features of the

instrumental temperature spectra (the power-law, annual period energy, and interannual energy) are all tightly linked. Analysis of an instrumental compilation of surface temperatures²¹ yields similar relationships.

Further indication of a link between the annual cycle and the continuum comes from auto-bicoherence in surface temperature variability. Nonlinear interactions often produce phase dependencies between different frequencies. Auto-bicoherence measures nonlinear interaction by comparing the phase of two frequencies with the phase of their sum and difference frequencies²². An estimate of the global auto-bicoherence of surface air temperatures is obtained by averaging 330 individual estimates made using those records in an instrumental compilation²¹ having over 99% data coverage during the last century. A highly significant auto-bicoherence ($p = 0.01$) is found between the annual period and nearly all longer periods (fig. 1f), supporting the inference that the temperature continuum is closely linked to the annual cycle. This bicoherence pattern can be modeled using multiplicative noise. For example, if weather variations are modeled as a stochastic white noise process and then multiplied by an annual cycle such that variability is greater during the winter, an auto-bicoherence pattern similar to fig. 1f is obtained.

The two regions having the greatest contrast in temperature spectra are the tropical oceans and the high-latitude continents (fig. 1). To trace the behavior of these contrasting environments out to longer time-scales two separate sets of paleorecords are compiled, one from each region, both spanning monthly to million year time-scales (see fig. 2 and supplementary material). Although noise and other climatic effects are present, the simplest interpretation of each paleorecord is as a proxy for temperature. Spectral estimates at most frequency bands are available

from at least two independent proxies and agree well with one another, providing confidence in the result. We first discuss the concentrations of spectral energy (i.e. the peaks) in the proxy temperature spectrum and then the continuum.

Both the high-latitude and tropical spectra show significant ($p=0.05$) spectral peaks associated with insolation forcing. At high-latitudes, the annual cycle is massive, accounting for 80% of the variance at monthly to million year time-scales, while in the tropics the annual cycle only accounts for 25% of the total variance. Periods longer than 10 ky contain 10% of the high-latitude variance and 50% of the tropical variance. At long periods, a 23 ky precession period is found in tropical planktonic $\delta^{18}\text{O}$ records and, to a lesser extent, Mg/Ca records. 41 ky obliquity variations are directly present in the insolation forcing, and correspond to peaks in tropical planktonic $\delta^{18}\text{O}$, tropical alkenone, and high-latitude icecore $\delta^{18}\text{O}$ records. The most energetic low-frequency band is associated with the ~ 100 ky glacial cycles.

Turning now to the continuum of temperature variability, between annual and centennial periods the tropical marine compilation has $\beta = 0.56 \pm 0.08$ while the high-latitude compilation has $\beta = 0.37 \pm 0.05$, both in agreement with results shown in fig. 1. The magnitudes of the tropical and high latitude spectra approach one another as one moves from annual to longer periods and nearly converge at centennial periods. At periods longer than centuries, however, steeper power-law relationships exist. In the tropics $\beta = 1.29 \pm 0.13$ and at high-latitudes $\beta = 1.64 \pm 0.04$. With this change in slope the spectra diverge as one moves from centennial to longer time-scales. The tropical and high-latitude continua are most similar at centennial time-scales. Conversely, the high-latitude continuum is more than an order of magnitude more energetic near the annual and Milankovitch periods. Apparently, the continuum is more energetic at locations

which have greater insolation variability and at timescales neighboring those of the insolation forcing.

Whereas the annual and Milankovitch period climate variations tell us primarily about the forcing, the continuum tells us about the dynamical processes governing climate variability. The existence of two separate scaling regimes above and below centennial periods suggests the presence of distinct controls on the climate variability. Possibly, the climate system has a memory associated with the oceans which causes high-frequency variability to accumulate into progressively larger and longer period variations²³, and a Milankovitch driven low-frequency response which transfers spectral energy toward higher frequencies, possibly involving nonlinear icesheet dynamics. These low and high-frequency temperature responses appear to be of nearly equal magnitude at centennial time-scales, midway in log-frequency space between the annual and Milankovitch bands. Interannual temperature variability may also follow different power-laws during glacial and interglacial periods, but assessment of this further possibility awaits a global set of high-resolution glacial climate records.

What would the background continuum look like in the absence of annual or Milankovitch variations? Variations would presumably still exist owing to adjustments in the equator to pole temperature gradient, providing a background of climate variability upon which variations owing to Milankovitch and annual period changes are superimposed. The diurnal cycle is also expected to cause a local continuum response, but we have restricted the analysis to the more climatically relevant longer period responses.

Discussion of long-term climate variability is commonly divided between deterministic¹⁵

and stochastic components¹² — often associated with spectral peaks and the continuum respectively¹⁰. The analysis presented here indicates that the annual and Milankovitch energy are linked with the continuum and together represent the climate response to insolation forcing.

These observations have implications for understanding future climate variability. The distinction between the magnitude of low and high-latitude climate variability²⁴ may become smaller toward centennial time-scales. Furthermore, the physics controlling centennial and longer time-scale temperature variability appears to be distinct from that of shorter time-scales, raising questions of whether climate models able to represent decadal variations²⁵ will adequately represent the physics of centennial and longer time-scale climate variability. Finally, because the annual and Milankovitch cycles are deterministic, a greater understanding of their influence on the continuum may lead to improved predictability of interannual and longer time-scale climate variability.

1 Methods

Spectral analysis

Spectra are estimated using Thomson’s multitaper method¹⁸ with three windows. To reduce the influence of a small bias present at the lowest frequencies in the multitaper spectral estimates²⁶, the three lowest frequency estimates are dropped when estimating β . For paleorecords, when spectral estimates from the same proxy type overlap, a weighted average is taken. Weightings are proportional to frequency resolution so that better resolved records contribute more heavily. Spectral energy, or more precisely *spectral energy density*, is measured in

$^{\circ}C^2/ds$. In this case *energy* refers to the squared quantity, $^{\circ}C^2$ (not Joules), and *density* refers to energy per unit frequency, ds , where ds equals one over the length of the record in years. The energy density of the spectral continuum is independent of record duration.

The power-law, β , is estimated by a least-squares fit to log-frequency and log-power-density estimates. To more uniformly weight the estimate, spectra are binned into uniform log-frequency intervals and averaged prior to fitting β . For the instrumental records, monthly anomalies are used when estimating β in order to filter out spectral energy associated with the annual cycle and its higher harmonics. To preclude effects from a small residual annual cycle, power-law fits and computation of the average continuum energy exclude frequencies between $1/0.8$ to $1/1.2 \text{ yr}^{-1}$ and $1/1.8$ to $1/2.2 \text{ yr}^{-1}$. For paleorecords, β is estimated between $1/100$ and $1/15,000 \text{ yr}^{-1}$ to minimize the influence from the Milankovitch bands. Uncertainties reported for β are the standard error of the least-squares fit. In the case of the auto-bicoherence statistic, the energy contained at each frequency band is first normalized to unity so that only the phase information is retained, thus ensuring that the magnitude of the annual cycle does not bias the results.

The fraction of variance at the annual cycle is calculated by integrating the estimated spectral energy between frequencies of $1/0.95$ to $1/1.05$ and then dividing by the total spectral energy. The integration accounts for variations in the frequency spacing so that changes in record length do not influence estimates of the energy at the annual period. At high-frequencies, only instrumental estimates are used as these are more accurate. Furthermore, tropical $\delta^{18}O_{\text{calcite}}$ records are excluded to minimize influence from non-temperature effects. To permit direct

comparison between the continuum and annual period energy in fig. 2, the amplitude of the annual cycle and its harmonics are increased to the expected value for a record one million years in duration.

Another technique commonly used to estimate scaling relationships is Detrended Fluctuation Analysis^{4,5,7} (DFA) which yields a coefficient, α , related to the spectral power-law by $\alpha = (\beta + 1)/2$. Results presented here were checked using DFA and are in agreement; this is as expected because DFA and Fourier estimates are mathematically equivalent up to the choice of weighting terms²⁷. For ease of comparison, other author's DFA results are reported as β values.

Data

The NCEP reanalysis¹⁹ of two-meter air temperatures has global coverage but only spans the period 1949 to 2002. Paleo-temperature proxies are necessary to resolve centennial and longer period temperature variability. Following ref 1, we piece together spectral estimates from records of differing durations and resolution. Two separate spectral patch-works of surface air temperature are made: one using high-latitude continental records and another using tropical marine records. At high-latitudes $\delta^{18}\text{O}_{\text{ice}}$ icecore records and lake sediment data constrain surface air temperature variability. Tree-ring records are excluded because low-frequency variability can only be reconstructed over large spatial scales²⁸, and this analysis is restricted to localized temperatures. In the tropics we use foram assemblages, Sr/Ca from corals, alkenones, $\delta^{18}\text{O}_{\text{calcite}}$, and Mg/Ca_{calcite} records to constrain sea surface temperature variability. References for the records and pertinent statistics are provided in the supplementary material.

The entire $\delta^{18}\text{O}_{\text{calcite}}$ signal is converted into temperature variability, not correcting for the ice-volume component, because we expect higher-frequency variability to reflect rapid changes in temperature and no frequency dependent correction is available. At low-frequencies, this leads to an overestimate in the amplitude of $\delta^{18}\text{O}_{\text{calcite}}$ temperatures by roughly a factor of two, but at high-frequencies $\delta^{18}\text{O}_{\text{calcite}}$ variability is in good agreement with the other temperature proxies. Spectral power-laws are estimated in this higher-frequency region ($> 1/15$ ky), mitigating effects from the ice-volume component of the $\delta^{18}\text{O}_{\text{calcite}}$ variability.

There are numerous uncertainties associated with the interpretation of paleo-proxies. Uncertainties directly influencing the shape of the spectra include rectification and aliasing²⁹ — potentially first order effects considering most proxies are affected by but do not resolve the annual variability. Spectral estimates are also subject to errors or assumptions built into the age-model³⁰. All records use their published age-models except for ODP677 and ODP927 where a depth-derived age-model³⁰ is used, not making orbital assumptions.

The scope of error owing to non-temperature effects, observational uncertainty, age-model uncertainty, aliasing, and rectification is unclear. However, some confidence is provided in that various proxies, sensitive to differing environmental factors and measured at different locations, yield commensurate spectral estimates at most frequency bands. Furthermore, at annual to centennial time-scales, the proxies reproduce the same scaling structure evident in the instrumental records.

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Supplemental Information is linked to the online version of the paper at www.nature.com/nature.

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Figure 1 Temperature scaling at instrumental periods from NCEP. **(a)** Map of the spectral energy at the annual period in log-base-ten units and **(b)** the zonal average (black) along with land-only (red) and ocean-only (blue) averages. **(c)** β computed between two months and thirty years after removing the annual period energy and its higher harmonics and **(d)** the associated zonal averages. Note that the colorbar in **c** and x-axis in **d** are reversed. **(e)** Spectra binned according to annual period energy and averaged. Line colors correspond to the colorbar in **a**. The β and average magnitude of the continuum both scale with the amplitude of the annual cycle. **(f)** Auto-bicoherence estimate of instrumental surface air-temperatures²¹. The approximate 99% confidence level is 0.3. Black lines indicate frequencies coupled with the annual cycle.

Figure 2 Patch-work spectral estimate using instrumental and proxy records of surface temperature variability. The more energetic spectral estimate is from high-latitude continental records and the less energetic estimate from tropical sea-surface temperatures. High-latitude spectra are estimated from Byrd, Taylor, and GISP2 icecore $\delta^{18}\text{O}$; Vostok and Dome C icecore δD ; Donard lake varve thickness; the Central England Time-series (CET); and the Climate Research Unit's (CRU) instrumental compilation. From low-latitudes we use ODP846 marine sediment-core alkenones; W167-79, OCE205-103, EW9209-1, ODP677, and ODP927 calcite $\delta^{18}\text{O}$; PL07-39 and TR163-19 Mg/Ca; ODP658 foram assemblages; Rarotonga coral Sr/Ca; and the Climate Analysis Center (CAC) and CRU instrumental compilations. Temperature spectral estimates from records of the same data-type are averaged together ($\delta^{18}\text{O}_{ice}$ and δD_{ice} are also averaged). Power-law estimates between 1.1-100 yr and 100-15,000 yr periods are

listed along with standard errors and indicated by the dashed lines. The sum of the power-laws fit to the long and short period continuum are indicated by the black curve. The vertical line-segment indicates the approximate 95% confidence interval, where the circle indicates the background level. Mark at 1/100 yr indicates the region mid-way between the annual and Milankovitch periods. At bottom is the spectrum of insolation at 65°N sampled monthly over the last million years. The vertical black line indicates the 41 ky obliquity period.