Global Interdecadal and Century-Scale Climate Oscillations during the Last Half Millennium

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The recognition of natural modes of climatic variability is essential to better understanding the factors that govern climatic change. Recent modeling suggests that interdecadal (roughly 15-35 year period)[1−4] and century-scale (roughly 50-150 year period)[5−7] climatic variability may be intrinsic to the climate system. While there is some evidence for the existence of interdecadal[8,9] and century-scale[9,10] oscillations in instrumental temperature records, confident detection from short (100–140-year) instrumental records is difficult[11,12]. Interdecadal[13−16] and century[5,17] timescale oscillations have also been detected in isolated long climate proxy or historical records, but the large-scale spatial structure has not been investigated systematically. We report the multivariate analysis of a *globally-distributed* set of temperature proxy records of several centuries duration. Our spatiotemporal analysis strengthens evidence for persistent 15-35 year period "interdecadal" and 50-150 year "century-scale" climatic oscillations, and reveals both the spatial patterns and temporal histories of these signals.

Evidence for truly global climate signals must demonstrate consistent variations in data from widely separated localities, using records that are long enough to resolve the timescales of interest. To isolate possible climatic signals, we have compiled a small (35), but globally distributed, set of high-quality temperature proxy reconstructions (Figure 1) over the last half millennium. These data include tropical[18] and extratropical[19] ice cores, tropical corals[14] (also Lough, J., personal communication) dendroclimatic reconstructions [19,20,21] (also Earle, C., personal communication) and a handful of very long historical records[19]. Some seasonal inhomogeneity may be present in these data series because the extratropical records, unlike the tropical records, chiefly reflect summer season variability[19]. However, recent analyses[22] suggest that large-scale, low-frequency surface temperature variability is largely independent of the seasonality of sampling. Thus, we expect that such inhomogeneity will have little impact on signal detection. We employed a frequency-domain Singular Value Decomposition (SVD) method that is designed to isolate and reconstruct quasiperiodic or unstable oscillations that are spatially coherent but may exhibit phase-lags from site to site[9,23].

The sparseness of the dataset argues for a cautious interpretation, but the analysis suggests greater potential of our spatiotemporal approach applied to expanded networks of climate proxy data. We balanced spatial coverage, duration, and time resolution (annual vs decadal) by grouping the proxy data into four subsets that were analysed independently: (A) 27 shorter records (1730–1969) with annual resolution, (B) 21 medium duration (1615–1969 AD) records with annual resolution (C) 35 shorter (1730–1960 AD) records with decadal resolution and (D) 12 longer (1400–1960 AD) records with decadal resolution.

We compared the proxy network against instrumental data in sampling large-scale climatic variability. We performed parallel analyses of data during the last century based on (i) the global distribution of instrumental temperature data from 1890–1989 used by Mann and Park[9], (ii) proxy data set A using the abbreviated interval 1890–1969, and

(iii) a sparse sub-sampling of the instrumental data during the interval 1890–1969 chosen to mimic the spatial distribution and seasonal sampling of the proxy data. A perfect spatial match between data sets (ii) and (iii) is not possible, largely due to a paucity of high-latitude instrumental data. The "SVD spectra" in Figure 2 show the fraction of data variance in a narrow frequency range that can be explained by a single correlated signal. All three data sets exhibit correlated interdecadal (15–20 year period) variability that we estimate as significant at the 95% confidence level. A roughly decadal (10–12 year) peak corresponding to variability in the high-latitude North Atlantic and North America during the last century[9,23] is less consistently observed. Within the secular regime (corresponding to periods greater than the 40 (ii,iii) or 50 (i) years), two distinct modes of variability are significant in each data set, corresponding to a secular warming trend and a weaker variation that resembles one cycle of a century-scale oscillation. The associated spatial patterns of variation (not shown) of these signals in cases (ii) and (iii) are broadly consistent with their counterparts in (i) shown by Mann and Park[9]. The proxy data network thus appears capable of capturing the large-scale climatic processes evident in recent instrumental-based analyses, at least on certain timescales.

The SVD spectra corresponding to the full-length series for data groups A–D (Figure 3) yield statistically significant peaks on roughly interdecadal (15–35 year) and century (50–150 year) timescales. We isolate a quarter-millenial ($\sim$240 year) oscillation in data group D where longer-period variability can be resolved from a secular trend. This identification is tentative, however, as less than three "cycles" are present, and the signal can not be independently confirmed from the other data groups. Only groups A and B can properly resolve the interdecadal signals, as the Nyquist frequency for 10-year sampling corresponds to a 20-year period. Higher frequency signals related to the El Nino/Southern Oscillation ("ENSO") that are observed in the A and B analyses[24] will be discussed elsewhere. Comparing the spatial patterns of the interdecadal and century-scale signals reveals distinctions that are consistent among the data groups. Peaks of correlated variance fall roughly into interdecadal and century-scale bands. The variation of the location and magnitude of the peaks within these bands suggests quasiperiodic signals with amplitudes and frequencies that drift over time.

The time-evolving amplitude and frequency of quasiperiodic signals can be examined with an "evolutive" analysis (Figure 4), in which the SVD analysis is applied in a moving window through the data series. The short duration, combined with decadal resolution, precludes a meaningful evolutive analysis for data group C. Evolutive analyses of the other data groups demonstrate that coherent interdecadal oscillations, centered near 20-25 year periodicity, were weakly evident before 1800. The oscillations subsequently strengthen in significance and drift to roughly 16-18 year period in the final window (1869–1969), which agrees with the dominant timescale of oscillations observed in instrumental surface temperature data[9] during the last century. Time windows that resolve century-scale variations (200 year width) can be employed for data group D. Before 1650, a coherent signal with roughly 50 year period appears intermittently. After 1650 this oscillation strengthens in its significance and drifts to a 60–70 year periodicity. In the 19th century, these "century-scale" oscillations appear to drift to slightly longer period, becoming indistinguishable from secular variability in a 200 year moving window. The improved frequency resolution of data group D allows for a clearer separation of the interdecadal and century-scale variability than is possible with groups A and B.

Figure 5 shows reconstructions of the spatial patterns of variation for the (a) interdecadal, (b) century-scale, and (c) quarter-millennial signals. In the spatial reconstructions, sources of systematic bias in the individual temperature reconstructions may lead to unreliable phase and amplitude at specific sites. Calibration of proxy data at longer periods, and various corrections that are made to proxy records (e.g., subtraction of individual long-term growth trends for dendroclimatic records) are potential sources of such bias. Thus, it is the regional trends evident in these patterns that are most meaningful.

The interdecadal signal (Figure 5a) exhibits variability in the tropics and subtropics that is largely in-phase. Mid-latitude variations are of similar magnitude, but phase relationships are more variable, consistent with the signature of extratropical teleconnection patterns. Such patterns can be resolved by our data network only in part. Nevertheless, the alternating pattern of phase from Greenland, to eastern and then western mid-latitude North America (with a nodal point in central North America) is consistent with the alternating warm and cold advection of the three-lobed "Pacific North American" (PNA) pressure anomaly pattern. In-phase tropical/extratropical temperature variability coupled with such an extratropical pattern has been noted as a signature of the global-scale ENSO phenomenon in instrumental records[9,25]. Studies of both instrumental climate data[9,23,26] and isolated long-term proxy records[27] suggest that interdecadal climate variability is closely associated with the PNA pattern. A connection has also been found with low-frequency changes in ENSO[26]. While the dynamics of such a linkage are still unclear, our study indicates a possible long-term connection between interdecadal climatic oscillations and low-frequency changes in ENSO. Recent model simulations indicate that the origin of this variability may lie in extratropical ocean-atmosphere interaction[3].

The pattern of the century-scale mode (Figure 5b) exhibits high-amplitude variability largely confined to the North Atlantic and Arctic, out-of-phase with weaker variability in the Pacific basin. These features resemble the pattern of a single "oscillation" detected in a century of gridded surface temperature data[9,10]. Aside from the Svalbard site in the boreal Atlantic, there is a tendency towards opposing, though not *opposite*, phase anomalies (ie., $\approx 45^o$–135^o phase difference) between the eastern and western margins of the North Atlantic. Such a phase pattern suggests a combination of in-phase and out-of-phase components in the two regions. An out-of-phase component could arise from differential temperature advection on either side of an alternating center of low and high pressure over the North Atlantic. Changes in northward oceanic heat transport would generate an in-phase component of basinwide warming and cooling. The combination of these effects is consistent with coupled ocean-atmosphere model simulations[7], in which century-scale (40–60 year) oscillations in sea-level pressure over the North Atlantic coincide with oscillations in the thermohaline circulation.

The quarter-millenial oscillation has a spatial pattern that is largely in-phase globally, although the phase-lags in the reconstruction correspond to time-lags as large as 100 years between warm or cold periods at different sites. The time reconstruction (not shown) suggests that this oscillation describes a global-scale transition from warmer conditions before 1500 to the colder conditions of the 16th–18th centuries[19,28].

We find some *empirical* evidence for persistent, if variable, low frequency global-scale climatic oscillations on interdecadal and century time scales. The spatial reconstructions of these signals fuel hypotheses for the possible underlying processes e.g., a connection between interdecadal climate variations and low-frequency ENSO variability, and a connection between persistent century-scale oscillations and low frequency variability in the thermohaline circulation. While speculative given the limited spatial distribution of the present dataset, such hypotheses can be tested more rigorously with similar analyses of the expanding network of high quality climate proxy reconstructions.

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Figure Captions

Figure 1. Distribution of proxy temperature reconstructions used in the present study. Squares denote historical records, Circles denote lake varves, Stars denote ice core/ice melt measurements, symbols denote dendroclimatic reconstructions, and "C" symbols coral reconstructions. In constrast to other reconstructions, the dendroclimatic reconstruction corresponding to the indicated southwestern U.S. "site" was actually based on the spatial averaging of data over a larger region[19]. Records indicated by yellow are available from 1400 to 1969 and have annual resolution, records indicated by green are available from 1400-1960 and have decadal sampling, red symbols correspond to records available from 1615 to 1969 with annual resolution, blue symbols records from 1620-1960 and decadal sampling, black symbols records from 1730-1969 and annual resolution. Thus, data group "A" makes use of the 27 yellow, red, and black records, data group "B" the 21 yellow and red records, data group "C" all 35 records, and data group "D" the 12 yellow and green records.

Figure 2. SVD spectra (local fractional variance explained by principal mode in the SVD within a narrow band about f as a function of frequency–see Figure 3) for (i) instrumental data of Mann and Park[9], (ii) proxy data set (A), (iii) sparse distribution of instrumental data as described in the text. The local fractional variance scale corresponds to (i), with the scales adjusted for (ii) (-0.03), (iii) (-0.07) to align the the position of the 95% confidence level owing to varying effective spatial degrees of freedom in the different analyses. Confidence limits are higher within the secular band (corresponding to variability longer than half the record lengths) owing to decreased spectral degrees of freedom near zero frequency.

Figure 3. SVD spectra for each of the data group "A-D". Convention similar to above,

but with 90%,95%, and 99% confidence limits indicated. Boxes group spectral peaks into approximately 15-35 year interdecadal and 50-150 year century-scale bands. 90%,95%, and 99% confidence limits determined from resampling method indicated by horizontal dashed lines.

Method: We calculate the tapered Fourier transform of a set of M time series of uniform length N years, using multitaper spectral analysis to provide a small number (K) of independent spectral estimates for each time series ${x_n}^{(m)}$ in a narrow frequency band centered at frequency f,

$$ {y_k}^{(m)}(f) = \sum_{n=1}^{N} w_n^{(k)} {x_n}^{(m)} e^{i2\pi f n \Delta t} $$

where $\Delta t = 1$ month is the sampling interval and $\{w_n^{(k)}\}_{n=1}^{N}$ is the kth member in an orthogonal sequence of leakage resistant data tapers.

We construct the M by K matrix

$$ \mathbf{A}(f) = \left[\omega_m {y_k}^{(m)}(f)\right] $$

where $m = 1, \ldots M$, $k = 1, \ldots K$, each row calculated from a different grid-point time series (normalized by its standard deviation). We use $K = 3$ as a tradeoff between spectral resolution and degrees of freedom. The relative weights for different series (ω_m) are chosen so that a large number of nearby sites do not combine to have disproportional weight in the analysis. We perform the complex singular value decomposition,

$$ \mathbf{A}(f) = \sum_{k=1}^{K} S_k(f) \mathbf{u}_k(f) \otimes \mathbf{v}_k^*(f) $$

into K orthonormal left ($\mathbf{u}_k^*$) and right ($\mathbf{v}_k$) eigenvectors, which can be used, respectively, to recover spatial and temporal patterns. The singular value $S_k(f)$ scales the amplitude of the kth mode. The spectrum of "local" fractional variance explained by the principal mode is described by $S_1^2(f)/\sum_1^K S_k^2(f)$, with narrow peaks in the spectrum indicating potential quasiperiodic signals. Confidence limits for peak significance are obtained by resampling methods[9].

Figure 4. Evolutive SVD Spectra. A common year (1800) is indicated by a thick dashed line to allow visual alignment of the time axes for the three plots shown. For each case, the local fractional variance spectrum is indicated by a color scale shown to the right of the plot. The color convention is chosen so that any features clearly visible above the background are significant well above the 95% level. Window timelengths τ_w are chosen to be long enough to allow high frequency resolution, while short enough to provide insight into the evolving character of signals. The center of the moving windows defines its time coordinate, so information for the first and last $\tau_w/2$ years are lost. Periods longer than $\tau_w/2$ cannot be distinguished from secular variability in the evolutive analyses, and are not shown.
(top) Evolutive SVD spectrum for data group "A" using a 100 year moving window evaluated in 2 year steps. Century-scale variability cannot adequately be distinguished from significant secular (greater than 50 year timescale) variability for this data group. Significance levels for the local fractional variance spectrum are given by 90% (0.55), 95% (0.565), and 99% (0.60).
(middle) Evolutive SVD spectrum for data group B using a 100 year moving window evaluated in 2 year steps. The significance levels are the same as for data group A.
(bottom) Evolutive SVD spectrum for data group D using a 200 year moving window evaluated in 5 year steps. For this data subset, century-scale oscillations are largely resolved (although variability on timescales *longer* than 100 years is indistinguishable from the secular band). Significance levels are given by 90% (0.58), 95% (0.60), and 99% (0.64). Note the different frequency/period scale in this case.

Figure 5. Reconstructed spatial patterns. For the purpose of displaying patterns in unnormalized units of *temperature*, the few records that have not been calibrated in temperature ($^\circ$C) units, are scaled using the annual and decadal variances of nearby

instrumental gridpoint temperature data.

(a) Spatial pattern of interdecadal oscillation based on the signal reconstruction for the ~ 24 year period peak in data group C (which provides the greatest spatial coverage). Reconstructed patterns are qualitatively similar for each peak in the 15-35 year "interdecadal" range in the three data groups. Phase relationships indicate relative time-lag between peak (or minimum) amplitude variability at different sites (positive lags corresponding to counter-clockwise rotation, with 360^o equal to the periodicity, 24 years in this case), while the size of arrows indicates relative magnitude of variability as provided by the scale shown. If we define zero phase (ie, 3 O'Clock) as when the tropics are warmest, peak warmth in northern Eurasia occurs 90^o (or, roughly 6 years) later. Amplitude scale is set so that the largest arrow corresponds to the regional maximum amplitude of the oscillation of $\sim 0.6^o$C peak-to-peak.

b) Spatial pattern for century-scale signal oscillation reconstructed for the 65 year period variance peak of data group C. Plot conventions are analogous to those above, with 360^o phase difference associated with 65 year period. Pattern maximum is a $\sim 2^o$C peak-to-peak oscillation (e.g., central Europe).

c) Spatial pattern for the quarter-millenial oscillation. Variations are largely in phase, spread out (with a few exceptions) over about 90-120^o in phase (ie, 60-80 years). Pattern maximum is a $\sim 1.5^o$C peak-to-peak oscillation.