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The Spatial Extent of 20th-Century Warmth in the Context of the Past 1200 Years

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Periods of widespread warmth or cold are identified by positive or negative deviations that are synchronous across a number of temperature-sensitive proxy records drawn from the Northern Hemisphere. The most significant and longest duration feature during the last 1200 years is the geographical extent of warmth in the middle to late 20th century. Positive anomalies during 890 to 1170 and negative anomalies during 1580 to 1850 are consistent with the concepts of a Medieval Warm Period and a Little Ice Age, but comparison with instrumental temperatures shows the spatial extent of recent warmth to be of greater significance than that during the medieval period.

Establishing the history of hemispheric or global temperatures is one fundamental requirement for identifying the contributions of different natural forcings to past climate variability and for quantifying the significance of greenhouse gas–induced warming during the 20th century (*1*–*3*). A number of studies (*1*, *4*–*14*) have selected, combined, and then calibrated multiple climate proxy records to provide assessments of temperature variability on near-hemispheric scales for the past few hundred to two thousand years. Both individually and taken as a whole, these reconstructions have been used to support the conclusion that it is likely that the late 20th century was the warmest period during the past millennium (*15*, *16*) or longer (*11*, *12*, *17*) in the Northern Hemisphere (NH).

Assessing whether these recent temperatures are unprecedented depends on comparing the recent instrumental temperature record with the earlier proxy-based temperature reconstructions. Quantitative calibration of the reconstructions is essential, and the comparison with the instrumental record is only valid if it takes account of the uncertainties associated with interpreting a specific reconstruction as an estimate of the "actual" temperature. Of the studies cited above, some do not provide reconstructions that cover the whole of the millennium (*1*, *8*, *13*, *14*), whereas some others either do not estimate reconstruction uncertainty at all (*4*, *6*, *7*, *10*) [note that reconstruction uncertainty for (*4*) was later estimated by (*16*)] or do not estimate reconstruction uncertainty in a way that is appropriate for assessing the significance of very late 20th-century warmth (*9*, *12*); see (*18*). There are, therefore, currently only three studies (*5*, *11*, *16*) that allow a formal quantitative comparison of late 20th-century instrumental temperatures against reconstructed temperatures for the past 1000 years or more. These three studies all found that recent temperatures are above the 95% uncertainty range estimated to be appropriate for their reconstructions of all earlier temperatures.

The published uncertainties were calculated from the regression residuals during the calibration period (*19*) and probably underestimate the true uncertainties, because additional unquantified error might arise (i) from nonstationarities in proxy-climate (*5*), interseason, (*20*) or land-ocean (*21*) relationships; (ii) from the use of the same period to select and calibrate temperature-sensitive proxies as well as for estimating uncertainty; or (iii) from biases inherent in the calibration method (*22*) [but see (*23*)]. For these reasons, the Intergovernmental Panel on Climate Change (*15*) correctly judged that the conclusion that recent warmth is unprecedented in the context of the past 1000 years could be made with only 66 to 90% confidence, despite recent temperatures exceeding the published 95% uncertainty ranges of all earlier reconstructed values (*5*, *11*, *16*).

A separate analysis on a record-by-record basis of many environmental and climate proxies concluded that the 20th century was probably not the warmest of the last millennium (*24*). This study has been criticized (*25*) for its lack of rigour in assessing whether the proxies used are useful indicators of temperature, for not distinguishing between regionally restricted anomalies and hemispheric-scale warmth, and for providing no calibration or uncertainty estimates that would enable comparison with late 20th-century temperatures. Here, we investigated whether a more carefully designed assessment of proxy records on an individual basis supports the conclusion that recent NH temperatures are unusual in the context provided by these records. We only used proxy records that are positively correlated with their local temperature observations, and, critically, periods with synchronous "warm" or "cold" anomalies in many proxies were used to infer hemispheric-scale climate anomalies as distinct from asynchronous warming or cooling in different regions. This restricts the analysis to those proxy records that are accurately dated. Analysis of synchronous anomalies in a number of independent records is indicative of the geographical extent of anomalous temperatures.

The criteria that proxy records must be well dated and sufficiently resolved and up to date to allow a quantitative comparison with instrumental temperatures eliminates many of the records used by (*24*). Here, we have pooled all of the proxy records used by (*9*) and (*25*) with those high-resolution NH series used by (*11*), then removed duplicates and those that were not positively correlated with their local temperature observations (*26*). Table S1 provides details of the 14 proxy series used here.

The 14 proxy series were each smoothed to remove variations on time scales shorter than 20 years and then "normalized" (*26*) to have zero mean and unit standard deviation (SD) over the full period of analysis, 800 to 1995. The analysis was not continued beyond 1995 because fewer than five of the proxy series were available after 1995. Individually, these records present a relatively complex picture of variability over the last 1200 years (Fig. 1). Although there are periods with coherent changes across a number of records, the implications of such periods cannot be quantified or adequately intercompared by a purely visual analysis.

The proxy records were analyzed simply by counting the fraction of those series that have data in any given year whose smoothed and normalized values exceed certain thresholds (*26*). The thresholds used are the series mean and 1 or 2 SD above or below the mean. The differences between pairs of these fractional exceedance time series were also analyzed (i.e., the fraction of records at least 1 SD above the mean minus the fraction that are at least 1 SD below the mean). All proxies are given equal weight in this analysis.

The statistical significance of the difference time series was established by using a Monte Carlo approach (*26*). The values in each smoothed proxy time series were shifted by a randomly chosen number of years, with values that were shifted beyond the end date of the record cycled back to the start date of the record. The random shifting of the records destroys the calendar alignment between values in different proxy records but maintains the autocorrelation structure of the individual series. The exceedances, differences, and filtering were recalculated from the randomly shifted records, with the entire procedure repeated 10,000 times to build up a distribution of possible values.

Although there are some individual years when the smoothed records are all positive or all negative, these are not sustained sufficiently long for the 20-year smoothed counts of the fractional exceedances to reach one (Fig. 2). Nevertheless, almost all of the series are posi-

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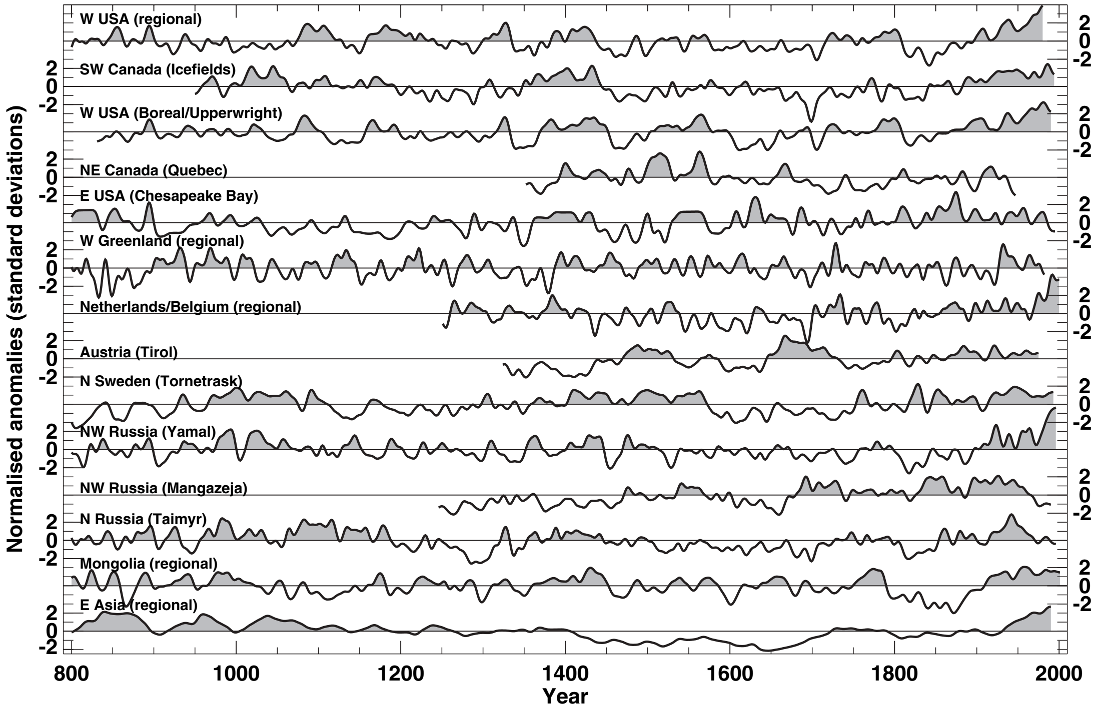

Fig. 1. The 14 temperature-related proxy records used in this study, filtered to remove variations on time scales less than 20 years and then normalized to have zero mean and unit standard deviation during the period from 800 to 1995 [with adjustments made to the shorter records (*26*)].

tive for much of the 20th century, peaking in number between 1935 and 1955. At the end of the analysis period in the early 1990s, 70% of the records have positive values whereas 30% are negative. Of the 70% with positive values, all exceed 1 SD above their respective mean and half exceed 2 SD above their mean, whereas throughout the 20th century the number of records more than 1 SD below their mean is nearly zero. The pre-20th-century periods when no series fall below –1 SD occur mostly between 890 and 1100, and at these times typically 30 to 40% of series simultaneously exceed +1 SD (light red shading in Fig. 2). The periods when no series exceed +1 SD or at least 30% fall below –1 SD (light blue shading) occur mostly between 1230 and 1360 or 1575 and 1840.

The fraction of positive records and the fraction of negative records do, of course, provide the same information, and thus their difference (Fig. 3A) has the same shape, with the highest value being reached in the mid-20th century and the lowest in the first half of the 17th century. These values far exceed even the 1st and 99th percentiles of the Monte Carlo results, providing support for a climate signal that deviates significantly from the overall mean state. The significance levels in all three panels of Fig. 3 vary through time according to the number of series that are available in each year; the greatest number are available between 1352 and 1947, and the detectability of significant anomalies is enhanced during this period (*27*). The value (Fig. 3A) at the very end of the analysis period would have exceeded the 95th percentile if it had occurred when the full set of proxy records were available, but because

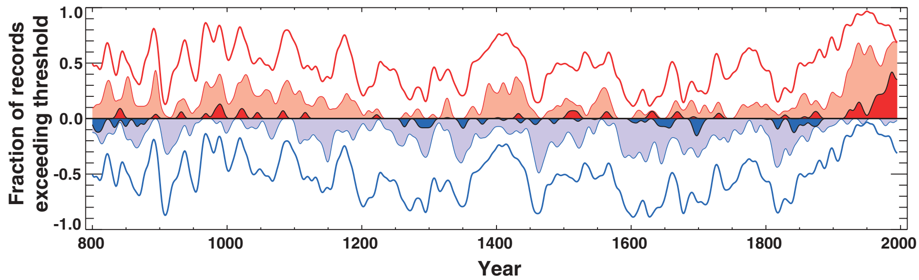

Fig. 2. Fraction of the records available in each year that have normalized values > 0 (red line), > 1 (light red shading), > 2 (dark red shading), < 0 (blue line), < –1 (light blue shading), and < –2 (dark blue shading), with the latter three series multiplied by –1 before plotting. The series are shown from 800 to 1995 and have been filtered to remove variations on time scales less than 20 years.

of the widening of the percentiles after some series end in the late 20th century, the 1995 value falls on the 90th percentile. Significant positive deviations also occur at intervals between 890 and 1170 and near to 1400, whereas significant negative deviations occur between 1200 and 1350, near 1460, and in the late 1600s and the early 1800s.

A similar picture emerges when considering the difference between counts of records more than 1 SD above and below their means (Fig. 3B), except that the values at the end of the analysis period (early 1990s) are similar to those in the mid-20th century. The 20th century is the most anomalous period in the record, with values far exceeding both the 99th percentile of the Monte Carlo results and all earlier values, right through to 1995.

The difference between the high and low 2 SD exceedances (Fig. 3C) shows only small deviations from zero throughout the analysis period except during the late 20th century, which exceeds all other periods, including the mid-20th century. This conclusion relies on the very small number of records whose values depart by more than 2 SD from their means at this time and is more sensitive to the selection of the proxy records than the results obtained using the less extreme thresholds (Fig. 3, A and B). There are earlier intervals with predominantly positive or negative deviations, but very few of these periods lie outside the range expected by chance.

Direct comparison of these results with instrumental temperatures is not possible because the latter records cannot be normalized over the 800-to-1995 period. The proxy data analysis was instead repeated with each series normalized over the 1856-to-1995 period of overlap with the instrumental temperatures. The difference between the fraction of proxy records with positive versus negative anomalies, relative to the shorter 1856-to-1995 reference period mean (Fig. 3D), shows a similar time evolution as the longer 800-to-1995 reference period re-

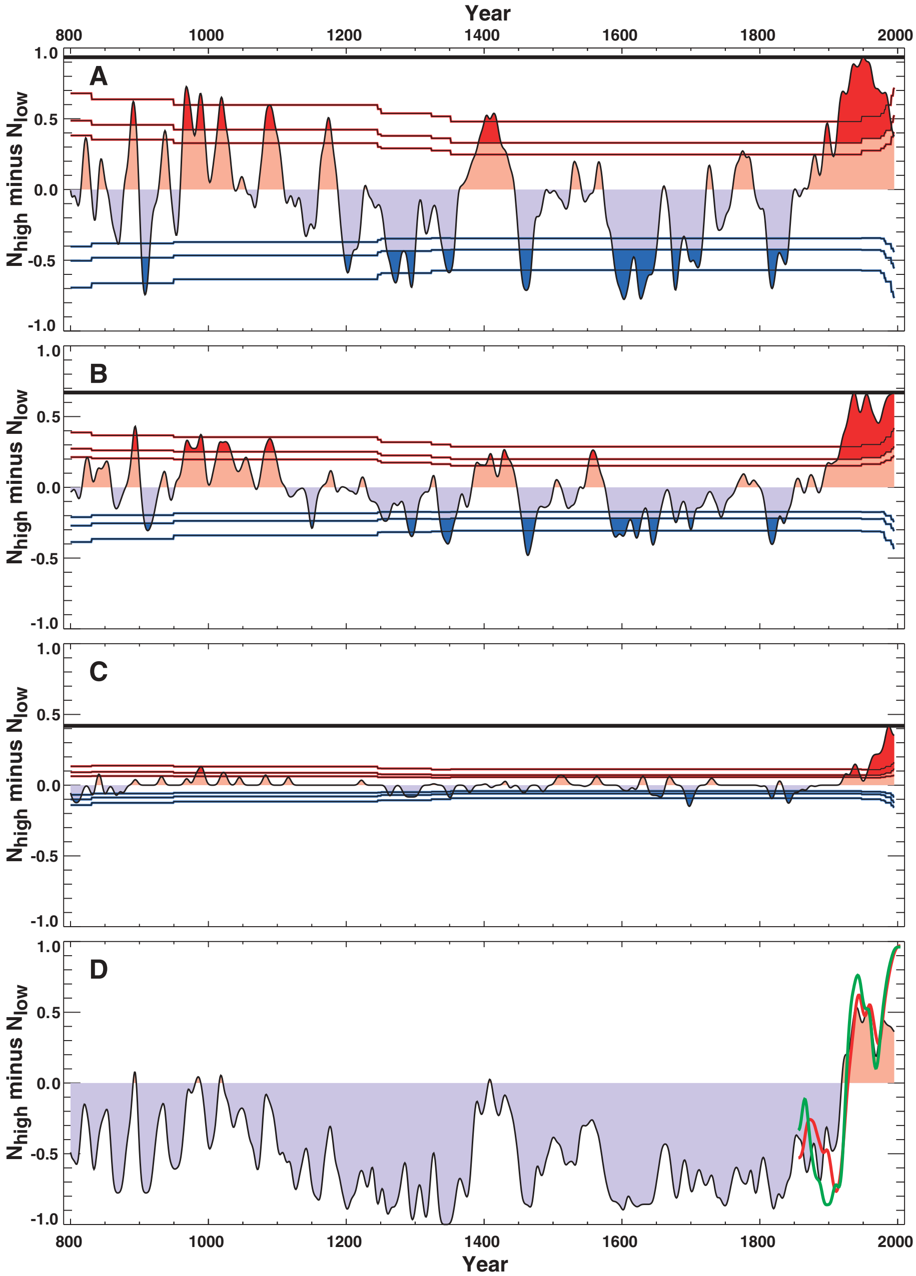

Fig. 3. Difference between the fraction of the records available in each year that have normalized values (**A**) > 0 and < 0, (**B**) > 1 and < –1, (**C**) > 2 and < –2, and (**D**) as (A) but using a shorter (1865 to 1995) reference period for normalization. The difference series are shown for 800 to 1995 and have been filtered to remove variations on time scales less than 20 years. Zero indicates that the number of series exceeding the upper threshold equals those with values below the lower threshold. In (A) to (C), the highest values achieved by each difference series are indicated by the horizontal black lines; the red and blue lines show the 99th, 95th, 90th, 10th, 5th, and 1st percentiles of distributions obtained by repeating the analysis 10,000 times with each proxy time series shifted randomly in time; and dark red and blue shading indicates times when the difference series exceeds the 95th or 5th percentiles. In (D), results based on annual-mean instrumental temperatures from grid boxes throughout the NH (red curve) or only in regions close to the proxy records (green curve) are shown for 1856 to 2004 (also normalized over the period from 1856 to 1995).

sults (Fig. 3A), although shifted vertically, of course.

The same analysis (filtering, normalizing, and counting values that exceed the various thresholds) was also applied to annual mean instrumental temperatures (*28*) from all grid boxes with data available in the NH or alternatively only to grid boxes close to the locations of the 14 proxy records. The similarity of the two instrumental temperature curves (Fig. 3D) indicates that the 14 proxy sites provide sufficient coverage to estimate the NH temperature behavior and that the limiting factor is likely to be the skill with which each proxy chronicles its local temperature variations. The instrumental temperature results show a close correspondence with the proxy records, particularly for the early 20th century increase and the variations during the 1930 to 1975 period. Each of the proxy records undoubtedly includes some variance that is unrelated to local temperature variations, and the characteristics of this "noise" determine the extent to which the signal shown by the counts of threshold exceedances and their differences will be expressed. The slight underestimation by the proxy results of the early 20th century rise and the absence of a further increase at the end of the records could both be examples of the expected consequences of noise in the proxy records. Virtually every grid-box instrumental temperature series in the NH exceeds its 1856 to 1995 mean level by the end of these records in 2004.

Similar results are obtained for the 1 or 2 SD thresholds, but these results are not shown here because estimating the SD of 20-year smoothed time series using this relatively short reference period (140 years) results in larger uncertainty in the counts of exceedances than for the results shown in Fig. 3D.

The multidecadal intervals (Figs. 2 and 3) with significantly widespread positive anomalies between 890 and 1170 and significantly widespread low proxy values between 1200 and 1850 (interspersed by periods with high or near-zero anomalies) provide support for the concepts of anomalous medieval (*29*) and Little Ice Age (*30*) periods (particularly from the late 1500s to the mid-1800s), although they are clearly discontinuous in time (with consequently ill-defined dates of onset and termination) and geographically restricted. The 20th century is the most anomalous interval in the entire analysis period, with highly significant occurrences of positive anomalies and positive extremes in the proxy records. These results are not dependent on the inclusion of specific individual proxies or the choice of reference period (figs. S2 to S6).

The approach used here is complementary to those studies that combined multiple proxy records into a calibrated time series of past large-scale or NH mean temperatures. By analyzing the raw proxy records themselves, some of the issues associated with the combination and calibration of records have been avoided [e.g., choice of optimum regional or seasonal temperature (*13*, *20*); sensitivity to calibration period, time scale, and regression method (*13*, *31*); and potential bias in some regression methods (*22*, *23*)]. In avoiding these issues, however, we have been compelled, thus far, to restrict the interpretation of our results to periods of "unusually high or low" proxy values rather than as indicative of "warm" or "cool" periods.

There is support, however, for interpreting the results of Figs. 2 and 3 as indicators of NH temperature: (i) there is strong evidence for a common environmental signal in the proxy records because the counts of simultaneous threshold exceedances lie well outside the ranges obtained by the Monte Carlo simulations; (ii) this environmental signal is most likely to be a climate signal because the departures from the Monte Carlo ranges do not just occur during the twentieth century, when very widespread nonclimatic anthropogenic disturbances could arguably have driven a common response in some proxies; (iii) this climate signal is likely to be, at least partly, a temperature indicator, because the proxy records were screened so that only those that were positively correlated with their local instrumental temperatures were selected (table S1); (iv) the analysis of instrumental temperatures indicates that 14 good temperature proxies are sufficient to represent NH mean temperature on 20-year and longer time scales; and (v) the comparison of results using proxy records and instrumental temperatures confirms that the analysis of these proxy records is a useful indicator of NH temperatures.

On this basis it is reasonable to conclude that this study provides evidence for intervals of significant warmth in the NH within the so-called Medieval Warm Period and for significantly colder intervals during the so-called Little Ice Age period. The most widespread and thus strongest evidence indicative of a significantly warm period occurs during the twentieth century [see also Supporting Online Material (SOM) Text], when greenhouse gas concentrations were at their highest during the analysis period. The proxy records indicate that the most widespread warmth occurred in either the mid- or late-twentieth century, but instrumental temperatures provide unequivocal evidence for continuing geographic expansion of anomalous warmth through to the present time.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/311/5762/841/DC1
Materials and Methods
SOM Text
Figs. S1 to S6
Tables S1 and S2

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Histone H4-K16 Acetylation Controls Chromatin Structure and Protein Interactions

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Acetylation of histone H4 on lysine 16 (H4-K16Ac) is a prevalent and reversible posttranslational chromatin modification in eukaryotes. To characterize the structural and functional role of this mark, we used a native chemical ligation strategy to generate histone H4 that was homogeneously acetylated at K16. The incorporation of this modified histone into nucleosomal arrays inhibits the formation of compact 30-nanometer–like fibers and impedes the ability of chromatin to form cross-fiber interactions. H4-K16Ac also inhibits the ability of the adenosine triphosphate–utilizing chromatin assembly and remodeling enzyme ACF to mobilize a mononucleosome, indicating that this single histone modification modulates both higher order chromatin structure and functional interactions between a nonhistone protein and the chromatin fiber.

DNA in eukaryotes is present as chromatin, which is an assembly of histones, DNA, and chromatin-associated proteins. The basic building block of chromatin is the nucleosome, which contains two copies of histones H2A, H2B, H3, and H4 (*1*). Fifteen to 38 amino acids from each histone N terminus form the histone "tails," providing a platform for posttranslational modifications that modulate the biological role played by the underlying DNA (*2*). One prevalent modification is H4-K16Ac (*3*), which has roles in transcriptional activation and the maintenance of euchromatin (*4*, *5*).

Recent work has focused on the ability of histone marks to modulate the binding of nonhistone proteins to the chromatin fiber, such as the yeast silencing factor Sir3 and the *Drosophila* chromatin-remodeling enzyme ISWI (*6*, *7*). We were interested in testing whether histone modifications might control higher order chromatin structures. Indeed, random hyperacetylation of histone tails (>6 acetates per octamer) disrupts intramolecular folding of nucleosomal arrays into compact, 30-nm-thick fibers (*8*). Additionally, the H4 tail, and particularly residues 14 to 23, are uniquely important for the formation of these fibers (*1*, *9*). The acetylation of H4-K16 occurs within this region, providing a potential mechanism to regulate chromatin folding.

We used a native chemical ligation strategy to generate recombinant histone H4 homogeneously acetylated at K16 (*10*, *11*). In this strategy, an H4 N-terminal peptide (amino acids 1 to 22), with a C-terminal thioester and an acetylated lysine 16, was synthesized. A recombinant

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Reports: "The spatial extent of 20th-century warmth in the context of the past 1200 years" by T. J. Osborn and K. R. Briffa (10 Feb. 2006, p. 841). Data used in the analysis are available at www.ncdc.noaa.gov/paleo/pubs/osborn2006/osborn2006.html. The URL for these data was not included in the paper because it was assigned only on the day of publication of the manuscript.