Documenting Natural Climatic Variations: How Different is the Climate of the Twentieth Century from That of Previous Centuries?

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ABSTRACT

Changes in decadal-mean surface temperature and its variance for different land areas of the Northern Hemisphere are examined. In the last 100 years, changes in surface air temperature have been greatest and most positive in the period since about 1970. Interannual variability, particularly at the largest spatial scales has also increased, although it differs according to regions. The most unusual decade of the last 100 years in the contiguous United States may have been the 1930s, although that of the 1980s is probably a close second, and in some regions perhaps the most anomalous. Both the 1930s and the 1980s experienced significant warming together with enhanced climatic variability.

To incorporate a longer-term perspective than is obtainable from the modern instrumental record, we used summer-temperature reconstructions based on tree-ring records, and on $\delta^{18}O$ ratios extracted from different ice-core records. Although none of these records is a simple or even direct temperature proxy, we present them as general indicators of prevailing environmental temperatures. The data were averaged by decades in order to focus on decadal-scale variability. With the exception of the data from tropical ice cores, the proxies indicate that the recent decades were not very unusual, either in regard to the mean or in terms of increased variability. While seasonal and annual temperature changes in the last two decades have been rather large in most areas of the Northern Hemisphere, the available paleoclimate evidence suggests that in many areas there have been decadal periods during the past several centuries in which reconstructed temperatures were comparable to those of the 1970s and 1980s, with climatic variability as large as any recorded in recent decades. Natural variability on decadal time scales is comparatively large—typically about half as large as the interannual variance.

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INTRODUCTION

Considerable effort has been expended over the last 25 years to improve our knowledge and understanding of climate processes and mechanisms associated with changes in climate (Saltzman, 1983; Trenberth, 1992). A major impetus for much of the recent climate research has been the global and regional climate projections made with physical climate models (the so-called general-circulation models, or GCMs) for a doubling of carbon dioxide concentration in the atmosphere.

Most assessments of the climatic impact of increases in the "greenhouse" gases (CO_2, methane, nitrous oxide, chlorofluorocarbons) have concluded, more or less consistently, that global temperatures should rise (under a doubling of the most abundant of these greenhouse gases, CO_2) from 1.5°C to 4.5°C (NRC, 1982; Bolin et al., 1986; IPCC, 1990; Schlesinger, 1984, 1991). Such changes, should they occur, will be superimposed on the natural variability of the climate, which is quite large at all time scales (Karl et al., 1989). Depending on a number of assumptions, the amount of global warming that should have been realized by now appears to be more consistent with the lower end of the above estimates (Bloomfield, 1992).

Karl et al. (1991b) performed a variety of tests using output from three different GCMs to ascertain, given their different climate sensitivities, when a statistically significant greenhouse signal might be detected in the central United States. They concluded that it was likely that a greenhouse signal had been masked, to date, by natural climate variability, and that it would likely take another two to four decades before the greenhouse signal in temperature and precipitation might be unambiguously detected in this region.

We should note the possibility that other human-induced factors may be acting to counteract the radiative effects of increased greenhouse-gas concentrations in the atmosphere. Recent work has indicated that sulfate aerosols, which act to increase the planetary albedo (Charlson et al., 1992; Hansen and Lacis, 1990; Wigley, 1989, 1991) may have counteracted to some degree the enhanced infrared warming (see Michaels and Stooksbury, 1992). These and other factors, whether anthropogenic in origin or not (e.g., changes in vulcanism), will undoubtedly "muddy" the climate picture and may make it more difficult to identify unequivocally a contemporary greenhouse signal.

In this paper, we consider two aspects of climate-change detection that we feel bear strongly on the issue of natural versus anthropogenic climate variability. One aspect of the problem is, in effect, at what point one rejects the null hypothesis (no climate change) and accepts the premise that the climate of the last few decades belongs to a different sample population. The difficulty there arises because we are evaluating a relatively short observational record with the knowledge that the climate has fluctuated in the past few

centuries by an amount that may be of the same magnitude a the fluctuations observed in the recent record (see Bradle and Jones, 1992).

A second aspect of the problem of climate change versu natural variability, which we consider here, is tempora changes in that variability, i.e., in the variance. Changes ii climatic variability are important, since they are likely t have a greater effect on a society's ability to mitigate an adapt to climatic changes than a slow alteration in th mean climate patterns. We have examined a variety o observational records of various lengths (typically 100 t 150 years), which are representative of different spatia scales (from hemispheric to regional basins). We will focu on decadal time scales, since one could argue that climati changes will be better gauged at time scales that to som extent average out the high-frequency climatic "noise' associated with seasonal variability and other air-sea pro cesses operating on annual time scales (e.g., the El Niño Southern Oscillation system). We compare these instrumen tal series with a suite of high-resolution climate prox records—namely, tree rings and oxygen isotopes extracte from ice cores—spanning the last 300 to 800 years. Ou aim is to give the reader some feeling for the range of thi intermediate-frequency (decade-to-century-scale) climati variability, as well as some appreciation of the uncertaintie inherent in the existing records (instrumental, historical, anc paleoenvironmental).

We note that the "fingerprint" climate-change-detectior technique (Barnett, 1986; Barnett and Schlesinger, 1987 Barnett et al., 1991) provides a very useful methodology foi testing a hypothesis (the GCM climate-change projections) against observations. We will attempt here to highlight some aspects of climatic variability at decadal and longer time scales and will re-emphasize the conclusion of Barnett et al. (1991), who noted that the existence of a high degree of "unexplained" interdecadal climatic variability (see alsc Ghil and Vautard, 1991, and Karl et al., 1991b) will greatly complicate the detection of a greenhouse climate-change signal.

THE MODERN (INSTRUMENTAL) RECORD

Characteristics of Decadal-Scale Changes of Area-Mean Temperature Indices

The available data suggest that during the past century decadal-scale changes in global-scale mean annual temperature are on the order of 0.1°C to 0.3°C (see Folland et al., 1990). Figure 1 illustrates the annual and seasonal temperature changes for the Northern Hemisphere land areas. The plotted data, from Jones et al. (1986a) with subsequent updates, are consecutive 10-year area-weighted averages from 1891-1900 through 1981-1990 of gridded temperature anomalies referenced to the 1951-1970 period. On this "dec-
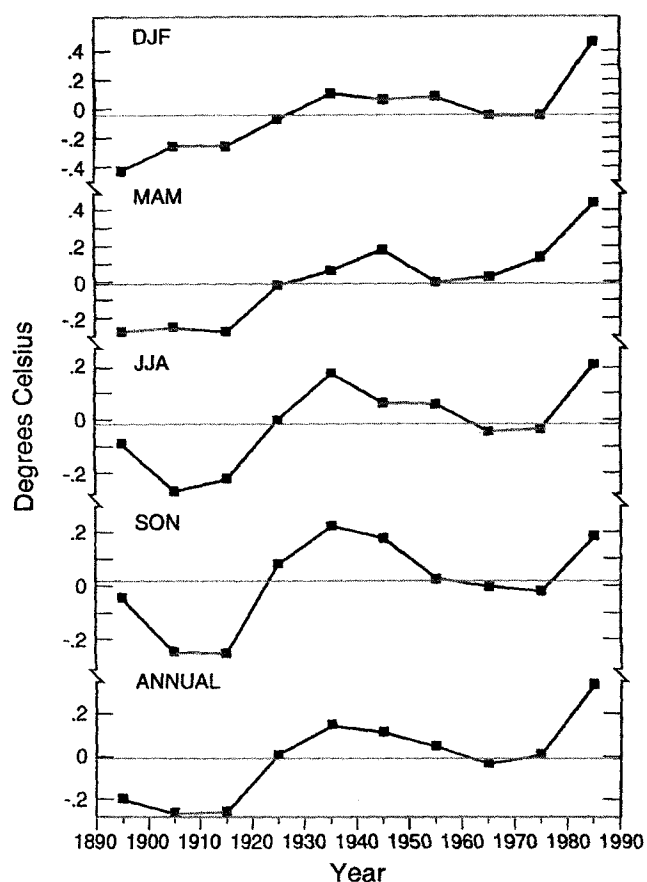
FIGURE 1 Decadal-mean seasonal and annual temperature anomalies (in °C) for land areas of the Northern Hemisphere. Data is from Jones et al. (1986a), with subsequent updates.

adal" time scale, the warming of the 1980s relative to the 1970s (0.32°C for the hemisphere) is comparable to the warming that occurred in the 1920s relative to temperatures in the 1910s (0.26°C). Some seasonal differences can be noted, with northern summer and fall showing the least warming trend and winter and spring showing the greatest warming trend over the last 100 years.

The twentieth century contains many examples of decadal-scale climatic variations of sufficient magnitude to have significantly affected societies. The two-decade-long drought in the African Sahel is perhaps the best-known example. The words "climate change" have become overused, and climatic variations from seasonal to multi-year are often lumped together. Until the mid-1970s, "climate change" was used to refer to climatic changes on time scales of 10^4 to 10^6 years (essentially, Milankovitch time scales). Variations of less than 10 years were generally considered to be part of the natural climate noise associated with interannual variations of the various components of the climate system and their nonlinear interactions, whereas variations on time scales of 10 to 10^3 years are now thought

to be strongly driven by ocean-atmosphere heat exchanges resulting from changes in the ocean's thermohaline circulation.

Because of the changes in the earth's radiative balance imposed by human activities during the past century, climatologists have been trying to detect climatic-change signals that hitherto have typically been associated with time scales of millennia. The climate record available for such studies, even with the aid of high-resolution paleoenvironmental records, is sufficient to define only continental to hemispheric changes on decadal time scales, and perhaps regional (less than about 10^5 km²) changes on century time scales.

In the United States, perhaps the singular climatic event of this century was the severe, widespread, and persistent drought of the 1930s. This event has been widely chronicled in both scientific (e.g., Skaggs, 1975) and popular literature. Other climatic events that persisted for more than one year and affected relatively large areas of the United States were the drought of the 1950s in south central areas of the United States (Chang and Wallace, 1987), and the drought of the 1960s in the Northeast (Namias, 1966). Periodic drought of variable duration has affected all areas of the contiguous United States to varying degrees (Diaz, 1983). Indeed, multi-year climate anomalies are a characteristic feature of the climate of the United States and of other parts of the world (Karl, 1988; Folland et al., 1990).

In Figure 2, decadal-mean seasonal (December-February for winter, March-May for spring, etc.) and annual temperature anomalies for various areas of the Northern Hemisphere are examined. Although Eurasia and North America (Figure 2a) have broadly similar seasonal trends over this period, differences can be noted in all seasons as well as in the annual averages. Figure 2b illustrates decadal temperature changes for the contiguous United States for the last century. The data used are from the adjusted divisional values (solid curve) described in Karl et al. (1984b). For comparison, the equivalent Jones et al. (1986a) gridded values are given as the dashed curve in Figure 2b. The decadal averages for the lower 48 states exhibit much smaller long-term trends than those noted for the continental-scale regions. Figures 2c and 2d illustrate the decadal temperature changes recorded in subregions of the United States, namely, the eastern and western halves of the United States (divided roughly along the 100th meridian), the state of Colorado, and a single state climatic division in Colorado where the city of Boulder is located. Again we note regional differences that can depart substantially from the temporal behavior of the larger spatial averages.

We have tabulated the mean temperature change from one calendar decade to the next over the 100-year period 1891 to 1990 for each of the above regions. No particular pattern emerges, except that at the largest space scales, the greatest decade-to-decade warming occurs mostly from the 1970s to the 1980s, whereas the time of the largest such
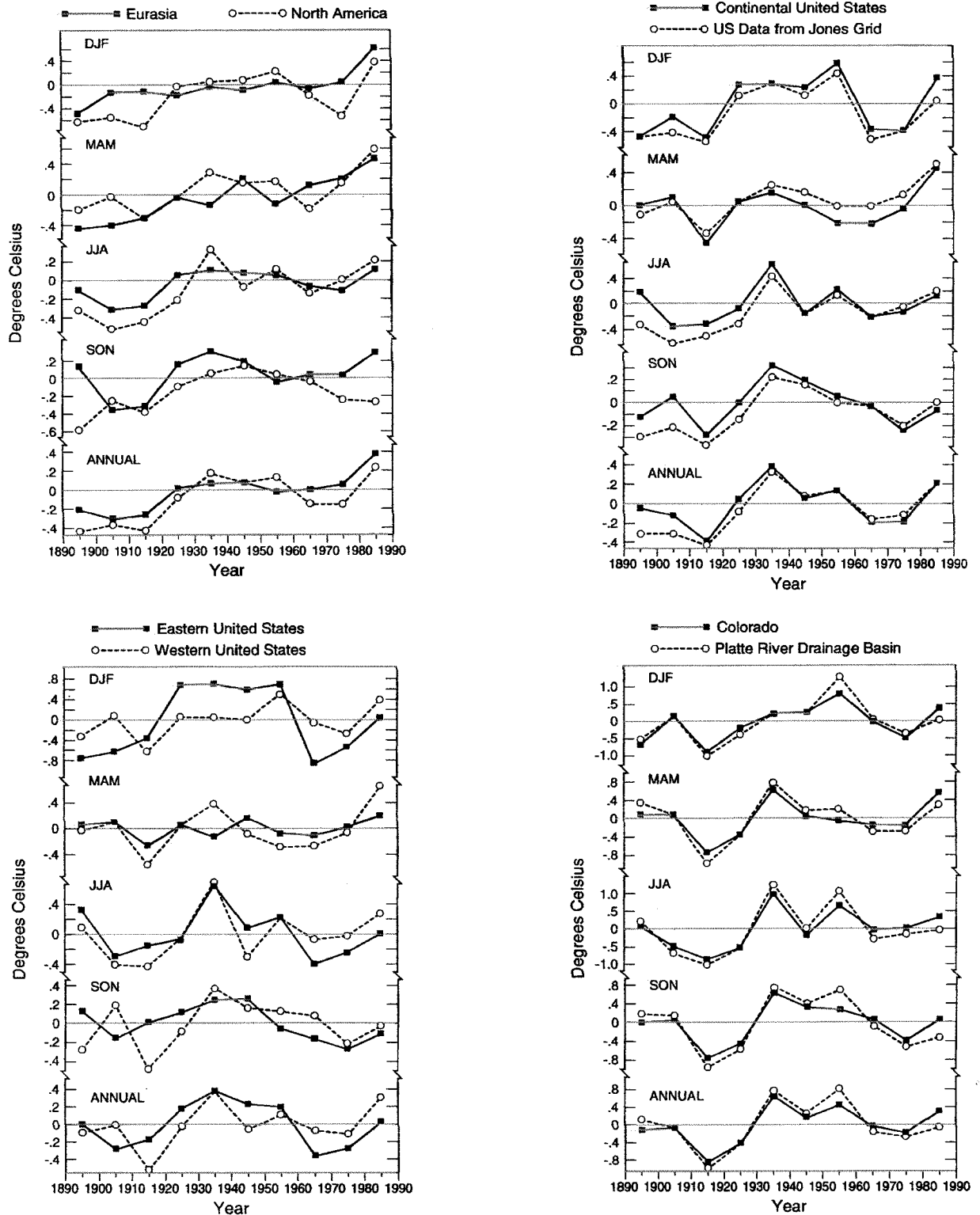
FIGURE 2   Decadal-mean seasonal and annual temperature anomalies (in °C). (a) For the Eurasian (solid line) and North American (dashed line) land masses. (b) For the contiguous United States, using data from the National Climatic Data Center described in Karl et al. (1984b) (solid line) and from the gridded temperature anomaly fields of Jones et al. (1986a) (dashed line). (c) For the eastern (solid line) and western (dashed line) United States. (d) For the state of Colorado (solid line) and the Platte River climatic division of Colorado (dashed line).

changes varies for the smaller regional averages, with most areas of the contiguous United States experiencing their greatest decadal changes during the first half of this century.

Recent studies have documented some rather pronounced and relatively rapid shifts in the climate system that occurred on decadal time scales. In particular, the atmospheric circulation in the extratropical North Pacific underwent a major shift in the mid-1970s that lasted over 10 years (Trenberth, 1990; Ebbesmeyer et al., 1991). This change was accompanied by a tendency for climate patterns in the tropical Pacific to exhibit conditions reminiscent of El Niño/Southern Oscillation (ENSO) warm-event conditions—weaker trades, warmer equatorial sea surface temperature (SST), anomalous rainfall patterns, etc.—relatively more frequently than during previous decades. Gordon et al. (1992) have also reviewed some of the relatively abrupt changes in water properties and surface climate in the Atlantic Ocean that have occurred in the past several decades, including sudden changes in SST anomalies in the South Atlantic compared to those of the North Atlantic, and the so-called "great salinity anomaly" in the North Atlantic from about the late 1960s to the early 1980s (Dickson et al., 1988). Certainly the sudden decrease of rainfall in the Sahel of Africa, a feature that has lasted for two decades, is a good example of how the climate can undergo significant, sudden, and prolonged change over relatively large spatial scales.

Clearly, increased knowledge of the behavior of climatic variability, from the interannual through decadal and century time scales, is needed to improve our assessments of any future changes in climate from regional to global scales. Indeed, as was noted by Ghil and Vautard (1991), the ability to distinguish a warming trend from natural variability is critical for separating out the greenhouse-gas-induced signal.

As we noted at the outset, an important element of climate that is too often overlooked is the variance or the characteristic variability of climatic means. In determining climate impacts, the importance to society of short- to medium-term climatic instability (i.e., climate fluctuations occurring on interannual to interdecadal time scales) is perhaps equal to or greater than that of slow changes in the background mean. Below we have analyzed some aspects of low-frequency changes in the temperature variance of different regional means.

Changes in Temperature Variability

We have examined contemporaneous variation of two measures of temperature variability, the standard deviation in running 15-year segments, and decadal means of the root-mean-square differences between successive yearly values of seasonal and annual regional temperature anomalies. The latter index is defined as

$$\text{Ind}V \equiv \left[(N-1)^{-1} \sum_{i=1}^{N-1} (x_{i+1} - x_i)^2 \right]^{1/2}. \tag{1}$$

Since the x_i are deviations from a reference mean and have approximately zero mean,

$$\text{Ind}V = [2\sigma^2(1 - r_1)]^{1/2}, \tag{2}$$

where σ^2 is the series variance, and r_1 is the autocorrelation of the time series with a lag of 1 year. We will use this measure, rather than the standard deviation, as the key index of interannual variability. Note that this index, Ind$V$, amplifies changes in the high-frequency part of the variance spectrum.

Figures 3 and 4 illustrate the changes in the interannual variability of the regional groupings discussed earlier. The curves differ from one season to another and from one region to another. For the largest continental-sized regions, there appears to be an increase in interannual variability in the last couple of decades. At smaller spatial scales, there does not seem to be a consistent trend; instead, the interan-
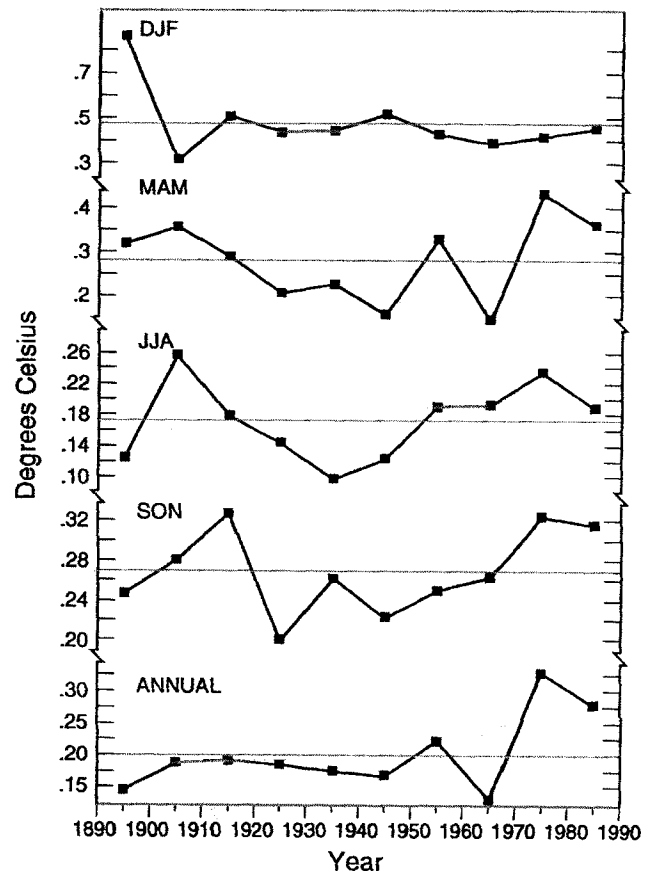

FIGURE 3   Index of interannual variability (in °C) for the Northern Hemisphere land areas. Values correspond to decadal means of the root-mean-square difference between successive seasonal and annual temperature anomalies over the last 100 years.
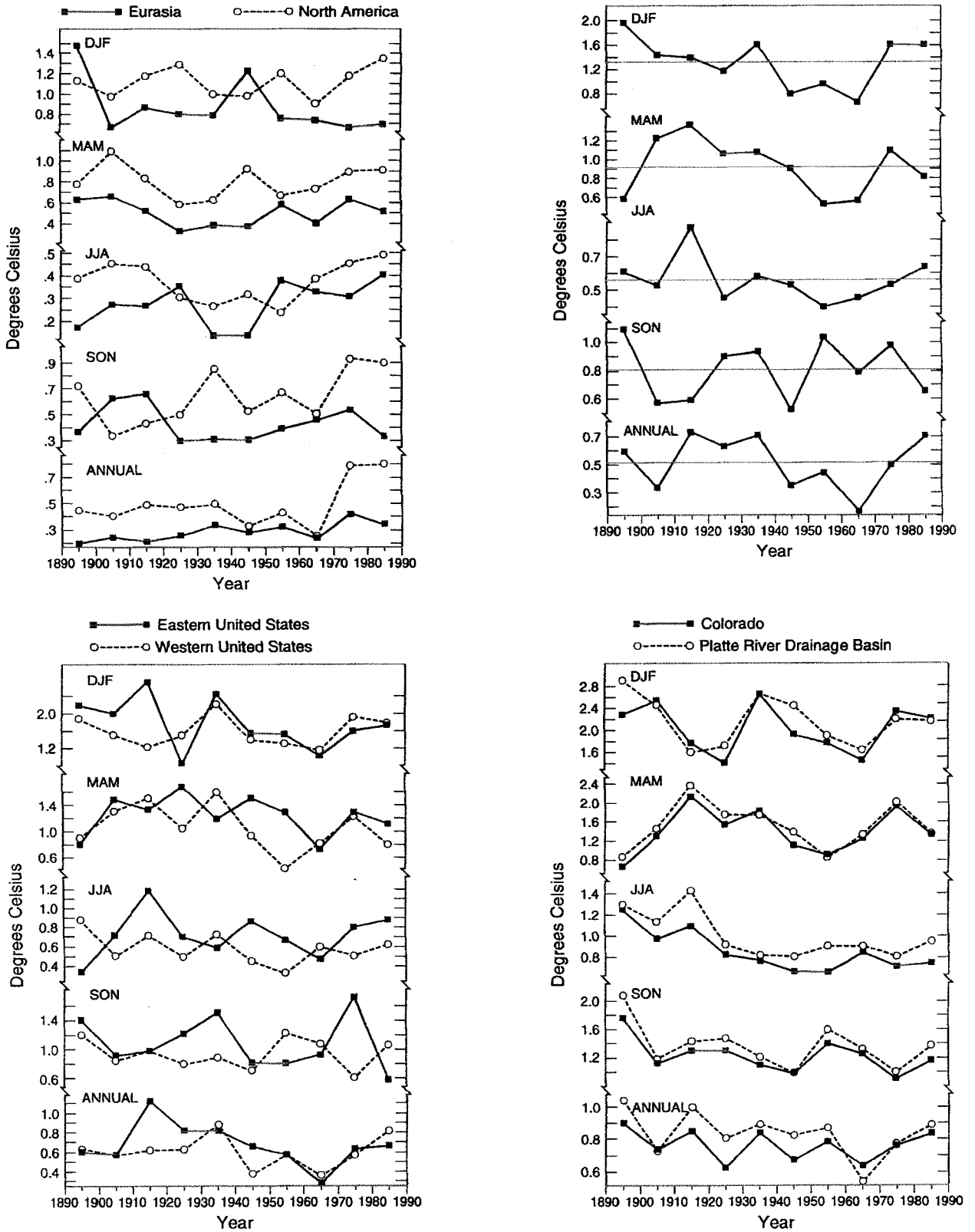
FIGURE 4   Indices of interannual variability, as in Figure 3. (a) For the Eurasian (solid line) and North American (dashed line) land masses. (b) For the contiguous United States, using data from the National Climatic Data Center. (c) For the eastern (solid line) and western (dashed line) United States. (d) For the state of Colorado (solid line) and the Platte River climatic division of Colorado (dashed line).

nual variability wanes and waxes over the last 100 years. The corresponding curves for the standard deviation (not shown) reveal similar patterns, with increases in variance at the largest spatial scales with time but no consistent trends in the standard deviation of the smaller regions. As one would expect, there is a well-defined log-linear relationship between the magnitude of the interannual variability and the size of the area comprised by the various indices (see Figure 5). The inherently higher variability at smaller regional scales should be kept in mind when interpreting the paleoclimate record, which is based on limited regional samples.

The question of whether a warming climate will exhibit increased short-term variability is still open. Previous studies have been generally inconclusive on this subject (van Loon and Williams, 1978; Diaz and Quayle, 1980). Certainly, there is no consistent relationship between interdecadal changes in average temperatures and interdecadal changes in variability. Climatic variability may increase, decrease, or stay the same, in response to an arbitrary change in decadal mean temperatures. On the basis of the above results, we can say that, considering surface temperature variations during the last century, there has been a recent increase in variability at large spatial scales (continental to hemispheric-scale averages). This increase in variability is also concurrent with relatively large temperature increases over those areas. However, this is not the case for earlier warming episodes.

THE PRE-INSTRUMENTAL PERIOD

Prior to the late 1800s, reliable quantitative data on climate variations are sparse, and conclusions about the magni-

tude of these changes on large spatial scales necessarily contain significant degrees of uncertainty. There is ample evidence that multi-decadal temperature changes occurring over regions the size of Europe and China have been at least of order 1°C (Bradley and Jones, 1992). This suggests that it is quite plausible, if not likely, that temperatures as warm as those prevailing since the end of the Second World War may have been experienced at regional spatial scales of about 10^5 to 10^6 km^2 for periods of one to several decades during some portions of the past thousand years under what amounts to natural (i.e., with negligible human influences) conditions.

Below we present some examples of long-term variability in a set of climate-sensitive paleotemperature records. The climate indices used here are discussed in several chapters of Bradley and Jones (1992). A listing of them, together with the source references and periods of record, appears in Table 1; each of them has been assigned a number for use in later tables comparing their data. Because of its very long record, the instrumental temperature series for central England (Manley, 1974) is considered in this section for comparison with other paleoclimate indices.

Tree-Ring Indicators

There is an extensive body of work relating climate variations to growth changes in particularly climate-sensitive trees (e.g., Fritts, 1976; Fritts et al., 1979; Hughes et al., 1982; Cook and Kairiukstis, 1990). We have selected a suite of climate-sensitive tree-ring records to study possible changes in climatic variability. Two main considerations were applied in the selection of these indices. First, we chose
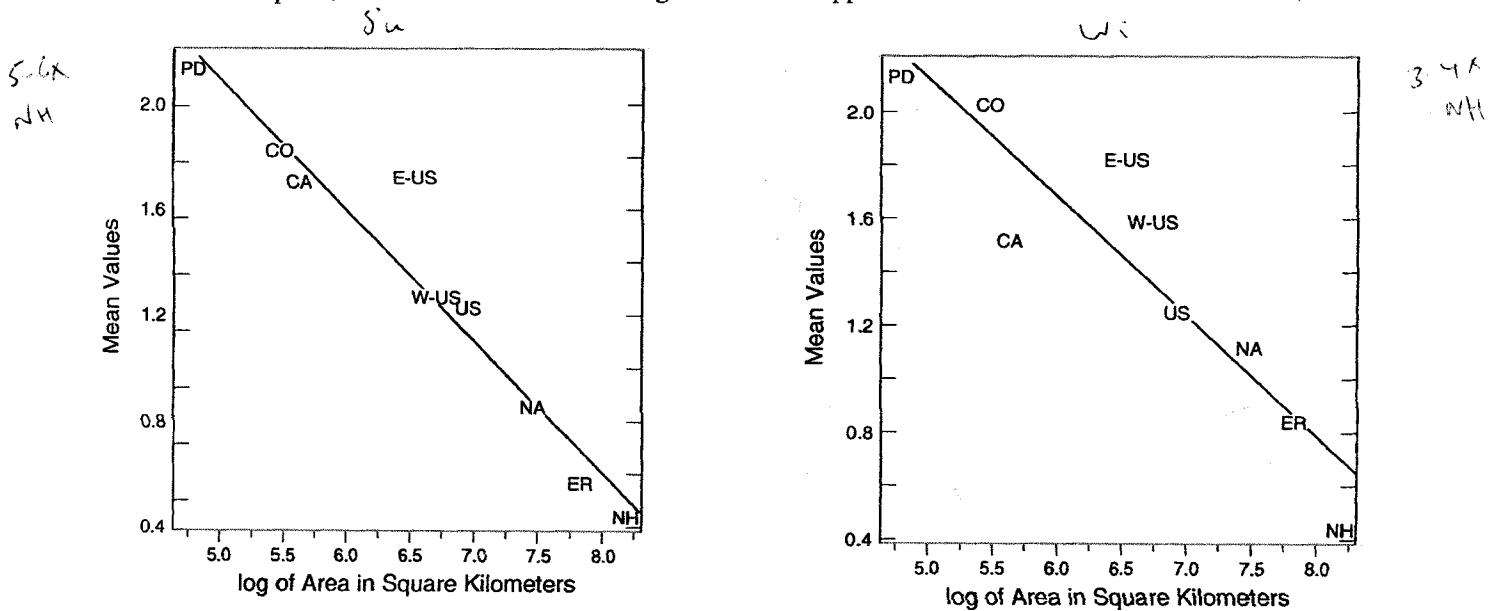

FIGURE 5   Interannual variability (in °C) as a function of the regional area. Values shown are for northern summer (left panel), and winter (right panel). Area is plotted as log$_{10}$ values.

TABLE 1   Temperature Indices Used in This Study

Type of Record	Time Coverage	Reference	Index No.*
Ice-core $\delta^{18}O$			
Agassiz Ice Cap (Ellsmere Is.)	A.D. 1349-1977	Fisher and Koerner (1983)	1
Devon Island Ice Cap	A.D. 1512-1973	Koerner (1977)	2
Camp Century (Greenland)	A.D. 1176-1967	Johnsen et al. (1972)	3
Milcent (Greenland)	A.D. 1176-1967	Hammer et al. (1978)	4
Quelccaya Ice Cap (Peru)	A.D. 1481-1981	Thompson et al. (1986)	14
Dunde Ice Cap (China)	A.D. 1606-1987	Thompson et al. (1990)	15
Temperature reconstructions from tree rings			
Western U.S. (annual)	A.D. 1602-1961	Fritts (1991)	
summer			5
Eastern U.S. (annual)	A.D. 1602-1961	Fritts (1991)	
summer			6
Western U.S. & SW Canada (annual)	A.D. 1602-1961	Fritts (1991)	
summer			7
Northern Treeline (North America) (annual)	A.D. 1601-1974	D'Arrigo & Jacoby (1992)	9
U.S. & SW Canada (April-September)	A.D. 1600-1982	Briffa et al. (1992b)	8
Northern Scandinavia (April-August)	A.D. 500-1980	Briffa et al. (1992a)	12
Northern Urals (June-July)	A.D. 961-1969	Graybill and Shiyatov (1992)	13
Tasmania, Australia (November-April)	A.D. 900-1989	Cook et al. (1992)	16
Patagonia, Argentina (December-April)	A.D. 1500-1974	Boninsegna (1992) & Villalba et al. (1989)	17
Rio Alerce, Argentina (December-February)	A.D. 870-1983	Villalba (1990)	18
Instrumental			
Central England Temperature (annual)	A.D. 1660-1987	Manley (1974)	
Dec-Jan-Feb series			10
June-July-Aug series			11

*These numbers are used in text and later tables to identify the various indices.

climate-sensitive tree-ring records that have been thoroughly documented in the refereed scientific literature. Second, we chose the longest of those records in order to maximize the temporal coverage, and tried, as far as possible, to select samples from representative geographical areas.

A number of problems are inherent in any climate reconstruction. These problems are discussed in detail in the original published papers; however, we will briefly highlight here the more critical ones as they may affect the results presented below. Because we have analyzed changes in variability, temporal changes in the composition of the tree-ring network used for the reconstructions will, in general, affect the high-frequency variance, and to some degree the low-frequency variance as well. In interpreting the temperature reconstructions shown here, we have taken into account these potential sources of biases as much as possible.

Regardless of whether one uses the width of the annual

growth rings or the maximum latewood density to reco struct a particular climate variable (generally, growin, season temperature and/or precipitation), a process standardization is required to account for different rates tree growth as a function of age. This standardization achieved by fitting a growth curve to the series of annu values, usually a cubic smoothing spline (see Cook ar Kariukstis, 1990), and taking residuals about the smooth curve. The degree of smoothing and the functional form of the growth curve partly determine the spectral properti of the residual series. In order to develop a climate recoi struction from these records, it is necessary to formulate transfer function to convert the tree-growth index into, sa a temperature index. The procedure usually involves a cal bration phase, in which a set of regression coefficients derived that convert the tree-growth parameter into a cl matic estimate, and a verification phase (see, e.g., Coo

and Kariukstis). Verification is usually done against an independent set of predictors. The reader is urged to review the reference sources listed in Table 1 for specific details regarding each paleotemperature reconstruction.

Another feature of long-term reconstructions from tree rings that should be borne in mind is that the composition of tree-ring samples that make up each yearly value is variable. In general, an index value for a given site is composed of a number of tree samples from several individual trees. These may vary in age, and in some cases may come from both dead as well as living trees. The number of samples making a particular ensemble average will vary with time, although this is more generally the case near the beginning and end of a particular chronology. These extraneous factors can introduce "noise" and spurious fluctuations into the reconstructions. Nevertheless, the tree-ring indices considered here, while suffering to varying degree from the above-named shortcomings, comprise a high-quality set of proxy temperature records that are of value to compare.

Figures 6 through 8 show decadal-mean values of various tree-ring reconstructions, generally representing summer (or growing-season) mean temperature. For the most part, these tree-ring reconstructions do not sample the 1980s; nevertheless, it is clear from the degree of interdecadal variability that it would be hard to point to any particular recent period as being unique or exceptional. The November-to-April

FIGURE 7   Decadal mean values of reconstructed summer-temperature anomalies for Scandinavia and the northern Urals. Units in °C.
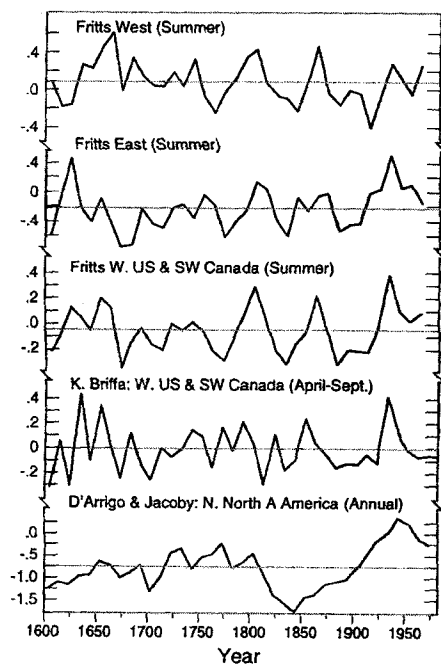

FIGURE 6   Decadal mean values of reconstructed summer-temperature anomalies for various North American regions. The top three graphs are in standardized units, the bottom two are in °C. See Table 1 for source information.
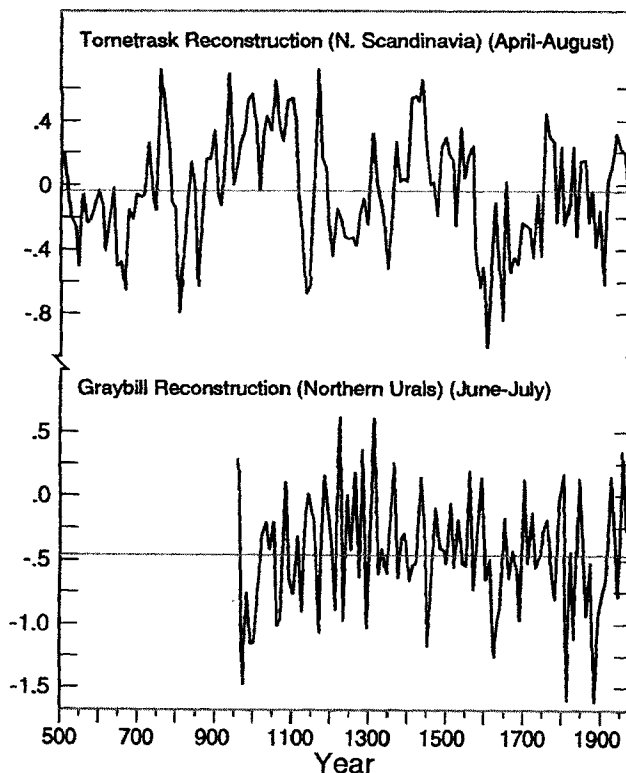
temperature reconstruction for Tasmania (Cook et al., 1992) does indicate that the last two decades of that record (1970s and 1980s) exhibit significantly greater tree growth (Figure 8) and hence higher reconstructed mean growing-season temperatures than previously, but it would seem premature to conclude that a "climatic change" has taken place in this region of southern Australia. We also note that, unlike the North American and Scandinavian reconstructions, this one is based on tree samples from only one location.

Some unique features are evident for a few of the temperature indices. For example, the curve of D'Arrigo and Jacoby (1992) is a reconstruction of annual mean temperature based on several sites along the northern North America treeline, stretching from Alaska to the Northwest Territories, plus a site located in northern Quebec Province. This reconstruction exhibits a pronounced warming from a very cold period during the mid-1800s to a maximum around 1940. By comparison, the two other high-northern-latitude sites discussed here—the indices from northern Scandinavia and from the northern Urals (Figure 7)—do not exhibit quite the same type of variations. The reader should note, however, that a much longer time period is sampled by these other two reconstructions, and that a seasonal (April to August for the Tornetrask index, and June to July for the

TABLE 2   Century Means of Interannual and Interdecadal Variability for 18 Temperature Indices (index sources identified in Table 1)

Century		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
500s	(ann.)	x	x	x	x	x	x	x	x	x	x	x	.84	x	x	x	x	x	x
	(decad.)	x	x	x	x	x	x	x	x	x	x	x	.20	x	x	x	x	x	x
600s	(ann.)	x	x	x	x	x	x	x	x	x	x	x	.79	x	x	x	x	x	x
	(decad.)	x	x	x	x	x	x	x	x	x	x	x	.27	x	x	x	x	x	x
700s	(ann.)	x	x	x	x	x	x	x	x	x	x	x	.64	x	x	x	x	x	x
	(decad.)	x	x	x	x	x	x	x	x	x	x	x	.40	x	x	x	x	x	x
800s	(ann.)	x	x	x	x	x	x	x	x	x	x	x	.63	x	x	x	x	x	x
	(decad.)	x	x	x	x	x	x	x	x	x	x	x	.35	x	x	x	x	x	x
900s	(ann.)	x	x	x	x	x	x	x	x	x	x	x	.70	.27	x	x	x	x	.87
	(decad.)	x	x	x	x	x	x	x	x	x	x	x	.31	.18	x	x	x	x	.41
1000s	(ann.)	x	x	x	x	x	x	x	x	x	x	x	.66	1.95	x	x	.53	x	.71
	(decad.)	x	x	x	x	x	x	x	x	x	x	x	.25	.53	x	x	.25	x	.28
1100s	(ann.)	x	x	x	x	x	x	x	x	x	x	x	.69	1.70	x	x	.62	x	.46
	(decad.)	x	x	x	x	x	x	x	x	x	x	x	.43	.56	x	x	.20	x	.14
1200s	(ann.)	x	x	1.36	1.25	x	x	x	x	x	x	x	.69	1.85	x	x	.43	x	.59
	(decad.)	x	x	.53	.85	x	x	x	x	x	x	x	.22	1.02	x	x	.16	x	.29
1300s	(ann.)	.93	x	1.10	1.36	x	x	x	x	x	x	x	.68	2.47	x	x	.42	x	.68
	(decad.)	.39	x	.65	.68	x	x	x	x	x	x	x	.30	.66	x	x	.30	x	.19
1400s	(ann.)	.70	x	1.38	1.27	x	x	x	x	x	x	x	.68	2.02	x	x	.42	x	.65
	(decad.)	.47	x	.68	.33	x	x	x	x	x	x	x	.23	.47	x	x	.18	x	.32
1500s	(ann.)	.78	.59	1.13	1.18	x	x	x	x	x	x	x	.60	1.75	1.86	x	.42	.96	.62
	(decad.)	.85	.69	.65	.67	x	x	x	x	x	x	x	.37	.56	.74	x	.17	.23	.14
1600s	(ann.)	.89	.71	1.27	1.43	.45	.32	.31	.63	.22	x	x	.69	1.63	1.80	1.12	.50	.56	.66
	(decad.)	.50	.64	.59	.47	.30	.41	.21	.42	.25	x	x	.43	.53	.66	.49	.14	.14	.19
1700s	(ann.)	.84	.62	1.05	1.36	.42	.31	.25	.53	.23	1.81	.98	.74	1.85	2.01	1.11	.49	.53	.65
	(decad.)	.96	.27	.87	.54	.21	.26	.14	.20	.34	.77	.25	.43	.40	.70	.55	.22	.18	.28
1800s	(ann.)	.97	.78	1.25	1.21	.52	.35	.29	.54	.21	1.89	1.18	.84	1.64	1.67	1.10	.45	.53	.75
	(decad.)	1.07	.55	.62	.77	.26	.29	.21	.23	.26	.31	.50	.35	.95	.96	.29	.17	.18	.38
1900s	(ann.)	1.51	1.02	1.38	1.67	.51	.33	.29	.53	.27	1.67	1.14	.71	1.78	1.24	1.28	.45	.62	.76
	(decad.)	.52	.49	.72	.44	.30	.33	.23	.23	.27	.53	.35	.27	.68	1.10	.59	.21	.22	.33

TABLE 3   Long-term Means of Interannual and Interdecadal Variability for 18 Temperature Indices (index sources identified in Table 1)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
LTM (ann)	.95	.75	1.24	1.33	.47	.33	.29	.56	.23	1.86	1.09	.71	1.91	1.74	1.15	.46	.66	.68
LTM (dec)	.75	.55	.66	.62	.27	.33	.20	.29	.28	.59	.41	.33	.67	.82	.49	.20	.19	.27
Ratio (%)	79	74	54	46	56	100	69	51	122	32	38	47	35	47	42	44	29	39

northern Urals set) interval rather than annual periods is considered.

The two summer temperature reconstructions for South America (Figure 8) are of widely different lengths. A comparison of the overlap period indicates that the Boninsegna series (see Table 1) exhibits a warming trend over the period of record. By contrast, the longer Villalba series exhibits some low-frequency variations but little if any trend over both the full data period and that of the Boninsegna period, beginning about the mid-fifteenth century.

Because of the longer record available, a variability index (described in the section on instrumental data above) was computed using the decadal averages, instead of the annual values. Our purpose here is to examine interdecadal temperature variability, with records spanning several centuries, noting that climate-sensitive tree-ring records are particularly useful for studying decadal-scale climatic fluctuations (Fritts, 1991). The changes in reconstructed climatic vari-
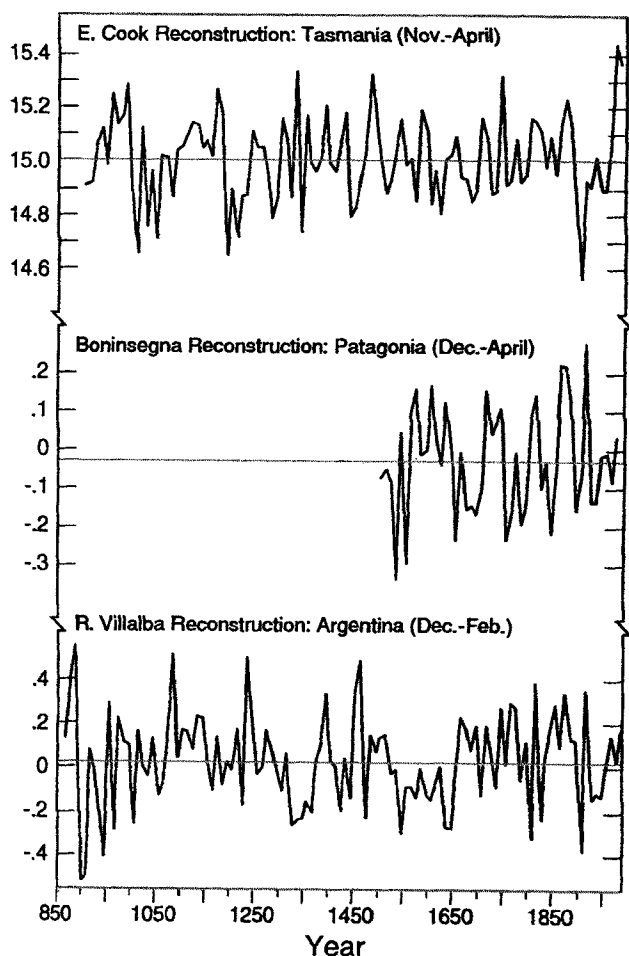

FIGURE 8   Decadal mean values of a reconstruction of summer temperatures for Tasmania, Australia (shown as actual temperatures) and two separate reconstructions for regions in Patagonia, Argentina (shown as anomalies). Units in °C.

ability have been summarized on a century-by-century basis in Table 2. For comparison, we also show in Table 3 the mean values of interannual and interdecadal variability for the full-length record. The variability index was calculated by applying equation (1) to both the annual and decadal-average reconstructed series. We fail to see any consistent trends in interdecadal variability associated with these tree-ring temperature reconstructions (see indices 5-9, 12-13, and 16-18 in Table 2). Interdecadal variability is typically about half the interannual values. This implies that substantial low-frequency variance is present in the paleotemperature record, so that recent high values of reconstructed decadal-mean summer temperature may yet represent an oscillation within the range of natural variability.

Oxygen Isotopes

The oxygen-isotope record has not been directly calibrated against temperature, as has been done for the tree-ring record. However, it is well established that the oxygen-isotope ratio ($\delta^{18}O$) is dependent primarily on the temperature of formation of the precipitation, with increasingly negative $\delta^{18}O$ ratios associated with decreasing temperature. The problems lie in the interpretation of a local ice-core record, not only with respect to local temperature variations, but even in terms of the larger-scale temperature patterns. Several factors control the oxygen-isotope composition of the snow that falls on a given ice body, and temperature is only one of them. The sensitivity of these records to annual temperature variations has been discussed in a number of papers, including the source articles referred to in Table 1. Whether or not these oxygen-isotope records accurately represent a "local" temperature record, we consider them to be sensitive indicators of prevailing climatic conditions within a suitably broad source region. Since our stated purpose is to compare recent changes in a suite of climate-sensitive paleoindicators, we have included them in our comparisons.

Figures 9 and 10 illustrate the changes in decadal averages of the oxygen-isotope ratio of glacier ice cores for different locations in northern Canada and Greenland, and for two low-latitude, high-elevation glaciers (the Quelccaya ice cap in the Peruvian Andes and the Dunde ice cap in the Tibetan Plateau region of China (see Table 1 for sources)). The polar ice $\delta^{18}O$ record, which ends before 1970, shows relatively less warming (trend toward smaller negative values of $\delta^{18}O$) than do the tropical ice cores. Furthermore, the warmest decades in the tropical record occur in the most recent time. The relation of this tropical $\delta^{18}O$ signal to air-temperature changes in the general location of these records may be partially evaluated with independent observations. It is known that significant melting took place at the Quelccaya site during the 1980s (Thompson, personal communication). Increases in tropospheric
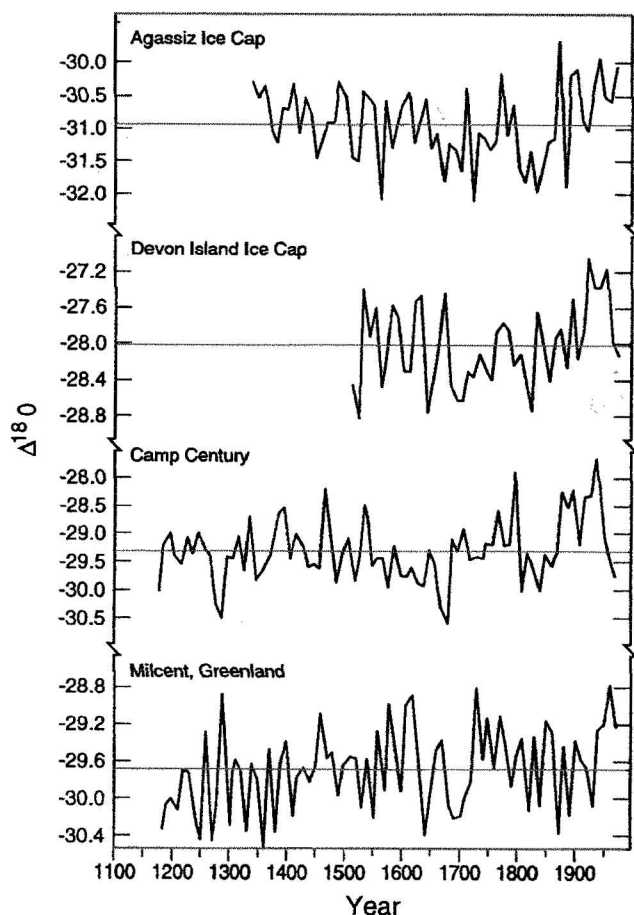
FIGURE 9   Decadal-mean values of $\delta^{18}O$ ratios from different polar-region ice cores. (See text for details.)

FIGURE 10   The same as Figure 9, but for two tropical ice cores (Quelccaya ice cap, Peru, and Dunde ice cap, China).

temperatures and water vapor obtained with tropical radio-sondes for the past couple of decades have been documented by Flohn et al. (1992), although the drift toward less negative $\delta^{18}O$ ratios appears to have begun earlier in the ice-core record than in the instrumental climate record.

Changes in interdecadal variability are summarized in Table 2 (see indices 1-4 and 14-15). There is a suggestion that decade-to-decade changes in $\delta^{18}O$ ratios have increased in amplitude at most of these sites. In particular, the calculated interdecadal $\delta^{18}O$ variability at Quelccaya has increased sharply in the last 100 years. This increase is evident even though the greater number of samples in the upper part of the record permitted better averages to be created for the recent decades than for earlier periods. A similar signal is apparent on the Dunde ice cap as well. These changes, however, may reflect a more localized temperature signal, changes in moisture sources for snowfall on the ice caps, or some other unknown cause unrelated to climate. It should also be noted that these two sites are located at very high elevations, and thus differ from most of the other paleoclimate indices, which are derived from locations at much lower elevations.
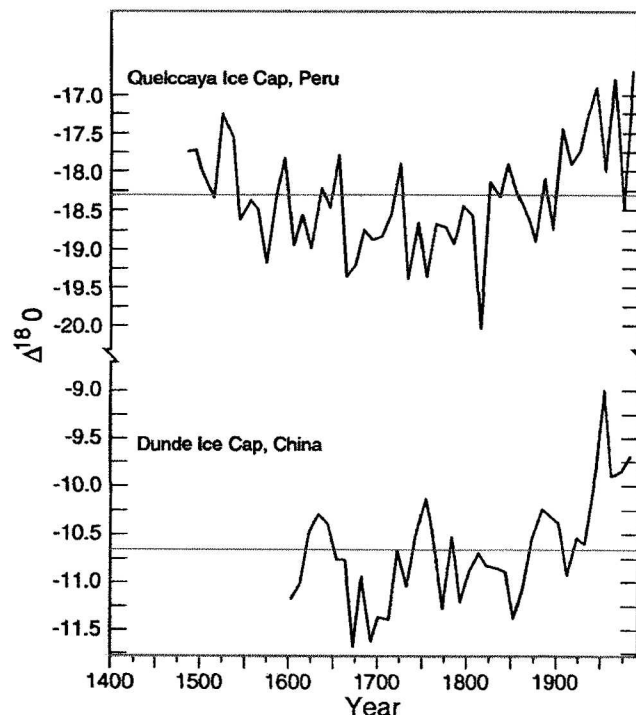
Central England Temperature

Decadal means of winter (December-to-January) and summer (June-to-August) mean temperature for central England (Manley, 1974, and subsequent updates) from 1700 to present are shown in Figure 11. The recent decades do not appear to be exceptional in comparison with the total record. The variability curves (not shown) indicate little overall change, with a tendency for the summer and winter seasons to have opposite changes in interdecadal variability (when one increases, the other tends to decrease). Jones and Bradley (1992, their Figure 13.1) have compared the central England temperature record with 12 other long-period station records in Eurasia and North America. Although there are obvious differences among the various climatic series, the twentieth century does not stand out as being a period of higher decadal-scale temperature variability. Most records (although not all) do exhibit the general warming trend of the past two centuries that is associated with the rebound from the Little Ice Age (see Bradley and Jones, 1992).

SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate whether the climate in recent decades was "changing," both with regard
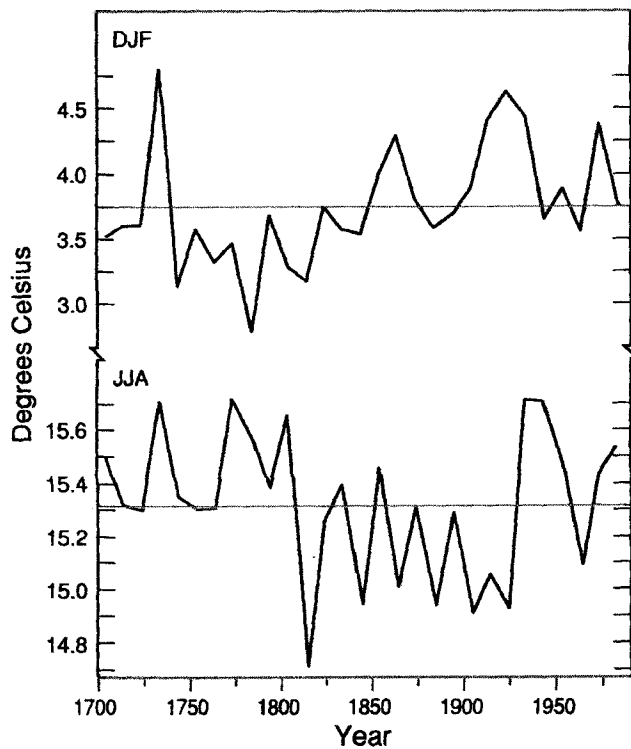
FIGURE 11   Decadal-mean values of central England winter and summer temperature (in °C).

to its mean value as well as with respect to changes in the variance on different time scales. Our findings are mostly mixed, in that the answer depends on the spatial scales selected for analysis.

For the period encompassing the last 100 years, changes in surface air temperature have been greatest and most positive in the period 1970 to 1990. Interannual variability at the largest spatial scales has also increased, although with seasonal differences. By and large, however, increases in variability at these spatial scales are not unique. When one considers smaller regions (in particular different portions of the contiguous United States) the picture changes, so that

the 1980s do not necessarily show up as being a unique period in the instrumental climate history of the country.

In order to have a longer perspective on climatic variations, we utilized data from several paleoclimatic reconstructions of growing-season temperature based on tree-ring records and on $\delta^{18}O$ ratios extracted from different ice-core records. Data from the latter were also taken as a measure of the prevailing air temperature. Annual values were averaged by calendar decades in order to focus on lower-frequency climatic variability. With the exception of the tropical ice cores, the recent decades were not generally unique, in terms of either the average values or increased variability. We note that tropical sea surface temperatures have been generally above the long-term mean since the mid-1970s. It seems plausible that this recent warmth would be reflected in low (less depleted) $\delta^{18}O$ ratios on the Quelccaya and Dunde ice caps, although more positive $\delta^{18}O$ ratios were already evident by the 1950s. It should be emphasized again that the exact relationship between actual past climate and these two high-elevation tropical indices is not fully known. Certainly, the period encompassed by the Little Ice Age is reflected in relatively low $\delta^{18}O$ values, particularly in the Quelccaya record. The development of additional independent ice-core sequences from the Cordillera Blanca in Peru and from extreme western China by L. G. Thompson and colleagues should help in the interpretation of the nature of the climate signals present in these records (e.g., Thompson et al., 1995).

Do we have an answer to the question posed by the title of this study, namely, whether the climate of the twentieth century is different from that of previous centuries? Obviously, the response is not an unequivocal "yes" or "no." As in most instances when one deals with climatic time series, the answer is "It depends." There appear to be differences in regional responses, and they are evident in both the proxy and the instrumental climate records. Insofar as the United States is concerned, the most unusual decade of the last 100 years may have been the 1930s, although the recent period is probably a close second. We can only say that, for most areas of the coterminous United States, the climate of the most recent decades cannot be considered unique, even in the context of the last century.

Commentary on the Paper of Diaz and Bradley

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When Drs. Diaz and Bradley present a paper, it always provides an enormous amount of information. The central question, in terms of a synthesis of the wealth of information provided in this paper, is the question posed by the title: "How different is the climate of the twentieth century"— more specifically the past few decades—"from that of earlier centuries?" In addressing this question the authors examined temperature, decade-to-decade temperature changes, and changes in interannual and interdecadal variability on various spatial scales.

The problem in any analysis of this type, of course, is that of inadequate data distribution in time and space. Thus, the analysis was largely limited to the land areas of the Northern Hemisphere, where both instrumental and proxy data are most plentiful.

It may be well to note that changes in the spatial distribution of observations from decade to decade may affect both the computed area average and the variability. Figure 10 in my paper, which appears later, illustrates the effects of using different data distributions in synthesizing global averages of SST, where the problem is probably more severe than it is over the land areas.

Figure 1 in this commentary also shows estimates of the variability in SST obtained from two different analysis schemes. Two estimates of variability are obtained. One is from the optimal averaging (OA) analysis technique of Vinnikov et al., and I think Dr. Groisman will tell us about that one. Another is derived from the simple box average that has been used—for example, by the U.K. Meteorological Office—in deriving SST area averages. The curves in Figure 10 of my paper show the low-frequency variations, i.e., periods longer than 30 years. There are some differences, but they are not too great, about 0.15 degrees around 1910 and 1920, with the OA staying a little bit closer to the mean for the entire period. Now, if we remove the low-frequency variations so that only the variations on time scales less than 30 years remain (Figure 1 in this commentary), and look at that difference between the two analysis schemes, we see that the level of higher-frequency variability may also depend on the first guess used. The box method and the OA with the previous month as the first guess are similar, but the OA with climatology as a first guess shows less variability during the earlier decades of the series. Thus, relative to the box method, the OA shows an increasing variability with time. This comparison illustrates that one
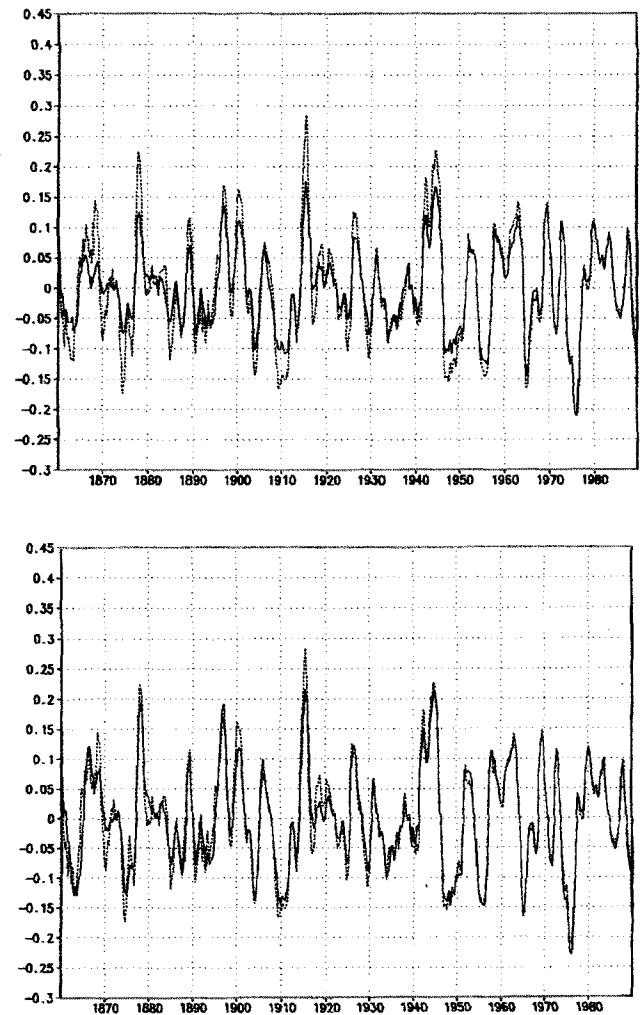

FIGURE 1 Time series of high-frequency variability (periods less than 30 years) of globally averaged sea-surface temperature. Top panel: Dashed curve is obtained by box method (Bottomley et al., 1990). Solid curve is obtained from optimal averaging using climatology as a first guess (Vinnikov et al., 1990). Bottom panel: Curves derived as above except that optimal averaging is obtained by using previous month as the first guess.

must be a bit careful in deriving conclusions about changes in variability from area averages. The estimates of variability may be sensitive to changes in data distribution and the particular analysis scheme used.

Data limitations become extremely severe when one attempts to quantify natural variability on decade-to-century time scales from proxy records. What information can we really derive regarding the patterns of large-scale variability from widely scattered proxy measurements? I think that further effort is required in two areas to maximize and better quantify the information content of the entire climate data base, both instrumental and proxy. First, we need more studies along the lines of data system tests. More specifically, using the more dense data distribution of recent decades, we should determine the loss of information as the distribution of observations is decreased. This will help establish confidence limits for estimates of large-scale averages based on the sparse distribution of observations and proxy series obtained during earlier decades and centuries.

Second, we need to place more emphasis on integration of information from various proxy sources, with the goal of obtaining a better picture of the *pattern* of global variability during earlier centuries. This is admittedly a formidable task when one is dealing with decade-to-century time scales. I do not believe that the concept of an overall integration of information in decade-to-century variations has yet to take root in the proxy community, but I think it should be strongly encouraged as a long-term goal.

Discussion

GROISMAN: Two quick comments, one for Gene and one for Henry. Gene, I just wanted to note that the SST variability does not reflect conditions over the Arctic. There is about a 25 percent difference in amplitude between SST and marine air temperature over the open ocean, the latter being higher, so there may be other reasons for the difference you cite. Henry, the problem with tree rings is that there are very few 1000-year-old trees, so in a time series you can't resolve the same mean variance.

DIAZ: I used only air temperature over land, no SSTs. Also, I started in 1891, when we had fairly good coverage. The changes in data distribution don't have much influence on the large-scale averages. As for the tree rings, we did try to compensate by looking at decadal means and interdecadal variability, and I don't think the middle section has much of a problem.

KEELING: I have a figure that is based on the Jones-Wigley temperature record, with a slightly different smoothing. Some of the early variability and the apparent biennial signal are probably the result of sparse data; beginning in 1951 the record is fairly homogeneous. You can see the 1958, 1961, 1963, 1982 El Niños. I'd like to know whether there is some difference in the quantity of data, or in its processing now that satellite data and ground data are being mixed, that has changed data variability in the last decade.

TRENBERTH: Perhaps when you fit the spline you are taking out more of the variance at the end.

GHIL: Henry, I was puzzled by the apparently much higher interdecadal variability in the second of your first two tree-ring figures.

JONES: It's partly due to the indexing procedure that there is more low-frequency variance in the top curve than the bottom one, though some of it could be real.

KARL: It's important to remember that there are many different ways to classify variability. I suspect that I could show more or less of it just by defining it differently. On this particular figure, I think we need to be aware that one is for a longer season than the other, and the shorter period of a time series will give you higher variability.

DIAZ: Another point is that getting longer time series from proxy records may not improve our understanding of climate change mechanisms.

GROOTES: I want to comment on the Quelccaya ice-core records you used. As you go down from the surface, the seasonal cycle disappears. It reappears about 1880 and continues significant to about 1480. Apparently when there are low values the record is smoothed so little that the seasonal cycle is preserved. As temperature changes it becomes more difficult to calibrate the isotope changes; you may be looking at post-depositional changes rather than the signal itself. Tree rings and ice cores both require particular attention to understanding exactly what you're recording, especially if you are talking about temperature.

MYSAK: For anyone who's interested, I'd like to mention that Brian Luckman at the University of Western Ontario has tree-ring records from the Canadian Rockies for about the last thousand years. He's showing a nice cycle of 150 years or so.

MCGOWAN: Are you comparing tree rings taken from similar altitudes at those different locations? Also, how does the variance of instrumentally measured mountain temperatures compare with that of lowland temperatures?

DIAZ: Most of the data sets are from moderate elevations. As for the high/low elevation temperature variances, the trends are reduced with respect to surface, but they're still comparable.