GLOBAL CHANGES OF THE PAST

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Instrumental Records of Past Global Change: Lessons for the Analysis of Noninstrumental Data

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Introduction

It is often stated that certain periods in the past were warmer than today. For example, the mid-Holocene "Hypsithermal" or "Climatic Optimum" is frequently cited as having been 1–2°C warmer *over the globe* than today, yet determining the mean temperature over such a large region is extremely difficult, even for the modern period when observations are relatively abundant. The problem gets more difficult as we go back in time. Determining global climatic variations from instrumental data and from proxy data involves similar problems. Here we consider some of these difficulties, using the observational period as a basis for discussion.

Data Coverage: How Much Is Enough for Global Estimates?

There has been great concern in recent years over climatic changes related to increases in greenhouse gases in the atmosphere (National Research Council, 1983; Royal Society, 1989). Model simulations indicate that global mean annual temperatures may increase 2–4°C with a doubling of CO_2 and related gases. Much attention has focused on whether global temperatures have already increased due to the buildup of such gases. Determining global (or even hemispheric) temperature variations is not easy. Ideally, one would like to have geographically well-distributed records from all parts of the globe, or hemisphere, in order to examine large-scale temperature variations through time. Since such a data network does not exist, inferences extended back into the 19th century. In reality, the "hemispheric land record" from the 1850s and 1860s is largely made up of data from western Europe. Is this a meaningful time series for the hemisphere as a whole? One way to answer this question is to examine the composite time series, using only station records that were available in the 1850s (a "frozen grid"), and to compare this with the time series obtained from the expanding network which reached its maximum extent in the 1951–70 period (Figure 2) (cf. Jones et al., 1986a). This demonstrates that the limited (1856) data set does mimic the low-frequency character of the hemispheric record. Similarly, in an analysis of instrumentally recorded temperature data from China, a strong correlation with the Northern Hemisphere land record was found in the low-frequency domain (Figure 3) (Bradley et al., 1987). However, in both these examples, the data

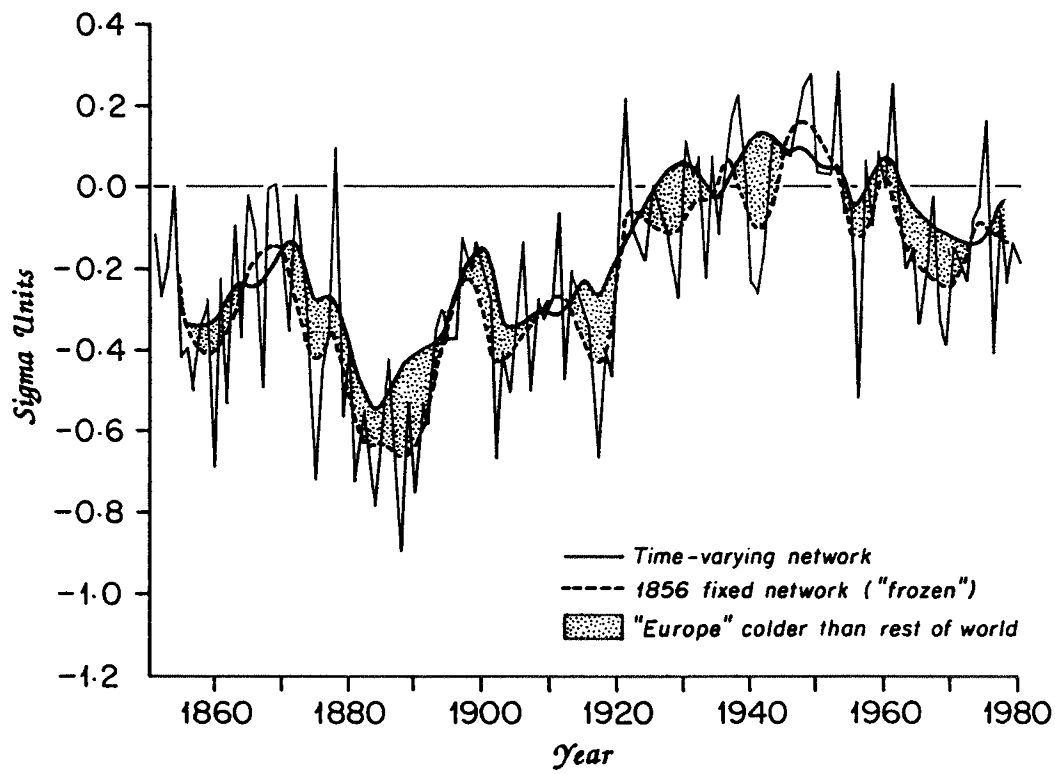

Figure 2. Normalized temperature anomalies (from the 1951–70 reference period) for the Northern Hemisphere as a whole (based on a time-varying grid network, as shown in Figure 1) and for a fixed network of grid points which represent the available data coverage in 1856. Monthly data at each grid point were normalized with respect to the standard deviation at that site in the period 1951–70, and the average is then the mean of each normalized grid value. Interannual values shown for the fixed grid network; data smoothed with an 11-year binomial filter.

being compared have been normalized to take into account the different variance in each region in relation to that of the hemisphere as a whole. Variance of temperature is generally greater at high latitudes than at lower latitudes and in continental interiors compared to oceanic sites.

In absolute terms, the regions in question cannot provide a direct indication of the magnitude of temperature change over the hemisphere unless it can be established that temperature variations in each region are (in some way) proportional to that of the hemisphere as a whole. There is some evidence that this may in fact be so. Budyko et al. (1989) argue that (at least for warm periods in the past) zonal temperature anomalies at high latitudes (north of 70°N) were generally three times greater than for the Northern Hemisphere as a whole, whereas from the equator to ~40°N, temperature anomalies were less than half of the hemispheric mean (Figure 4). Although the data set on which such conclusions are based is very limited, they argue that similar ratios have been found in modeling studies of global climates with 1x and 2x CO_2 concentrations, at least in winter months. (Summers show little latitudinal change in the ratio of zonal to hemispheric temperature change.) Theoretically then, a limited data set from high northern latitudes might provide an amplified view of hemispheric temperature change, whereas tropical data would be a less "sensitive" index. In this regard, the recent results of Jacoby and d'Arrigo (1989) are of interest.

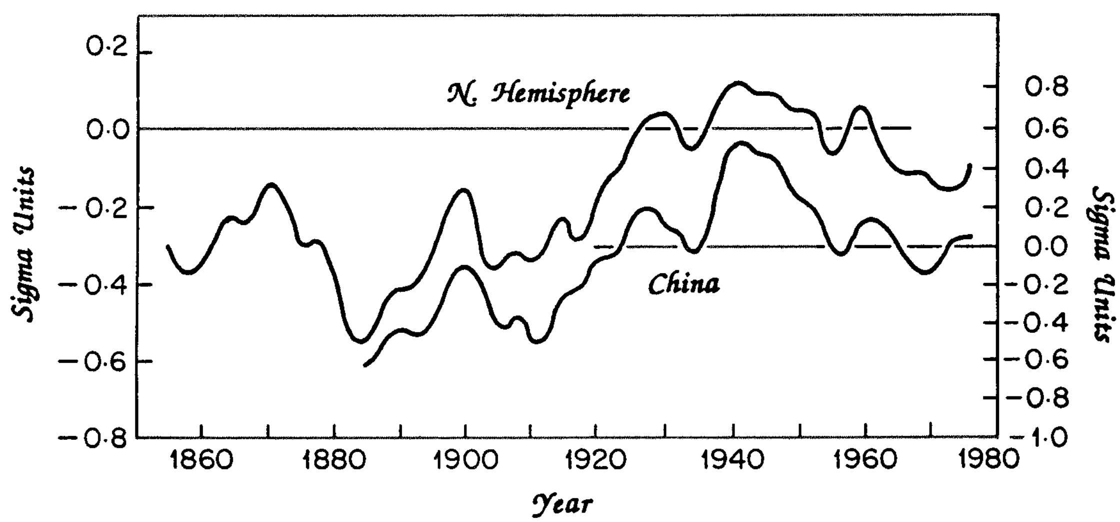

Figure 3. Normalized mean annual temperature anomalies over China (right scale) compared to the normalized Northern Hemisphere record (left scale). Reference period 1951–70 in each case. Chinese series displaced down to facilitate comparison. Data smoothed with an 11-year binomial filter (from Bradley et al., 1987).

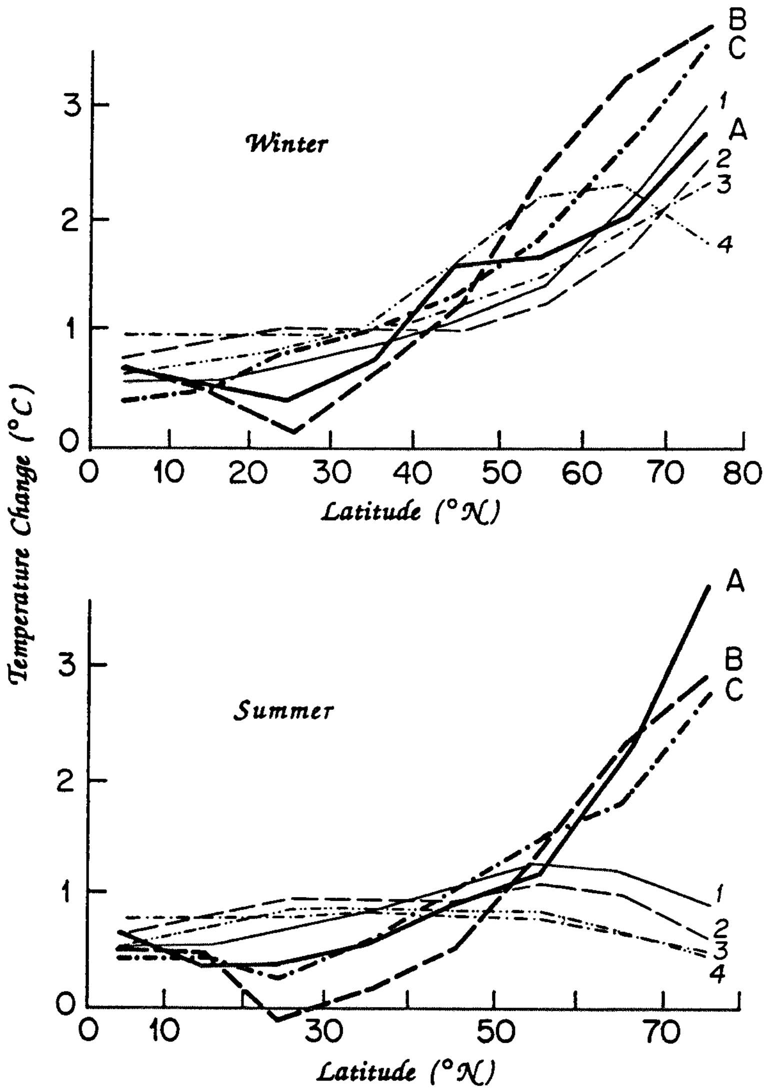

Figure 4. Relative changes in surface air temperature for winter and summer months versus latitude (°N) relative to a 1°C change in the overall Northern Hemisphere temperature. Values are based on empirical data and on four GCM simulations for a doubling of CO_2 concentration in the atmosphere: A = the "Holocene Optimum," B = the last (Eemian) interglacial, and C = the "Pliocene Optimum"; model results are from: (1) Manabe and Wetherald, 1987; (2) Schlesinger and Mitchell, 1987; (3) Hansen et al., 1984; and (4) Washington and Meehl, 1984. All values are scaled for a 1°C change in temperature over the Northern Hemisphere as a whole (after MacCracken et al., 1990, Chapter 6).

They demonstrate a high correlation between tree-ring widths from a network of trees along the northern treeline of North America and Northern Hemisphere land temperatures over the last century, mainly in the lower-frequency variations (Figure 5).

All these studies suggest that the phase of large-scale (hemispheric) low-frequency changes (with periods of, say, >20 years) may be represented by individual regional records, though the amplitudes may differ, depending on the region. It could be argued that this supports the notion (common in studies of proxy records) that a specific record has significance far beyond the site of its deposition. It is reasonable to assume that a record from one site represents the record for some distance beyond the immediate site, since there is generally significant spatial coherence (particularly for temperature fluctuations). However, the precise relationship between the spatial scale of climatic variation and the temporal scale is difficult to specify, though in general terms, low-frequency changes in climate tend to be represented over greater spatial scales. The difficulty is determining how representative a single record (or regional composite record) might be of climatic changes over even larger areas. For example, which areas are most highly correlated with the hemispheric record? In a general study of this problem, Jones and Kelly (1983) showed that although certain geographic regions were

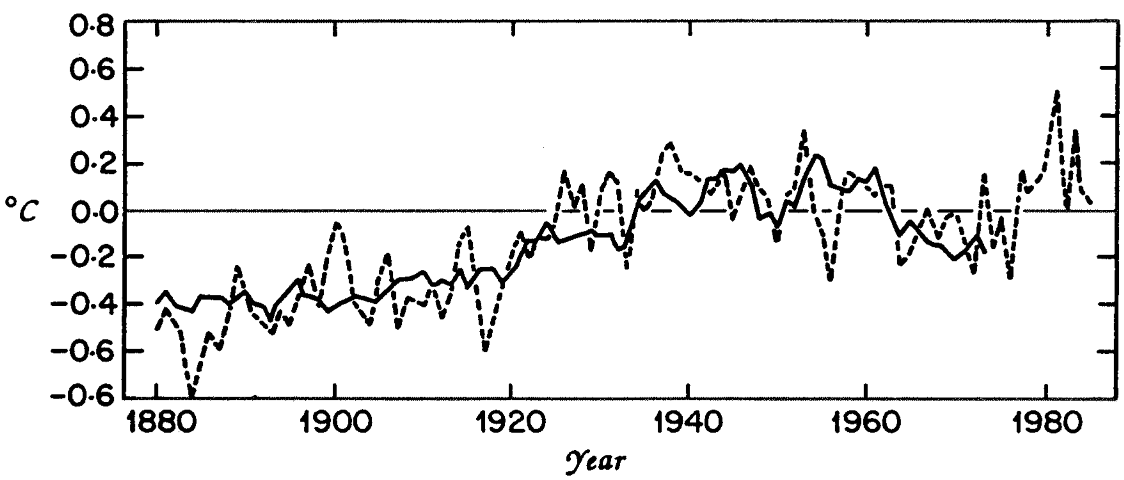

Figure 5. Annual temperature anomalies reconstructed from a set of North American tree-ring widths (solid line, averaged for a network of trees stretching from Alaska to Labrador) and Northern Hemisphere temperature anomalies (from Jacoby and d'Arrigo, 1989). Note that the tree-ring data have been scaled in terms of Northern Hemisphere temperatures and so there is a good match between the overall amplitudes of temperature variation in both series.

strongly correlated with the Northern Hemisphere land temperature record, in a comparison of two 30-year periods the correlation field did not remain constant over time. This raises questions about whether any single region can be selected as the optimum surrogate for hemispheric-scale climate variations. It may be that this study, of such short intervals, only reflects changes in the correlation field of high-frequency variations. Certainly, Figures 2, 3, and 5 suggest lower-frequency variations can be represented by records from specific regions. Alternatively, perhaps a distributed set of data can represent hemispheric-scale climate, even if the correlation field varies over time. Additional research on the temporal and spatial scale of climatic change is needed to resolve these questions.

Can individual (regional) records be used to approximate *global* temperature variations? Here the problem becomes extremely difficult because of the large area of the globe which is oceanic (~70%) and for which we have relatively few data. Figure 6 shows an attempted reconstruction of "global" temperature variations since 1851 using a geographically weighted combination of data from both land and sea

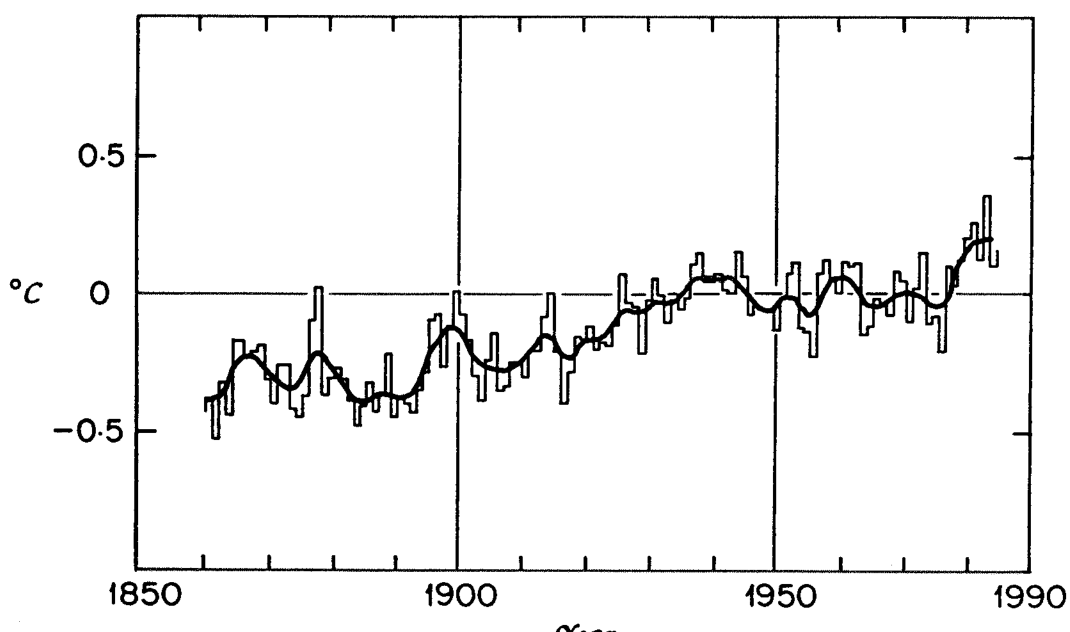

Figure 6. "Global" temperature variations for the last ~120 years based on areally averaged temperature records from Northern and Southern Hemisphere continents and from the world oceans (from Jones et al., 1986b).

areas (Jones et al., 1986b). Unfortunately, as shown in Figure 7, data coverage for the world oceans decreased dramatically before about 1945 so that most of the oceanic areas of the world provided no data to use in a "global" average record. Much of the "global signal" thus reflects those limited regions where data have been collected throughout the period. Of course, if those regions are representative of the global ocean, they may provide an adequate sample of the overall signal. Temperature anomalies tend to be more spatially coherent over oceanic regions, and so fewer regions need to be sampled to represent

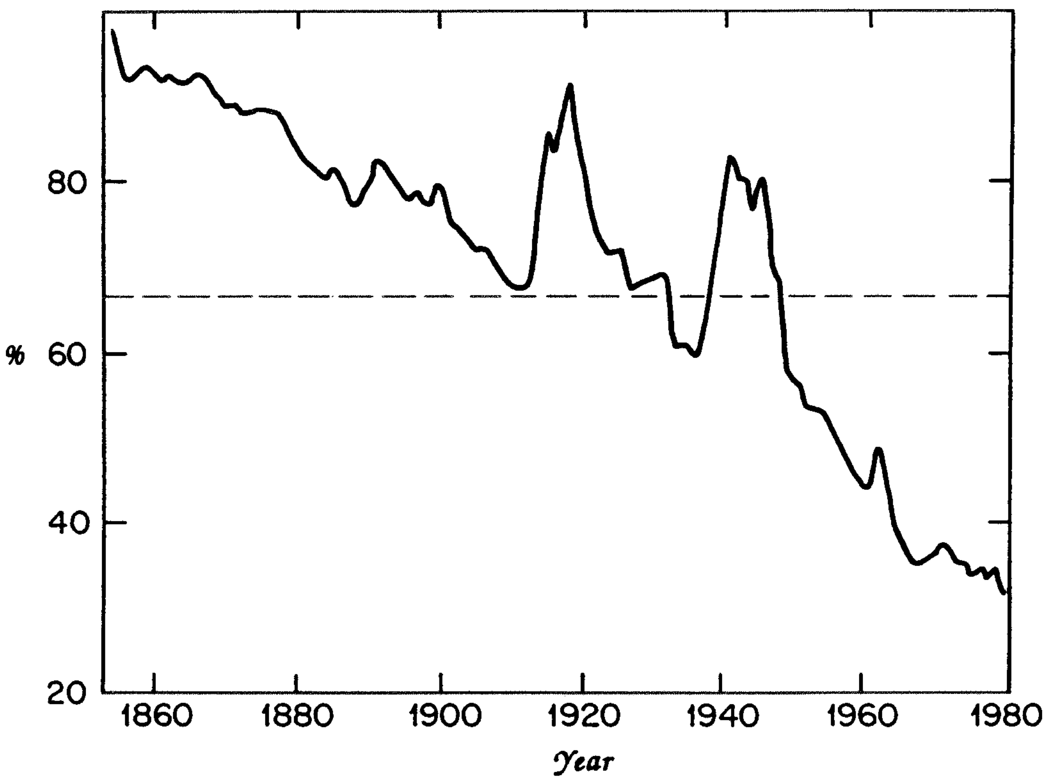

Figure 7. Sea surface temperature data coverage over the world ocean. Percentage of world ocean area having <1 observation per month (based on division of ocean area into 2° x 2° boxes and calculating for each year the area of those boxes with <1 observation per month in relation to the world ocean area) (unpublished data from S. Woodruff, personal communication).

the whole. However, it *is* necessary to have samples from a wide geographical distribution because certain modes of anomalies may be opposite in sign from one part of the ocean to another. If the reduced network of the period before World War II does not adequately sample this variability, the "global" record which results may be unrepresentative of the "true" global signal of the last 100 years. A frozen grid approach could be used to assess the extent of this problem, but even in the 1980s, 60% of the world ocean area has fewer than four observations per month in a 2° x 2° grid box, so even the most recent period is relatively poorly sampled. In short, even in the period of instrumental records, current estimates of mean global temperature change over the last century are inadequate because of the limited spatial data coverage. This problem is even more acute when considering how to assess "global" climatic changes from paleoclimate (proxy) records. It is not clear that we are in a position to assess, for example, how mean global temperatures differed from today during the Holocene, the last glacial period, or the last interglacial, based on the limited networks of proxy data currently available.

Further studies are needed to identify the minimum network necessary to capture most of the variance of large-scale (hemispheric and global) climatic variations. The coverage in such networks might differ from winter to summer conditions and be different if the focus is on low- or high-frequency changes. In addition, further research is needed on the relationship between the amplitude of climatic fluctuations at different latitudes in relation to hemispheric or global averages. Both empirical and modeling studies can be applied to these problems.

What Is "Today"?

Whenever proxy records of past climate are examined, we inevitably want to compare the past climatic record with that of today. After all, being able to put today's climate in a longer-term perspective is one of the principal objectives of paleoclimatology. However, this poses an awkward problem: What do we mean by "today"? Climate is, by definition, a statistical abstraction which involves time. In instrumental climatology, statistical moments are based on a specified period of data collection, generally 30 years or more in length (World Meteorological Organization, 1966). Hence, "today" presumably means the most recent 30-year period. But the most recent 30 years have been markedly warmer in some regions than in previous decades; in fact, it appears that the last decade was one of the warmest, globally, for at least 140 years and perhaps for several centuries (Jones et al., 1988). Calculation of temperature *differences* between today and the past may therefore produce different results depending on what we mean by today. This problem is compounded in many parts of the world by the poor documentation of climatic data; a paleoclimatologist may only be able to obtain "modern" climatic data for, say, 1931–60 or perhaps worse, a shorter interval of a decade or less. This is especially true for oceanic regions; oceanic maps and atlases commonly used in paleoclimatic research to represent the climate of "today" may be based on a composite of very short-term records derived from different time intervals. In other parts of the world (such as Antarctica) virtually no instrumental climatic data are available before 1957 (the International Geophysical Year), so any comparison of the past with "today" must refer to the last 30 years, or some period within it.

This may seem like a trivial problem in terms of temperature, since decadal mean seasonal temperature differences in the 20th century have been <1°C in most places, and temperatures reconstructed by proxy data are often on the order of several degrees Celsius different from 20th-century averages. However, the problem is not insignificant when one is reconstructing more subtle variations of the recent past, for example, decadal-scale variations of temperature over the last few hundred years when temperature anomalies may have been within 1° or 2°C of recent averages. Neither is it unimportant when parameters other than temperature are involved. Precipitation, for example, may vary greatly from one decade to the next, and anomalies may change dramatically in sign across regions, depending on the period selected for analysis. Consider the large changes in Sahelian drought over the last few decades. Should precipitation amounts of the last three decades be used to represent "today," or should the preceding decades be averaged in? This could significantly alter the interpretation of how much climate has changed since some period in the past. The difficulty is not confined to proxy data, either. Experimental results from general circulation models are often presented as maps of some future (or past) condition showing the difference from "modern" conditions. Of course, in such cases the modern state is that derived from a model run of "present-day" climate, but the veracity of these conditions is tested by comparison with the spatial pattern of climatic conditions of "today." Models that do not mimic today's climate very well are tuned until they do. It is instructive to examine what modelers use as their calibration data sets of "today's climate." A common source of calibration is the Schutz and Gates (1971) compilation of temperature, pressure, and precipitation over a gridded network. In this data set, temperature statistics are based on the period 1931–60, but precipitation data are derived from a Soviet atlas where the main period of record is 1950–1956. Clearly, this is not an adequate period on which to base judgment about the veracity of modeled precipitation. In the Great Plains of the United States, for example, the 1950s was a period of extreme drought.

Other modeling groups use Oort's data set based on the 16-year period 1958–1973. How all the climatic statistics differ from those of the longer period 1931–60 is not known, though the later period was characterized by a general fall in temperatures globally. Recent attempts to produce an improved "modern" data base of global climate (Legates and Wilmott, in press) will not help, since data from many different time intervals are merged together.

Defining "today" is also important in the calibration of proxy data for paleoclimatic reconstruction. All proxy records have to be calibrated with modern data to enable a meaningful climatic interpretation to be made. In sedimentary records, core-top material is often taken to represent the proxy response to "modern" climate, yet the core-top sediments may actually represent centuries, or even thousands of years of sedimentation. For example, Imbrie and Kipp (1971) note that the core-top samples used in their CLIMAP reconstructions of conditions at 18,000 yr B.P. include material from much of the late Holocene: "most [core-top samples] represent ... the last 2000 to 4000 years and ... some may contain materials deposited in the age range 4000–8000 years B.P." (Imbrie and Kipp, 1971). These were then calibrated with sea surface data derived from limited observations, largely made before World War II (Defant, 1961). Often these represent very short periods of time, yet conditions in the world ocean may change significantly on decadal time scales (e.g., Wahl and Bryson, 1975; Levitus, 1989). To what extent estimation of temperature differences in the past is affected by these mismatches of supposedly "modern" proxy data with instrumentally recorded data is not known. Imbrie and Kipp (1971) considered this problem to be one of the largest sources of error in their paleoclimatic reconstructions. It could be argued, perhaps, that temperature changes on glacial to interglacial time scales in many parts of the world ocean were so large that such calibration problems are not important. However, over extensive regions temperature changes from maximum glacial conditions to today are thought to have been <2°C (CLIMAP, 1976), and so it seems likely that much smaller changes have characterized most of the last 120,000 years. Estimating these changes is a challenge that requires very careful calibration between "modern" proxy data and the climate of "today."

Concluding Remarks

Determining how the climate of the globe, or of each hemisphere, has changed over time involves the analysis of a large number of instrumental or proxy records. In either case, there are mutual problems in establishing how much data coverage is adequate to characterize large-scale conditions and to select an appropriate baseline for the climate of today. Studies of *global* change evolve from local, regional, and continental scale data sets. Determining how changes at each of these levels relate to those at the hemispheric or global scale is an important challenge for future research.

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