The Spectrum of Temporal Climatic Variability: Current Estimates and the Need for Global and Regional Time Series

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Introduction

Climate varies on all time scales. Illustrating this fact should be a key goal for global change research. Therefore, a spectrum of data sets is needed that can portray the natural variability at different temporal scales and thus can give readers a zoom-lens view of how climate varies from decades up to millions of years. This zoom-lens sequence should contain data representing comparable spatial scales and show the magnitude, rate, and timing of change for the same climate variable at each time scale. By illustrating the natural variability of the climate system, figures displaying time series for different time spans help climatologists discern the various factors and mechanisms that control or influence climate. Such understanding is critical for evaluating how predicted future changes compare to past variability. Because many forecasts are for global mean temperature, I focused my review on past records interpreted to be global or hemispheric means.

One of the first attempts to illustrate the spectrum of climatic change from scales of 100 years up to 1 million years appears in the 1975 National Academy of Sciences report *Understanding Climate Change* (U.S. Committee for GARP, 1975) (Figure 1). It focuses on temperature and illustrates how warming since the end of the Little Ice Age, about 1850 A.D., contrasts with glacial-interglacial variability of the past 850,000 years. Its legend is clear about different spatial scales being represented by each time series, but subsequent replotting of this figure with modification or replacement of some of its time series has led to several figures (Figures 2–6), some of which claim to show global or hemispheric variations in temperature (mean annual is implied but never stated) for each time scale. The purpose of my paper is to examine these figures (Figures 1–6) critically in order to assess our current state of knowledge about global temperature change and to point out where major uncertainties exist requiring future research. I note the empirical basis for each time series and the assumptions used in calibrating the indirect measures of temperature.

To illustrate how climate varies temporally, Bernabo (1978) replotted Figure 1 from the U.S. Committee for GARP report (1975). His figure (Figure 2) shows a more or less uniform step-by-step magnification of the time axis, and I have modified it myself in a subsequent publication (Figure 3; Webb et al., 1985). In a different replotting of the data from Figure 1, Clark (1982) obtained some estimates of the temperatures represented for each time scale and plotted them along a uniform temperature scale (Figure 4). When used as "cartoons," these figures provide information on the general nature of temporal climate variations and can help organize the description about past climate change (Bernabo, 1978; Webb et al., 1985; Clark, 1982; Saltzman, 1983; Davis, 1986). Each of these figures contains uncertainties and certain inconsistencies. My critical review is designed to point out some of these problems and to note where global change research can lead to improvements.

My initial focus on global and hemispheric averages arises for several reasons. First, in a global change program, knowledge of global and hemispheric averages would seem fundamental. Even though prediction of regional variations may be more important for impacts assessment than prediction of global mean variations, knowledge of what the globe on average is doing and has done should be available. Second, many of the estimated magnitudes for the global warming that may be induced by greenhouse gases are given in terms of changes in the global mean temperature, and time series of past changes are needed to help evaluate these predictions. Third, most of the time series in Figures 1–6 were chosen to represent global or hemispheric averages and can only be assessed by a focus on these scales. One of my chief criticisms of these times series, however, is that several may not be representative of either global or hemispheric averages.

Temporal Variability

The ideal version of Figures 1–6 should contain time series of surface temperature estimates representative of global or hemispheric averages for each time scale. The empirical basis for each time series should be known and available for analysis in terms of time control, global representativeness, and standardization and calibration methods. Either global arrays of data or local time series of data that record a global signal should yield the global and hemispheric averages. The precision of the temperature estimates should be one-tenth the temperature range for a given time scale, and seasonal as well as annual average values should be available.

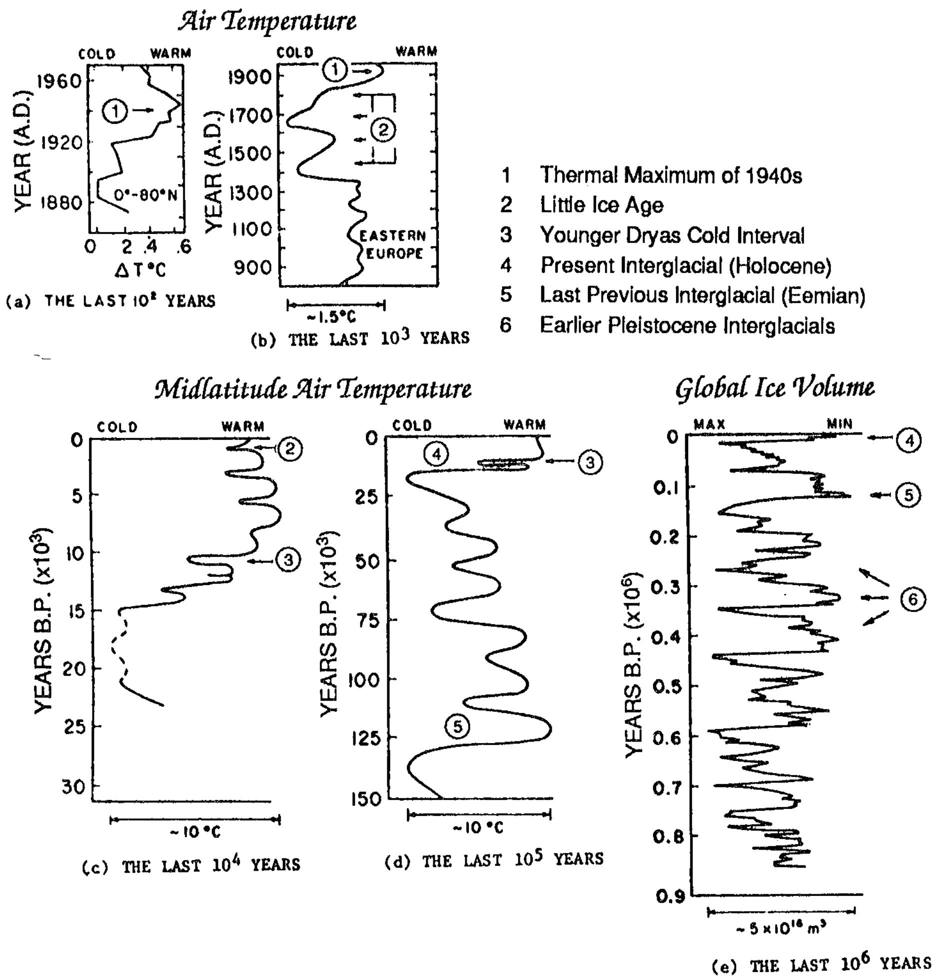

Figure 1. Generalized trends in global climate for the past 850,000 years (reprinted from U.S. Committee for GARP, Understanding Climatic Change, *1975, with permission from the National Academy of Sciences, National Academy Press, Washington, DC). (a) Changes in the five-year average surface temperatures over the region 0–18°N during the last 100 years (Mitchell, 1961). (b) Winter severity index for eastern Europe during the last 1000 years (Lamb, 1969). (c) Generalized midlatitude Northern Hemisphere air temperature trends during the last 25,000 years, based on changes in treelines (LaMarche, 1974), marginal fluctuations in alpine and continental glaciers (Denton and Karlen, 1973), and shifts in vegetation patterns recorded in pollen spectra (van der Hammen et al., 1971). (d) Generalized Northern Hemisphere air temperature trends during the last 150,000 years, based on midlatitude SST and pollen records and on worldwide sea level records. (e) Fluctuations in global ice volume during the last 850,000 years as recorded by changes in isotopic composition of fossil plankton in deep-sea core V28–238 (Shackleton and Opdyke, 1973).*

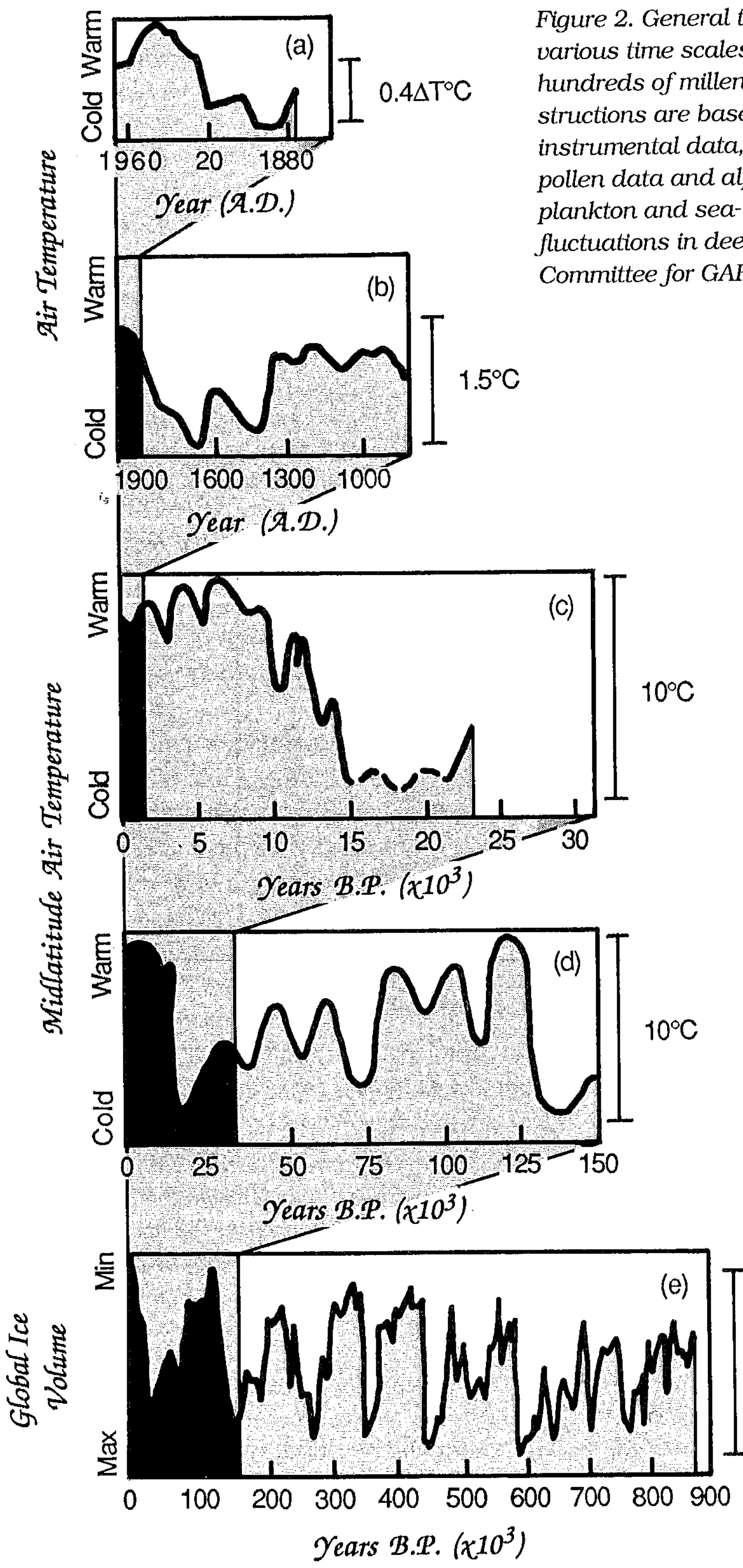

Figure 2. General trends in global climate for various time scales ranging from decades to hundreds of millennia. Climatic change reconstructions are based primarily on records from (a) instrumental data, (b) historical information, (c) pollen data and alpine glaciers, (d) marine plankton and sea-level terraces, and (e) isotopic fluctuations in deep sea sediments (after U.S. Committee for GARP, 1975; from Bernabo, 1978).

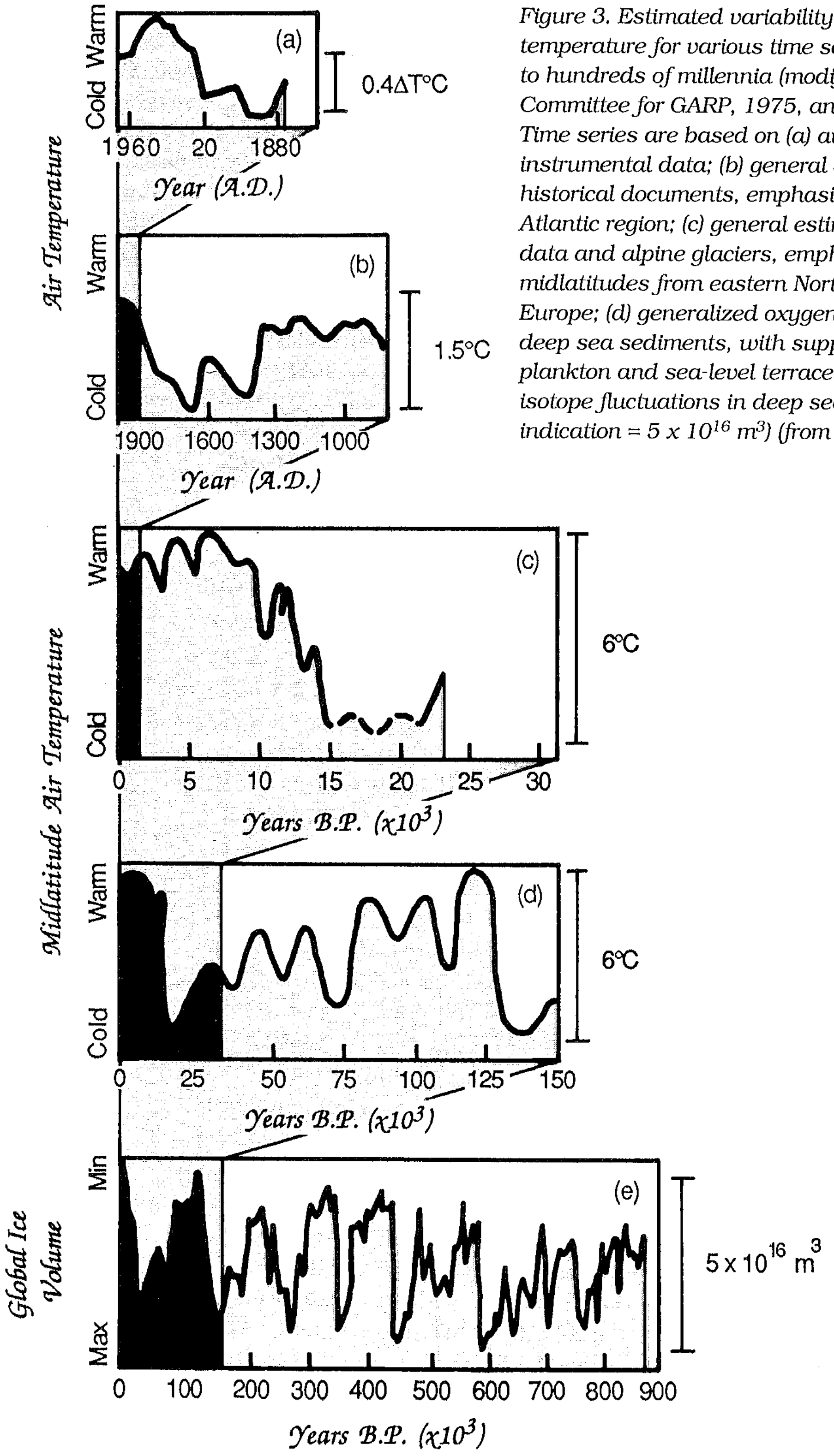

Figure 3. Estimated variability of the global mean temperature for various time scales from decades to hundreds of millennia (modified from U.S. Committee for GARP, 1975, and Bernabo, 1978). Time series are based on (a) averages from instrumental data; (b) general estimates from historical documents, emphasis on the North Atlantic region; (c) general estimates from pollen data and alpine glaciers, emphasis on midlatitudes from eastern North America and Europe; (d) generalized oxygen isotope curve from deep sea sediments, with support from marine plankton and sea-level terraces; and (e) oxygen isotope fluctuations in deep sea sediments (volume indication = 5 x 10^{16} m^3) (from Webb et al., 1985).

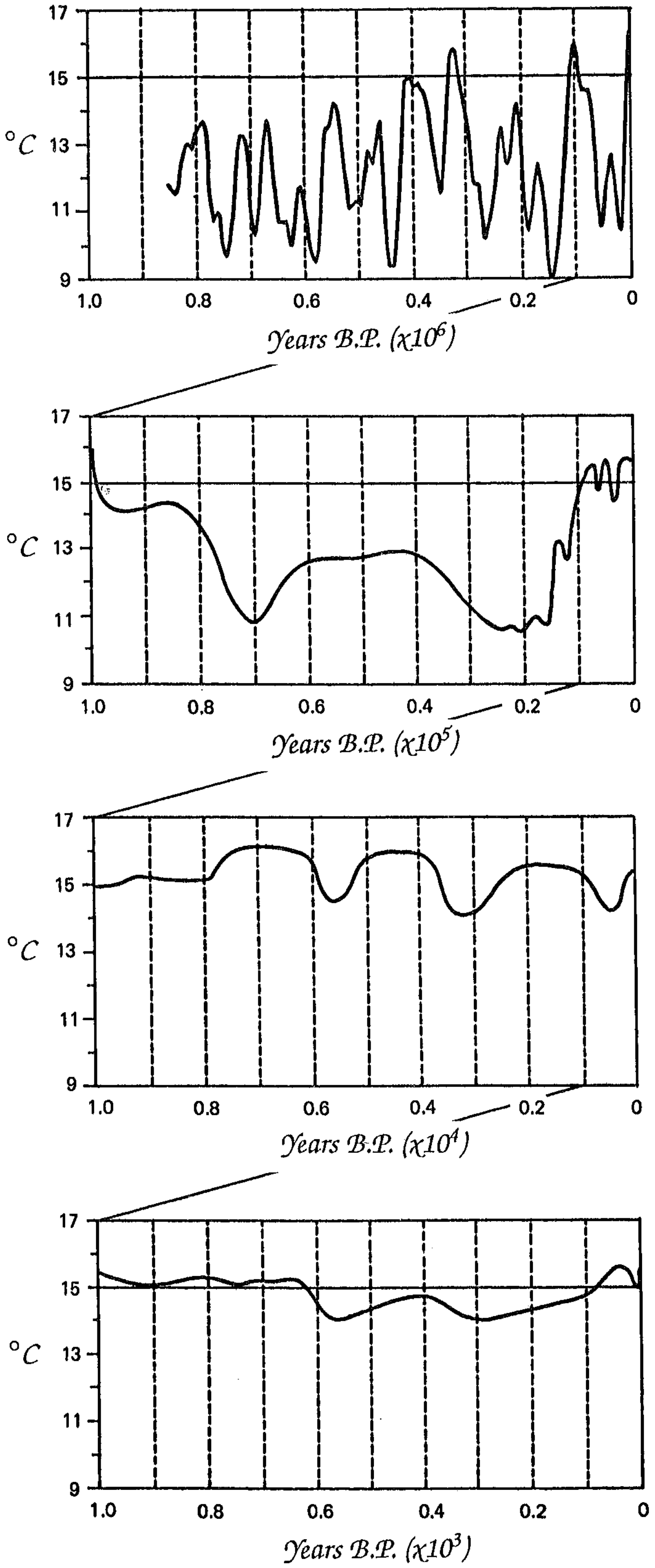

Figure 4. An approximate temperature history of the Northern Hemisphere for the last 850,000 years (reprinted with permission from William C. Clark (ed.), 1982, Carbon Dioxide Review*). The panels are at the same vertical scale. The top panel shows the past million years, the second panel amplifies the past 100,000 years, the third panel the past 10,000 years, and the bottom panel the past 1000 years. Data were digitized from Matthews (1976) and Mitchell (1979).*

In Figure 1, time series covering the shortest and longest time spans (100 yr and 1 million yr) come closest to meeting the ideal of representing empirically derived estimates of global average or hemispheric average temperatures. These time series are based either on data that represent a complex global signal (e.g., the $\delta^{18}O$ variations in deep sea cores over the past 100,000 to 1 million years) or on local data that are from a broad enough distribution of stations to allow calculations of an approximate global average (Jones et al., 1986a; see also Bradley, this volume). In the following discussion, I start with descriptions of these time series in order to set a standard for the time series at the other scales and end with a description of the time spans (25,000 and 1000 years) for which knowledge of the hemispheric and global variations is the most uncertain.

The Past 100 Years

Figure 1a contains a time series of one estimate of Northern Hemisphere temperature variations from A.D. 1880 to 1970 that Willett (1950) and Mitchell (1961) constructed by averaging the records from a hemispheric-wide network of land-based thermometers. Coverage was uneven, with fewer samples and less quality control for the tropics and ocean regions than for the northern midlatitude land surface, and the data set was less uniform the farther it extended back in time. These and other problems (e.g., heat island effects near cities) are fully acknowledged and recently have received much critical attention (Jones et al., 1986b, 1986c, 1989; Bradley, this volume). In fact, Jones et al. (1986a, 1986b) have subsequently updated and improved the data set of thermometer records and expanded it to include marine data and data from the Southern Hemisphere; Bradley (this volume) reviews this work and that of others (e.g., Hansen and Lebedeff, 1987). The main improvement needed for Figures 1–3, therefore, is to replace the Northern Hemisphere time series from Mitchell (1961) with either that from Jones et al. (1986b) for the Northern Hemisphere or that from Jones et al. (1986a, 1989) for the globe.

One advantage in having a global set of time series is that investigators can check how well specific local or regional records match the time series for the hemispheric or global mean. For selected time intervals, some local and regional time series match parts of the global or hemispheric time series, but none of the former time series can serve as a proxy for all of the latter (Bradley, this volume). This comparison of time series from different scales is critical because some researchers assume that data from the local sections mirror global trends (Deevey and Flint, 1957). The evidence from the global set of thermometric records, however, suggests that this assumption is invalid. Changes in one region that may be abrupt may not be evident in other regions or be reflected in the global average. In fact, Jones et al. (1986c) comment that the commonly used land surface temperature record for the Northern Hemisphere is not the best proxy for the global mean land-sea record.

The Past 1 Million Years

At the other temporal extreme, the past million years, the time series is from a deep sea record of $\delta^{18}O$ from planktonic foraminifera (Figure 1e), which is inferred to be enough of a record of global ice volume (Shackleton and Opdyke, 1973; Shackleton, 1987) that the major variations represent a global (versus regional or local) signal. This inference makes this record notable (see previous discussion), because the $\delta^{18}O$ record from a single core can represent a global average. Such is also true for many CO_2 measurements in ice cores, but is not true for most geological records sensitive to standard climatic variables (e.g., pollen, tree rings, etc.). Nor is it true for $\delta^{18}O$ records for the ice from ice cores.

In Figures 1–3, 5, and 6, the longest time series is scaled in terms of ice volume and thus shows directly the timing and duration of glacial and interglacial conditions, which represent some of the major climate variations during the Quaternary. By assuming that the global mean temperature varied in phase (+3000 yr) with global ice volume, the reader can infer the timing and magnitude of the associated changes in temperature. In Figure 4, Clark (1982) presented a rescaling of the time series, which can also be applied to records for the past 150,000 years (Figure 3), by using the general circulation model (GCM)-derived difference between 18,000 yr B.P. and today of 4–5°C to show a global mean temperature increase of 4–6°C between full glacial and full interglacial conditions (Hyde et al., 1989; Kutzbach, 1989; see Appendix in Webb, in press). This estimate of temperature difference was not available in 1975 and first became available when Gates (1976) and Manabe and Hahn (1977) ran general circulation models to simulate conditions at 18,000 yr B.P.

The inference that global mean temperatures varied in proportion to global ice volume seems reasonable. How closely in time the temperature variations match those in ice volume is not so clear but should be within 3000 years, which is small enough for a million-year time span. The exact temperature range to be estimated for the $\delta^{18}O$ curve is also uncertain and depends on the sensitivity of different climate models to full-glacial boundary conditions and on the existence of any overall bias in the model results (Kutzbach and Guetter, 1986; Harvey, 1989). Further research is also required concerning the dominance of the global ice volume signal in the $\delta^{18}O$ or adjusted $\delta^{18}O$ record (Shackleton, 1987).

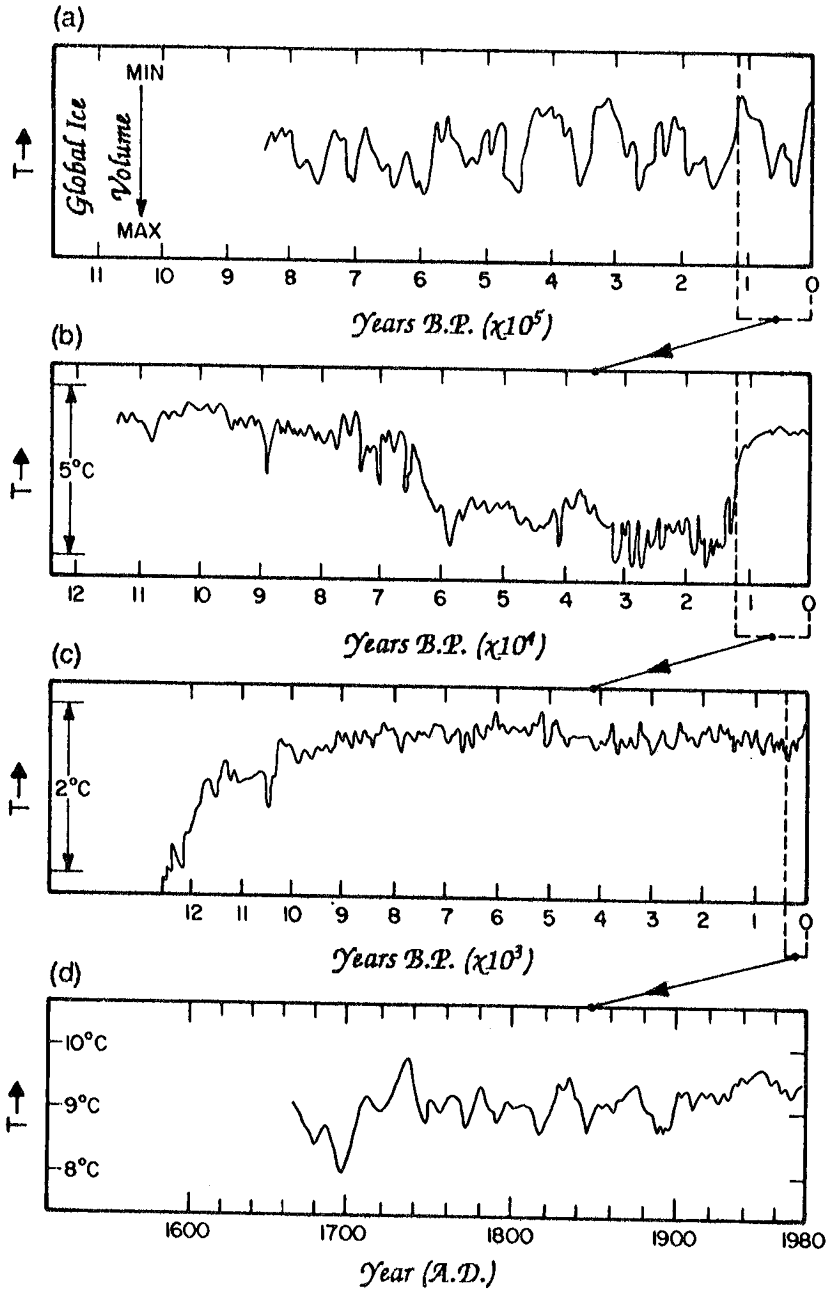

Figure 5. Selected climatic time series for the past 1 million years (reprinted with permission from Saltzman, 1983). (a) Global ice volume deduced from oxygen isotope variations of planktonic foraminifera in a deep sea core over the last 100,000 yr (Shackleton and Opdyke, 1973); (b) global mean temperature variations over the last 10,000 yr; (c) oxygen isotope variations in a Greenland ice core over the last 1000 yr (Dansgaard et al., 1971); and (d) thermometric measurements in England over the last 300 yr (Mason, 1976).

The Past 150,000 Years

The time series in Figure 1d was derived as a composite from several different records in Figure A.13 of U.S. Committee for GARP (1975) and most strongly resembles the temporal variations in the records of percent arboreal pollen from a Greek core (van der Hammen et al., 1971) and sea surface temperature (SST) estimates from a North Atlantic core (Sancetta et al., 1973). The temperature scale for midlatitude air temperature (Figure 1d) comes by inference from the latter record, but this estimate of 10°C appears to be an overestimate for the hemisphere or globe (CLIMAP, 1981; Kutzbach and Guetter, 1986). Because several of the oscillations in Figure 1d match those in the marine $\delta^{18}O$ record (e.g., stages 1–6 and substages 5a–5e), this plot may reflect global oscillations and therefore can be rescaled to record a temperature range of 5–6°C (Figures 3 and 4). This rescaling is the same as that for the million-year record of global ice volume, but should be more sensitive to the time constants linking variations in $\delta^{18}O$ and global mean annual temperatures.

Caution is needed in using the 150,000-year record in Figure 1d because its inclusion of a Younger Dryas oscillation has no strong empirical basis in time series of 150,000 years or longer, whose individual samples have a time resolution of ca. 2000 years, nor do any of the time series in Figure A.13 show much evidence for cooling since the mid-Holocene. These features were imposed by the originators of Figure 1 and are not evident in the high-resolution stacked $\delta^{18}O$ record in Figure 18 of Martinson et al. (1987). This latter record or one of the records from the Vostok ice core (Lorius et al., 1988) might be candidates for providing a new time series for this 150,000-year time scale. Recently Imbrie et al. (1989) have published a transect of time series of SST estimates from 54°N to 44°S. This data set could be averaged and provide an initial empirical basis for the global average sea surface temperature variations from 300,000 yr B.P. to present.

As an alternative time series to that in Figure 1d, Davis (1986) used a time series derived from several sources in Europe with an estimated temperature range of 10°C that is most likely too large for the Northern Hemisphere (Figure 6), and Saltzman (1983) used the $\delta^{18}O$ time series from a Greenland ice core calibrated in terms of temperature (Figure 5). The problem with ice-core $\delta^{18}O$ variations is that they can reflect storm track and SST changes as well as regional land surface temperature variations (White et al., 1989). With respect to the timing of its peaks and valleys, the $\delta^{18}O$ time series is representative only of Greenland or of the northern North Atlantic, at most; but its temperature range of 5°C may be within 1°C of being correct for the Northern Hemisphere.

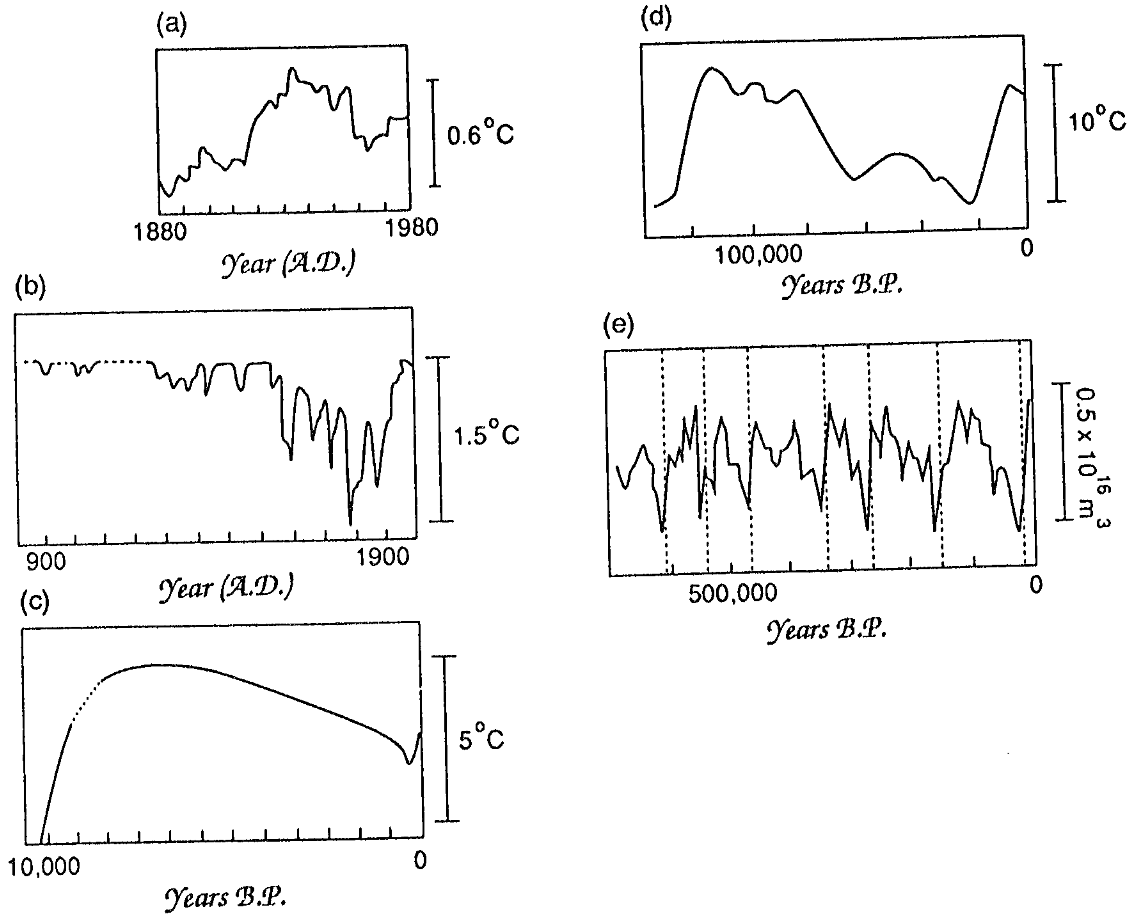

Figure 6. Temperature changes in the Northern Hemisphere for different time scales (reprinted with permission from M. B. Davis, 1986, in Community Ecology, *ed. by S. Diamond and T. J. Case (Harper and Row), p. 270. (a) Instrumental data for annual temperature, latitudes 23.6–90°N. (b) Air temperature during the past 1000 years, reconstructed from accounts of sea ice. (c) Annual temperature in northeastern United States over the past 10,000 years, inferred from fossil pollen data (Davis et al., 1980). (d) Annual temperature over the past 100,000 years in Europe, reconstructed from records of vegetation, sea level changes, and planktonic and geochemical changes in deep sea sediments. (e) Global ice volumes inferred from oxygen isotope variations in deep sea sediments.*

The Past 25,000 Years

The length of this time series is best set at 25,000 rather than 10,000 years. Extending the base of the time series back to 25,000 yr B.P. allows the time series to include the last glacial maximum at 18,000 + 2000 years B.P. (i.e., the radiocarbon-dated time of the $\delta^{18}O$ maximum in deep sea cores; Mix and Ruddiman, 1985) and the subsequent large changes in climate (contrast Figures 1–3 with Figures 4–6). The original time series in Figure 1c was derived from several sources and in its low-frequency form reflects the fact that its creator believed that a midlatitude hypsithermal period (i.e., the time of maximum temperatures for this interglacial) was global in extent and extended from 8000 to 4000 yr B.P. High-frequency oscillations were imposed on the time series to reflect the Little Ice Age (450 to 100 yr B.P.) and Younger Dryas (11,000 to 10,000 yr B.P.) as well as various neoglacial episodes at approximately 2500-year intervals (as postulated by Denton and Karlen, 1973). However, no global, hemispheric, or even northern midlatitude set of cores exists to support the details or even general timing of many of the features in Figure 1c (Webb and Wigley, 1985). Figure 1c is therefore much more speculative than the time series in Figures 1a, 1d, and 1e.

In support of the low-frequency trend, data from many sites in the Northern Hemisphere indicate a local or regional thermal maximum during the past 10,000 years (Iversen, 1944; Khotinskii, 1977; Davis et al., 1980; Ritchie et al., 1983; Bartlein and Webb, 1985; Huntley and Prentice, 1988; Diaz et al., 1989), and in most locations the thermal maximum occurred somewhere around 6000 + 3000 years. Evidence also exists that demonstrates that the thermal maximum was time transgressive (see COHMAP, 1988, and Bartlein et al., 1984) and, if related to orbital forcing, may only have been a maximum in summer temperatures in the Northern Hemisphere (Ritchie et al., 1983; COHMAP, 1988) except possibly in northwestern Europe (Kutzbach and Gallimore, 1988). What the true hemispheric and global average would look like is not yet clear. One hypothesis comes from the National Center for Atmospheric Research GCM, which simulated no variation in the global mean annual temperature from 9000 yr B.P. to present (Kutzbach and Guetter, 1986; Hyde et al., 1989), but those results depend strongly on the assumption that the SSTs, which were prescribed in the GCM, were the same as those for today from 9000 yr B.P. to the present. Adequate documented data sets with temperature estimates are not yet broad enough in coverage to check this result (Webb, 1985), but research is in progress that may soon yield coverage that matches the grid of the thermometers used by Jones et al. (1986b) for A.D. 1930 and earlier.

Reviews of the alpine glacier records by Grove (1979, 1988) do not support the 2500-year periodicity suggested by Denton and Karlen (1973), but the existence of global or hemispheric oscillations in the global mean temperature of 1°C for the Little Ice Age and Younger Dryas is possible but not yet proven. The global or hemispheric nature of the other neoglacial episodes is far from established, however (Grove, 1988).

Saltzman (1983) and Davis (1986) were therefore appropriately cautious in not using the time series in Figure 1c, but the records that they chose (a $\delta^{18}O$ record in a Greenland ice core for Figure 5 and an interpretation of paleobotanical remains from New England cores for Figure 6) are too regional to be representative of hemispheric conditions. Much new evidence is required from the past 12,000 and 25,000 years before the full details of the short- and long-term changes in the Northern Hemispheric or global average will be known.

The Past 1000 Years

The winter severity index for eastern Europe from Lamb (1969) was used to derive the time series of temperature for the past 1000 years in Figure 1b. The time series looks similar to the winter severity index for the Paris-to-London region in Figure A.9a of U.S. Committee for GARP (1975). Both figures were derived from Figures 24, 25, and 27 in Lamb (1969), but the origin of the temperature scale in Figure 1b is not clear. Its range of 1.5°C may be correct for a region like eastern Europe, but is probably too large an estimate for the Northern Hemisphere or globe over the past 1000 years. (One has to remember that changes in mid- to high-latitude land surfaces have to offset or overwhelm what are often small changes in the tropics—i.e., 40% of the earth's area—and over the oceans, if the global mean is to show much change.) A more realistic estimate might be a range of 1.0°C.

The main features in the time series (Figure 1b) are the Little Ice Age from 450 + 50 to 100 + 30 yr B.P. and warmer periods before and after this time. The temperature record of the past 100 years helps establish that global average and hemispheric averages during the end of the Little Ice Age were at least 0.5°C lower than those today, but the exact temporal extent and definition of the Little Ice Age are still open to discussion (Lamb, 1969; Landsberg, 1980; Grove, 1988; Eronen, 1989). Landsberg (1980) is correct in noting that Northern Hemisphere temperatures from A.D. 1600 to 1880 were not uniformly lower than those from A.D. 1941 to 1970, but many Alpine glaciers were larger from 450 to 100 yr B.P. than subsequently and their expansion gave the Little Ice Age its name (Grove, 1988).

The evidence for the Medieval Warm Period is best in Europe and the North Atlantic (Lamb, 1969; Williams and Wigley, 1983). An exact definition for the timing and nature of this period is not available and its expression in other regions of the globe is unknown. For example, in the Quelccaya ice cap, Peru, the $\delta^{18}O$ values resemble those of today from A.D. 980 to 1520 (Thompson et al., 1988), but this record reflects atmospheric circulation and air mass stability over South America (Grootes et al., 1989) and its tie to the changing conditions in Europe is unclear.

Again, Saltzman (1983) and Davis (1986) used other time series than the one used in Figure 1b, but the records from thermometers in central England (Figure 5) and derived from sea ice (Figure 6) are regional time series and therefore may not represent hemispheric or global averages. The central England record is from Manley (1953) and is one of the longest based on thermometers. Manley (1974), however, notes that most of the record from A.D. 1659 to 1723 is from data from Utrecht or from estimates from prevailing air masses (Bradley, 1990). Landsberg (1980) has reconstructed Northern Hemisphere temperature estimates from A.D. 1579 to 1975 by using tree rings and several historical sources for the interval A.D. 1579 to 1880, and his time series or others like it (see Bradley, 1990) might be used as a partial replacement for the 1000-year time series in Figures 1–4. But data from the tropics, the Southern Hemisphere, and the oceans are needed if the time series is to be representative of a global average.

Discussion

Sets of climatic time series plotted at increasing powers-of-ten scales illustrate how climate has changed and can change at various spatial scales. One goal of global change research should be to improve the current set of Figures 1–6. These have broad utility in constraining model results and require a firm empirical basis. It is ironic, however, that immediate improvements to Figure 1 can be made for the two time series (those for the last 100 and for the last 1 million years) that started out with the most information about global variations. Data from Imbrie et al. (1984) and Martinson et al. (1987) allow us to update the original time series from Shackleton and Opdyke (1973) for the past million years, and data from Jones et al. (1990) permit the earlier estimates for the past 100 years Mitchell (1961) to be revised.

At intermediate time scales, variations over the past 150,000 years are better known than for either the past 25,000 or the past 1000 years. The globally representative $\delta^{18}O$ record for the deep sea can serve as a guide for the low-frequency outline of the past 150,000 years, and the transect of time series from Imbrie et al. (1989) can provide data sets to

check this inference. But broad networks of sites are needed to provide representative averages that can illustrate the timing and magnitude of most variations during the past 1000 and 25,000 years. Networks currently available indicate considerable spatial variation in the time series for these time periods (COHMAP, 1988; Williams and Wigley, 1983). For these two periods, the major variation is either between the Little Ice Age and bracketing warmer periods or between full glacial and interglacial conditions, but both the timing and global-scale temperature variations of shorter-term oscillations (e.g., the Young Dryas within the past 25,000 years) are still uncertain.

Many regional records are well known for the past 1000 and 25,000 years, but caution is needed in using these regional records to represent the major global or hemispheric trends and features. Regional time series may not mirror global trends. The linkage between global and regional trends is far from simple. Such a complex linkage is to be expected for a highly nonlinear system like the climate system. In fact global forcing by orbital factors or by CO_2 may not induce globally synchronous trends in all regional time series. A check of the SST anomaly maps between 18,000 yr B.P. and today (CLIMAP, 1981) shows how poorly the global average curve represents the temperature change for many oceanic regions between 18,000 yr B.P. and today. In large areas of the tropical Pacific Ocean, the planktonic foraminifera indicate warmer temperatures at 18,000 B.P. than today. The resulting time series of temperature from this region does not match inferred global or hemispheric time series in Figure 1–6. Regional and global records for the past 100 years are also known to differ (Bradley, this volume).

A global view of climate is not the only one needed, however. Individual plants, farms, cities, and humans respond to local or regional changes in climate. Such changes are often larger and more rapid than the global-scale variations. A useful set of figures might therefore show zoom-lens figures of time series from various regions, e.g., the North Atlantic or Western Europe, where many records exist. A sequence of SST records might be assembled for the northern North Atlantic to cover intervals from 100 years back to 3 million years and thus record both warming since the Little Ice Age and the impact of the initiation of Northern Hemisphere glaciation. The range of marine changes over these time scales might be compared to the range and timing of changes in $\delta^{18}O$ records from Greenland ice cores or the range and timing of estimated changes in terrestrial temperatures from Scandinavia, France, or the British Isles. Such a comparison could show whether climate variations among regions in the North Atlantic sector are similarly linked on all time scales or whether the regions link up differently depending on the time scales. Such an exercise could produce much insight about the climate system and climate variability and might be more valuable for some purposes than the previous focus on assembling time series estimates of hemispheric or global averages. The focus on regional patterns is also needed if data sets are to be available to test the ability of GCMs to simulate past regional patterns in climate.

Recommended Research

Research that will help to improve the time series in Figures 1–6 and will meet the standards described earlier includes the following.

1. Data sets indicative of climatic variations for time scales from 1000 to 100,000 years should be expanded to provide global coverage. The data sets should include quantitative estimates of annual and seasonal temperature and precipitation with precision to +0.5°C for temperature and +10% for precipitation.

2. The data sets should include the exact location of sites, the dating control and dating uncertainties, and bibliographic references to the published data (see Peterson et al., 1979; Webb, 1985).

3. The uncertainties need checking in the interpretive scheme that links $\delta^{18}O$ from deep sea cores to global ice volume to global mean temperature for time scales of 10,000 to 1 million years.

4. The dating of control points in the $\delta^{18}O$ curve from deep sea cores needs improvement; e.g., Mix and Ruddiman (1985) show that the radiocarbon age for the last glacial maximum ranges from 13,000 to 19,000 yr B.P. Even the date for the last interglacial (oxygen isotope 5e) can still elicit discussion (Lorius et al., 1988).

5. The climatic calibration of the data from ice cores, pollen, marine plankton, and other paleoclimatic sources needs checking and the spatial and temporal scale over which these time series are representative needs specification (White et al., 1989; Bartlein and Webb, 1985; Mix and Ruddiman, 1985). Such studies will show how best to average data together from different sources.

6. Climatic calibration of the global data sets of pollen and lake-level data from the past 25,000 years requires further development and production (COHMAP, 1988). The coverage in these data sets for the Northern Hemisphere is similar to that for the hemispheric data set of thermometers for 1900 and earlier and could soon match that of the 1930s and back (Jones et al., 1986b).

7. Much work is needed to develop time series of temperature and moisture estimates for the past 1000 years in the tropics, Southern Hemisphere, and oceans. Without precise SST estimates for the past 1000 years, it will be almost impossible to estimate global temperature variations.

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