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RECONSTRUCTIONS OF CLIMATE FROM A.D. 1000 TO THE PRESENT

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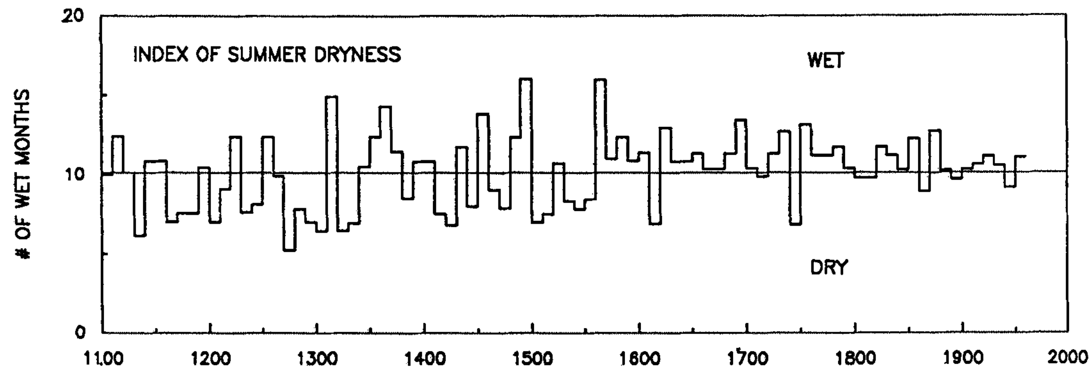
1. INTRODUCTION

In most parts of the world our ability to characterise the climate of a region, through instrumental records of temperature and precipitation, is limited by the short period over which measurements have been made. Generally, instrumental records are less than a century in length and, in inhospitable areas such as polar and desert regions, records may only be available for a few decades. As a result, our perspective on climate variability, both spatial and temporal, is quite limited and this poses particular problems when trying to assess the impact of anthropogenic effects on the climate system. Human influences will be superimposed on any underlying 'natural' climatic variations, and it is therefore essential to understand what changes have occurred in the past. We have a general picture of how climate has changed over the last 150,000 years (through the last glacial-interglacial cycle) but only in terms of very large-scale, low frequency changes. Our understanding of climatic changes at higher frequencies -- variations on the decade to century timescale -- is very poor, yet it is this timescale which is most relevent to current environmental concerns (Bradley and Jones, 1992). Contemporary climatic variations must be viewed in the context of changes which have occurred *before* global-scale anthropogenic impacts on the environment. This requires a perspective extending back many centuries, using records which can be resolved to an individual year or season. This is not an easy task, since there are few natural archives of past climatic history which provide the necessary resolution and the clarity of signal to enable climatic conditions in the past to be reconstructed. For the last 1000 years, such archives include tree rings, ice cores, historical documents, annually laminated (varved) sediments, and banded corals. As with the longest instrumental records, these natural archives are generally restricted to a few regions; ice cores are obviously limited to polar and high alpine environments and even there, only a handful of records spanning the last millennium in any detail are available. Tree ring records are limited to those areas where a clear climatic influence on tree growth can be detected, generally either semi-arid environments where water-stress is important, or high latitudes and high altitudes where tree growth is limited by growing season temperature (Hughes, 1991). Historical documents may be found throughout the world, but written records are unavailable for large continental regions prior to about A.D. 1500, and for some regions, even later (e.g., much of North and South America, Africa, Australasia and Antarctica). Varved sediments may be widely available, but few sites have been investigated; this also applies to banded corals, and in addition their widespread utility for palaeoclimatic reconstruction has yet to be demonstrated. At present, there are virtually no high resolution archival records of past climatic variations from the inter-Tropical zone, or from most of the world's oceans. Any conclusions about past climatic conditions in such regions must be inferred either from more poorly resolved records (e.g. marine, lacustrine or eolian sediments) or from discontinuous types of information (e.g. lake level changes, glacier fluctuations). Finally, it should be noted that each natural archive of past climate generally only provides information about a particular season of the year when the influence of climate on the archival material is strongest. Thus, palaeoclimatic reconstruction of climate over the last millennium requires careful retrieval of the archive, calibration of the climatic signal it incorporates, and reconstruction of the past climatic record. Confidence in these reconstructions can only be provided by comparison with other independent sources of information which may support or verify the reconstruction. In this way, it may be possible to assess whether the 'observed' climatic changes were of more than local significance, and to identify large-scale changes which may be related to causes (forcing factors) of global (or at least hemispheric) significance.

In the following section, a number of long-term records are examined to try and determine the overall characteristics of climatic change during the last 1000 years. Most records do not cover the entire period and, not surprisingly, the geographical coverage decreases more and more before the 20th century. Consequently, it becomes increasingly difficult to be certain about how climate may have changed spatially and temporally as we peer further back in time. Nevertheless, the emphasis here is on features of the record which seem to have more than regional significance.



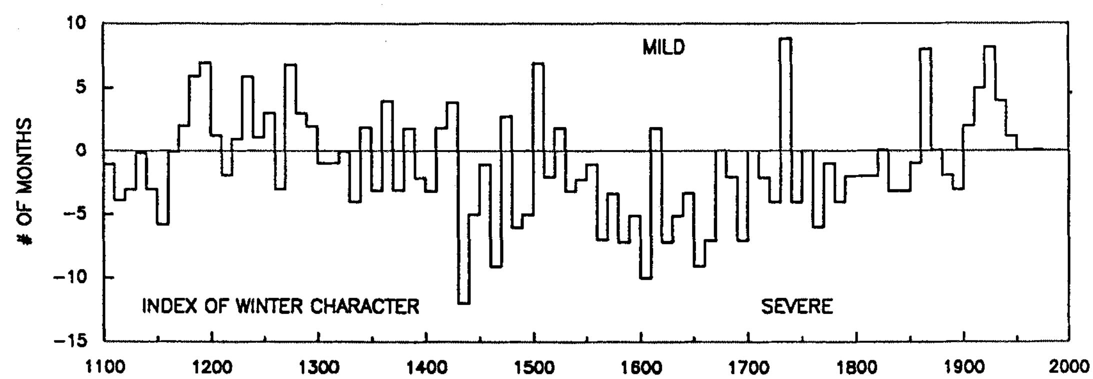


Figure 1. Summer dryness/wetness index, and winter mildness/severity index for England, A.D. 1100-1959 (from Lamb, 1965).

2. EUROPE

A wealth of historical data is available for Europe and this is one of the few regions of the world where it may eventually be possible to reconstruct regional climatic variations, season by season, for the last millennium. Early studies by Lamb (1963, 1965) identified the salient characteristics of climatic variations over this interval (Figure 1). In particular, Lamb argued that Europe experienced "a prevailing warm epoch with dry anticyclonic character, especially in summer ... between about 1000 and 1300 A.D.". He termed this the Early Medieval Warm Epoch (Lamb, 1965). Lamb's concept of this warm period was based on a variety of discontinuous historical and phenological data. More recently, a carefully calibrated tree ring record from northern Scandinavia has provided a continuous ~1500 year perspective on summer (April-August) temperature (Figure 2; Briffa et al., 1990). This record confirms that a warm period also occurred in this region, but places the limits earlier, from ~A.D. 870 to ~1120, and ~1150-1200, with distinct cold intervals in the early 12th century and throughout the 13th century. Further east, a tree ring record from the northern Ural mountains shows the highest average summer temperatures of the last 1000 years were in the interval A.D. 1150-1450 (Figure 3; Graybill and Shiyatov, 1992). In detail there are significant differences with the Scandinavian record, but both records show a prolonged cool episode from about A.D. 1600 to (intermittently) the early 20th century, a period which is generally known as the "Little Ice Age" (Jones and Bradley, 1992). This is very well documented in historical, tree ring and glacial geological records (Grove, 1988) though the precise timing and magnitude of the cool episode varies from region to region. In central Europe (Pfister, 1984) and western Russia (Borisenkov, 1992) historical records demonstrate that the cooling is more apparent in winter and spring months than in summer and autumn, particularly in the first half of this period (Figures 4 and 5). Indeed, historical evidence from northwestern Bohemia (Czechoslovakia) shows that summers were relatively warm throughout this interval (Brazdil, 1990). Especially noteable are the warm summers in the 18th century, both in Bohemia, as well as in central Europe and in the northern Urals (Figures 3 and 5).

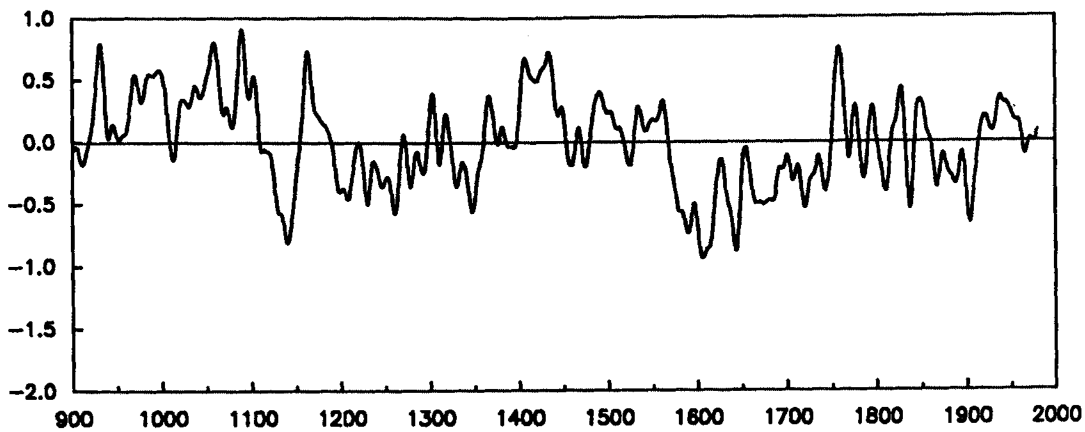


Figure 2. April-August mean temperature anomalies (°C) relative to the long-term mean, reconstructed for northern Fennoscandia (from Briffa et al., 1991).

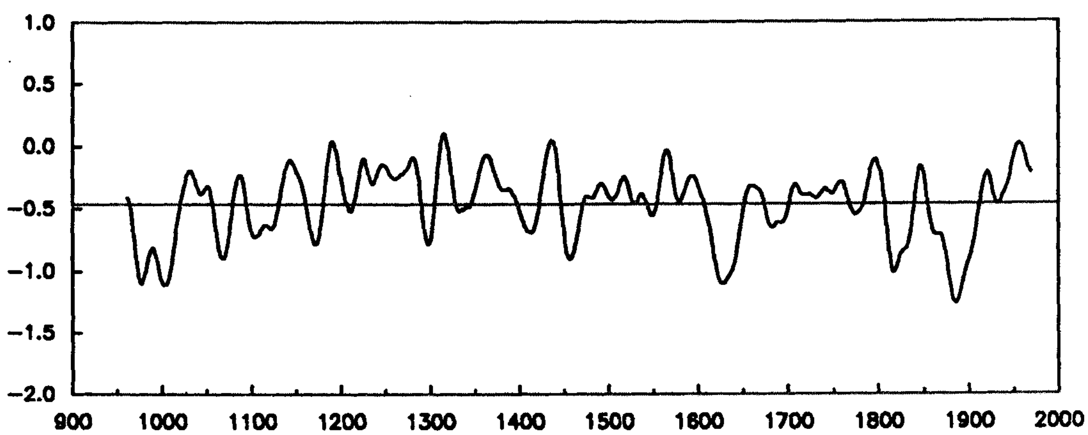


Figure 3. Summer temperature anomalies in the northern Ural mountains (65°N, 70°E) expressed in °C, relative to the mean for 1951-80, reconstructed from temperature-sensitive tree rings (Graybill and Shiyatov, 1992).

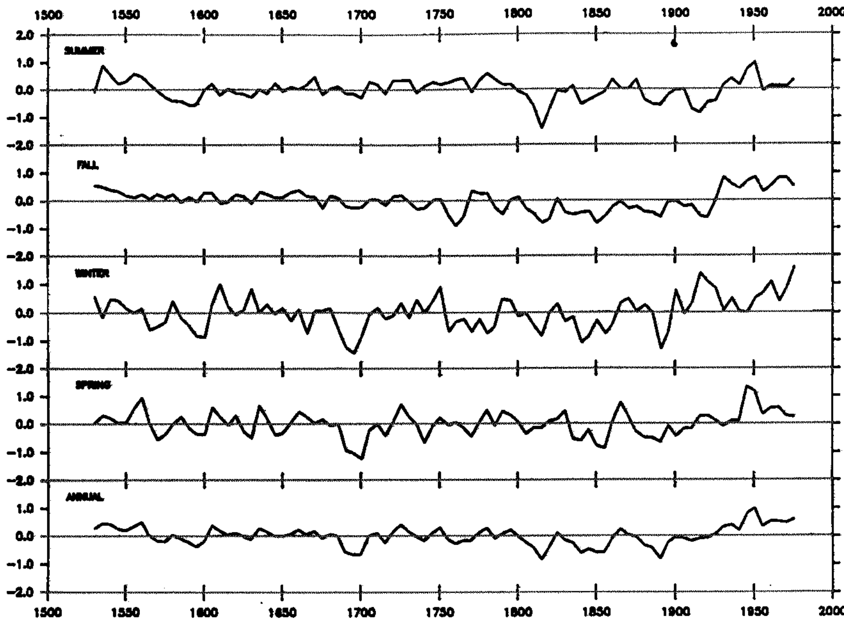


Figure 4. Seasonal and annual temperature anomalies (°C) derived from thermal indices, reconstructed for central Europe from historical and phenological records (from Pfister, 1984).

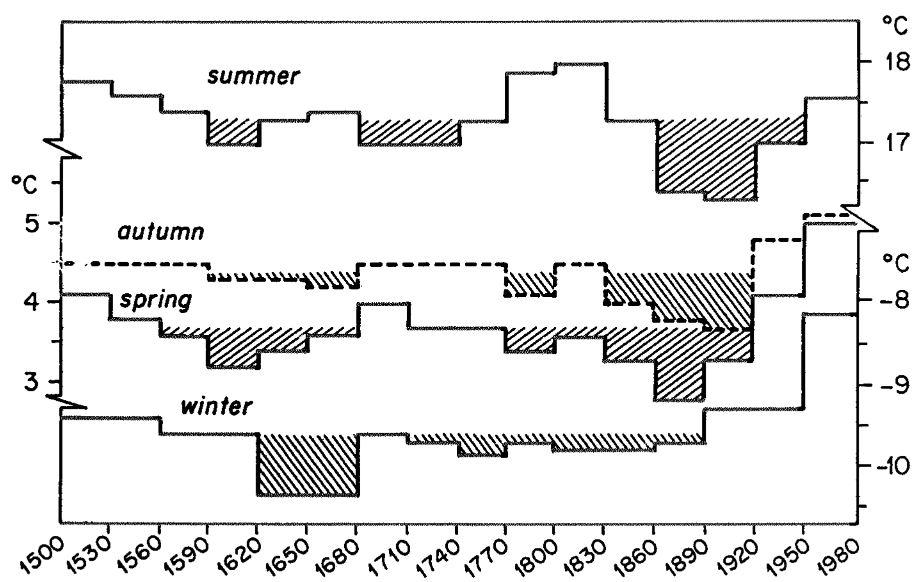


Figure 5. Seasonal temperature anomalies (30 year means) in western Russia from A.D. 1500 to 1980, reconstructed from historical records (from Borisenkov, 1992). Autumn and Spring scale on the left (°C) Summer and Winter scale (°C) on the right.

3. EAST ASIA

Historical records are also plentiful in East Asia where considerable effort has been expended to extract climatic information from them. Figure 6 shows estimates of decadal mean annual temperature anomalies in North and East China from the average for 1880-1970 (Wang and Wang, 1990). As in Europe, a cold interval in the 16th and 17th centuries, somewhat warmer conditions in the 18th century, and a cold 19th century are noteable. There are sparse phenological records suggesting that summers may have been warmer during the time of the European Medieval Warm Epoch, but at present no complete analysis of this interval has been published. Recently, an ice core from Dunde Ice Cap (on the north-central Qinghai-Tibetan plateau) has been recovered and a high resolution $\delta^{18}O$ record has been derived (Thompson et al., 1988, Thompson, 1992). A conventional interpretation of this record (in which lower $\delta^{18}O$ values correspond to lower tempertures) would also suggest cooler conditions in the 19th and 17th centuries, but warmer in the 18th century. However, the 16th century would appear to have been relatively warm, and the 15th century perhaps the coldest period of the last millennium. There is no evidence for an unusually warm interval, at least as far back as A.D. 1050, if this interpretation is correct. Further study of the $\delta^{18}O$-climate connection is required before too much confidence can be placed in this simple reading of the record.

4. NORTH AMERICA AND GREENLAND

A more direct measure of temperature in ice cores is provided by the record of melt layers visible in the crystallographic structure of the ice. This is a direct indicator of summer warmth and is subject to fewer problems of interpretation than $\delta^{18}O$ records. Melt records are available from Devon Island and Agassiz Ice Caps in the North American Arctic (Koerner, 1977; Fisher and Koerner, 1983) as well as southern Greenland (Kameda et al., 1992; Herron et al., 1981) and Svalbard (shown in Figure 7; Tarrusov, 1992). These records point to a prolonged cool period prior to ~A.D. 1900, punctuated by warmer intervals in the early to mid-1800s (Svalbard/southern Greenland), in the late 1400s/early 1500s, in the 12th and 13th centuries (especially in southern Greenland from ~A.D. 1240-1360) and perhaps also in the mid to late 12th century. These warmer intervals thus occur

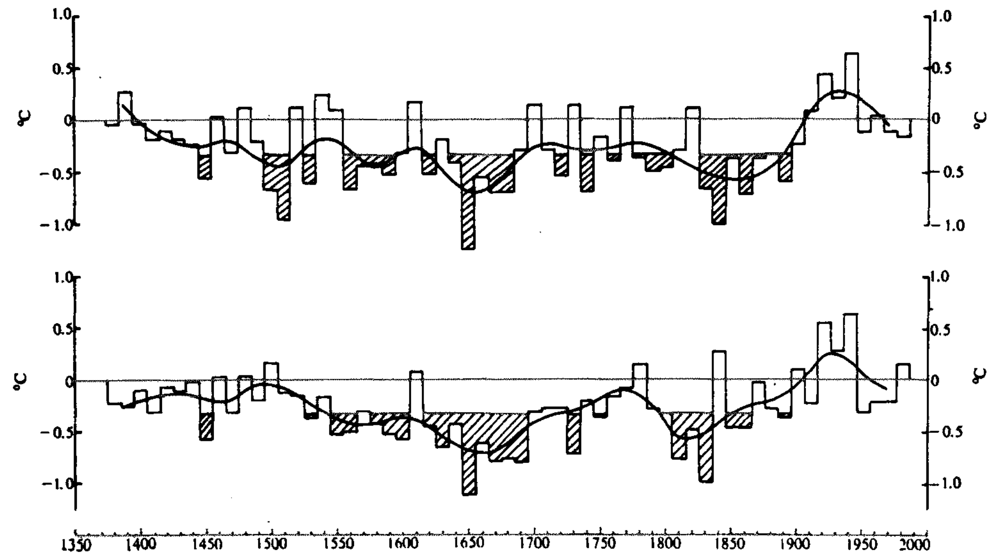


Figure 6. 10 year mean annual temperature anomalies (°C) (from the 1880-1970 average) for East China (upper) and North China (lower). Curved line is the 50 year running mean. (from Wang and Wang, 1991).

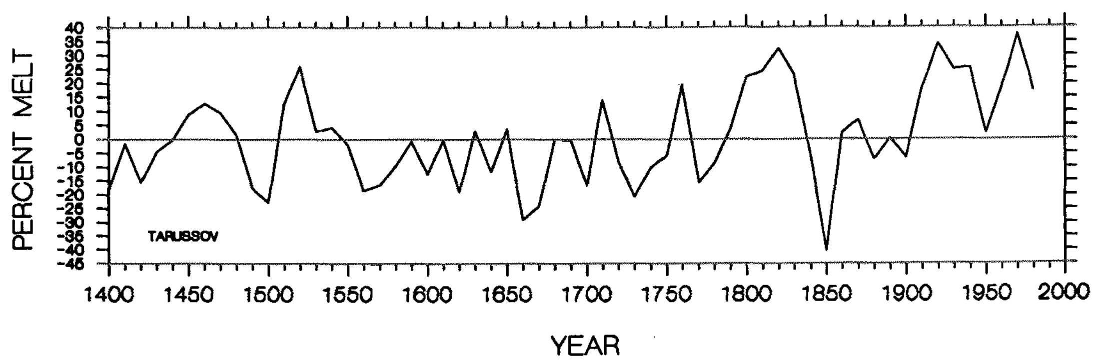


Figure 7. Indices of melting episodes on the Austfonna Ice Cap, Svalbard, indicative of summer temperature variations (from Tarrusov, 1992). Percentages refer to the amount of a given ice core which has evidence of melting, expressed as departures from the long-term mean.

during the broader interval Lamb referred to as the early Medieval Warm Epoch (A.D. 1000-1300). It is interesting that high latitude tree ring records from North America also indicate exceptionally cold conditions during the 19th century and warmer conditions in the 18th century (as noted earlier for Europe).

Long-term palaeoclimatic information from the rest of North America is almost entirely based on tree ring reconstructions, most of which primarily record variations of precipitation or the incidence of drought (Fritts, 1991). Precipitation changes are highly variable, generally showing periods of above or below average conditons lasting for a few decades at most. There is, however, some evidence for lower precipitation levels during the cooler interval from the mid-17th century to 1800 or 1850 in some southern records (e.g. Stahle et al., 1985, 1988). This pattern of relatively dry conditions during periods of the "Little Ice Age" was also noted by Pfister (1984) in his central European studies. However, studies of pollen in varved sediments from northern Wisconsin and northeastern Pennsylvania suggest relatively dry conditions in these areas up to ~A.D. 1350, and wetter conditions thereafter. Pollen spectra of well-dated sediments from the northeastern United States have been converted to summer temperature estimates by comparing the modern pollen rain across the region with the spatial distribution of temperature. Several of these reconstructions indicate warmer conditions in this region prior to A.D. 1000, and a general decline in temperature (of 1-2°C) until the late 19th century (Bernabo, 1981; Gajewski, 1988). Tree ring records from the upper treeline of the White Mountains, California suggest a period of high summer temperatures in the 13th century, but cooler for several centuries both before and after this interval (LaMarche, 1978). By contrast, recent studies of a network of trees distributed throughout the western United States provide no evidence for cooler conditions in this region since A.D. 1600; indeed, average conditions may have been *warmer* in this area from A.D. 1600-1900 than in the 20th century (Fritts and Shao, 1992). This finding is intriguing, since in many parts of the northern hemisphere the period 1600-1900 was generally cool, as discussed earlier. Further analysis of other records from this region are needed to verify these reconstructions.

5. THE SOUTHERN HEMISPHERE

Evidence of climatic variations in the southern hemisphere over the last 1000 years is extremely sparse. Only a few long tree ring and ice core records are currently available. Recent studies of tree ring records in Tasmania (Cook et al., 1991) suggest that the coldest periods of the last 700 years were in the 17th and early 20th centuries. In contrast to northern hemisphere records, the period 1700-1900 was generally warm, as were the late 15th and 16th centuries. Similar evidence is provided by tree ring studies in the central Patagonian Andes (Boninsegna, 1992).

A high altitude ice core record from the Quelccaya Ice Cap in Peru has provided a $\delta^{18}O$ record spanning the last 900 years (Thompson and Mosley-Thompson, 1989). Pronounced changes in accumulation and lower $\delta^{18}O$ values from A.D. 1550-1880 are the most noteable features of the record. Higher $\delta^{18}O$ values prior to A.D. 1500 are found in the Quelccaya record and also (though with more variability) in an ice core from the South Pole (Mosley-Thompson, 1992). This record shows particularly low $\delta^{18}O$ values in the late 16th and early 17th centuries.

6. DISCUSSION

Although there are relatively few high resolution records of climatic conditions spanning the last millennium, some general conclusions may be drawn from the available evidence. Firstly, the notion of an "Early Medieval Warm Epoch", as defined by Lamb (1965), lasting from A.D. 1000-1300, can find some support in a wide variety of records from various parts of the world. However, the available evidence suggests that there was not a long, continuous warm interval which was synchronous throughout the world, or even throughout the northern hemisphere. Rather, it appears that different regions experienced warm conditions *relative to the ensuing centuries* at various times prior to the 15th century. In some areas, the warmest period may have been within the interval A.D. 900-1200 (e.g. northern Scandinavia) and in other areas from A.D. 1200-1300 (e.g. southern Greenland, western U.S.). In the southern hemisphere, we simply do not have enough information to say anything meaningful about this interval. In short, it can not be assumed that the "Early Medieval Warm Epoch" (as defined by Lamb) was of more than regional significance, and as more detailed studies of *continuous* records become available (as for northern Scandinavia and the northern Urals) it may become increasingly apparent that the interval contained both warm and cold sub-periods.

Evidence for markedly cooler conditions in the 17th and 19th centuries is noticeable in records from a wide variety of sites throughout the northern hemisphere. Indeed, some of the longer records (e.g. from China) indicate that cooler conditions were apparent before the 15th century. This is the period which is often referred to as the "Little Ice Age". The use of this term is unfortunate, for it implies a monotonic episode of uniformly cold conditions. This is clearly not the case; a number of records point, in particular, to the 18th century as having been relatively warm, and (where seasonal records are available) it is clear that summers were hardly affected in some areas. Furthermore, in the southern hemisphere, the coldest interval was not in the 18th and 19th centuries. It appears that the 16th and 17th centuries were cooler, as indeed was the early 20th century. Thus, the term "Little Ice Age" serves to obfuscate rather than clarify the real nature of the climate of the last few centuries, and its continued use, without defining how it is being used, should be avoided.

From these diverse records it is apparent that the instrumentally recorded increase in temperature from the mid to late nineteenth century is exceptional in the context of the last 1000 years. However, this perspective is highly coloured by the generally cooler conditions prevailing for much of the last 500 years (and perhaps longer in some areas). Extending our view further back in time reveals warmer episodes which may have been similar in magnitude to recent decades. Thus to ascribe the temperature increase of the last century to anthropogenic factors requires a significant leap of faith. It is clear that our extensive network of instrumental records really began at around one of the coldest periods of the last 1000 years, in the northern hemisphere at least. Indeed, the late 19th century may have been one of the coldest periods of the entire Holocene. Most of the temperature increase in the last century has been confined to two short intervals, in the 1915-35 period and in the 1970s and 1980s (Figure 8; Folland et al., 1990). It is difficult to explain such changes in terms of anthropogenic forcing and it seems likely that much, if not all, of the temperature increase of the last century is a natural oscillation of climate, of the sort seen in numerous records spanning the last millennium.

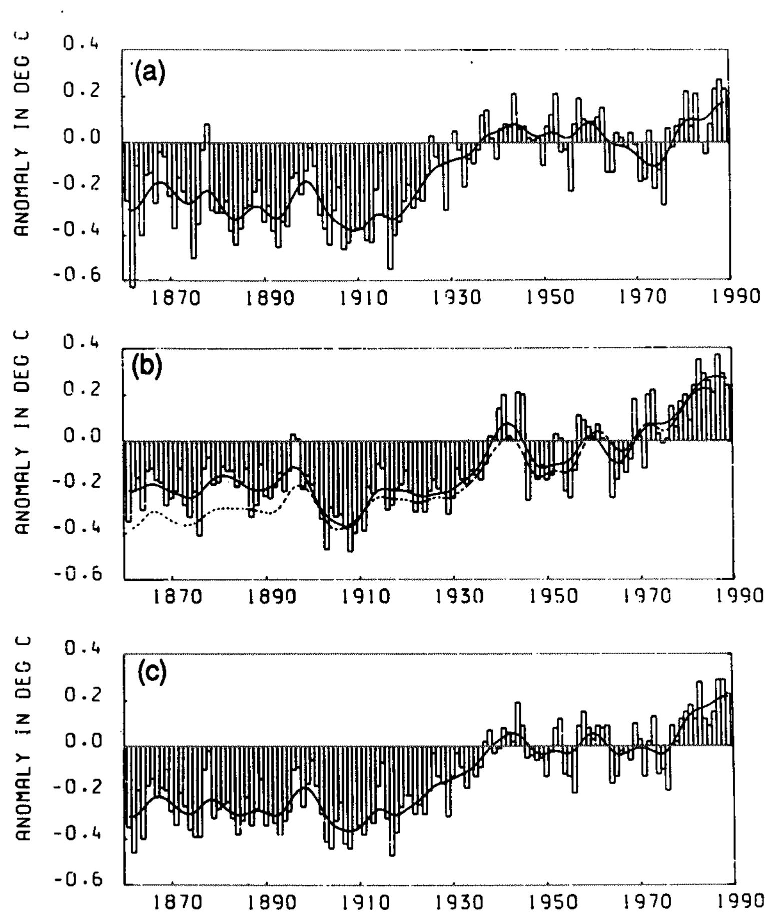


Figure 8. Instrumentally recorded temperature variations compiled from a time-varying network of continental air temperature measurements and sea-surface temperature records, 1861-1989. Values are expressed as anomalies from a reference period of 1951-80. a) Northern Hemisphere, (b) Southern Hemisphere, (c) Globe (from Folland et al., 1990).

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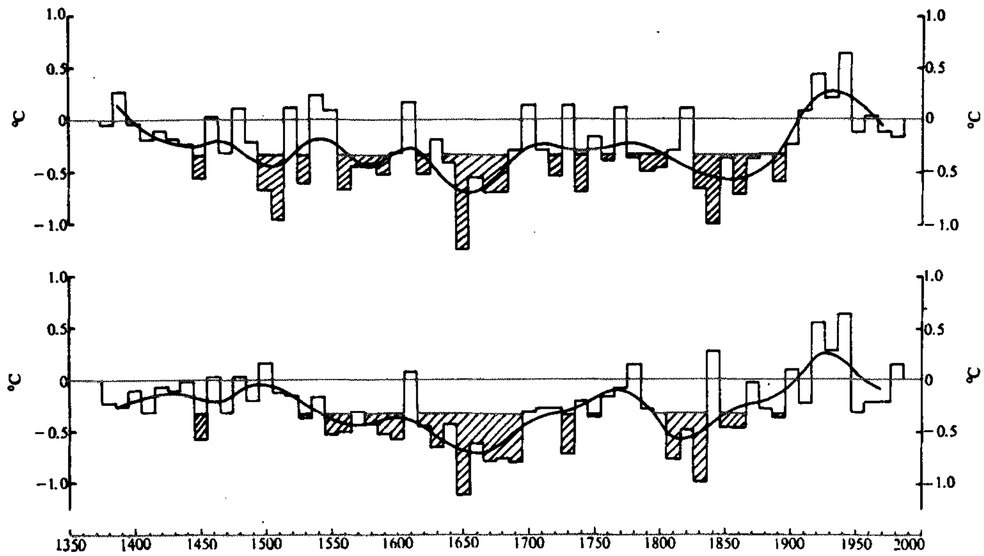

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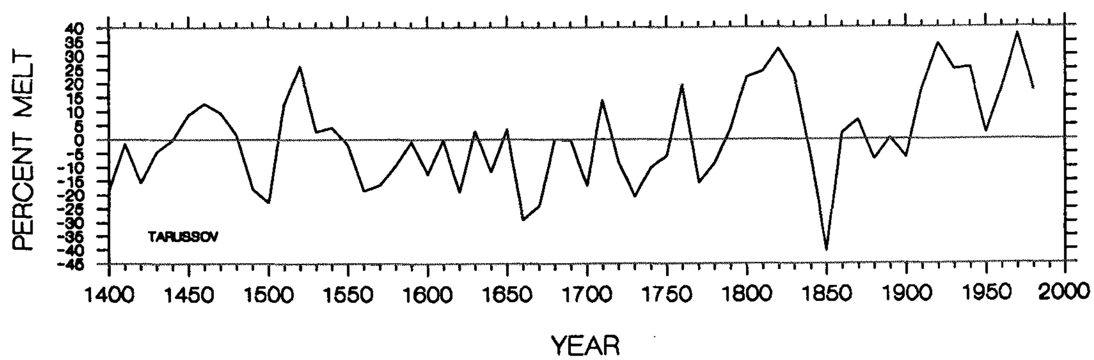

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