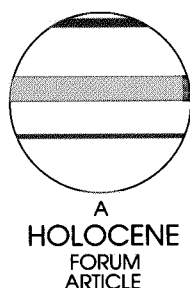


'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends

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Abstract: Climatic changes resulting from greenhouse gases will be superimposed on natural climatic variations. High-resolution proxy records of past climate can be used to extend our perspective on regional and hemispheric changes of climate back in time by several hundred years. Using historical, tree-ring and ice core data, we examine climatic variations during the period commonly called the 'Little Ice Age'. The coldest conditions of the last 560 years were between AD 1570 and 1730, and in the nineteenth century. Unusually warm conditions have prevailed since the 1920s, probably related to a relative absence of major explosive volcanic eruptions and higher levels of greenhouse gases.

Key words: 'Little Ice Age', summer temperatures, climatic change, global warming, historical evidence, tree-rings, ice cores.

Introduction

Although there is considerable uncertainty about the rate and magnitude of any future warming which may occur as a result of human activities, one thing is not in dispute: any human-induced changes in climate will be superimposed on a background of natural climatic variations. Hence, in order to understand future climatic changes, it is necessary to have an understanding of how and why climates have varied in the past. Of particular relevance are climatic variations of the last few centuries leading up to the recent warming trends observed in instrumental records, which rarely span more than the last 150 years.

Early studies of past changes in climate relied on the dramatic evidence of environmental change commonly observed in mountainous areas of the world. Such observations led Matthes to introduce the term 'little ice age'. He stated, 'we are living in an epoch of renewed but moderate glaciation – a little ice age that already has lasted about 4,000 years' (Matthes, 1939). He later went on to note that 'glacier oscillations of the last few centuries have been among the greatest that have occurred during the 4,000 year period ... the greatest since the end of the Pleistocene ice age' (Matthes, 1940). This period of glacial advances in the late Holocene is now generally referred to as the Neoglacial period, and only the latest and more extensive episode of glacial activity is described as the 'Little Ice Age' (Moss, 1951; Porter and Denton, 1967; Grove, 1988).

Glacier advances, particularly during the nineteenth century, are well documented by written and photographic evidence from many parts of the world. Such lines of evidence, supplemented by paintings, sketches and early travel accounts, are particularly abundant in western Europe, where changes in a number of glaciers can be quite precisely reconstructed for the last 200–300 years (Röthlisberger, 1976; Messerli *et al.*, 1978; Zumbühl, 1980; Röthlisberger *et al.*, 1980; Orombelli and Porter, 1982; Zumbühl and Holzhauser, 1988). However, documenting changes in glacier positions in other parts of the world is more problematical since such detailed observations rarely exist. In most regions, therefore, glacier fluctuations have been dated by radiocarbon analysis of material over-ridden or disturbed by advancing ice, or (less commonly) in some way revealed by retreating ice (e.g., Röthlisberger, 1986). Such dates provide only maximum or minimum limiting dates, respectively, on the ice position, and indeed where the most recent advances were extensive, they may have obliterated evidence of earlier glacier fluctuations, biasing the record of past glacier dynamics towards the most recent, extensive ice advance (Porter, 1981). Glacial deposits provide little quantifiable information about periods of negative mass balance, when glaciers may have receded up-valley. Furthermore, ^{14}C dates in the range of 100 to 500 years BP provide non-unique calendar year ages, which creates considerable uncertainty in reconstructing glacier positions over this interval (Stuiver and Pearson, 1986). Dating glacial deposits by the use of ^{14}C -calibrated lichenometric growth

curves is problematical for the same reasons. Alternative dating by dendrochronological methods can provide a more precise data (Luckman, 1986), but a complete chronology of ice advance and retreat by such methods would be fortuitous and, for most glaciers, relevant dendrochronological records do not exist.

Added to these dating problems is a more fundamental issue: glacier advances are episodic events which result from cumulative increases in mass balance and the interactions of these changes with each glacier's unique dynamic system. The terminal position of a glacier is often determined by local climatic conditions (as, for example, where a confined valley glacier enters a broad open valley) so that terminal position (the main sort of historical record available) may not be linearly related to climate. Hence records of glacier terminal positions are not easily ascribed to specific changes in climate (Oerlemans, 1989). Mass balance changes can be brought about by a variety of climatic perturbations (such as changes in snowfall and/or temperature and/or solar radiation, etc.) and hence evidence of former glacier advances does not always provide unequivocal evidence of past cool temperature periods.

In view of these problems, another approach towards understanding the nature of the 'Little Ice Age' and its cause(s) is to examine *continuous* climatic and palaeoclimatic records from around the world to determine the principal climatic characteristics of the last 500–600 years and thereby to determine what was different about climate in the recent past. Among the most important high-resolution (annually or seasonally resolved) palaeoclimatic proxy records available for studying the climate of the last few centuries are those derived from studies of historical documents, tree-rings and ice cores (for a discussion of the procedures used in each of these approaches, including issues of calibration and verification, see Bradley, 1985; Bradley and Jones, 1992a). Although such records have their own limitations, they can be precisely dated and enable high-frequency climatic variations to be examined for many areas of the world.

Here we compare a number of such records, divided into regions where several series can be assembled. Each proxy record generally reflects conditions in a specific period of the

year, most commonly summer. Where seasonal reconstructions of climate have been carried out, it can be seen that the record of climatic variations may not be the same in all seasons (Pfister, 1985; Wang, 1991a; 1991b; Borisenkov, 1992). Care must therefore be taken to assemble regional networks of data that reflect climatic changes during the same season of the year. This is particularly important with regard to oxygen isotope records from annually resolved ice cores. Although these sources provide important information, only rarely have such isotopic data been rigorously calibrated against contemporaneous instrumental station data from the region (e.g., Jouzel *et al.*, 1984). Usually, the spatial pattern of isotopic change (which is influenced by such factors as distance from the moisture source, elevation, air mass sources, etc.) is related to mean annual temperature (derived from 10 m firn temperatures). These relationships in the spatial domain may not be appropriate for reconstructing temperatures in the time domain, at least on the decadal time-scale (Jones *et al.*, 1993). Where appropriate calibrations have been attempted, only 25–35% of the variance in annual temperature is generally accounted for by oxygen isotope data (Robin, 1983; Jones *et al.*, 1993). Furthermore, isotopic data provide a record of conditions at the time of snowfall, which is usually at a maximum in early winter. They are unlikely to provide a useful record of summer conditions.

In the following section, only records of summer temperature are compared. Figure 1 shows the locations of archival records discussed below. In general, only those records which were continuous up to (at least) 1960 were selected, to enable conditions in the twentieth century to be placed in a longer-term perspective.

The evidence: a global survey

Europe

The longest instrumental records of climate come from western Europe, but there is also a wealth of historical evidence documenting environmental, phenological and agricultural conditions (Frenzel, 1992). This can be supplemented

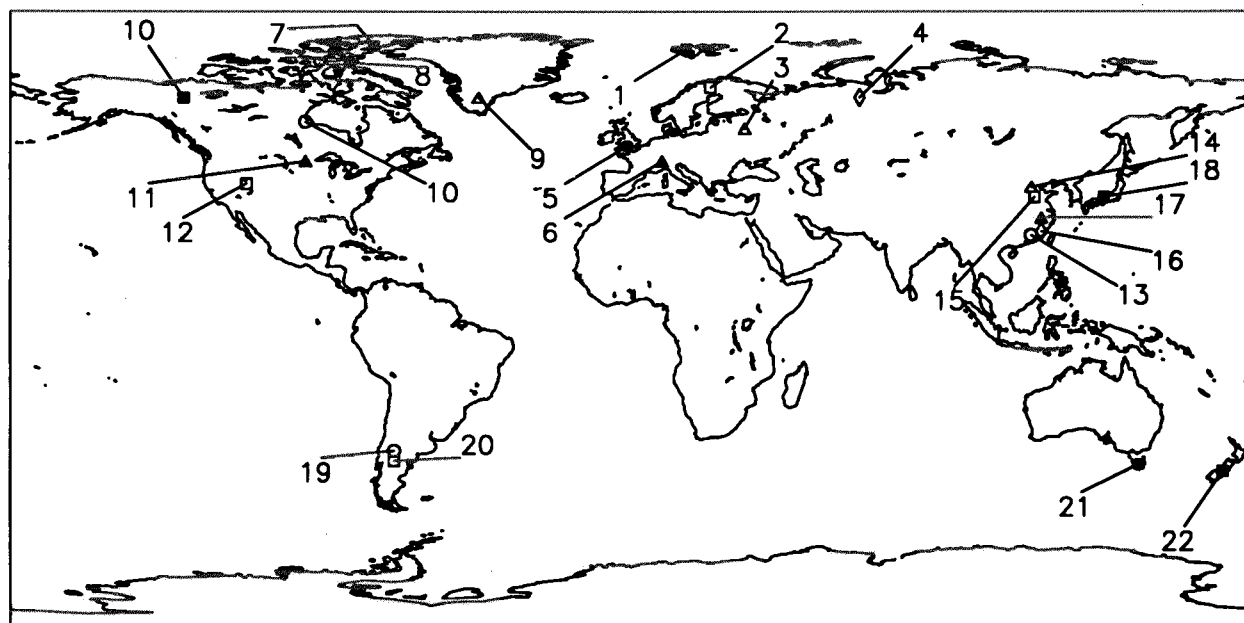


Figure 1 Location of sites and regions discussed in text. Numbers refer to time series plotted in Figures 2–5.

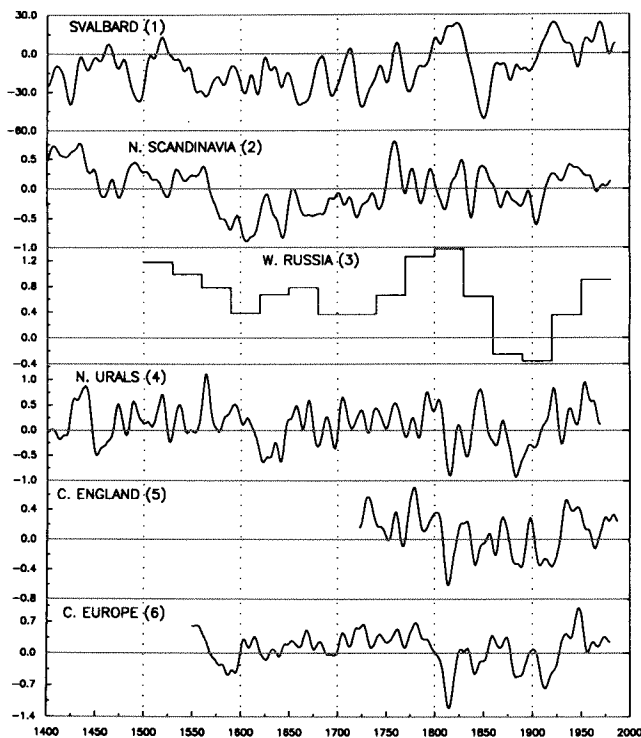


Figure 2 Reconstructed summer temperature anomaly series for Europe (referenced to the mean of each series for 1860–1959). The Svalbard record is of summer melt from the Lomonosov ice cap in Svalbard (Spitsbergen – Tarussov, 1992); the northern Scandinavia series is based on a network of tree-ring density records from *Pinus sylvestris* at the northern tree-line of Sweden (Briffa, Bartholin *et al.*, 1990; Briffa, Jones *et al.*, 1992); the western Russian record is derived from historical documentary sources (Borisenkov, 1992); the northern Urals record is based on tree-ring widths in a set of *Larix sibirica* trees from the Urals of western Russia (Graybill and Shiyatov, 1992); the central England series is based on instrumental records (Manley, 1959, 1974); the central European record is derived mainly from documentary sources in Switzerland (Pfister, 1985). All units are °C, except for the Svalbard record, which is the core area affected by melting, expressed as percentage departures from the mean.

with dendroclimatic and glaciological evidence of past climatic changes.

At the northwestern edge of Europe, a record of summer melting on the Lomonosov ice cap, Svalbard, shows cool summer conditions for most of the last 600 years (Tarussov, 1992; and Figure 2). Only the early nineteenth century and a brief interval in the 1520s appear to have been as warm as the twentieth century. The 1830s–1860s were especially cold, but the most prolonged cold episode was from ~1550 to ~1750. This long cool period is also clearly shown by tree-ring density data from the northern tree-line of Scandinavia (Briffa *et al.*, 1990; 1992a). Summer temperatures were ~0.5°C warmer than in the twentieth century from 1400 to 1440, followed by a century of conditions similar to those of the twentieth century. Temperatures rapidly declined after ~1560 and reached their lowest levels in the seventeenth century, particularly in the 1600s and 1640s. Temperatures were equal to, or above, twentieth-century values for much of the period from ~1750 to 1850 in this region, then were below the 1860–1959 average in the latter half of the nineteenth and early twentieth centuries.

Historical data from western Russia also show relatively warm summer temperatures from 1750 to 1850, preceded by ~150 years of cooler conditions (Borisenkov, 1992). In the late nineteenth and early twentieth centuries, summer temperatures appear to have been the coldest since 1500, with

temperatures increasing since the turn of the century. In this area the period 1860–1920 was colder than the seventeenth century, but the overall pattern of change is similar to that recorded by tree-ring data from northern Scandinavia.

Further to the northeast, a record of tree-ring widths from the northern tree-line in the Ural mountains shows that temperatures were similar to those of the twentieth century for much of the last 600 years (Graybill and Shiyatov, 1992). However, here too, cold episodes in the first half of the seventeenth century and in the early and late 1800s (particularly ~1810–1830 and 1870–1900) are quite noticeable. The long, composite instrumental record from central England (Manley, 1959; 1974; Parker *et al.*, 1992) and historical, phenological and other data from Switzerland (Pfister, 1992) show the lowest temperatures in the 1810s and 1880s, as well as in the first two decades of the twentieth century. In both records, the nineteenth century was the coolest period of the last 200–300 years, and the eighteenth century was generally warmer than the twentieth century. A cold period, comparable to that of the late nineteenth century, was apparent in Switzerland in the latter half of the 1500s.

In summary, European records suggest that summer temperatures were relatively cold in the seventeenth century (but perhaps not in the area of Switzerland) as well as during the early nineteenth century and the late nineteenth/early twentieth centuries. Except in Svalbard, the twentieth-century record (generally to the 1970s) does not appear unusual in the context of the last 500 years.

North America

Compared to Europe, there have been relatively few studies of North American documentary records to obtain climatic information. The most extensive investigations have been carried out using Hudson's Bay Company records from remote trading posts in northern Canada (Moodie and Catchpole, 1975; Catchpole, 1992; Ball, 1992; Wilson, 1992). In the same general area, tree-rings provide a temperature-sensitive record of conditions along the northern tree-line (Jacoby *et al.*, 1988; Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1992). North of this region, ice cores provide additional information, derived from the amount of summer melting which has occurred at the ice core site (Koerner, 1977; Herron *et al.*, 1981; Koerner and Fisher, 1990). In the USA, tree-ring data from extensive sampling networks in the western USA provide regional palaeotemperature reconstructions (Schweingruber *et al.*, 1991; Briffa *et al.*, 1992b; Fritts, 1991), whereas dendroclimatic studies in the eastern USA have generally focused on drought reconstructions. In the north central and northeastern USA, pollen extracted from laminated lake sediments has yielded an index of growing season temperatures resolved to 20–30 years over the last few centuries (Gajewski, 1988).

Figure 3 shows summer temperature reconstructions for the North American locations shown in Figure 1. The high-latitude ice melt records, trees at the northern limit of growth and pollen data from Minnesota all show lower temperatures prior to the twentieth century, with coldest conditions in the early and late 1500s, around 1700 ± 20, and 1840 ± 15. Historical records from Hudson Bay Company posts (not shown) clearly confirm the exceptionally cold conditions of the early nineteenth century (Wilson, 1992). Low summer temperatures prevailed from ~1580 to ~1730 and ~1815 to ~1870. In some locations, late eighteenth-century temperatures were comparable with those in the twentieth century. In the fifteenth century, conditions appear to have been warm in Minnesota, and perhaps (for part of the time) at higher latitudes.

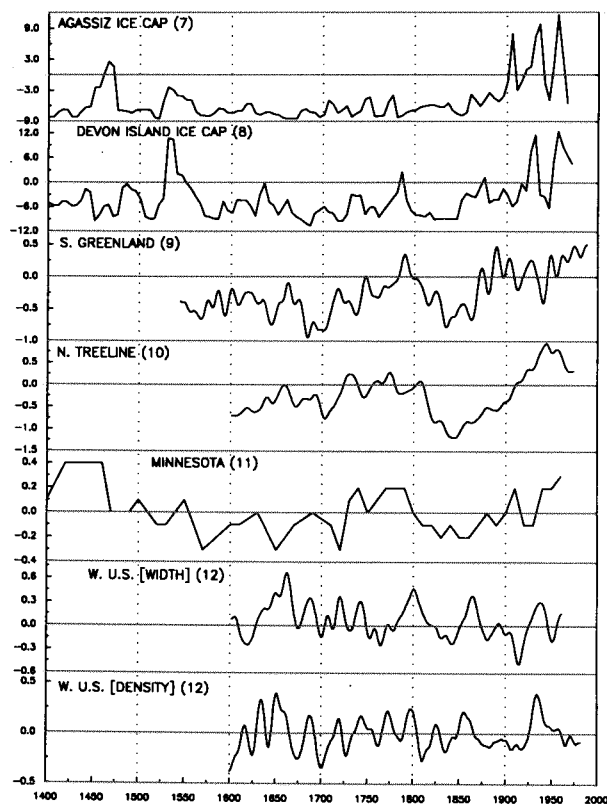


Figure 3 Reconstructed summer temperature anomaly series for North America (referenced to the mean of each series for 1860–1959). The series from Devon Island ice cap and Agassiz ice cap (Northern Ellesmere Island, Canada) are based on ice core studies (Koerner, 1977; Koerner and Fisher, 1990). The southern Greenland series is also derived from ice core melt studies, converted to a summer temperature scale (Kameda *et al.*, 1992; and pers. comm.). The northern tree-line series is from a network of trees (mainly *Picea glauca*) across northern and northwestern North America (Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1992); the Minnesota record is derived from pollen in laminated sediments from Lake of the Clouds (Gajewski, 1988); the western North American series are based on networks of coniferous trees across a wide area of the western USA (Fritts, 1991; Schweingruber *et al.*, 1991; Briffa, Jones and Schweingruber, 1992). All units are °C, except for the Agassiz and Devon Island ice cap records, which show the core area affected by melting, expressed as percentage departures from the mean.

Densitometric data from a network of temperature-sensitive trees in the western USA also indicate that generally cold conditions occurred in the nineteenth century and around 1700. They do not show the strong trend observed in trees at higher latitudes (Figure 3) and indicate that temperatures were quite comparable with twentieth-century averages for much of the seventeenth and eighteenth centuries, interrupted by several cold episodes of 10–20 years duration. Summer temperatures reconstructed from tree-ring widths have a slight trend towards lower values in the twentieth century (with their lowest values in the 1910s). These have been interpreted as showing that warmer (and drier) conditions prevailed in the western USA prior to the twentieth century, especially in the mid-seventeenth century (Fritts and Shao, 1992). Both density and ring width networks indicate warm conditions centred on 1650–1660, 1800, 1860 and 1930. According to the density network, the coldest conditions were in the early 1600s and early 1800s, with the longest uninterrupted episode of below average temperatures from ~1860 to ~1930. The tree-ring width data also indicate that periods

in the late nineteenth and early twentieth centuries were cold, with cool conditions in the periods 1750–1765 and 1830–1850.

Growing season temperatures, derived from pollen assemblages in several laminated lake sediments from the north-central USA, show a consistent pattern of temperature decline from the fifteenth century to minima in the mid-seventeenth century and in the first half of the nineteenth century. Some records show relatively warm conditions in the eighteenth century, followed by a cold nineteenth century; thereafter, temperatures rose to mid-twentieth-century levels not experienced for at least several hundred years (Gajewski, 1988). By contrast, pollen data from the northeastern USA (not shown) show that temperatures were warmer prior to the nineteenth and twentieth centuries, with the coldest conditions in the late nineteenth century. This region thus has more in common with the western USA tree-ring width record than with records from the mid-continent, or from locations further north.

East Asia

The longest documentary records of environmental conditions in the past come from China, Korea and Japan. Meticulous studies of dynastic records, diaries and local histories have revealed the important features of past climatic conditions (Zhang, 1988; Zhang and Gong, 1979; Zhang, 1980; Kim, 1984; 1987; Wang, 1991a; 1991b; Maejima and Tagami, 1983; 1986). The region is rich in other types of high-resolution proxy record, but these are only now beginning to be exploited. Dendroclimatic studies in western China (Wu, 1992) have yielded some reconstructions, but verification remains a problem because of the shortness of instrumental records. Isotopic records from high elevation ice cores, such as the Dunde and Guliya ice caps, provide high-resolution records (Thompson, 1992), but their relevance for summer temperature reconstruction is not clear.

Studies of documentary records for palaeotemperature reconstruction have been mainly carried out for the region of China, east of 110°E (Wang, 1991a; 1991b; Wang and Wang, 1990; Wang *et al.*, 1991). The majority of studies deal with winter conditions, but there are several summer temperature reconstructions. These are based on a variety of climatic indices derived from such factors as the dates of last and first frosts, in the spring and autumn respectively, the occurrence of unusual snowfall events, and precipitation patterns which can be related to anomalous temperature conditions. The regional indices are then calibrated against instrumentally recorded temperatures at representative sites (such as Beijing or Shanghai) to enable the preinstrumental record to be interpreted as temperature anomalies (Figure 4).

Several records suggest that temperatures declined from around 1500 to a pronounced minimum in the mid-seventeenth century. The 1650s were exceptionally cold throughout eastern China and Korea (Kim, 1984). Temperatures then rose, reaching levels comparable with those of the early twentieth century during brief periods in the eighteenth century. Cooler conditions again prevailed, with low temperatures in the early to mid-nineteenth century. In the twentieth century, temperatures again increased to a maximum in the 1920–1940 period, after which a cooling trend set in which has levelled off in recent years.

Documentary data from Korea also indicates that the mid-seventeenth century was the coldest period of the last 500 years (Kim, 1984; 1987). Indeed, Kim and Choi (1987) believe that summers in the period 1631–1740 were the coldest of the past 1000 years. However, in Japan, a simple index based on the frequency of unusually warm or cold summers suggests

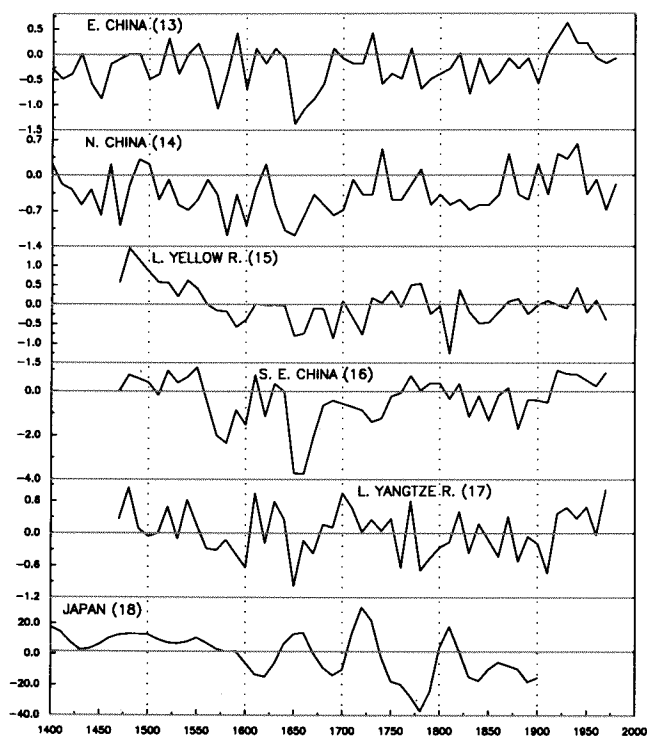


Figure 4 Reconstructed summer temperature anomaly series for East Asia (referenced to the mean of each series for 1860–1959, except for Japan; see below). All series are based on historical documentary sources. The North China series is derived from sources in Beijing, Hebei, Henan, Shandong and Shaanxi provinces (Wang, Shaowu, 1991a; 1991b); the Lower Yellow River series is from Wang, Risheng and Wang, Shaowu (1992); the East China series is based on sources in Shanghai, Jiangsu, Jiangxi, Anhui and Zhejiang provinces (Wang, Shaowu and Wang, Risheng, 1990); the southeast China series is from Wang, Risheng *et al.* (1991); the Lower Yangtze regional record is from Wang, Risheng and Wang, Shaowu (1992); the Japanese series is based on diaries from Honshu and comprises an index of summer weather type frequencies positive values indicating a higher frequency of hot summers), expressed as anomalies from the long-term mean (1400–1900 – Maejima and Tagami, 1986).

that the latter half of the eighteenth century was the coldest period from 1400 to 1900, followed by cool conditions in the late nineteenth century (Maejima and Tagami, 1986). This is quite similar to the record from the lower Yangtze in eastern China. The 1650s were relatively warm, perhaps indicating that Japan was under the influence of a (blocking) anti-cyclonic circulation, while further west, eastern China experienced cool conditions under a pronounced trough of low pressure. However, temperature estimates for northern Honshu (Hirosaki) are at odds with this interpretation (Maejima and Tagami, 1983). Only further studies of high-resolution data will solve this problem.

Southern Hemisphere

There are very few high-resolution records of past climatic conditions over the last millennium from the Southern Hemisphere. Historical records are sparse and dendroclimatic studies have been limited to a few areas. Ice core isotopic records are available from Antarctica and Peru, but these are not considered to be proxies of summer temperature (Mosley-Thompson, 1992; Peel, 1992; Thompson 1992; Jones *et al.*, 1993). Overall the vast areas of ocean in the Southern Hemisphere limit the number of potential high-resolution proxy records, and it is difficult to generalize about the few records that are available. Even studies from similar regions within temperate South America (Boninsegna, 1992; Villalba,

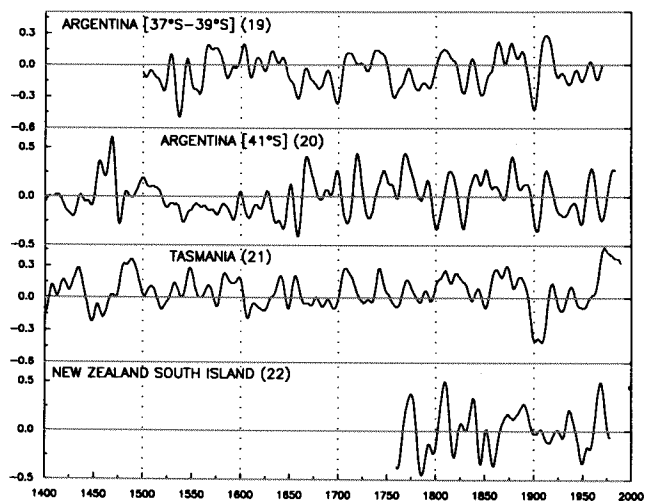


Figure 5 Reconstructed summer temperature anomaly series for Southern Hemisphere locations (referenced to the mean of each series for 1860–1959). The northern Patagonian record (37–39°S) is a reconstruction of December–May temperatures, based on 20 chronologies of *Araucaria araucana*, and the central Patagonian series (~41°S) is of December–February temperatures, based on three chronologies of *Fitzroya cupressoides* (Boninsegna, 1992). The Tasmanian record is based on a chronology of *Lagarostrobos franklinii* (Cook *et al.*, 1991; 1992). The New Zealand record (South Island, ~43°S) is of December–March temperatures, based on ten chronologies of *Nothofagus menziesii* and *N. solandri* (Norton and Palmer, 1992).

1990) show few similarities (Figure 5). Villalba's tree-ring width series from Argentina (~41°S) suggests that twentieth-century climatic conditions have been very similar to those since about 1660. Only the period ~1530–1650 stands out as a period of prolonged cool summer temperatures. By contrast, Boninsegna's tree-ring series from northwestern Argentina (37–39°S) indicates that three cold periods occurred in the last 500 years: the early sixteenth century, the late seventeenth century and the late eighteenth century. Tree-ring width records from Tasmania show summer climate over the last 500 years was warmer than most of the twentieth century (Cook *et al.*, 1991; 1992). This was also true in New Zealand (over the last 200 years) according to tree-ring studies in that area (Norton and Palmer, 1992). In Tasmania, only the period from ~1890 to ~1920 stands out as exceptionally cold. Interestingly, an unusually cold episode at this time is also seen in the South American tree-ring records, but not in those from New Zealand (though this cold period is seen in the instrumental records from New Zealand – Salinger, 1979). Clearly, many more records from the Southern Hemisphere are needed before a more coherent picture of climatic changes over the last few hundred years can be assembled.

Composite indices of climate over the last 500 years

We have attempted to highlight common features of the various series discussed by combining the records into composite regional and hemispheric averages. Selection was restricted to series that are available at a resolution of a decade or better, and which span almost all the period from AD 1600 to as close to the present as possible. To combine the series for each region, we first normalized each of the constituent series (expressed as decadal averages) using the mean and standard deviation for the 1860–1959 period, based on ten decadal values. We then averaged the decadal values

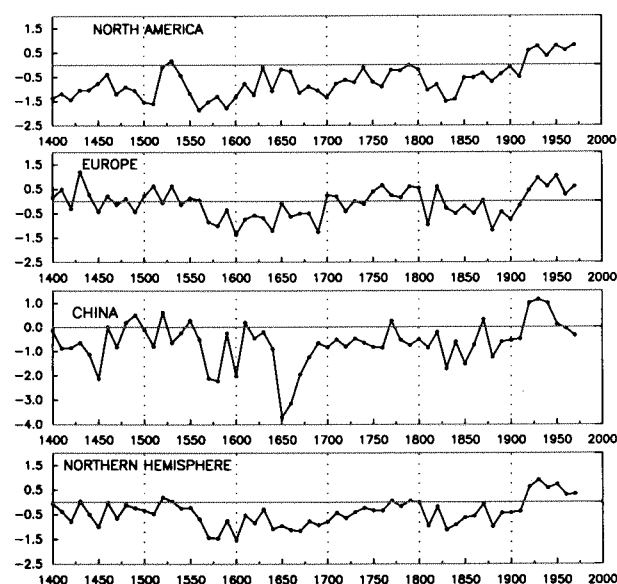


Figure 6 Composite temperature anomaly series for Europe, North America, East Asia and all the Northern Hemisphere series shown in Table 1. These series were derived from normalized decadal averaged anomalies (with reference to the period 1860–1959).

for each of the series in each region. Six series were used for North America (those in Figure 3, excluding the Lake of the Clouds record which did not have the necessary resolution), five for Europe and five for East Asia. The resulting regional averages are shown in Figure 6. The Northern Hemisphere series is the average of 16 series from the three regions. With this limited number of series, it is difficult to justify a more complex averaging technique, but we note that the number of series from each of the three Northern Hemisphere regions is approximately proportional to their relative areas. Nevertheless, there are still extremely large areas for which we have no data, and the composite record implicitly assumes the available regions are representative of the entire hemisphere. To test this hypothesis, we have used the more extensive instrumental data set for the last century. Figure 7A com-

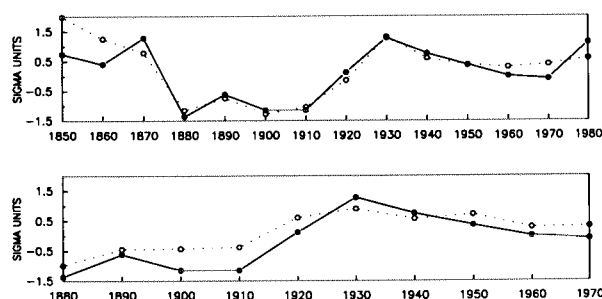


Figure 7(A) Normalized decadal summer temperature anomalies (based on instrumental records) for the Northern Hemisphere as a whole (solid line) and for the three regions where proxy records were used in constructing the 'Northern Hemisphere' series in Figure 6. The first two decades have relatively little data. Overall, $r = 0.87$; for the period 1870–1980, $r = 0.95$. **(B)** Normalized decadal summer temperature anomalies for the northern hemisphere, based on instrumental records (solid line) and on proxy records (dashed line). For the period 1870–1980, $r = 0.9$.

pares the normalized decadal mean values for the Northern Hemisphere as a whole, and for the average of the three regions where there are longer proxy records. It is clear that, on the decadal timescale, the average of the three regions captures most of the variance of the entire hemisphere and is therefore a useful indicator of smaller-scale (larger-region) changes. Figure 7B compares the reconstructed 'Northern Hemisphere' record (based on proxy data) with decadal averages of the Northern Hemisphere record derived from much more extensive instrumental data in the period of overlap during the last 100 years. The two series are highly correlated, providing further confidence in the reconstructed series.

Table 1 shows correlation coefficients for each individual series with the Northern Hemisphere average (derived, for each series, by averaging all records except the series being correlated). Of particular note is the high correlation between several Chinese series, which supports earlier arguments that this region 'tracks' large-scale temperature changes rather well (Bradley *et al.*, 1987). Tree-line series from northern North America and Scandinavia and the Northern Hemi-

Table 1 Correlation coefficients between normalized regional series and Northern Hemispheric composite series (after removing each regional series, in turn) for decadal means within the period 1600–1959

Location	Type of record	r	N
Southeastern China	Documentary records	0.64**	37
Northern China	Documentary records	0.61**	37
North American tree-line	Tree-ring widths	0.59**	36
Eastern China	Documentary records	0.55**	37
Agassiz ice cap	Melt record	0.53**	36
Devon Island ice cap	Melt record	0.53**	37
Lower Yellow River region	Documentary records	0.46**	34
Northern Scandinavian tree-line	Tree-ring densities	0.46**	37
Southern Greenland ice sheet	Melt record	0.45**	37
Central England	Instrumental records	0.43*	31
Lower Yangtse River region	Documentary records	0.38*	37
Svalbard ice cap	Melt record	0.37*	37
Western USA	Tree-ring densities	0.34*	37
Northern Urals	Tree-ring widths	0.32*	37
Central Europe	Documentary records	0.26	37
Western USA	Tree-ring widths	-0.19	35

Note: * Statistically significant at 95% level. ** Statistically significant at 99% level. N = number of decades.

sphere composite series are also well correlated, a fact noted (for the instrumental period) by Jacoby and D'Arrigo (1989). Significant correlations are also observed between records of summer melt on high-latitude ice caps and the hemispheric average series.

The composite European record (Figure 5) indicates that summer temperatures fluctuated around the 1860–1959 mean from 1400 until the 1570s, when temperatures declined and remained below the average until the 1690s. Warmer temperatures prevailed throughout the eighteenth century, but fell again in the nineteenth century, especially in the 1810s and 1880s. Thereafter, temperatures rose to levels higher than those in the late 1700s. A similar picture can be seen in the North American and (somewhat more variable) East Asian composite records, though the fifteenth century appears to have been cooler in these regions. It should be borne in mind, however, that the early parts of these series are based on fewer data sets and must be considered less reliable than later periods.

An estimate of the magnitude of hemispheric anomalies can be made by comparing the composite series with instrumental data from the last 100 years. For 1861–1960, the mean and standard deviation of Northern Hemisphere decadal average temperature (in summer) was -0.25°C and 0.12°C , respectively (relative to the 1950–1979 reference period). The largest decadal anomaly over the last 560 years was 1600–1609 (-1.54σ relative to 1860–1959). This corresponds to an anomaly of -0.43°C relative to the 1950–1979 period ($[-1.54 \times 0.12] - 0.25$). However, if more data were available to make up our 560-year hemispheric series, the standard deviation would be lower, and therefore this anomaly is likely to be a maximum estimate for the decade.

The twentieth-century record of instrumental temperatures has been viewed by a number of authors and by the recent IPCC assessments (Folland *et al.*, 1990; 1992). All conclude that temperatures have warmed this century, but mainly in two distinct phases, between 1920 and 1940, and since approximately 1975. The 1980s are clearly the warmest decade (in global terms) since 1850, warmer than the first decade of this century by 0.55°C . It seems likely, therefore, that the decade of the 1980s was the warmest over the Northern Hemisphere as a whole for at least the last 590 years. However, the decade was not warm everywhere, the notable exceptions being the North Atlantic, Greenland and the northern Pacific region, where temperatures have declined since the 1940s.

Overall, the 'Northern Hemisphere' composite record points to the period from ~ 1570 to ~ 1730 as the coldest period of the last 500 years, followed by the nineteenth century. The decade 1600–1609 was exceptionally cold. Conditions comparable to the decades from 1920 onward have not been experienced for several hundred years, at least. The record can be viewed in two ways. On the one hand, one

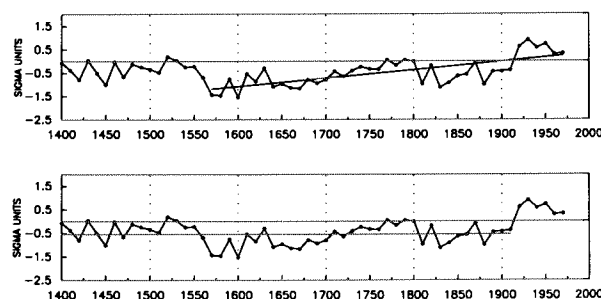


Figure 8 Alternative views of the 'Northern Hemisphere' normalized summer temperature anomaly reconstruction for the last ~ 600 years (see text for discussion).

could interpret it as showing a gradual rise in temperature from the late 1500s, interrupted by cooler conditions in the nineteenth century. Alternatively, one could argue that temperatures fluctuated around a mean somewhat lower than the 1860–1959 average, punctuated by cooler intervals in the late 1500s, 1600s and 1900s, and then underwent pronounced (and, since 1500, unprecedented) warming in the early twentieth century (Figure 8). Both perspectives provide fuel for arguments over the veracity of anthropogenic greenhouse-gas-induced climatic change. We note that significant increases in CO_2 and CH_4 ($>5\%$ above background) began only in the mid-nineteenth century (Oeschger and Siegenthaler, 1988; Ehrlert, 1988), so that if warming began in the early 1600s, it probably was not due to human activities.

Explosive volcanism, by increasing the stratospheric aerosol load and reducing solar radiation receipts in the lower troposphere, is often cited as having played an important role in modulating the temperature record (e.g., Porter, 1986). Although the chronology of explosive eruptions over the last 500 years is far from complete (Bradley and Jones, 1992b), ice core acidity records from Crête, Greenland (Hammer *et al.*, 1980), clearly show increased levels of acidity in the late sixteenth, seventeenth and nineteenth centuries, with reduced acidity levels from ~ 1735 to ~ 1790 , in 1850–1870 and after ~ 1920 . Such changes have a strong negative correlation with the reconstructed Northern Hemisphere summer temperature record (Figure 9). If the Crête record is interpreted as a proxy of overall (but primarily Northern Hemisphere, high-latitude) volcanic activity, one could conclude, (as others have done – Lamb, 1970; Porter, 1986) that explosive volcanism has played a primary role in controlling Northern Hemisphere temperatures over the last 500 years. With this interpretation, the periods when low acidity levels at Crête do not correspond to higher temperatures (~ 1700 – 1719 , 1730 – 1779 and 1830 – 1869) may have been times when low-latitude volcanism (not well recorded at Crête) was more

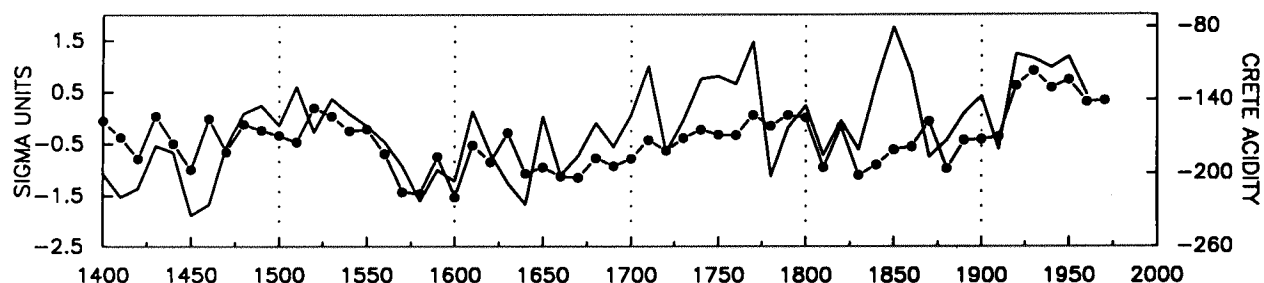


Figure 9 Decadal mean acidity record of an ice core from Crête, Greenland (Hammer *et al.*, 1980) (continuous solid line) versus normalized 'Northern Hemisphere' summer temperature anomaly reconstruction (line with dots). Acidity record is measured in electrical conductivity units, plotted inversely with temperature.

significant. The unusual temperatures of the twentieth century are coincident with both a cleaner atmosphere and higher levels of greenhouse gases.

The Crête acidity record may not, however, be a simple index of explosive volcanism. It can be considered to have two components: a high-frequency record ('spikes') which can be clearly linked to explosive eruptions, and a low-frequency component which reflects overall atmospheric chemistry (Crowley *et al.*, 1993). It is the low-frequency component with which the reconstructed Northern Hemisphere record is primarily in agreement. This component may indeed reflect higher levels of volcanism, but not just from very large explosive eruptions. For example, high-elevation, high-latitude volcanoes can inject material into the stratosphere (particularly in winter months, when the polar tropopause is at relatively low elevations) without the cataclysmic explosive activity required of lower-elevation, low-latitude eruptions. Thus, both the low frequency component and the spikes in the Crête record may reflect different aspects of hemispheric volcanic activity. An alternative interpretation is that the Crête acidity record is not simply a record of sulphate loading from explosive volcanism, but a reflection of overall atmospheric chemistry, and hence may not be a cause of temperature variation, but a product of it. This would mean that cooler conditions in some way led to more acidic (or less basic) materials entering the atmosphere during cooler episodes. This seems inherently unlikely; several studies suggest that cooler periods of the last few centuries were also drier, but this is more likely to result in higher levels of tropospheric dust, which is not generally acidic. Crowley *et al.* (1993) suggest that the low-frequency component of the Crête record reflects changes in oceanic productivity, which caused changes in atmospheric dimethyl sulphide (DMS) levels and an alteration of background acidity levels in Greenland snowfall. However, no evidence is cited to support this hypothesis. Until further chemical studies of new ice cores from Greenland are completed, we believe that the Crête acidity record offers a first-order explanation of summer temperature changes on the decadal scale, and that explosive volcanic activity has played an important role in modulating hemispheric summer temperatures over the last 600 years, at least.

Conclusions

The term 'Little Ice Age' is often used to describe a world-wide, 400–500-year long, synchronous cold interval. Our analysis indicates that the climate of last few centuries was more complex than this simple concept implies. It was a period of both warm and cold climatic anomalies which

varied in importance geographically. In the Northern Hemisphere, the coldest intervals were from ~1570 to ~1730 and during most of the nineteenth century, though not all individual records show this pattern. Changes in the general circulation result in positive anomalies in some areas at times when negative anomalies are recorded elsewhere. Such patterns are clearly seen in instrumental records for the present century (Briffa and Jones, 1993). The commonly used Northern Hemisphere average series (Jones *et al.*, 1986) masks all this spatial detail, the patterns of which may help in identifying causal factors. Such patterns are difficult to determine in the preinstrumental period, because data sets are rarely sufficiently extensive (geographically) to permit the mapping of anomaly fields (see, however, Schweingruber *et al.*, 1991; Fritts, 1991). Our average series (Figure 5) may therefore be biased in some periods because of limited geographical sampling. General circulation model (GCM) experiments may be helpful in understanding how climatic anomalies in different regions result from prescribed forcing factors (Overpeck and Rind, 1992; Rind and Overpeck, 1993), though the signal/noise ratio in current generation GCMs, for experiments involving small perturbations in forcing, may be too small to be useful. There is also considerable debate concerning variations of past forcing factors over the last 500 years. Even with the greater detail of the last 100 years, we cannot adequately explain the Northern Hemisphere temperature average series (Wigley and Barnett, 1990). In spite of these problems, as further research begins to fill the gaps in our knowledge, and more calibrated proxy records become available, a better understanding of the prevailing circulation patterns at various times in the past should emerge.

Current evidence suggests that explosive volcanism has played an important role in modulating summer temperatures in at least the Northern Hemisphere over the last few centuries. However, since the 1920s, temperatures in this hemisphere have been higher than those reconstructed, for at least 500 years, suggesting that other factors may have come into play during recent decades. Anthropogenic greenhouse gases are the most probable explanation.

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