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Pre-Instrumental Climate: How Has Climate Varied During the Past 500 Years?

R. S. BRADLEY
Department of Geology and Geography
University of Massachusetts
Amherst, MA 01003
U.S.A.

ABSTRACT. There is a need for a long-term record of global or hemispheric temperature which extends back in time beyond the limited (100–150 year) span of the instrumental record. The extent to which this can be achieved is discussed and attention is focused on climatic (mainly temperature) information that has been derived form historical (documentary) sources. Records from western Europe, East Asia, North America and Africa are examined and the characteristics that they have in common are identified. Although there are many differences among the regional records, all show that the 20th-century warming is unique in the context of the last 500 years. However, many types of documentary evidence tend to emphasize colder intervals and may underestimate warmer periods. The underlying trend in temperature depends on the time period selected and may differ by season. Maximum upward trends are given by a series beginning in the late 19th century and extending through the 1980s. There is little prospect of reconstructing a hemispherically representative record of temperature from historical data alone, and the best strategy may be to combine many different types of proxy data.

1. INTRODUCTION

Although considerable effort has been expended in trying to construct a globally representative record of climatic fluctuations for the last 100–130 years (Bradley *et al.*, 1985; Jones *et al.*, 1986a–c), a similar record for earlier periods remains an elusive goal. Indeed, some would argue that a meaningful "global" record of interannual climatic fluctuations does not exist even for the last 100 years and, therefore, the underlying trend in climate is really not known. At the same time, concerns over anthropogenic impacts on climate are increasing. Whatever the magnitude of these impacts, and their spatial distribution, there is no doubt that they will be superimposed on "natural" climatic processes that may amplify or subdue the anthropogenic effect. Since we need to know what the climate of the future may be, it is axiomatic that we learn more about the climate of the past. Only with such knowledge can we hope to place our contemporary climate in a longer time perspective and identify any underlying trend or periodicities in climate upon which future climatic changes might be superimposed. Only with such knowledge can we hope to isolate the causes of past climatic fluctuations which may continue to operate in the future and influence the course of forthcoming climatic events.

How can the climatic history of the world over the last few centuries be determined? Clearly, instrumental data become increasingly sparse the further back in time one goes. Most of the world is unrepresented in the instrumental record prior to 1850. In a fairly comprehensive search of long-term climatic data sources, Bradley *et al.* (1985) could locate only enough data to extend their gridded coverage of continental monthly temperature anomalies to 7% of the Northern Hemisphere in the mid-nineteenth century (Jones *et al.*, 1986a). For oceanic regions, and for the Southern Hemisphere as a whole, the situation is far worse and a spatially extensive network of instrumental data really exists only for the past few decades (Jones *et al.*, 1986b). Nevertheless, analysis of the limited mid-nineteenth century network suggests that if there had been no growth in network coverage through time, the low-frequency nature of climatic changes which were actually observed (by the ever-expanding network that eventually evolved) could have been recognized (cf. Jones *et al.*, 1986a). This is because there is significant spatial coherence in low-frequency climatic fluctuations (at least) which suggests some underlying large-scale forcing. Thus it is not unreasonable to expect that if a network of long-term records of climatic fluctuations can be assembled for many regions of the world (though perhaps not all regions), a meaningful picture of global climatic fluctuations might be constructed. How dense such a network must be has not been determined, and perhaps cannot be *a priori* because the nature of the climatic signal that one hopes to capture is unknown, both in its spatial and temporal characteristics. However, such a question may be of only academic merit since there is a limited range of potential data sources, and the networks that are realistically probable are likely to be sparse. Since our knowledge of climatic fluctuations over the last few centuries is still quite incomplete, any new pieces that can be added to the puzzle must be welcomed. Once the picture becomes clearer it may be possible to be more selective, but such a situation is still a long way off.

What data are available to place climatic fluctuations of the last century into a longer-term perspective? Continuous, instrumentally recorded temperature measurements extending back into the 18th century exist only for about 50 stations worldwide (90% of which are in western Europe) so we must turn to additional non-instrumental records from which climatic information can be derived. For the period of interest there is a limited range of proxy records that have the potential of providing interannual resolution of past climatic variations (Bradley and Jones, 1990). These are: historical records, tree-growth indices, ice cores, varved lacustrine (and in a few locations, marine) sediments and coral-growth increments. In each field specialized methods have been developed to extract the climatic signal from non-climatic noise (Bradley, 1985). Although these methods differ in detail, they all involve careful dating of the material, calibration with instrumental data (for a period of overlapping record), reconstruction of past climatic conditions (based on the calibration) and some attempt at verification of the reconstruction by independent lines of evidence. Here we will not attempt to review the multitude of paleoclimatic reconstructions in each field, but instead will focus on paleotemperature reconstructions from historical records. Since none of these records was made with the objective of long-term climatic monitoring, there are many uncertainties in using them for such a purpose (DeVries, 1980; Ingram *et al.*, 1981a). Consequently, no single record should be relied upon too much; only by assembling a variety of individual data sets can past climatic fluctuations be determined with any degree of confidence.

2. HISTORICAL DATA

Historical records contain a wealth of information about past climatic conditions. Providing that adequate precautions are taken in checking sources and evaluating non-climatic influences on the records, detailed interannual (and even intra-annual) climatic conditions can be assessed (Bell and Ogilvie, 1978; DeVries, 1980; Ingram *et al.*, 1981b). Unfortunately, there are only a few regions of the world where extensive studies of historical records, in terms of past climatic conditions, have been carried out. These are: western Europe, China and Japan, and some parts of North America and Africa; each of these regions is discussed below. Studies of historical documents from eastern Europe and the Soviet Union will add considerably to the climatic record of the last few centuries (Borisenkov, 1990). Apart from studies of southern Africa by Nicholson (1978, 1979, 1981), there is almost a complete absence of historical climate research for regions in the Southern Hemisphere.

2.1. European Evidence

Detailed studies of European climatic fluctuations based on historical records have been made by Le Roy Ladurie (1971), Pfister (1980, 1981, 1984, 1985, 1988), Alexandre (1986) and Ogilvie (1984). A variety of climate-related data has been used, including agricultural statistics (particularly harvest dates), records of snow occurrence or freezing/thawing events, phenological data and sea-ice occurrence.

European historical records are particularly rich in phenological data which can provide valuable insights into past climatic conditions. Perhaps the most useful of these are the long records of grape harvest dates from vineyards in northeastern France, Germany and Switzerland (Angot, 1885). Recently, over 100 of these series have been analyzed and statistically reduced to a single composite index of harvest dates for western Europe (representing an area centered near Dijon) for the period 1484–1879 (Le Roy Ladurie and Baulant, 1980). Additional (earlier) data for the Dijon (Cote D'Or) region have been presented by Pfister (1988) for the period 1370 to 1525. Since the two data sets overlap for 40 years in the late 16th century, and the two series are highly correlated in this interval ($r = 0.89$), the earlier Dijon series can be adjusted to the "western Europe" data standard to produce a comprehensive record of grape harvest dates for the last 500 years (1370–1879). Le Roy Ladurie and Baulant demonstrated that the grape harvest dates were inversely related to April to September temperatures in Paris ($r = 0.86$) based on the 1797–1879 (83-year) period of overlap between the grape harvest data and early instrumental Parisian records. Our own analysis of these data, and additional instrumental records from Strasbourg (1801–1879) gave correlation coefficients of 0.74 and 0.80, respectively, for April–September mean temperatures. Using the regression equation established for the period of overlapping records, a reconstruction of Parisian spring/summer temperatures back to 1370 can be obtained (Fig. 1). This reconstruction suggests that growing season temperatures have declined by 0.75°C over the last 600 years, with temperatures in the late 14th and early 15th centuries 1 to 1.5°C higher than in recent decades. The instrumental record from Paris continues this downward trend, despite the probable influence of urban warming on the 20th-century section of the record (Detwiller, 1978). A similar trend was found in the Strasbourg instrumental record, although this is incomplete for the early part of this century.

The most comprehensive set of European climate-related historical data has been assembled by Pfister (1985). Pfister combines a vast range of documentary evidence to rate the relative warmth or coldness of individual months. His sources include the occurrence and duration of lake freezing, extensive snow cover (or absence thereof), phenological

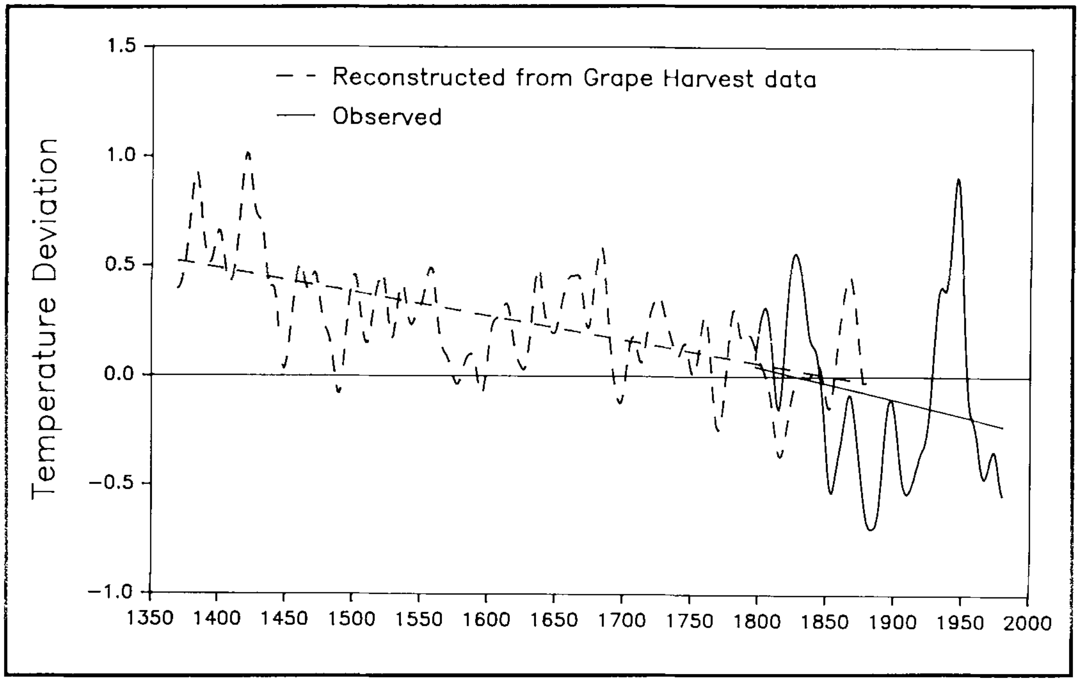

Figure 1. Reconstruction of April-to-September mean temperature at Paris, 1370–1879, and instrumental record from 1797–1976. Reconstruction is based on a regression of instrumental data on a composite record of grape harvest dates (see text) for the period 1797–1879 ($r = 0.74$; $y = -0.731x + 176.7$, where y = mean April-September temperature at Paris and x = mean grape harvest date at a network of vineyards, in days from September 1). Values plotted as anomalies from the average in the period of data overlap (1797–1879).

records (such as the dates of beech tree flowering or of cherry tree blossoming), tithe-auction records (related to harvest dates, which reflect early summer temperatures), vine phenology (first flowering, full flowering), grape-harvest dates, wine yields and quality, and tree-ring density (lower density indicative of cooler growing season conditions) (Pfister, 1981, 1988). Careful cross-checking of different sources enables him to establish a certain degree of reliability in his climatic interpretations. Similar evidence is used to assess the relative wetness or dryness of individual months and seasons. From these ratings, "thermal and wetness indices" for each season over the last 450 years have been assigned (Pfister, 1980, 1981). Although there is an inevitable element of subjectivity in rating these diverse phenomena in terms of temperature and precipitation, Pfister demonstrates a reasonably good correlation between his indices and composite records of temperature and precipitation, based on a network of instrumental data recorded on the Swiss Plateau in the period 1901–1960 (Pfister, 1980). Using such comparisons, Pfister converted the indices to temperature and precipitation anomalies from a 1901–1960 reference period (Pfister, 1984). His reconstruction (Fig. 2) clearly demonstrates the unusual characteristics of climate in this area during the 19th century, and the pronounced warming that has occurred since the 1890s. Mean-annual temperatures appear to have been about 0.25°C below the 1901–1960 mean for most of the last 450 years, with the coldest episodes (in the 1690s, 1810s, 1840s and 1850s, and the late 1880s) 0.8 to 1°C lower than 1901–60. A continuous rise of about 1°C in mean-annual temperature over the last century (from the 450-year minimum in the late 1880s) is a pronounced feature of

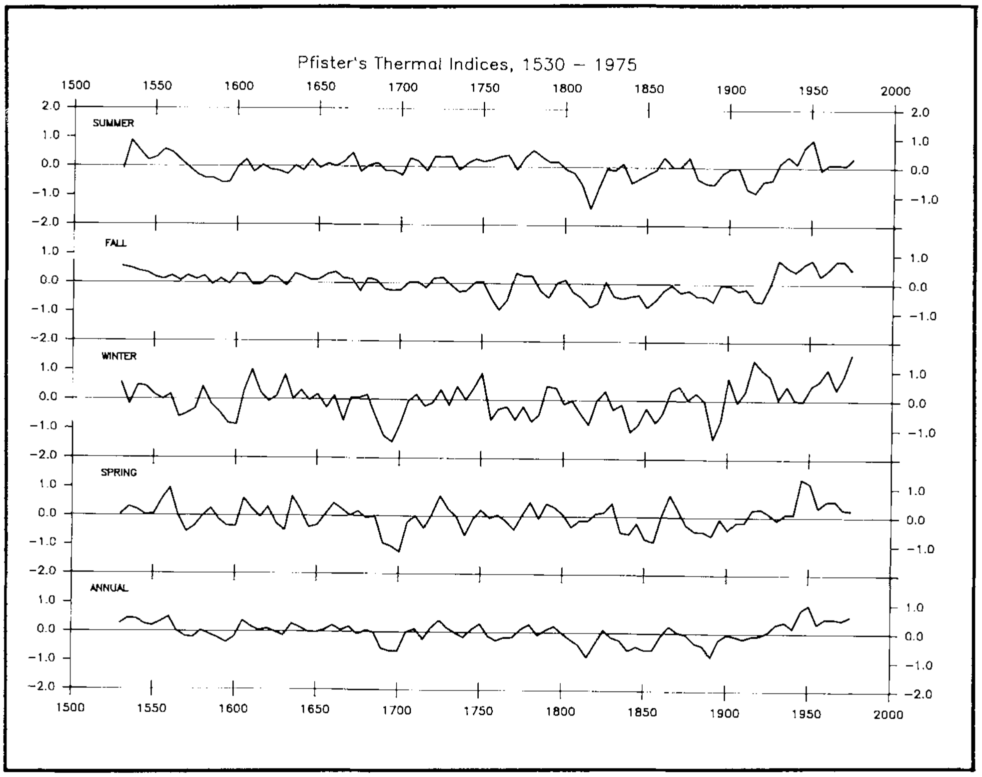

Figure 2. Seasonal and annual temperature anomalies in Switzerland from the 1901–1960 mean, derived from Pfister's thermal indices. [After Pfister, 1984.]

the reconstruction. Seasonal differences are apparent, however. Data representing summer conditions (shown in Fig. 3, with Paris temperatures reconstructed from grape harvest data) suggest that summer temperatures for much of the 18th century were similar to, or above, the 1901–60 mean, and may have been 0.5°C higher in the mid-16th century. The only cold periods comparable to the late 19th and early 20th century were in the late 1500s and in the 1810s, a period of exceptionally low summer temperatures. Winter temperatures, on the other hand, appear to have been markedly cooler than the 20th century mean (by an average of 0.6°C) for almost the entire 450-year period. Winters were coldest in the 1690s and there has been a general upward trend in temperature since then.

Precipitation anomalies also suggest that the climate of the last one hundred years in this region has been unusual in the context of the past few centuries. Precipitation was generally lower than in this century, with the lowest amounts in the 1820s, and somewhat of an upward trend since then, punctuated only by dry conditions in the late 1940s and early 1950s.

Some of the longest records of climate-related phenomena are available from Iceland, where commentaries about the occurrence of sea ice have enabled a proxy record of temperature to be reconstructed spanning several centuries (Koch, 1945; Bergthorsson, 1969; Sigtryggsson, 1972; Ogilvie, 1984; Grove, 1988). Sea-ice occurrence was far more prevalent from 1740–1900 than for most of this century; ice was a minor problem in the early 18th century and during 1640–1680, but was especially severe in the 1680s and 1690s, the 1740s and 1750s, and for much of the 19th century (Fig. 4). Kelly *et al.* (1987) caution against using the Icelandic sea-ice record as an indicator of more

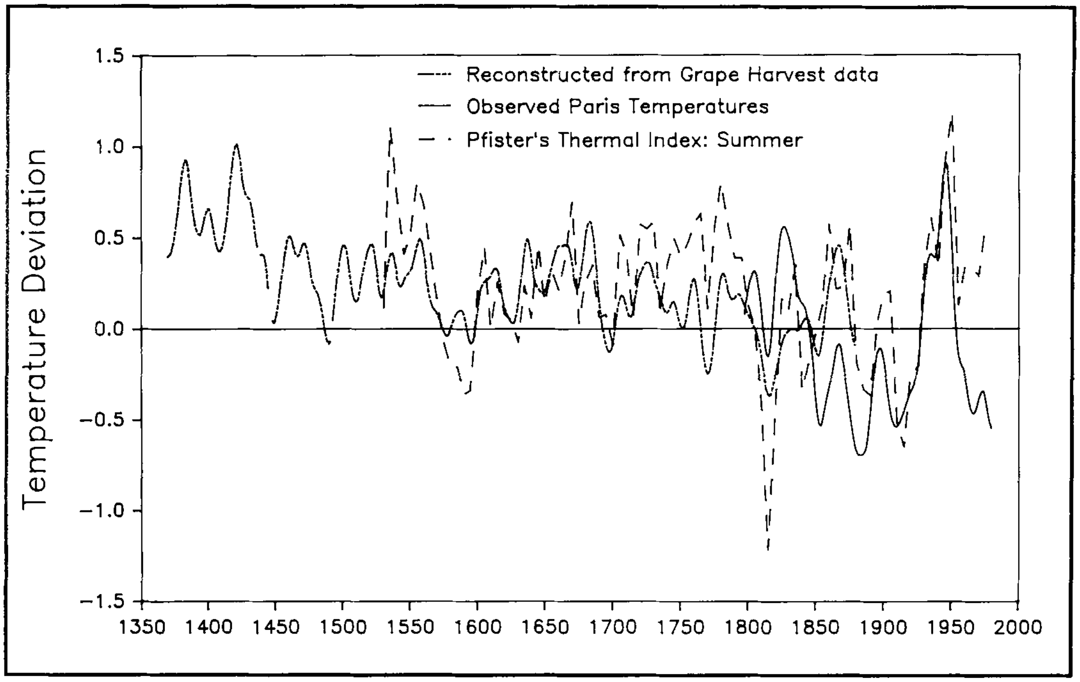

Figure 3. Reconstructed and observed summer temperatures in western Europe, 1370–1976, based on Pfister's thermal indices (converted to temperature anomalies), and Paris April–September mean temperatures reconstructed from grape harvest data, and instrumental records from Paris. Values expressed as departures from the mean for 1797–1879.

widespread conditions, but several of these periods (especially the 1690s) also stand out as extraordinarily cold in the instrumental winter temperature record from central England (discussed below) and in Pfister's winter and spring thermal indices for western Europe (Fig. 2), indicating widespread regional anomalies at these times.

Bergthorsson (1969) attempted to express sea-ice indices in terms of mean-annual temperature in Iceland by regressing the number of months of sea ice per year against mean-annual temperature (Fig. 5a). The resulting reconstruction appears to indicate the exceptional warmth of the 20th century, 1°C higher than prevailing conditions from 1600–1900 (Fig. 5b). However, this reconstruction illustrates a common problem in historical data where an index may be a useful indicator of cold conditions, but provides limited information about warm conditions. As Fig. 5a shows, once sea-ice occurrence drops to one month or less, it is no longer a useful predictor of mean-annual temperature. Consequently, the warm periods in Fig. 5b, before 1846, must be considered as only minimum estimates, and the 20th-century record of temperature in this area may not be quite so anomalous as Bergthorsson's reconstruction suggests.

The longest instrumental data set is that of Manley (1953, 1974) for central England (subsequently updated by the Climatic Research Unit, University of East Anglia, in their Monthly Bulletin). This record is shown in Fig. 6. The long-term trend for the entire 330-year record amounts to an increase in mean-annual temperature of 0.16°C per century. However, this trend is amplified by the fact that temperatures in the 1690s, near the beginning of the record, were exceptionally low. Although there is considerable documentary evidence for unusually cold conditions in the 1690s (Lamb, 1982), it is clear from Manley's writings that these early values are based mainly on estimates,

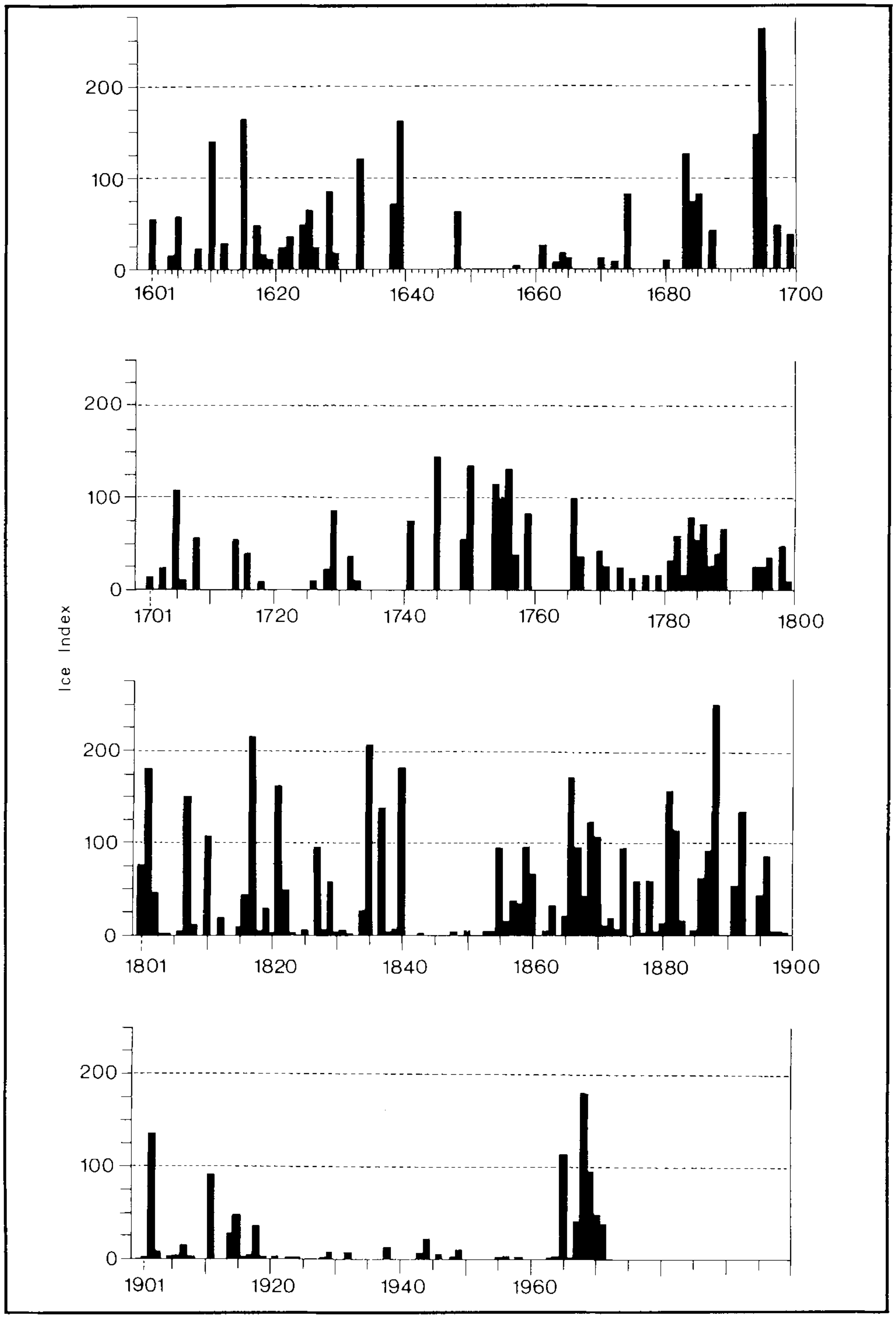

Figure 4. Incidence of sea ice around Iceland from the seventeenth to the twentieth century. [From Sigtryggsson, 1972.]

not instrumental data. For example, Manley (1974) states ". . . before 1723 we have a very troublesome gap . . . over the period January 1707 to October 1722 . . . this

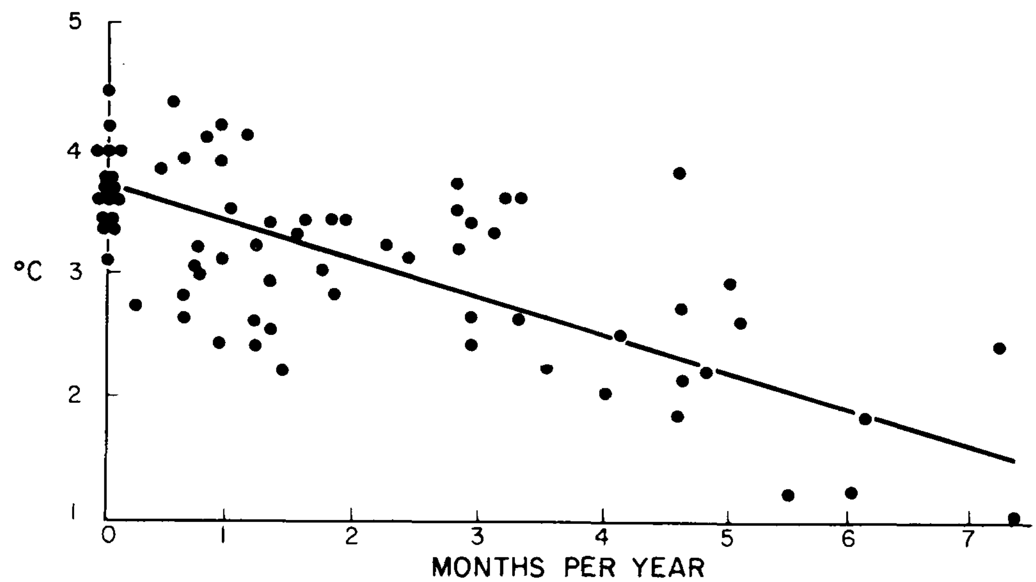

Figure 5a. Relationship between annual temperature and ice incidence off the coast of Iceland in months per year. Calibration period 1846–1919. [After Bergthorsson, 1969.]

gap was filled by reference to the Utrecht series . . . adjusted as far as possible from consideration of English non-instrumental 'wind and weather' diaries over that period." In fact, most of the data prior to 1707 is based entirely on the estimated temperature of prevailing air masses. In view of these uncertainties, it is probably wise to view the record before 1723 with caution. Mean-annual temperatures declined from 1723 to the 1810s, but have risen steadily since then. Looking at higher-frequency variations, there have been only a few periods with mean-annual temperatures equal to or higher than recent decades: the 1730s, 1865–75 and the 1910s–40s. However, this is not true of seasonal data; winter temperatures were considerably warmer in the 1910s and 1920s, whereas summer temperatures were well below average at that time (Fig. 6). Summer temperatures were highest in the 1770s when winters were among the coldest on record (cf. Fig. 2). Such differences are probably related to regional circulation anomalies. For example, a period of frequent blocking with anticyclonic conditions over Great Britain could result in both unusually warm summers and cold winters. By contrast, in the early 1900s winter warmth and summer cold are likely to reflect more zonal conditions. These strong seasonal differences highlight the dangers of interpreting proxy records or historical data (which are often indicative of a particular season) as representative of overall annual conditions. A combination of data reflecting all seasons is really needed to reconstruct past climate in individual decades (e.g., Pfister, 1984).

A long record of winter temperature for DeBilt, Holland has been presented by Van den Dool *et al.* (1978) based on a combination of instrumental data (from 1734 on) and records of Dutch canal freezing dates and winter barge trips between Haarlem and Amsterdam. Overlapping records enable the historical data to be calibrated in terms of winter temperature so that a composite record from 1634–1977 can be constructed. This is shown in Fig. 7 with the central England winter temperature record of Manley (1974) and Pfister's (1984) winter temperature estimates. Although there are clear differences in

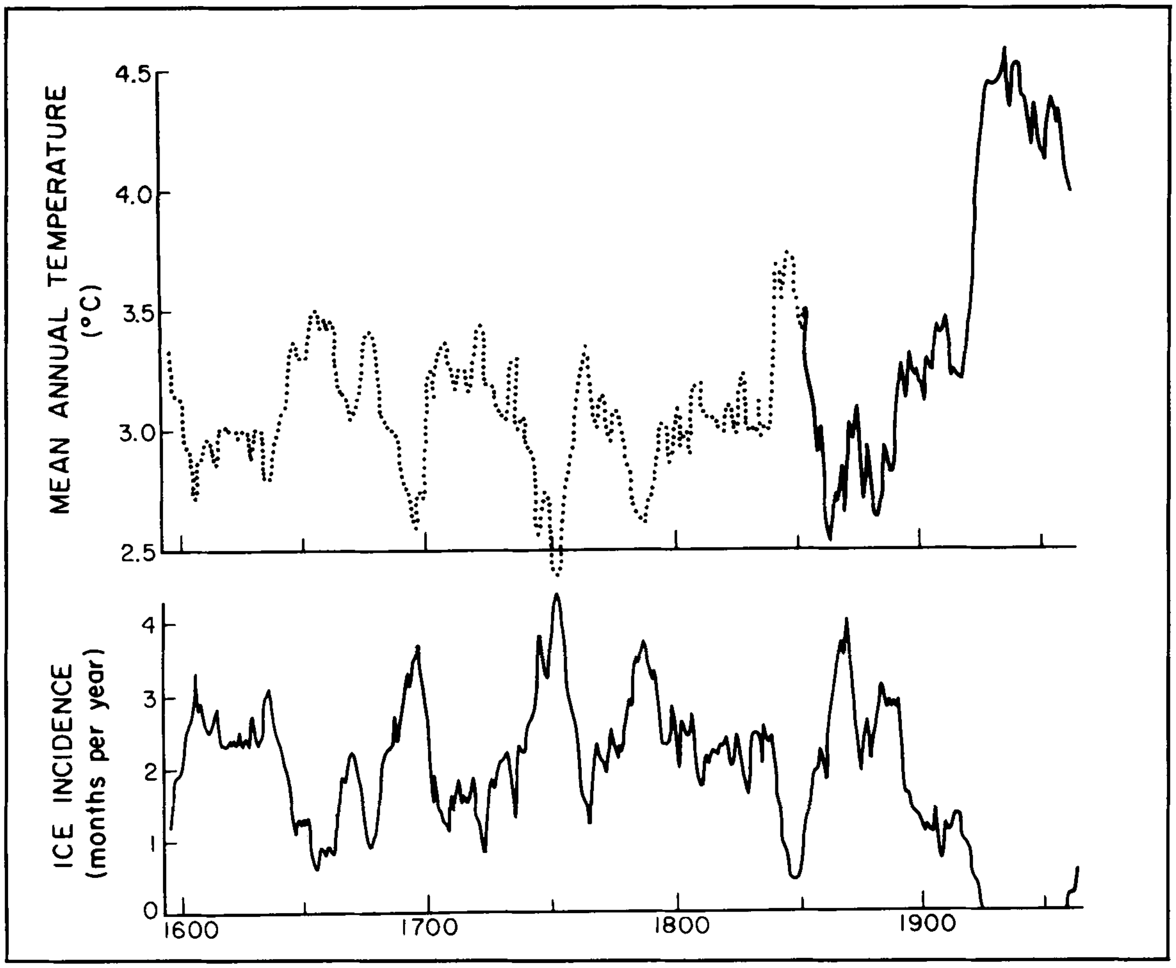

Figure 5b. Reconstruction of paleotemperature based on calibration shown in Fig. 5a. Decadal running means of mean-annual temperature (top) and ice incidence in months (below). Paleotemperatures are shown by dashed line. This record has been extended back to AD 950, but the earlier part of the record is considered to be unreliable. [After Bergthorsson, 1969.]

the high-frequency realm, the three records are remarkably consistent in depicting broad-scale changes in the winter climate of western Europe since the 17th century. The 1690s stand out as a brief period of exceptionally low temperatures, followed by relatively mild conditions in the early 18th century. Temperatures subsequently fell to the end of the 18th or early 19th century, and have steadily risen since then, interrupted by exceptionally cold periods in the 1810s, 1840s and/or 1850s and the 1890s.

2.2. Chinese Evidence

Chinese historical records are a particularly rich source of climate-related information (Wang and Zhang, 1988). Records were kept by official Imperial observers, as well as at the local level, permitting comprehensive spatial and temporal reconstructions to be obtained for the past several centuries, or (for selected regions) even longer periods (e.g., State Meteorological Administration, 1981). Much recent work has been reviewed by

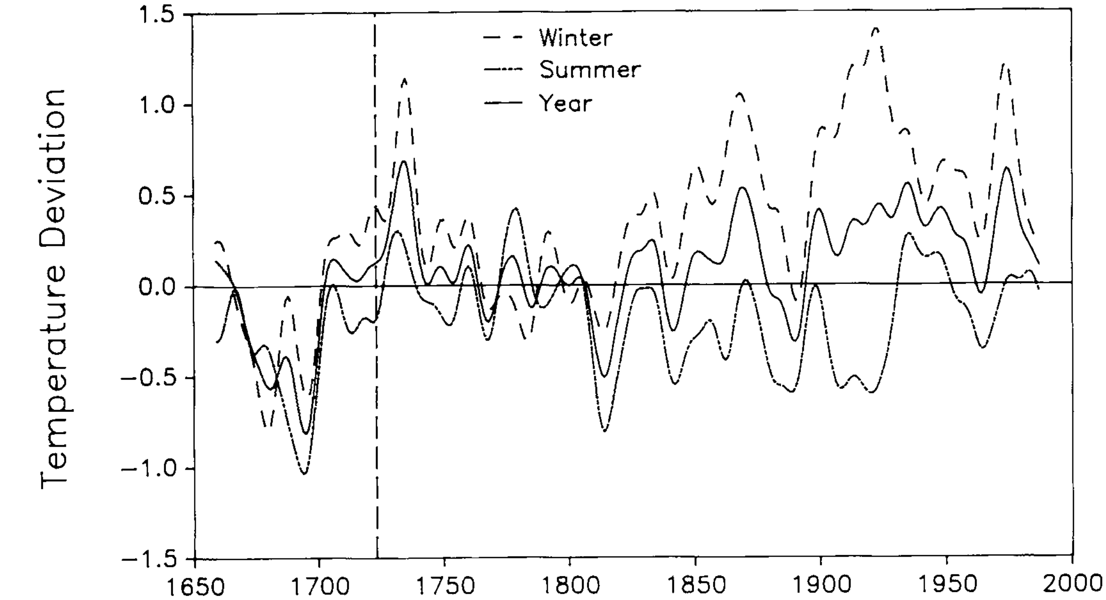

Figure 6. The instrumental record of winter, summer and annual temperature in central England, expressed as departures from the 1751–1800 period mean and filtered with a 21-term Gaussian filter (data from Manley, 1974). Note that data before 1723 are based largely on estimates and comparisons with records from Labrijn, Holland.

Zhang (1988) and Zhang and Crowley (1989). The vast majority of studies have focused on the long records of floods and droughts which have affected Chinese society over the centuries, but a few temperature reconstructions have also been published. It is worth noting that Chinese annual-temperature fluctuations over the last century mirror annual-temperature fluctuations for the northern hemisphere continents as a whole, and so low-frequency changes in long-term Chinese records may be a useful index of larger scale conditions (Bradley *et al.*, 1987).

In a very comprehensive study, Zhang (1980, 1988) examined over 1200 local histories and more than 4400 historical writings to construct a record of severe winter occurrence in eight different sub-regions of China. The reconstructions have been correlated with instrumental data to assess variations in winter temperature back to 1470. Winter conditions were rated by compiling records of river and lake ice occurrence, the freezing of wells, presence and extent of sea ice, snowfall frequency, snow depth and duration of snow cover, and damage to citrus crops or coconut groves. Mild conditions were typified by the absence of such severe conditions and by the early blossoming of peach and plum trees and other agricultural and phenological indicators. By comparing overlapping periods of winter temperature indices and instrumental data for Shanghai and Hankou (Wuhan) a rough index of temperature anomaly can be derived in which a change of two units in the thermal index approximates a change in winter temperature of 1°C (Zhang, 1988). A composite record for 5 regions of eastern China between 22–38°N and 108–122°W is shown in Fig. 8, based on decadal averages for each region. Zhang's reconstructions can be compared with an independent investigation of the frequency of cold winters (though perhaps not based on entirely independent sources) conducted by Zhang and Gong (1979). Both studies point to the periods 1500–1530, 1601–1700 and

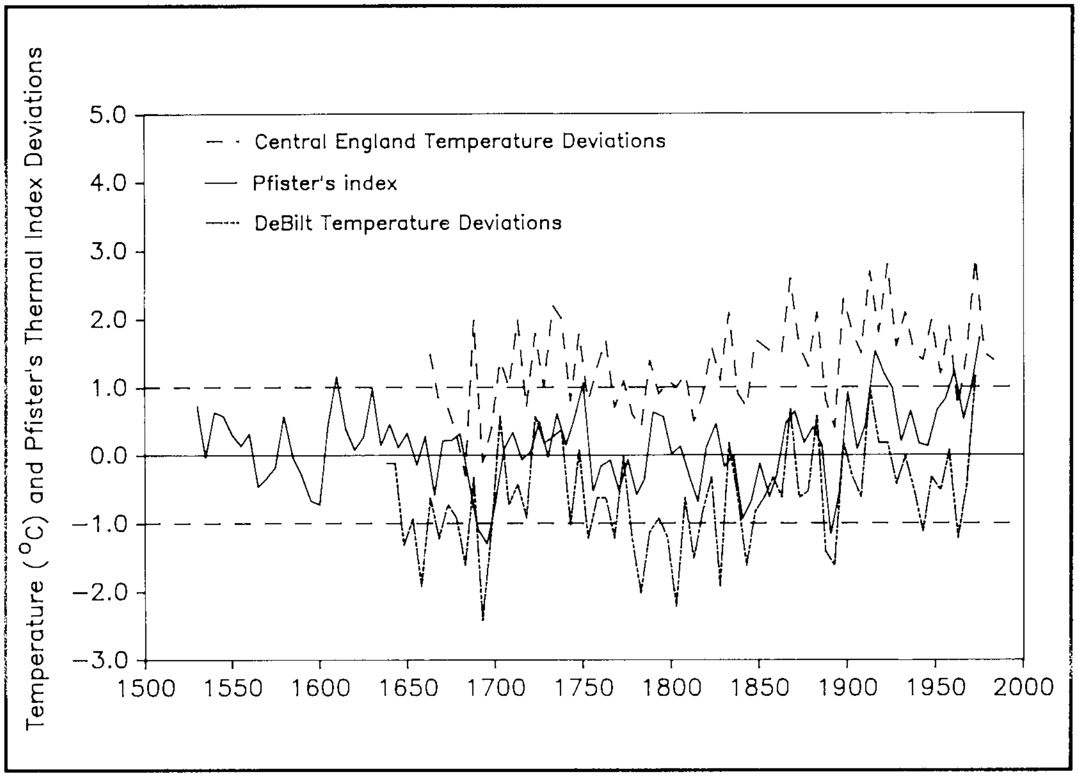

Figure 7. Instrumentally recorded winter (DJF) temperatures at De Bilt, Holland, 1727–1977, with reconstructed temperatures back to 1634 based on canal freezing records (see text), plotted with instrumentally recorded central England winter temperatures, from 1723, and Pfister's winter temperature estimates for Switzerland based on thermal indices. All values expressed as departures from the mean for 1751–1800 in each record. Note that the central England record has been displaced by +1°C and the De Bilt record by -1°C to avoid overlapping the series, i.e., the dashed lines at +1.0, 0.0 and -1.0 are the equivalent 1751-1800 means in central England, Switzerland and De Bilt, Holland, respectively.

1810–1900 as generally colder than in the 20th century, but with milder conditions in the mid-18th century. There is some correspondence with European data in terms of a relatively mild period in the mid-18th century and a colder 19th century, but apart from that, there are few similarities between the winter temperature records of China and Europe.

Historic summer temperature variations at Beijing have been estimated by Zhang and Liu (1987). Using the observed relationship between rainy-day frequency and July temperatures during the period of instrumental records, these authors have reconstructed July mean and maximum temperatures back to 1724 using historical records of rainy-day occurrence (Fig. 8). This reconstruction indicates lowest summer temperatures from 1780 to 1820 and from 1885–1900, with mild conditions from 1825–1875. Like the winter record, there is only minor correspondence with the European evidence; the cold period at the start of the 19th century began earlier in Beijing and the mid-19th century was considerably warmer in Beijing than in Europe. Further studies of temperature change are in progress and it will be of interest to see if these initial reconstructions are subsequently confirmed.

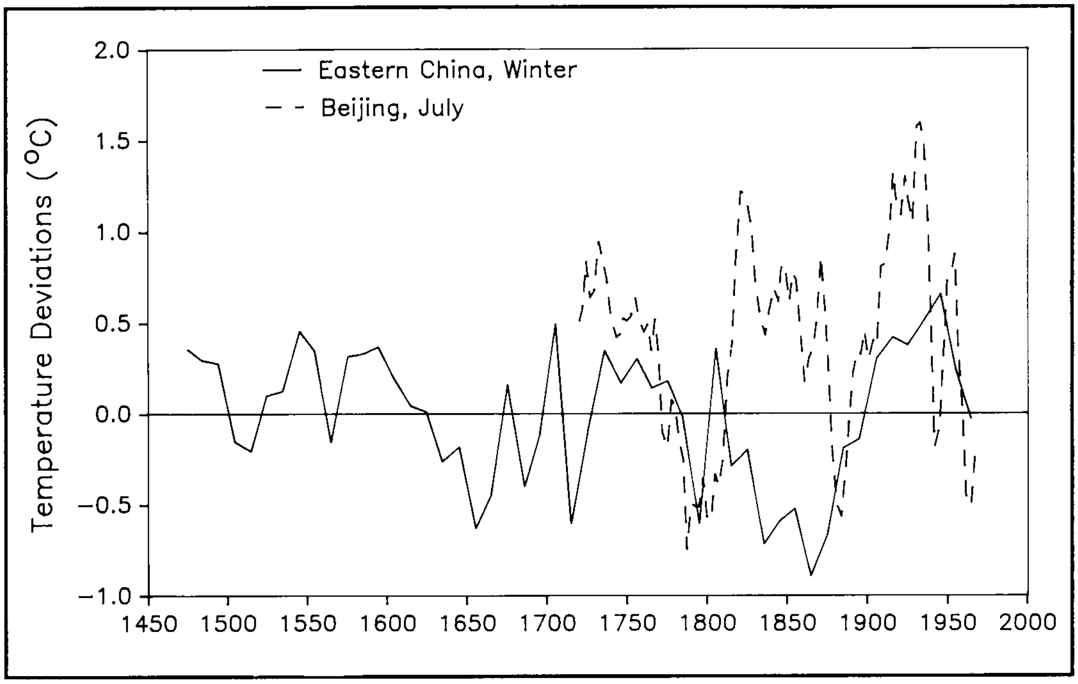

Figure 8. Mean July temperatures reconstructed for Beijing and a composite record of winter temperatures for eastern China, based on historical records. All values expressed as departures from the 1751–1800 mean.

2.3. Japanese Evidence

Like China, Japan has a wealth of historical documents containing information about climatic conditions of the past. One of the most carefully studied sets of material is that of the Tsugaru feudal clan who recorded daily weather conditions at Hirosaki (northern Honshu, 40.5°N, 142.5°E) almost continuously from 1661–1868 (Maejima *et al.*, 1983). From these records, Maejima and Tagami (1984) estimate that temperatures in the 20th century were generally warmer than for most of the preceding 250 years. Relatively mild conditions prevailed in the latter half of the 17th century and from 1741–1780 (also noted in China). However, from 1821–1880 conditions were "very cold" in winters (again, as in China), with heavy snowfalls common. Summers were coldest (with frequent rains) from 1781–1850. These conclusions reinforce Yamamoto's (1971) study of heavy snowfall years and river and lake freezing occurrences in southern Japan (near Lake Biwa) from the 17th to the 19th century. Exceptionally cold conditions were common in the 1750–1850 interval and especially in the early 1820s. Mean January temperatures from 1801 to 1850 are estimated to have been 1° to 2°C lower than in the 1890–1960 period (Yamamoto, 1971). Rice harvest data suggest a similar July temperature anomaly at this time. This seems to support the Chinese winter reconstructions of Zhang (1988), though summer temperatures in Beijing appear to have been quite warm after 1825.

Using records of the freezing dates of Lake Suwa, near Tokyo, Gray (1974) reconstructed December-to-February average temperatures from 1440–1950 (Fig. 9). This record gives a somewhat different picture than the reconstructions of Yamamoto and Maejima *et al.* Gray's reconstruction of Tokyo winter temperatures would indicate that the 1820s-1860s were relatively mild, with the highest winter temperatures of the last

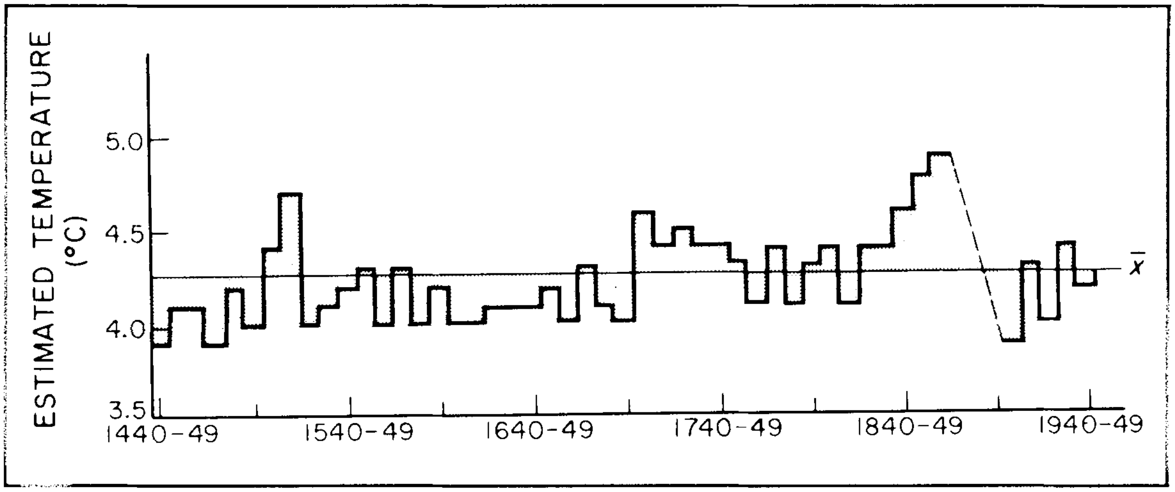

Figure 9. Winter (DJF)-mean temperatures reconstructed for Tokyo, based on the freezing dates of Lake Suwa. Values expressed as departures from the long-term mean. (After Gray, 1974).

500 years occurring in the 1850s and 1860s. Conditions were below the long-term mean from 1440–1820, apart from the first two decades of the 1500s and the period 1700–1750 (which was already noted as having been mild in both eastern China and western Europe). It is not easy to reconcile much of Gray's reconstruction with other Japanese historical records, and it would appear that the calibration of Lake Suwa freezing dates may need to be re-evaluated.

2.4. North American Evidence

Historical records of past climatic conditions in North America have received relatively little attention. The main exceptions are studies of Hudson Bay archives which have yielded much useful climatic information (e.g., Moodie and Catchpole, 1975; Catchpole *et al.*, 1976; Catchpole and Ball, 1980; Catchpole, 1980; Rannie, 1983) and the more limited studies of documentary records from New England (Baron and Gordon, 1985). Figure 10 shows the record of "first breaking" of ice in the estuary at Moose Factory on the shores of James Bay (51°19′N, 80°44′W) from 1738 to the late 19th century (Catchpole *et al.*, 1976) compared to the average date in recent decades. For the first half of the 19th century, and in the mid-18th century, freezing dates were generally a week earlier and break-up dates ten days to two weeks later, particularly in the 1810–1820 decade. This is supported by a similar freeze-up/break-up record from the Red River near Winnipeg, based on a variety of historical data (Rannie, 1983). Correlation of these data with contemporary instrumental data suggests that spring and fall temperatures were 2.5°C lower in the 19th century compared to the 20th century, resulting in the "ice-covered period" lasting 3 weeks longer in the 19th century. It is of interest that the ice break-up record shows similar fluctuations to the winter and spring temperature record reconstructed for Switzerland by Pfister (1984), indicating some large-scale teleconnection between the two areas.

Although many other parameters of climate in the 18th and 19th centuries have been documented for the Hudson Bay region (e.g., days with snowfall, frequency of rain and days with thunder; Catchpole and Ball, 1980), no overall pattern comparable with other regions can yet be discerned. The same is true of similar studies in New England (Baron and Gordon, 1985). Further analysis is required to place these reconstructions in a broad-scale perspective.

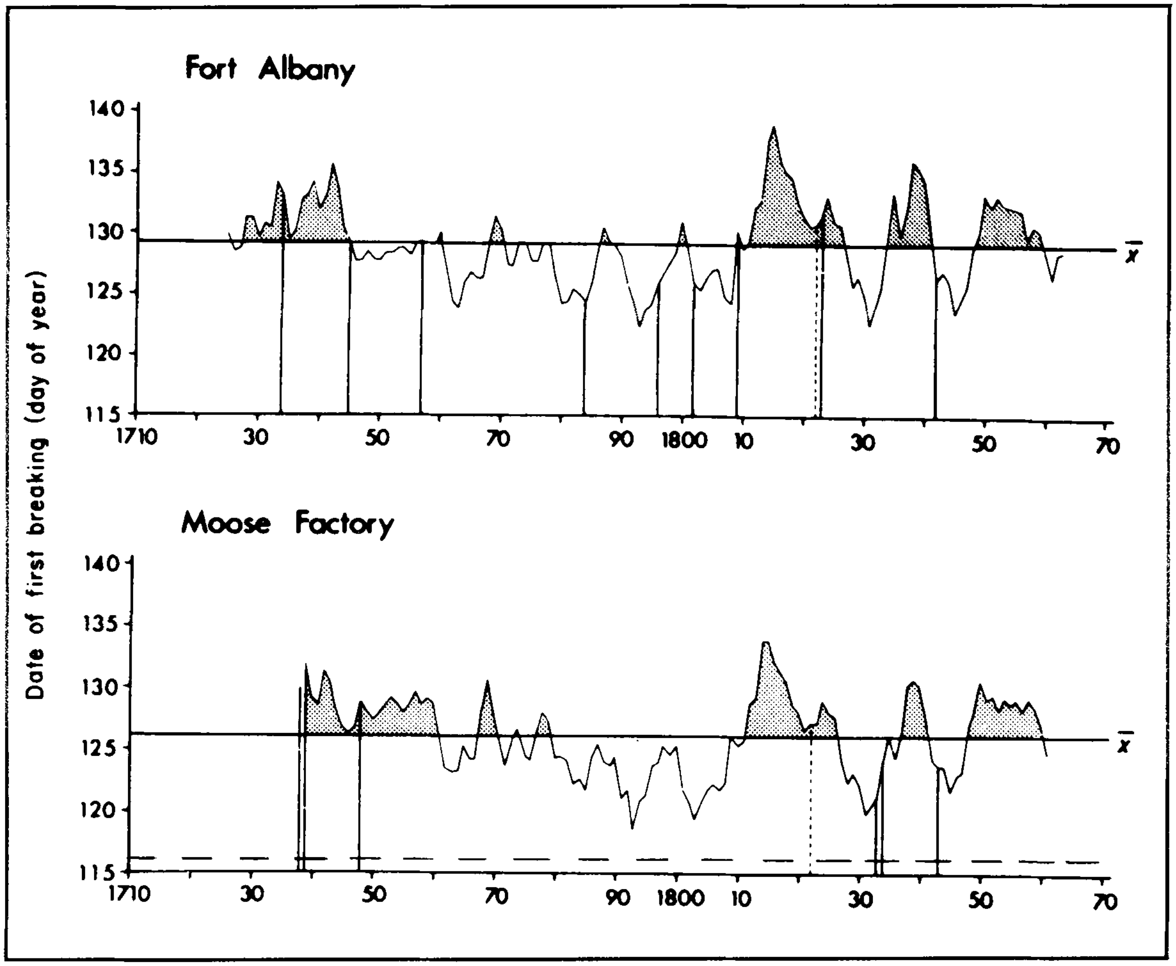

Figure 10. The record of "first breaking" of ice in Moose Bay (near Moosonee, James Bay) from 1738 (after Catchpole *et al.*, 1976) compared to the average of recent decades (Julian day 116 = April 26).

2.5. African Evidence

Historical data for Africa generally involve observations related to the abundance or absence of rainfall. At present there are very few observations that can be interpreted in terms of temperature (Nicholson, 1978). Certainly, there is strong evidence that the 16th to 18th centuries were generally more humid than recent decades throughout much of the Soudano-Sahelian region, although drought appears to have prevailed in the 1680s and in the early to mid-18th century (1738–1756) (Nicholson, 1981). Drought has been more frequent and more severe since then, particularly in the early 19th century (1800s–1830s) and throughout the 20th century. Indeed, rainfall was relatively low across much of Africa in the early 1800s and again in the early 20th century (Nicholson, 1981). Such trends towards more arid conditions suggest that temperatures may have increased throughout tropical Africa over the last three centuries, associated with increased aridity, but no quantitative estimates of how much warming may have occurred are yet available. Evidence of more frequent occurrence of snow and freezing temperatures in South Africa and eastern Namibia before the mid-19th century supports this notion (Nicholson, 1981), but further studies are required.

3. TRENDS IN CLIMATE RECORDS

What can these reconstructions tell us about trends in temperature over the past few centuries? Fitting a linear trend to the data reveals an overall upward trend in central England mean-annual temperature from 1723 to 1987 of approximately 0.1°C per century (the slope of the regression line). However, stepping through the record at one-year intervals and calculating the (linear) trend up to 1987 from each new point gives an upward trend of between 0.1°C and 0.4°C per century (depending on the date when one starts the analysis), except for the last 100 years when a downward trend is apparent (Fig. 11). The maximum upward trend is manifested with a record beginning in the early or late 19th century. An examination of seasonal data reveals further complexity; overall winter temperature trends are generally more strongly positive, but become strongly negative after about 1890; the trend from 1897–1987 is downward at –0.08°C per decade. Summer temperature trends are quite the opposite of those in winter—weakly negative when the overall period is considered, then increasingly positive until the early 1900s. A

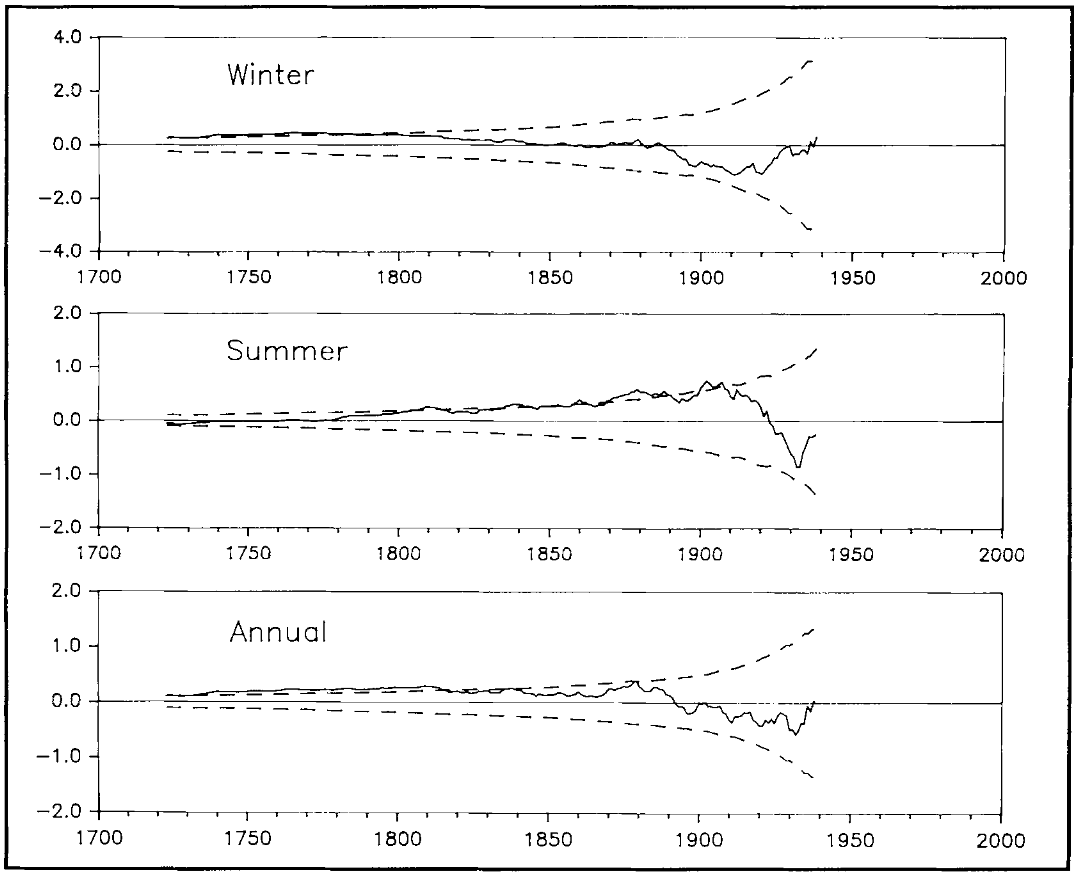

Figure 11. Linear trends (°C per century) in winter, summer and annual temperature data from central England, calculated year by year from the year at which the trend value is plotted to 1987. Minimum period for trend calculation is 50 years (1938–1987). Trends that exceed 95% significance fall outside the range delimited by the dashed lines.

similar analysis of temperature estimates from Pfister's thermal indices reveals a positive (upward) trend in temperature when considering the overall records from the 16th century to 1975, and from the late 19th century to 1975 (Fig. 12). However, over shorter intervals the trends are generally less positive, and actually negative over the last 50 years for summer months, as was observed for the central England temperature record. Winters, on the other hand, show a strong upward trend in the last 50 years. These records indicate that: a) the underlying trend in climate depends on the frame of reference chosen, and b) underlying trends may not be the same in all seasons. Thus determining the magnitude of the underlying trend in temperature, on which anthropogenic changes will be superimposed, is not a simple task.

4. CLIMATE OF THE LAST 500 YEARS: THE HISTORICAL EVIDENCE

There is unanimity in the available historical reconstructions that the 20th-century warming is unique in the context of the last 500 years, and it is necessary to go back to the early 15th and 14th centuries (1330–1450) to find evidence of temperatures similar to, or higher than, in recent decades. However, it is worth noting that many historical indices (particularly those currently available from East Asia) are based largely on the occurrence of extreme cold events, and the absence of such extremes does not necessarily imply unusually warm conditions. It is thus difficult to assess from these data whether temperatures ever reached 20th-century levels during the 18th and 16th centuries when conditions appear to have been "less severe" than at other times. Individual years in some areas clearly stand out as exceptionally warm (e.g., in Europe: 1540, 1473, 1420, 1336, 1331, 1270; Pfister, 1988), but whether these anomalies were only regional, or of more global, significance is not known at present. In fact, a comparison of individual years and decades from one region to another often shows little consistency in the magnitude, or even the sign of the anomalies. This is partly due to the use of different reference periods, and because reconstructions are generally presented as a running mean, in an attempt to smooth over the inadequacies of converting historical records to quantitative temperature estimates. Nevertheless, there appears to be a consistent signal from many regions that the 1690s, the 1810s and 1820s and the 1890s were exceptionally cold in the context of the last 500 years. Indeed, in many areas, almost the entire 19th century was cold, in stark contrast to conditions which have developed in the subsequent 100 years. Attention should be focused on identifying when temperatures were similar to 20th-century averages; in general terms it appears that such conditions have not prevailed for at least 400 years, though individual years and perhaps even decades (e.g., 1730s, 1780–1805) during the last 500 years may have been relatively warm, in some, if not all, seasons. Overall, interdecadal temperature fluctuations do not appear to have been more than ±1°C seasonally in most regions, although the rise in temperature from the low levels of the 1810s to the high point of the 1980s may be around +2°C in mean-annual temperature for many regions. There is little prospect of reconstructing, from historical data alone, a hemispherically representative record of temperature for the last 500 years without a significant increase in information about paleotemperature conditions in the tropics. There is even less hope of reconstructing southern hemisphere paleotemperatures from historical data since the written records are fewer and shorter, and the oceanic areas are so much more extensive. The best prospect for paleotemperature reconstruction over the past few centuries lies in the combined use of several different types of proxy data, to include historical data, tree-growth indices, ice-core data and sedimentary deposits. Only with such an approach can the required geographical coverage be achieved and the results from the many diverse approaches to paleoclimatic reconstruction be tested against each other.

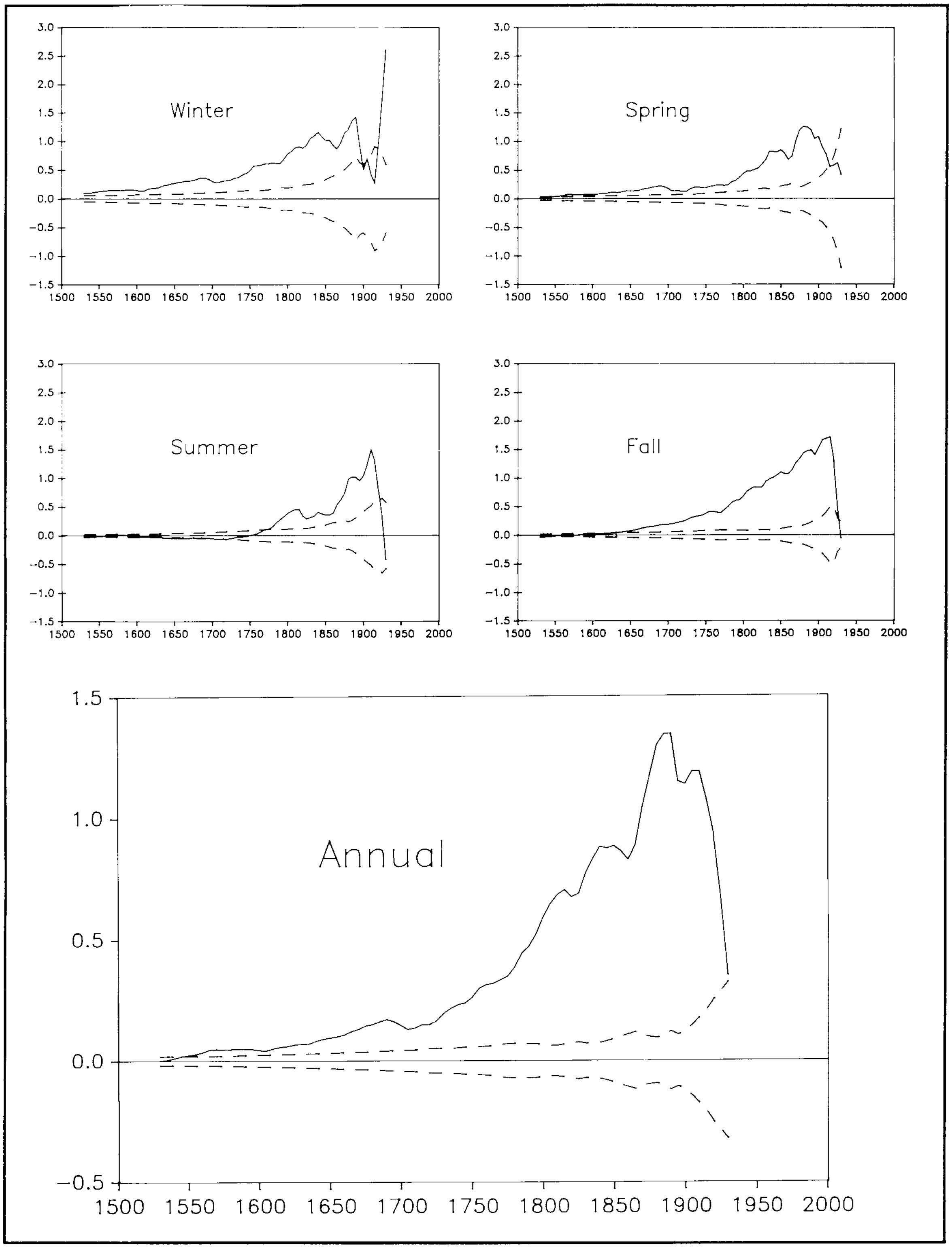

Figure 12. Linear trends in Pfister's (1984) thermal-index-based temperature estimates for Switzerland, year by year to the end of record (1975). Minimum period for calculation of trend is 46 years (1930–1975). Trends that exceed 95% significance fall outside the range delimited by the dashed lines.

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