Reprinted from 'Climate Since A.D. 1500', edited by R.S. Bradley and P.D. Jones, Routledge London (1992).

13 Climatic variations in the longest instrumental records

P. D. Jones and R. S. Bradley

13.1 Introduction

Routine observations of surface air temperature, precipitation and surface pressure began in western Europe during the late seventeenth and early eighteenth centuries, and gradually spread to most of the rest of the world by the twentieth century. The speed with which instrumental recording began in other parts of the world was not gradual but tended to occur around certain key dates. For example many countries set up meteorological agencies after the Vienna Meteorological Congress of 1873. Even now, coverage is sparse in both polar regions and recording did not start in parts of northern Canada and the Antarctic until the 1940s and late 1950s respectively.

One of the problems encountered in taking European-made thermometers elsewhere, particularly to the Soviet Union and Canada was that mercury froze at about -38°C (see,for example, Ball and Kingsley 1984). Alcohol thermometers were developed to overcome this problem. Other problems with early instruments and scales are summarised by Middleton (1966, 1969) and Lamb and Johnson (1966). Most of the early observers up to the middle of the last century were professional people such as doctors, physicists and astronomers. In some cases, the observations were published, but in many cases the original measurements have been lost. Climatology is fortunate that more data might have been lost if it were not for the efforts of the German meteorologist Heinrich Wilhelm Dove who collected and published, under the auspices of the Prussian Academy of Sciences, as much monthly mean air temperature data as he could obtain (Dove 1838 and later). During the 1860s he had built up a network of nearly 2000 stations, but his coverage was particularly sparse over the interior parts of Africa, Asia, South America and Australia. This data set allowed the Austrian meteorologist Wilhelm Köppen (1873) to attempt to assess whether mean global temperature had changed since 1750. Although Dove's data compilations are important, the lack of spatial coverage meant that the early hemispheric analyses are not of great importance.

The most comprehensive compilation of long-term instrumental climate (temperature and precipitation) data currently available is that of Bradley *et al.* (1985). This compilation built and improved on earlier data sets such as *World Weather Records and Reseau Mondial* by searching meteorological and other archives for published and manuscript sources of early data. The most important aspect of the compilation is that it contains details of the sources of all the station datasets and, where possible, details of the long term homogeneity of the climate time series (see technical reports, Bradley *et al.* 1985; Jones *et al.* 1985, 1986a). Clearly, if one is to study climatic change, it is vital to ensure homogeneity of time series data.

Station time series are said to be homogeneous if the variations are caused only by variations of the weather and climate (Conrad and Pollak 1962). Factors such as changes in instrumentation, exposure, location, methodological practices and environmental changes around the station can all cause inhomogeneities in station time series (Bradley and Jones 1985). All can seriously affect the station record, although, with the exception of environmental changes, the effects do not produce any consistent bias because they can act either to increase or decrease the measured temperature. Growth in towns and cities around stations would generally be expected to increase temperatures through the development of urban heat islands.

The homogeneity of many of the long European air temperature records has been assessed by the climatologists who have developed the series (e.g. Manley 1974 for Central England, Schaake 1982 for Berlin). Homogeneity of the other temperature data in the Bradley *et al.* (1985) data set was assessed by comparing neighbouring stations records. Often, each record was compared with a number of other records from sites from a few tens to a few hundred kilometers distant. Jumps and trends in the comparisons can generally be related to one or more of the above causes. Table 13.1 lists some of the longest air temperature records by continent (see Jones *et al.* 1985 1986a for details of their sources and homogeneity).

13.2 Climate from 1700 to 1850

13.2.1 Temperature

From Table 13.1, twelve of the longest and most spatially extensive surface air temperature records (indicated by asterisks in Table 13.1) were selected. All the time series come from the Northern Hemisphere. The only station with temperature data available before 1850 in the Southern Hemisphere is Rio de Janeiro. The results from this study therefore relate exclusively to the Northern Hemisphere. Furthermore, the long time series are all located between 40° and 64°N.

Seasonal and annual time series are shown for the 12 sites in Figures 13.1a-e. It is impossible to show here all the variations on the year-to-year timescale. Instead low-frequency variations are shown by season. The 10-year Gaussian filter used illustrates variations on decadal and longer timescales. For each site the seasonal and annual time series are plotted as departures from the 1901-50 reference period average. All but one of the time series was considered homogeneous over its entire station length by Jones *et al.* (1985). Corrections were applied to three series Geneva, Leningrad and New Haven. The only series which was not considered homogeneous was Toronto. Urban warming is evident in this record since the 1880s when compared with other nearby Canadian stations. Recently, however, an additional 70 years of data, extending the data back to 1770, has been found for this site (Crowe and Masterton 1990). It is included here because the record now represents the earliest instrumental time series from interior North America.

The four seasonal and one annual figure show a number of common features. Variability tends to be greatest in winter followed by spring, autumn and summer. Most of the longer time-scale variations evident in the annual data comes from the winter, spring and autumn series. In general, all annual series (Figure 13.1e) show some indication of warming from the beginning to the end of the record, although this is clearest in the case of the records which start during the nineteenth century. The very long European records from Central England,

Table 13.1 Early instrumental temperature records.

	Site	Country	Latitude	Longitude	First Year
Europe	Trondheim	Norway	63.4°N	10.5°E	1761*
	Stockholm	Sweden	59.4°N	18.1°E	1756*
	Central England	UK	~52.5°N	~2.0°W	1659*
	Stykkisholmur	Iceland	65.0°N	22.8°W	1846
	Godthaab	Greenland	64.2°N	51.7°W	1866
	Copenhagen	Denmark	55.7°N	12.6°E	1768
	De Bilt	Netherlands	52.1°N	5.2°E	1706
	Geneva	Switzerland	46.2°N	6.2°E	1753*
	Paris	France	48.8°N	2.5°E	1757
	Berlin	West Germany	52.5°N	13.4°E	1701*
	Munich	West Germany	48.1°N	11.7°E	1781
	Vienna	Austria	48.2°N	16.4°E	1775
	Prague	Czechoslovakia	50.1°N	14.3°E	1771
	Warsaw	Poland	52.2°N	21.0°E	1779
	Budapest	Hungary	47.5°N	19.0°E	1780
	Milan	Italy	45.5°N	9.2°E	1763
	Arkhangel	USSR	64.6°N	40.6°E	1813
	Vilnjus	USSR	54.6°N	25.3°E	1777
	Leningrad	USSR	60.0°N	30.3°E	1743*
	Kiev	USSR	50.5°N	30.5°E	1812
	Astrahan	USSR	46.4°N	48.0°E	1837
	Orenburg	USSR	51.8°N	55.1°E	1832
	Tbilisi	USSR	41.7°N	44.8°E	1844
	Fort Sevcenko	USSR	44.6°N	50.3°E	1848
Asia	Tobolsk	USSR	58.2°N	68.2°E	1832
	Irkutsk	USSR	52.3°N	104.3°E	1820
	Sverdlovsk	USSR	56.8°N	60.6°E	1831*
	Barnaul	USSR	53.3°N	83.8°E	1838*
Africa	Cape Town	South Africa	33.9°S	18.5°E	1857
North America	Sitka	USA	57.1°N	135.3°W	1832*
	Toronto	Canada	43.7°N	79.4°W	1770*
	Charleston	USA	32.8°N	79.9°W	1823
	New York	USA	40.7°N	74.0°W	1822
	New Haven	USA	41.3°N	72.9°W	1781*
	Boston	USA	42.4°N	71.0°W	1743
	Blue Hill	USA	42.1°N	71.2°W	1811
	Minnesota	USA	~45.0°N	~93.0°W	1820*
	Albany	USA	42.7°N	73.8°W	1820
	Rochester	USA	43.1°N	77.7°W	1830
South America	Rio de Janeiro	Brazil	22.9°S	43.2°W	1832
	Santiago	Chile	33.5°S	70.8°W	1861
	Buenos Aires	Argentina	34.6°S	58.4°W	1856
	Bahia Blanca	Argentina	38.7°S	62.3°W	1860
Australasia	Auckland	New Zealand	36.8°S	174.8°E	1853
	Wellington	New Zealand	39.5°S	174.8°E	1862
	Dunedin	New Zealand	45.9°S	170.5°E	1853
	Adelaide	Australia	35.0°S	138.5°E	1857
	Sydney	Australia	34.0°S	151.1°E	1859
	Djakarta	Indonesia	6.2°S	106.8°E	1866

*Time series included in Figure 13.1.

Figure 13.1 Low frequency variations of temperature at 12 selected sites with the longest records. The time series shown result from the application of a 10 year Gaussian filter. (a) Winter [DJF] (b) Spring [MAM] (c) Summer [JJA] (d) Autumn [SON] (e) Annual. Each tick mark on the vertical scale represents 1°C.

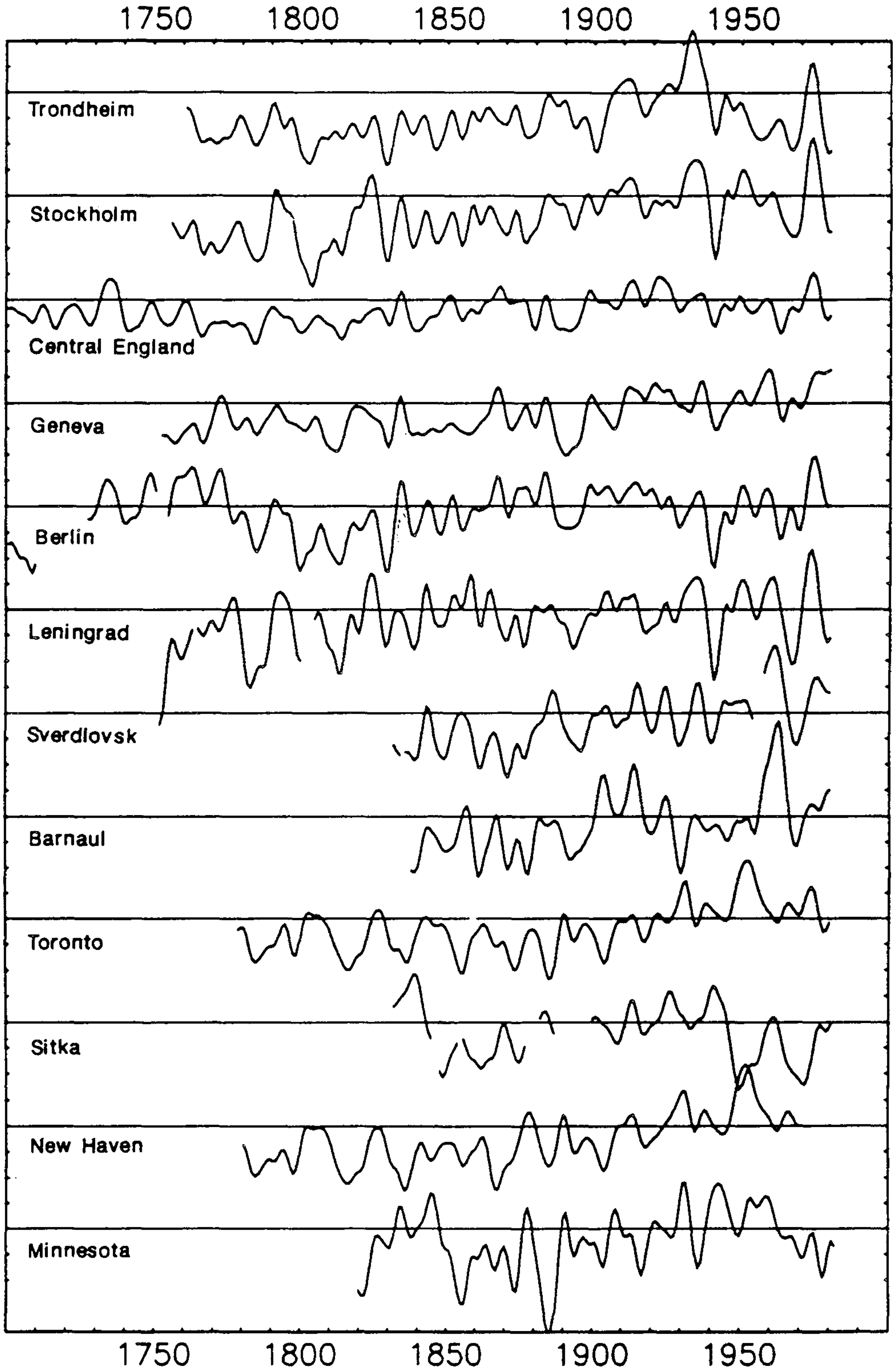
1750
1800
1850
1900
1950
Trondheim
Stockholm
Central England
Geneva
Berlin
Leningrad
Sverdlovsk
Barnaul
Toronto
Sitka
New Haven
Minnesota
1750
1800
1850
1900
1950

Figure 13.1(a)

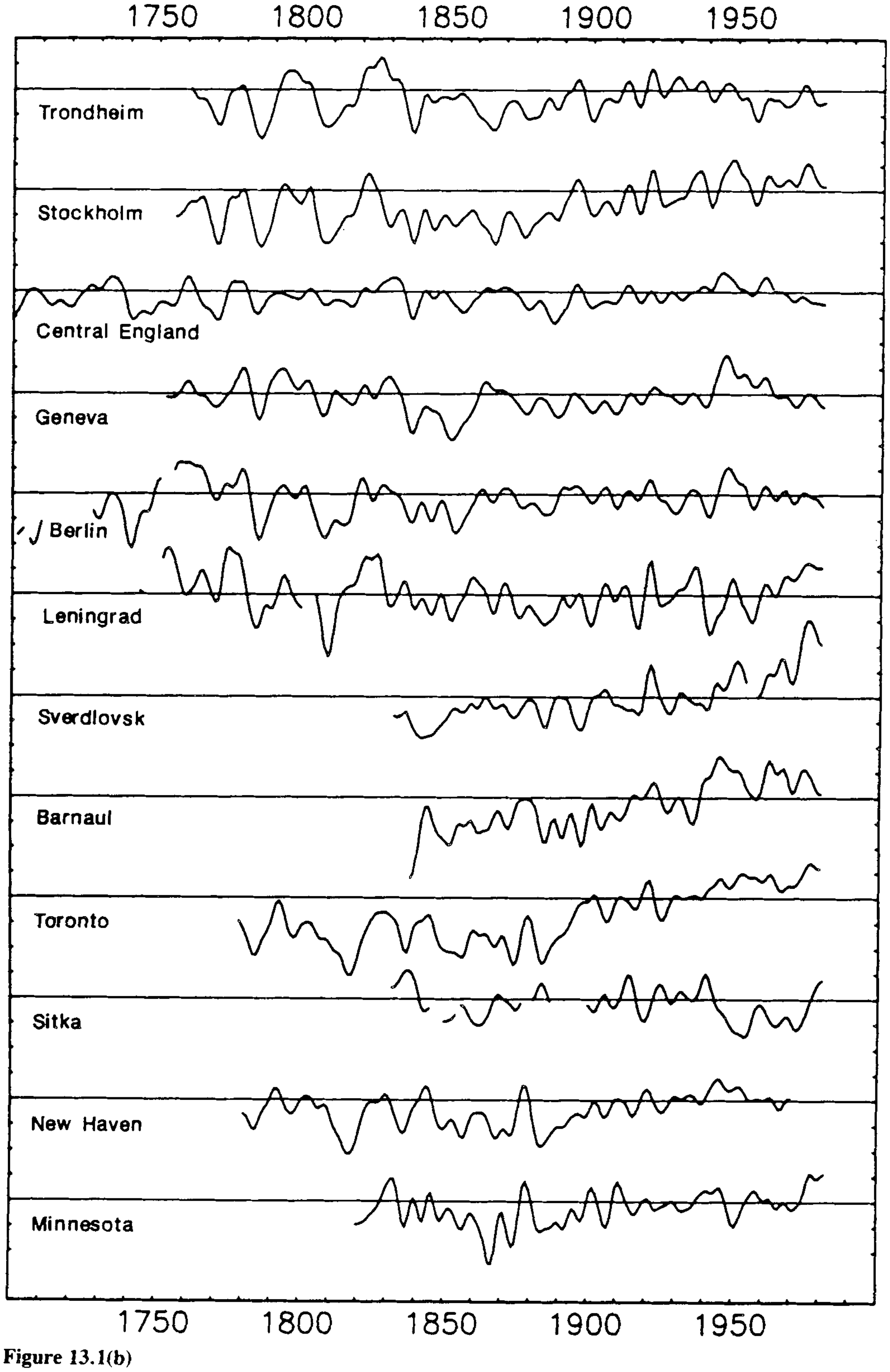
1750
1800
1850
1900
1950
Trondheim
Stockholm
Central England
Geneva
Berlin
Leningrad
Sverdlovsk
Barnaul
Toronto
Sitka
New Haven
Minnesota
1750
1800
1850
1900
1950

Figure 13.1(b)

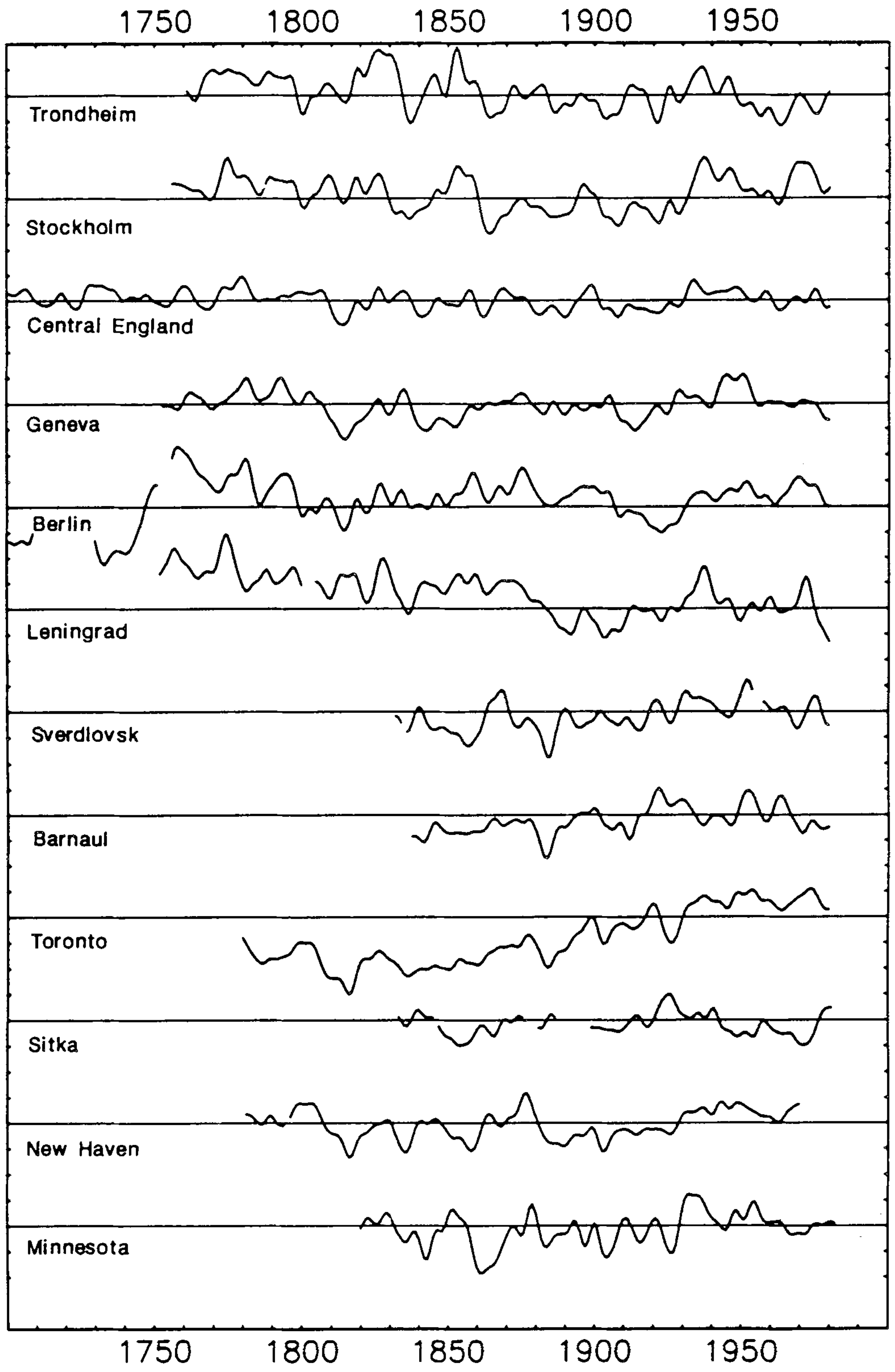
1750
1800
1850
1900
1950
Trondheim
Stockholm
Central England
Geneva
Berlin
Leningrad
Sverdlovsk
Barnaul
Toronto
Sitka
New Haven
Minnesota
1750
1800
1850
1900
1950

Figure 13.1(c)

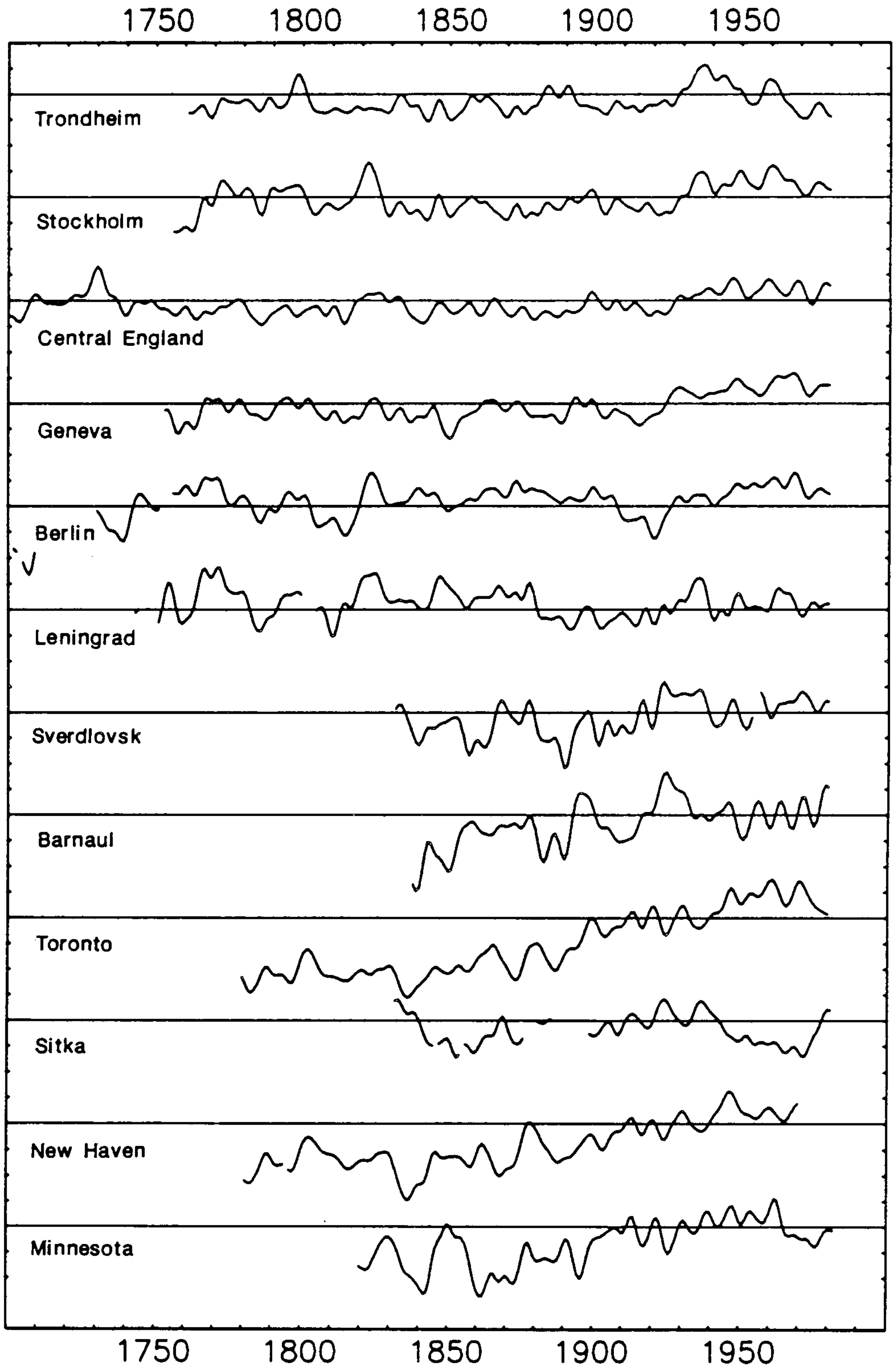
1750
1800
1850
1900
1950
Trondheim
Stockholm
Central England
Geneva
Berlin
Leningrad
Sverdlovsk
Barnaul
Toronto
Sitka
New Haven
Minnesota
1750
1800
1850
1900
1950

Figure 13.1(d)

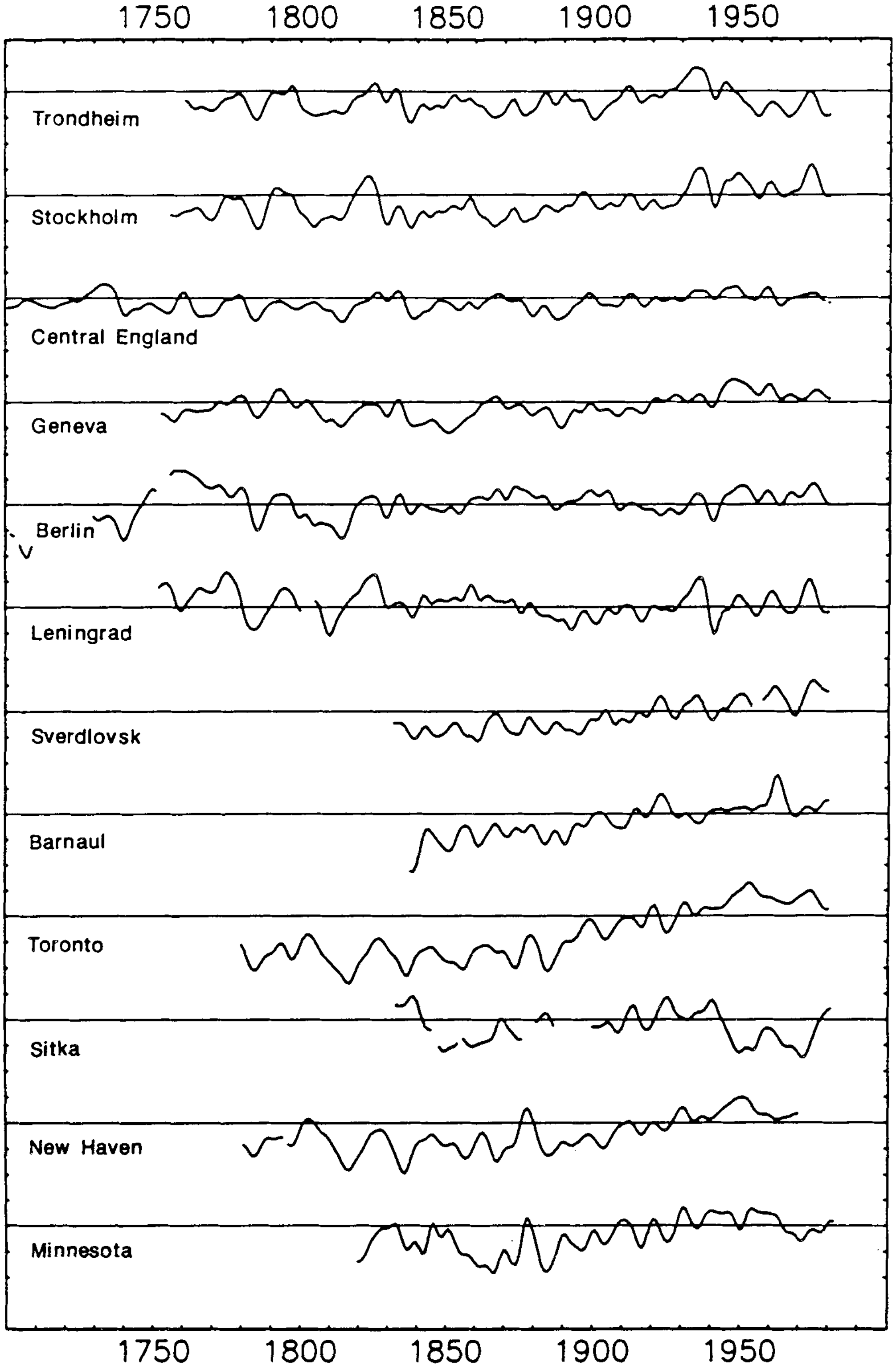
1750
1800
1850
1900
1950
Trondheim
Stockholm
Central England
Geneva
Berlin
Leningrad
Sverdlovsk
Barnaul
Toronto
Sitka
New Haven
Minnesota
1750
1800
1850
1900
1950

Figure 13.1(e)

Berlin and Leningrad hardly show any warming between the early 1700s and 1980. Long term warming is least evident during the summer season. Indeed both Berlin and Leningrad show a tendency towards cooler summers now than during the eighteenth century. The amount of annual temperature change explained by a linear trend is listed in Table 13.2 for various starting dates (e.g. 1700 1750 etc.). All sites show warming over the period 1851 to 1980, however a slight cooling is indicated in the longer central European records which begin in the early eighteenth century.

Comparison of the long European records shows a number of consistently cool and warm decades since 1700. Cool decades are evident during the 1740s, 1780s, 1800s and 1810s and the late 1830s and 1840s. Warm decades are limited to the 1820s only. The two Asian records show cool decades during the 1830s and 1840s as in Europe. The four North American records exhibit cold periods during the 1780s, 1810s and 1830s, again showing some similarities to the European record, though warmth is indicated during the 1800s, 1820s and to some extent during the 1840s.

Although there appears some agreement between warm and cool decades over the major northern land masses, more comprehensive studies of twentieth century temperature variations over the Northern Hemisphere have shown that no one region can be said to be representative of hemispheric-wide conditions (Jones and Kelly 1983). These and other workers have shown that the only way of producing a truly representative series for the Northern Hemisphere is to include station data from as many regions as possible. There is no short-cut method using only a few stations, such as has been tried by Groveman and Landsberg (1979). Clear examples of the differing trends are apparent here. North American stations indicate warmth during the 1800s and 1840s while European stations indicate cool conditions. Similar differences between decadal temperature trends in Europe, North America and Asia are also apparent since 1850. The most noted example concerns the early 1940s which were warm over North America and Asia but exceptionally cool over most of Europe (Jones *et al.* 1986a). This is particularly evident during winter (see Figure 13.1a).

Despite the problem of inferring hemispheric trends from a small number of stations it would appear that the Northern Hemisphere was cool during the 1780s, 1810s and the late

Table 13.2 Annual temperature change accounted for by the linear trend for various starting dates.

	1701-1980	1751-1980	1801-1980	1851-1980
Trondheim	-	0.23	0.31	0.15
Stockholm	-	1.02	1.27	1.40
Central England	-0.19	0.51	0.49	0.49
Geneva	-	0.66	1.05	1.07
Berlin	0.01	-0.04	0.71	0.10
Leningrad	-	-0.40	-0.09	0.08
Sverdlovsk	-	-	-	1.60
Barnaul	-	-	-	1.62
Sitka	-	-	-	0.00
Toronto[1]	-	-	3.01	3.00
New Haven	-	-	-	1.75
Minnesota	-	-	-	1.53

[1] The record for Toronto is clearly affected by an urbanization influence after about 1880.

1830s, with warmth dominating the 1820s. The cold-warm-cold oscillatory pattern between the 1810s and 1830s is particularly striking in the New Haven and Toronto records in North America and in the Stockholm and Leningrad records in Europe.

13.2.2 Precipitation

Most of the sites with long time series of temperature measurements also recorded precipitation amounts. Assessing the homogeneity of long time series is, however, generally more difficult for precipitation than for temperature. Precipitation is much more spatially variable than temperature and a denser network of stations is required to assess the homogeneity of long records. Precipitation records are particularly prone to growth of vegetation and/or building development around the site. Any interference to the wind eddies near the gauge can seriously distort the amount of rain caught (Sevruk 1986). In most cases the catch of rain is reduced from what should have been caught. The homogeneity of long time series is also affected by the methods used to assess the amount of snowfall. The ability of precipitation gauges to catch snowfall has been improved by the introduction of gauge shielding. With the shields, gauges catch more snowfall; thus precipitation totals for the winter part of the year during earlier periods must be adjusted. All gauge records in the Soviet Union must be modified for changes to gauge design during the 1960s (see Schver 1975).

Some of the longest and most continuous precipitation time series are listed in Table 13.3. Apart from Leningrad and the England and Wales, record all the European records were developed by Tabony (1980, 1981) from published sources and manuscript data held by national meteorological agencies. The England and Wales series (developed by Wigley *et al.* 1984 and updated by Wigley and Jones 1987) is a regional average based on between 5 and 35 site records spread over the region. All 35 gauge records were used after the 1820s. Averaging site precipitation data into regional series enables the underlying trends in precipitation to be more clearly seen. Local effects, specific to an individual site will tend to be smoothed out.

Table 13.3 Early instrumental precipitation records.

	Site	Country	Latitude	Longitude	First Year
Europe	Uppsala	Sweden	59.9°N	17.6°E	1774*
	Lund	Sweden	55.7°N	13.2°E	1748*
	England and Wales	UK	~52.5°N	~2.0°W	1766*
	Hoofdoorp	Netherlands	52.3°N	4.7°E	1735*
	Paris	France	48.8°N	2.5°E	1770*
	Marseilles	France	43.3°N	5.4°E	1748*
	Karlsruhe	West Germany	49.0°N	8.4°E	1779*
	Milan	Italy	45.5°N	9.2°E	1764*
	Padua	Italy	45.4°N	12.0°E	1725*
	Leningrad	USSR	60.0°N	30.3°E	1740*
Asia	Seoul	South Korea	37.3°N	127.0°E	1770
North America	Charleston	USA	32.8°N	79.9°W	1738*
	New Haven	USA	41.3°N	72.9°W	1804
	Philadelphia	USA	40.0°N	75.2°W	1830
	Boston	USA	42.4°N	71.0°W	1828
	Albany	USA	42.7°N	73.8°W	1826*
	Toronto	Canada	43.7°N	79.4°W	1841

*Time series included in Figure 13.2.

Figures 13.2a-e show seasonal and annual time series for 12 of the sites listed in Table 13.3 that are considered to be homogeneous. As with temperature it is not possible to show here the year-to-year variations. Low-frequency variations are shown instead. In order to compare time series which have marked differences in mean precipitation and in variability, the time series show standardized departures $(x-\bar{x})/\sigma$. The mean and standard deviation of the seasonal and annual precipitation time series were calculated over the 1901-50 period.

The longest precipitation records originate from Europe. For the period prior to the 1820s there is only an adequate time series to consider western European variations. Here decades from the 1780s to the 1810s were generally dry with the exception of the 1800s at Lund and Padua. Prior to this time, the few data sets that are available suggest that the 1760s and 1770s were wet with the 1730s 1740s and 1750s being dry. After the 1820s it is possible to consider precipitation variations over eastern North America. The available data suggest wetter conditions during the 1830s and from the 1850s to the 1880s at the two longest and most continuous records of Charleston and Albany. Over Europe the 1860s were generally dry with the 1850s also being dry over Northern Europe. Mediterranean stations were wet during the 1840s.

13.3 Changes between 1850 and the present

The last 140 years is the period for which we know most about global climate. The major expansion of instrumental recording took place with the establishment of national meteorological agencies between 1860 and 1900. Before 1850 station coverage was limited to Europe, parts of Asia and North America and some coastal areas of Africa, South America and Australasia. By 1900 there were only a few areas, in the interior of Africa and South America and the whole of Antarctica, without meteorological instrumentation.

The more complete hemispheric and global coverage allows the development of continental and hemispheric averages of temperature. Using the compilations of homogeneous stations records mentioned earlier, Jones *et al.* (1986a,b) have produced a grid point (5° latitude by 10° longitude) data set of surface air temperature anomalies for each month from January 1851. Interpolation of the basic station data is necessary to overcome the uneven spatial density of stations. Temperature data are expressed as anomalies from a common reference period to enable interpolation to be accomplished. Neighbouring stations, at different elevations and using different techniques to calculate monthly mean temperatures, will have different mean temperatures. Averaging the station data in absolute degrees Celsius will be affected by varying station numbers. The use of anomaly values overcomes these problems.

Time series of mean hemispheric temperature anomalies (annual and seasonal) are shown in Figures 13.3 and 13.4. The features exhibited by the two curves have been discussed before

Figure 13.2 Low frequency variations of precipitation at 12 selected sites with longest records. The time series shown result from the application of a 10 year Gaussian filter. The seasonal and annual precipitation series have been transformed to standardized anomalies by subtracting the mean and dividing by the standard deviation. The mean and standard deviation have been calculated over the 1901-1950 period. (a) Winter [DJF] (b) Spring [MAM] (c) Summer [JJA] (d) Autumn [SON] (e) Annual. Each tick mark on the vertical scale represents one standardized anomaly.

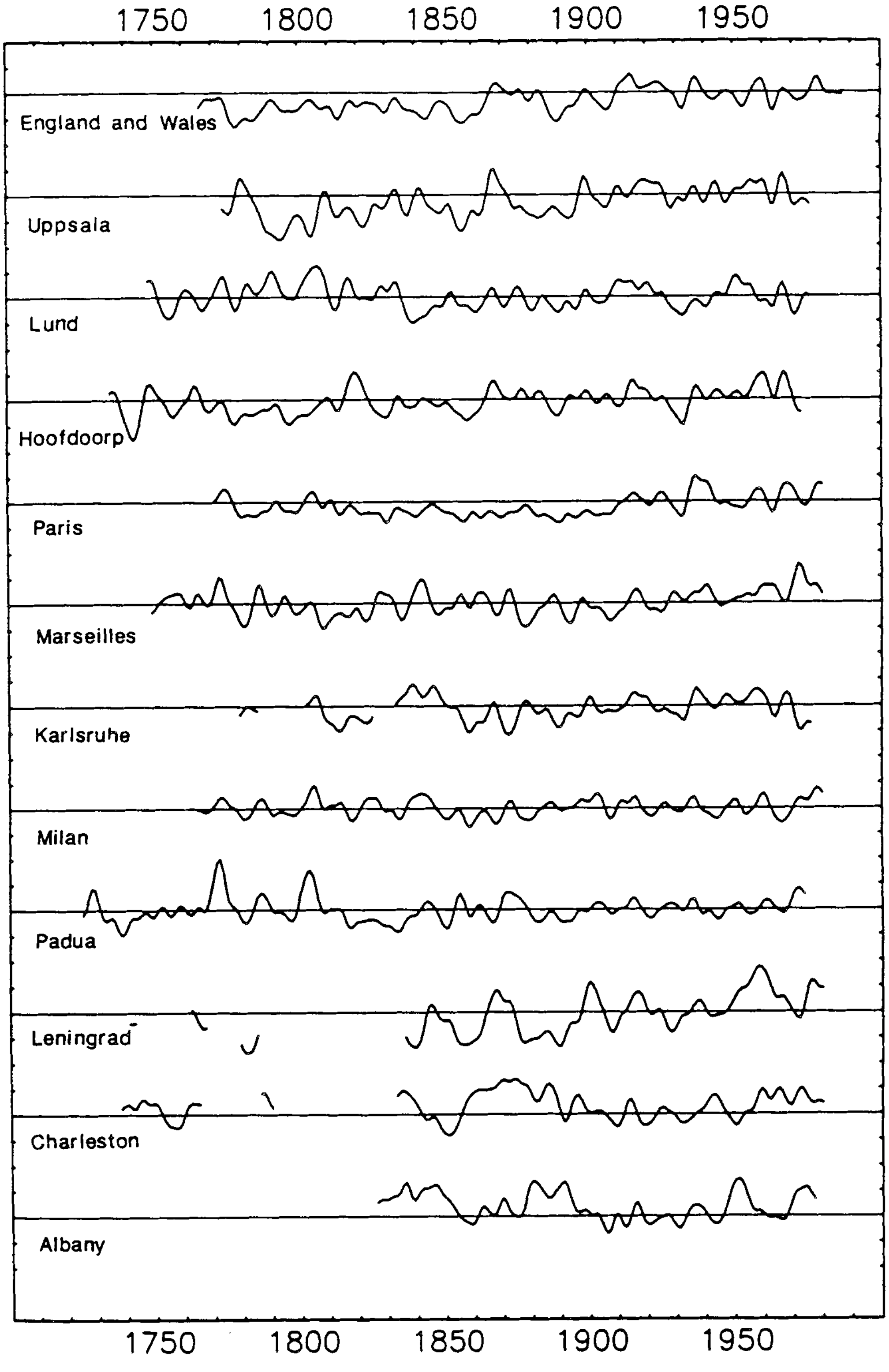
1750
1800
1850
1900
1950
England and Wales
Uppsala
Lund
Hoofdoorp
Paris
Marseilles
Karlsruhe
Milan
Padua
Leningrad
Charleston
Albany
1750
1800
1850
1900
1950

Figure 13.2(a)

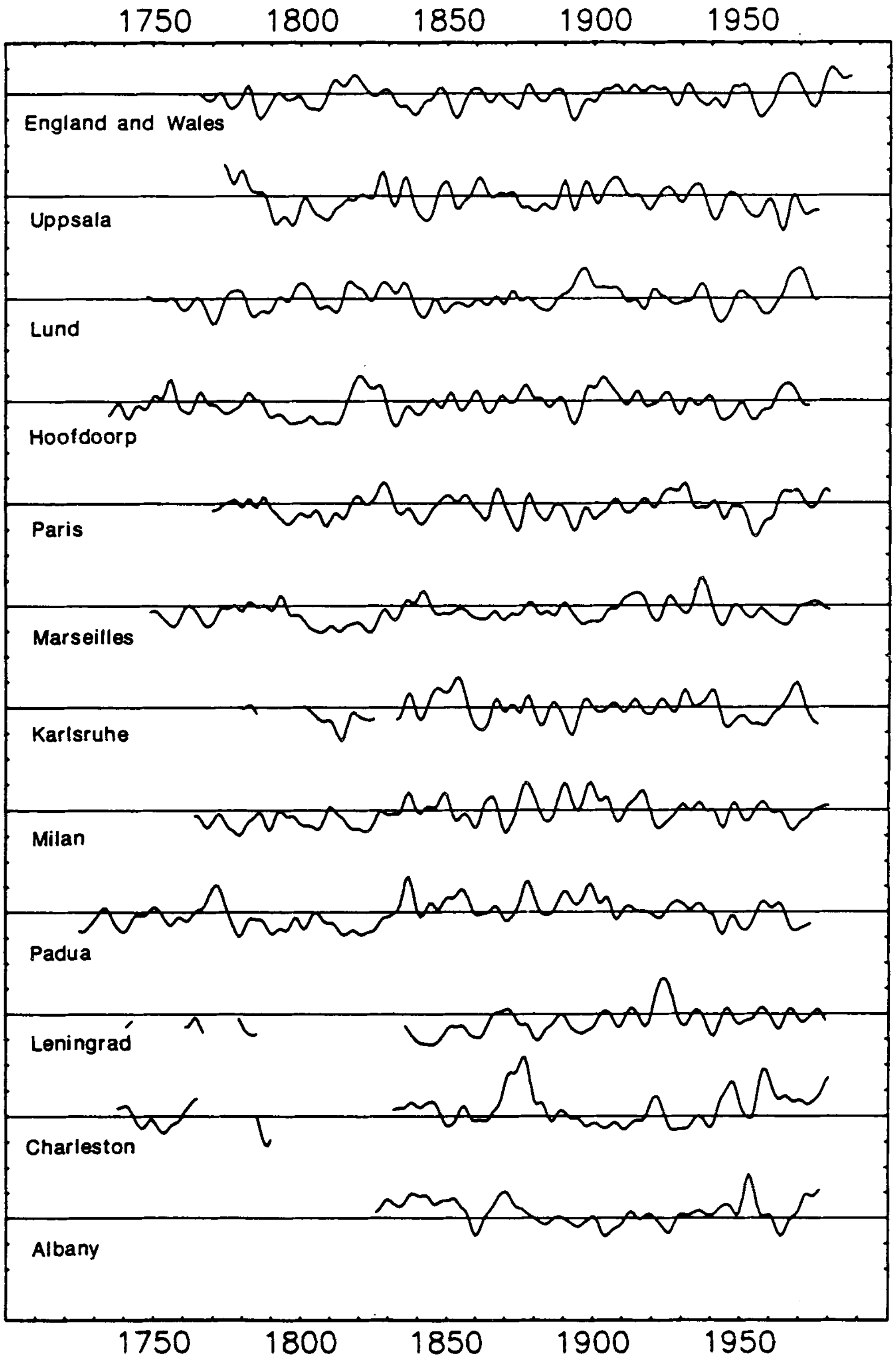
1750
1800
1850
1900
1950
England and Wales
Uppsala
Lund
Hoofdoorp
Paris
Marseilles
Karlsruhe
Milan
Padua
Leningrad
Charleston
Albany
1750
1800
1850
1900
1950

Figure 13.2(b)

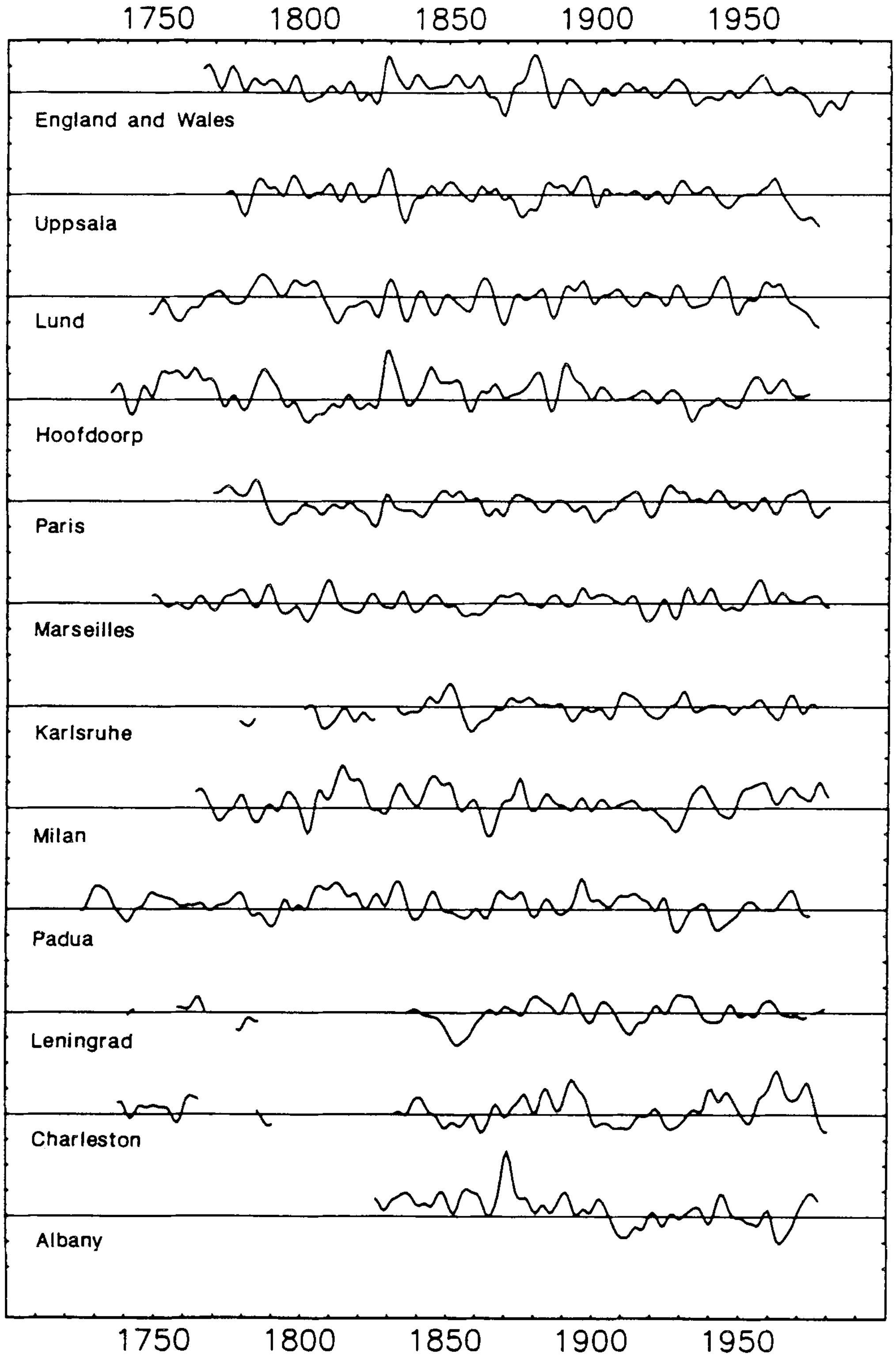
1750
1800
1850
1900
1950
England and Wales
Uppsala
Lund
Hoofdoorp
Paris
Marseilles
Karlsruhe
Milan
Padua
Leningrad
Charleston
Albany
1750
1800
1850
1900
1950

Figure 13.2(c)

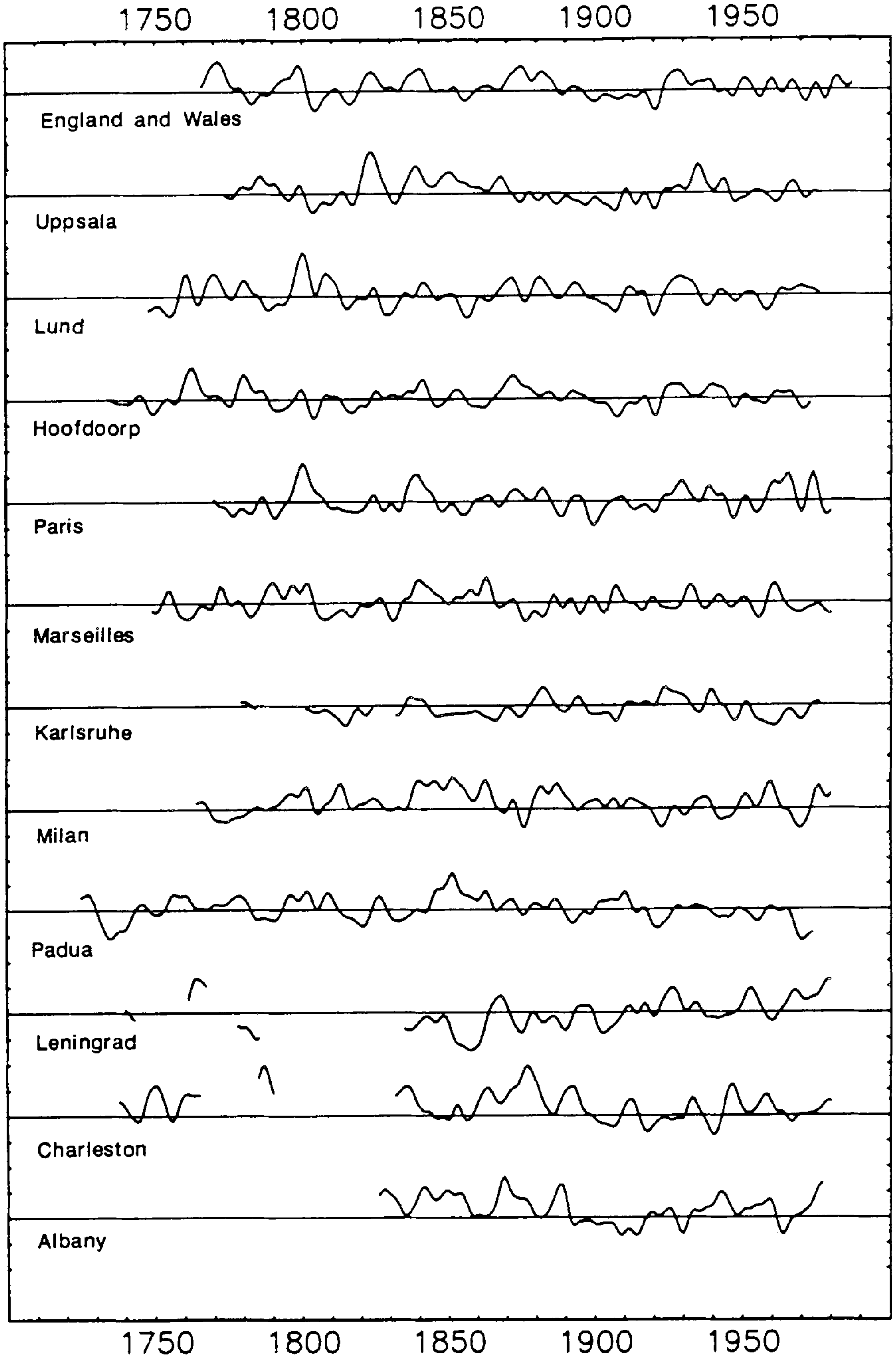
1750
1800
1850
1900
1950
England and Wales
Uppsala
Lund
Hoofdoorp
Paris
Marseilles
Karlsruhe
Milan
Padua
Leningrad
Charleston
Albany
1750
1800
1850
1900
1950

Figure 13.2(d)

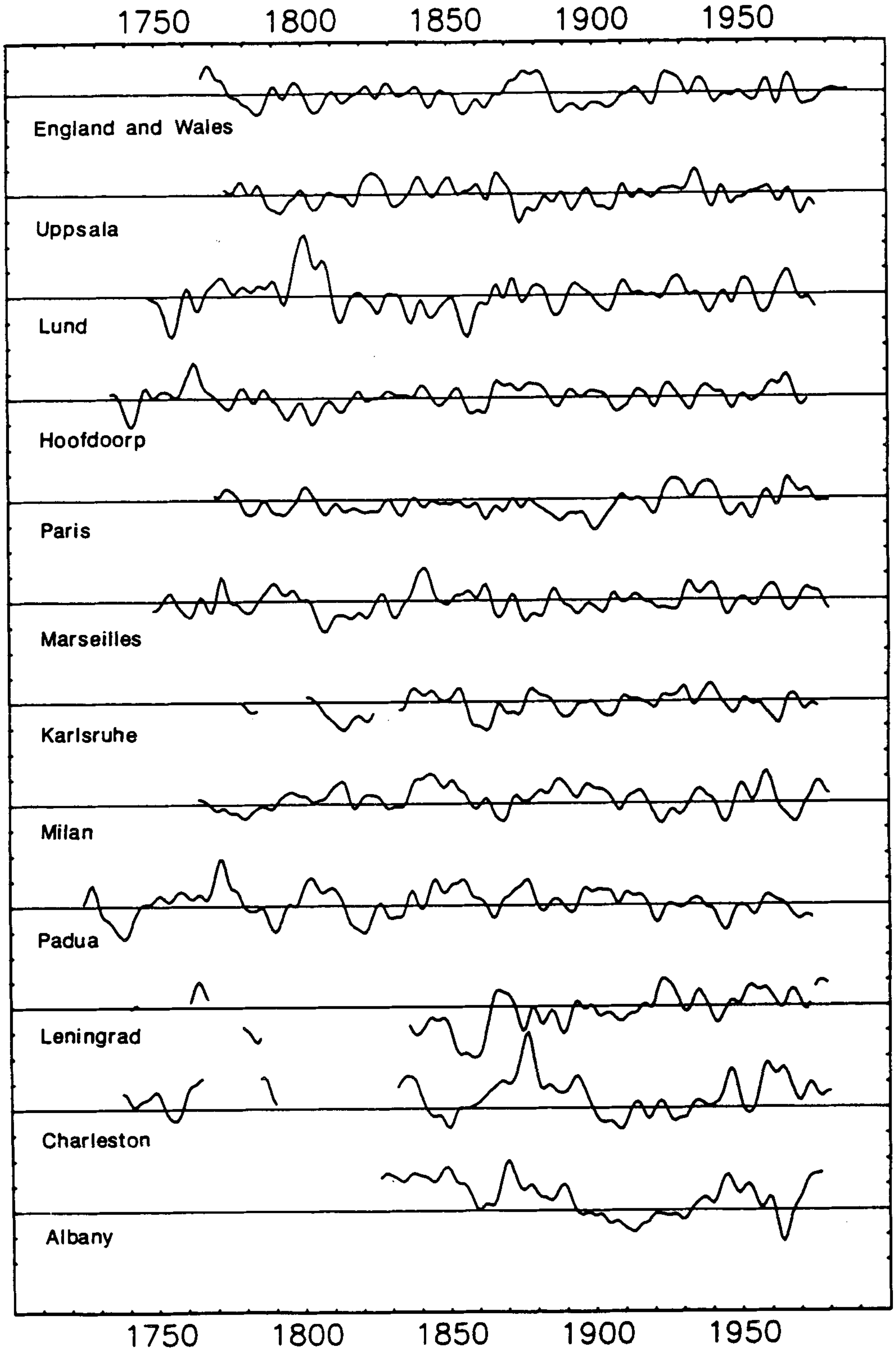
1750
1800
1850
1900
1950
England and Wales
Uppsala
Lund
Hoofdoorp
Paris
Marseilles
Karlsruhe
Milan
Padua
Leningrad
Charleston
Albany
1750
1800
1850
1900
1950

Figure 13.2(e)

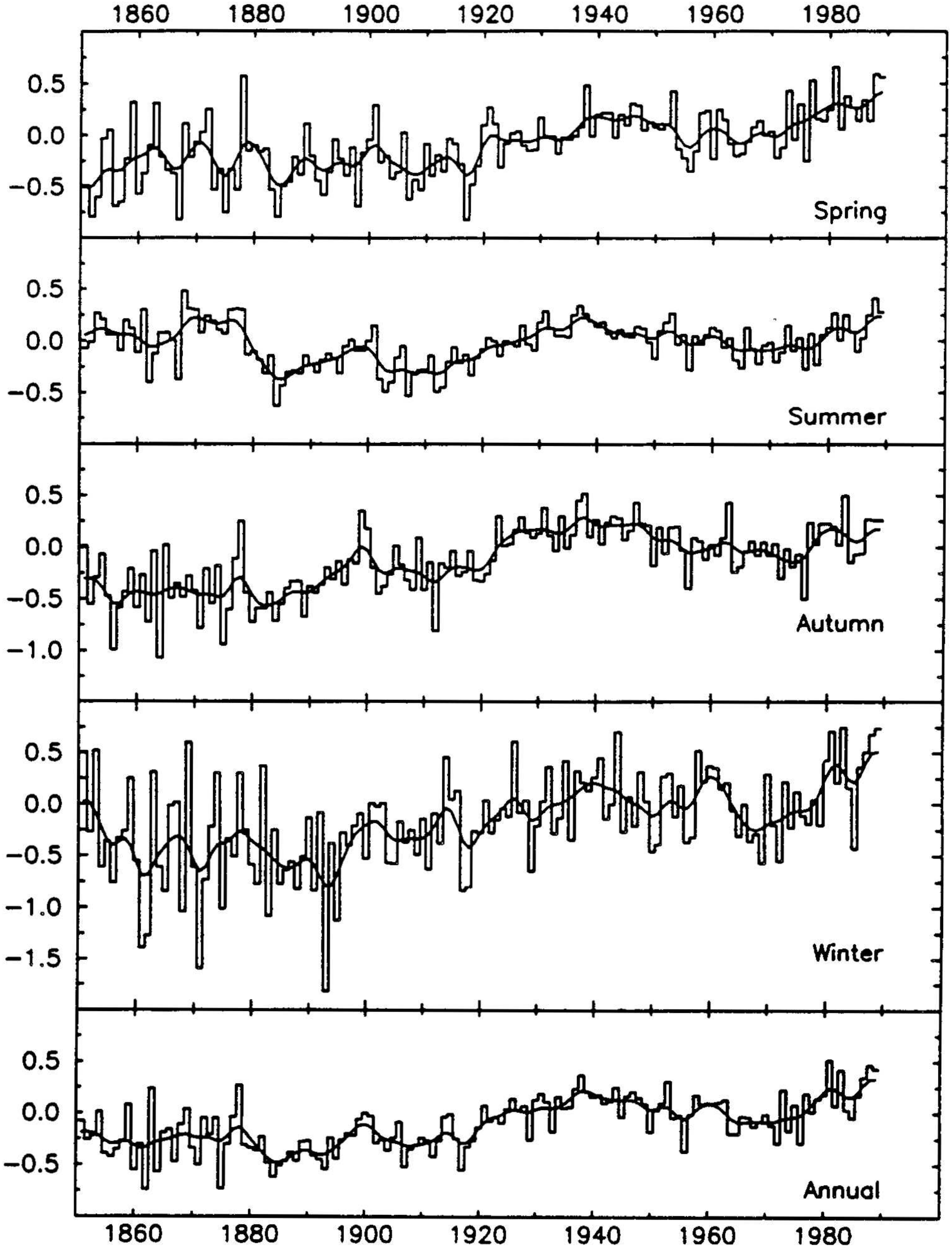

Figure 13.3 Northern hemisphere average temperatures by season and year based on land data. The smooth curve is a 10 year Gaussian filter which highlights variations on decadal and longer timescales. The temperatures are expressed as anomalies from the 1951–70 period.

(see, for example, Wigley *et al.* 1985, 1986). Both hemispheres show a warming of the order of 0.5°C since the mid-nineteenth century. The warming is more monotonic in the Southern Hemisphere with the greatest warming in the Northern Hemisphere occurring between 1920

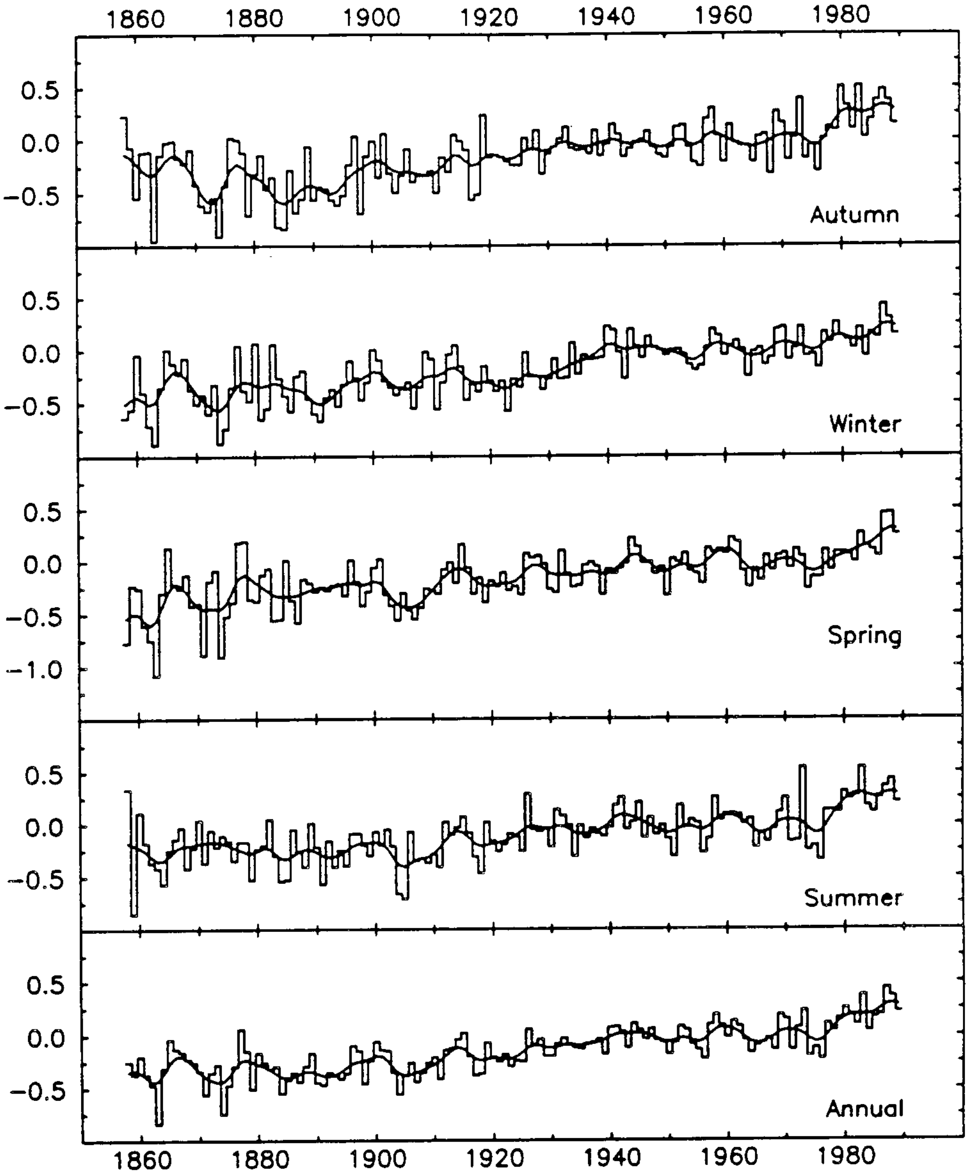

Figure 13.4 Southern hemisphere (0-60°S) average temperatures by season and year based on land data. The smooth curve is a 10 year Gaussian filter which highlights variations on decadal and longer timescales. The temperatures are expressed as anomalies from the 1951–70 period.

and 1940. Warming is evident in all seasons except summer where little if any warming has occurred since the 1850s. The 1980s are clearly the warmest decade in the Southern Hemisphere while in the Northern Hemisphere recent warming means that the 1980s are only slightly warmer than the 1940s. Comparison of the Northern Hemisphere time series with the 12 individual series in Figure 13.1a-e illustrates clearly that no region is representative of hemispheric conditions all of the time. Table 13.4 shows annual correlations between the 12

Table 13.4 Correlations between the 12 selected station annual temperature time series and the Northern Hemisphere annual time series. The correlations are given for three periods 1851-1915, 1916-1980 and 1851-1980. For the longer period the correlations are also calculated between low-frequency variations (resulting from a 10-year Gaussian filtered time series).

Stations	1851-1915	1916-1980	1851-1980	1851-1980
	Raw	Raw	Raw	Low
Trondheim	0.17	0.20	0.24	0.29
Stockholm	0.48	0.27	0.51	0.64
Central England	0.34	0.31	0.41	0.69
Geneva	0.12	0.32	0.43	0.71
Berlin	0.49	0.24	0.28	0.02
Leningrad	0.61	0.23	0.39	0.28
Sverdlovsk	0.59	0.24	0.57	0.73
Barnaul	0.31	0.25	0.46	0.69
Sitka	0.10	0.41	0.18	0.09
Toronto	0.38	0.35	0.62	0.76
New Haven	0.31	0.36	0.56	0.76
Minnesota	0.44	0.52	0.57	0.73

sites and the Northern Hemisphere average for the periods 1851-1915, 1916-1980 and 1851-1980. Correlations are given for both the raw series and the 10-year Gaussian-filtered time series. The correlations tend to be higher for the overall period and are markedly higher for lower frequencies. Stations with the highest correlations are generally in the continental interiors of Eurasia and North America.

The land areas represent only 29% of the Earth's surface. Until recently it was assumed that changes in air temperature over the ocean were similar to those over the land. Recent compilations of marine data taken by 'ships of opportunity' now enable this assumption to be tested. Since the 1850s ships have been obliged to take weather observations and measure the temperature of the sea surface every 6 hours. The force behind this collection was an American naval captain, Matthew Fontaine Maury, who persuaded the other major maritime nations to instruct their military and merchant navies to take measurements and record these in log books. Through his pioneering efforts in the 1830s and 1840s he helped to standardize the practice by which ships at sea collected meteorological observations, including measurements of sea surface temperature (SST) which were rare until that time. An international agreement to take, collect and exchange marine meteorological observations was signed in Brussels in 1853.

In the last twenty years, major international efforts have been made to put all of this log-book information into computer data banks. One such compilation is the Comprehensive Ocean-Atmosphere Data Set (COADS) produced by NOAA workers at Boulder, USA (Woodruff *et al.* 1987). COADS contains all the log book material that has been found so far, about 80 million non-duplicated sea surface temperature measurements between 1854 and 1988.

The marine data are, unfortunately, affected by inhomogeneities just like the land data. Sea surface temperature data were generally taken before World War II by collecting some sea water in an uninsulated canvas bucket and measuring the temperature. There was generally a few minutes delay between sampling and reading. During this time the water in the bucket generally cooled. Since World War II most readings are made in the intake pipes which take sea water on to ships to cool the engines. This change in measurement technique was quite abrupt, although there are still significant numbers of bucket measurements made today (buckets now made of plastic and thus better insulated) and some intake measurements were made prior to World War II.

Studies of the differences between the two methods indicate bucket temperatures are cooler than intake ones (James and Fox 1972). Correcting the SST data for this measurement change may, at first, seem like an intractable problem. Folland and Parker (1990) of the U.K. Meteorological Office, however, have developed a method of correcting the canvas bucket measurements based on physical principals related to the causes of the cooling. The cooling depends on the prevailing meteorological conditions, and so depends on the time of year and on location. Although the cooling is therefore a day-to-day phenomenon, the various influences are basically linear, so cooling amounts can be calculated on a monthly basis. The main free parameter is the time between reading and sampling. This is generally unknown and must be estimated from the data. The primary assumption in this estimation is that there have been no major changes in the seasonal cycle of SSTs over the period of record. Since the amount of evaporative cooling has a strong seasonal cycle in many parts of the world, an optimum exposure time can be chosen; namely that which minimises the residual seasonal cycle in the corrected data. As a check on the validity of the method, the implied optimum exposure time turns out to be quite consistent spatially.

The major problem with the technique is that it is not known with any certainty what type of buckets were used to take measurements during the nineteenth century. Assuming measurements were taken using canvas buckets rather than wooden buckets (which are

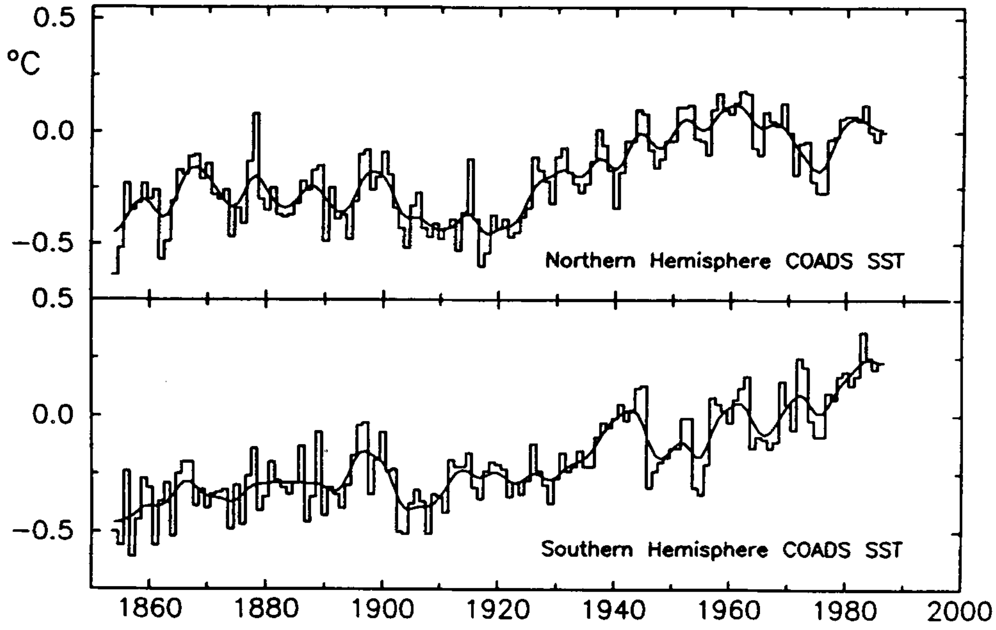

Figure 13.5 Hemispheric time series of COADS SST data corrected according to the bucket model described in the text. The temperatures are expressed as anomalies from the 1950–79 period.

better insulated) leads to corrections which result in SSTs warmer than land temperatures by about 0.2°C. The discrepancy almost disappears if wooden buckets are assumed. Although there is documentary evidence to support wooden bucket use during the mid-nineteenth century, considerable doubt remains about the transition from wooden to canvas buckets. The seasonal-cycle elimination method is not precise enough to choose between the two possibilities.

Time series of corrected COADS SST data for the two hemispheres are shown in Figure 13.5. These corrections have been derived using the wooden bucket assumption in the nineteenth century (see Jones *et al.* 1990, for details). Overall the various hemispheric land and marine time series show many consistencies. Even on the inter-annual time scale, hemispheric averages over land and ocean are strongly correlated, and virtually all longer time scale fluctuations in the marine data are reflected in the land data. Even today, however, there are still gaps in data coverage, especially over the southern oceans. Satellite data may help to resolve this problem, but only from the late 1970s.

Acknowledgements

This work was supported by the United States Department of Energy, Carbon Dioxide Research Division under Grant No. DE-FG02-89ER69017.

References

Ball, T. F. and Kingsley, R. G. 1984: (Instrumental temperature records at two sites in central Canada. *Climatic Change*, 6, 39-56.

Bradley, R. S. and Jones, P. D. 1985: Data bases for detecting CO_2-induced climatic change. In: M. C. MacCracken and F. M. Luther (Eds.) *Detecting the Climatic Effects of Increasing Carbon Dioxide*, U.S. Dept. of Energy, Carbon Dioxide Research Division, Washington D.C. 29-53.

Bradley, R. S., Kelly, P. M., Jones, P. D., Diaz, H. F. and Goodess, C. 1985: A climatic data bank for the Northern Hemisphere land areas 1851-1980. *Technical Report No. TR017*, U.S. Dept. of Energy, Carbon Dioxide Research Division, Washington D.C., 335pp.

Conrad, V. and Pollak, L. D. 1962: *Methods in Climatology*, Harvard University Press, Cambridge, Massachusetts, 459pp.

Crowe, R. B. and Masterton, J. M. 1990: Extension of Toronto temperature time-series from 1840 back to 1778 using United States and other data. In: C. R. Harrington (Ed.) *1816, the year without a summer*, National Museums of Canada (in press).

Dove , H. W. 1838+: Uber die geographische Verbreitung gleichartiger Witterungserscheiungen (Uber die nichtperiodischen Anderungen der Temperaturverteilung auf der Oberflache der Erde): *Abh Akad. Wiss. Berlin* I Teil (1838) 37, 285; 38, 286; 39, 345. II Tiel (1839) 40, 306-307. III Tiel (1844) 41 127. V Tiel (1852) 42, 3-4.

Folland, C. K. and Parker, D.E. 1990: Observed variations of sea surface temeprature. In: M. E. Schlesinger (Ed.) *Climate-Ocean Interaction*. NATO Workshop, Kluwer Academic Publishers (in press).

Groveman B. and Landsberg, H.E. 1979: Simulated Northern Hemisphere temperature departures 1579-1880. *Geophysical Research Letters*, 6, 767-9.

James, R. W. and Fox, P. T. 1972: Comparative sea-surface temperature measurements. Report No. 5. *Marine Science Affairs No. 366.* World Meteorological Organization, Geneva, Switzerland.

Jones, P. D. and Kelly, P. M. 1983: The spatial and temporal characteristics of Northern Hemisphere surface air temperature variations. *Journal of Climatology*, 3, 243-252.

Jones, P. D., Raper, S. C. B., Santer, B. D., Cherry, B. S. G., Goodess C.., Bradley, R. S., Diaz, H. F., Kelly, P. M. and Wigley, T. M. L. 1985: A grid point surface air temperature data set for the Northern Hemisphere 1851-1984. *Technical Report TR022.* U.S. Dept. of Energy, Carbon Dioxide Research Division, Washington D.C., 251pp.

Jones, P. D., Raper, S. C. B., Bradley, R. S., Diaz, H. F., Kelly, P. M. and Wigley, T. M. L. 1986a: Northern Hemisphere surface air temperature variations: 1851-1984. *J. Climate and Applied Meteorology*, 25 161-179.

Jones, P. D., Raper, S. C. B. and Wigley, T. M. L. 1986b: Southern Hemisphere surface air temperature variations: 1851-1984. *J. Climate and Applied Meteorology*, 25 1213-1230.

Jones, P. D., Wigley, T. M. L. and Farmer, G. 1990: Marine and land temperature data sets: A comparison and a look at recent trends. In: M. E. Schlesinger (Ed.) *Greenhouse-gas-induced climatic change*, Kluwer Academic Publishers (in press).

Köppen, W. 1873: Uber Mehrjahriger Perioden der Witterung, Insbesondere Uber die 11 Jahrige Periode der Temperature. *Zeitschrift der Osterreichischen Gesellschaft für Meteorologie*, 8, 241-248, 257-267.

Lamb, H. H. and Johnson, A. I. 1966: Secular variations of the atmospheric circulation since 1750. *Geophysical Memoirs* 110, H.M.S.O., London.

Manley, G. 1974: Central England temperatures: Monthly means 1659-1972. *Quarterly J. Royal Meteorological Society* 100, 389-405.

Middleton, W. E. K. 1966: *Invention of Meteorological Instruments.* Johns Hopkins Press, Baltimore, Maryland.

Middleton, W. E. K. 1969: *A history of the thermometer and its use in meteorology.* Johns Hopkins Press, Baltimore, Maryland.

Schaake, P. 1982: Ein Beitrag zum Preubenjahr 1981 en Berlin: *Beilage zur Berliner Wetterkarte des Instituts für Meteorologie der Frein Universitat Berlin*, 32/82, S04/82.

Schver, T. A. 1975: Annual amount of precipitation data in the USSR, according to corrected data. *Soviet Hydrology, Selected Papers*, 3 155-157.

Sevruk, B. (editor) 1986: Correction of precipitation measurements. *Proceedings of international workshop on the correction of preciptation measurements.* ETH/WMO/IAMS Zurich 289pp.

Tabony, R. C. 1980: A set of homogeneous European rainfall series. U.K. Meteorological Office 13 Branch Memorandum 104, Bracknell, U.K.

Tabony, R. C. 1981: A principal component and spectral analysis of European rainfall. *Journal of Climatology 1*, 283-291.

Wigley, T. M. L., Lough, J. M. and Jones, P. D. 1984: Spatial patterns of precipitation in England and Wales and a revised, homogeneous England and Wales precipitation series. *Journal of Climatology*, 4 1-25.

Wigley, T. M. L., Angell, J. K. and Jones, P. D. 1985: Analysis of the temperature record. In: M. C. MacCracken and F. M. Luther (Eds.) *Detecting the Climatic Effects of Increasing Carbon Dioxide.* U.S. Dept. of Energy, Carbon Dioxide Research Division, Washington D.C., 55-90.

Wigley, T. M. L., Jones, P. D. and Kelly, P. M. 1986: Empirical climate studies: warm world scenarios and the detection of climatic changes induced by radiatively active gases. In: B. Bolin, B. R. Doös, J. Jäger and R.A. Warrick (Eds.) *The Greenhouse Effect, Climatic Change and Ecosystems.* Wiley, 271-322.

Wigley, T. M. L. and Jones, P. D. 1987: England and Wales precipitation: a discussion of recent changes in variability and an update to 1985. *Journal of Climatology*, 7, 231-246.
Woodruff, S. D., Slutz, R. J., Jenne, R. J. and Steurer, P. M. 1987: A comprehensive ocean-atmosphere data set. *Bulletin American Meteorological Society*, 68 1239-1250.