Long-Range Forecasting and Climate Research

The Climate of the World

9. Climatic Change in the Instrumental Period

by

D. E. Parker and C. K. Folland

LRFC 27

July 1988

LS/MO13

LONG RANGE FORECASTING AND CLIMATE RESEARCH MEMORANDUM NO 27
(LRFC 27)

THE CLIMATE OF THE WORLD

9. CLIMATIC CHANGE IN THE INSTRUMENTAL PERIOD

by

D E PARKER AND C K FOLLAND

NOTES FOR AN ADVANCED LECTURE FOR THE SCIENTIFIC OFFICERS' COURSE, METEOROLOGICAL OFFICE, 1988

Met O 13 (Synoptic Climatology Branch)
Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ

July 1988

This Memorandum is the sixth in a series of seven on:

THE CLIMATE OF THE WORLD

by

C K Folland and D E Parker

Based on ten Advanced Lectures for the Scientific Officers' Course, 1988, and one Advanced Lecture delivered by D J Carson in March 1982.

INDEX TO SERIES

ADVANCED LECTURE NO 9

CLIMATIC CHANGE IN THE INSTRUMENTAL PERIOD

D E PARKER AND C K FOLLAND

MET O 13

SUMMARY

The reality and nature of fluctuations in climate in the last 300 years are discussed in the light of the quality and quantity of instrumental data. Emphasis is placed on comparisons between the "Little Ice Age" and the modern era and on evidence for climatic variation over the most recent century. The regional as well as global nature of many observed climatic variations is stressed. Agreements and apparent contradictions between the various instrumental indications of climatic variations are discussed.

9.1 INTRODUCTION

This lecture covers climatic fluctuations on time scales from a decade to a few centuries and bridges the gap between studies of interannual variability and palaeoclimatology. The approach to climatic fluctuations in the instrumental period has traditionally differed from the approach to interannual variability, with necessary emphasis on a few long well-documented local or global time-series of data, mainly those of air and sea surface temperature and mean-sea-level pressure. There has been less stress on the physical links between climatic changes in different parts of the globe. We are, however, now able to begin to depart from this approach by considering the regional, as opposed to global, nature of some of the observed climatic fluctuations. We are also better able to assess the reliability of some of the long-term data series, by investigating relationships with different types of data, as well as by traditional checks on self-consistency and cross-checks with series of the same type of data for nearby locations. As a result of these advances, we are increasingly confident that the measured climatic changes have been real.

We begin with presentations of climatic fluctuations observed in local, regional and hemispheric series of land air temperatures. The results are discussed in terms of instrumental inhomogeneities, urbanisation and other likely sources of bias. A corresponding treatment of marine temperatures is followed by comparisons between observed land and marine temperature trends. For the first time, long hemispheric as well as local series of rainfall are becoming available and these are discussed in Section 9.5 in relation to instrumental and procedural changes. Next, long-term fluctuations of the atmospheric circulation are described and related to local and regional changes of temperature and rainfall, including the recent dessication in the Sahel. In the more recent decades, upper-air data have been available: trends in temperature aloft are presented in Section 9.7 and compared with trends at the surface. A brief review of data on sea-level is given in Section 9.8. Finally, some possible causes of interdecadal and century-scale climatic changes are discussed. These causes include the effects of increasing greenhouse gases in the atmosphere, which are more fully covered in Lecture 10.

9.2 CHANGES IN SURFACE AIR TEMPERATURE OVER LAND

The beginning of the instrumental period around the early eighteenth century coincides with the latter part of the "Little Ice Age", and part of the problem that must be tackled is whether temperature, and atmospheric circulation, have really varied appreciably since that time. According to Fig 8.31, Lecture 8, $\delta^{18}O$ measurements from tree rings in W Europe suggest a rise of winter/early spring temperature exceeding 0.5°C between the late seventeenth century and 1940. Of equal interest is a marked increase in temperature in 1720-1740 followed by a rapid reversal. Fig 8.31 used temperatures for January to March in Central England for the period after 1700 to support these findings. Central England Temperature (CET) is the longest available instrumental temperature series and we shall therefore first look at CET in detail.

9.2.1 Central England Temperature and the problems of homogenising ancient thermometer readings

A fundamental problem in constructing a local time-series is to ensure that the data are as temporally homogeneous as possible: in other words, that a given meteorological reality has always resulted in the same value in the series. Only to the extent that this is true can the series be used to make reliable deductions about local climatic fluctuations. A reliable time series of temperature in a restricted locality may also reflect fluctuations of climate on a larger scale, because local temperature is sensitive to larger-scale changes in atmospheric circulation.

Manley (1974) constructed a monthly temperature series for Central England and a smoothed updated series (see Jones (1987)) is shown in Figure 9.1. Manley chose to represent an area, rather than to reduce his series to a single point, because of the scattered locations of most of the early observations, and because the only concentrated observations were in London and thus were eventually affected by heating resulting from urban expansion. He adjusted the monthly data to compensate for the following variables:

a) Different times of observation: the traditional mean temperature computed as $^1/_2$ (max + min) differs from eg the mean of 8 am and noon, by amounts which vary with season but can be estimated from modern data. The problem of different observation times can be quite acute when studying very long time-scale temperature changes.

b) The change of calendar in September 1752 when 11 days were omitted in that month. Daily data facilitated this adjustment.

c) Housing of thermometers: in the 18th Century this was often an unheated north-facing room attached to a house; in later years, use was often made of either north-wall observations, or of Glaisher screens, which preceded Stevenson screens. The problem of changing thermometer screens is a potentially serious problem which requires further investigation.

d) Types of thermometer: pressure corrections were needed for early thermometers which consisted of a U-tube with one open end. Also different scales had to be converted to modern units. Unreliable instruments were excluded from Manley's compilation.

e) Geographical region and site: Manley found from modern data that so long as frost-hollows and other unrepresentative sites are excluded, the monthly deviations from a long-term average, or the successive differences between months of the same name, are almost uniform for English inland stations. Thus he could work with temperature differences rather than absolute temperature values, and produce a single series from overlapping records at sites scattered through much of England. This technique also aided cross calibration of early temperature scales and detection and elimination of the effects of changing observing time and instrumentation.

Manley checked his compilation against a series for Utrecht (Holland) and found good agreement. Also, in periods of sparse data he noted observations of wind direction and snowfall.

9.2.2 <u>Local and regional climatic fluctuations as revealed by Central England Temperature</u>

It can be seen from Figure 9.1 that, except in summer, it has been warmer in Central England in much of the 20th Century than in the previous 250 years: the peak warmth was generally in the mid-20th Century but the mildest winters were in the early 20th Century. The late 17th Century was particularly cold, corresponding to the peak of the supposed "Little Ice Age". There was notable warmth in the 1720's and 1730's however. These features are also found in instrumental temperatures series for Utrecht and for other locations in Northwest Europe. Other major features are the warming in October between 1890 and 1975 and the sharp cooling in April in the past 25 years.

Figure 9.2(A) shows a power spectrum analysis of the unsmoothed annual mean CET data from 1659-1975. The most significant peak is labelled 76 years and mainly reflects the temperature fluctuations between about 1890-1975 and 1700-1770 (final diagram of Figure 9.1). Fig 9.2(B) shows a power spectrum reported by Lamb (1972a), due to Siren, of tree-ring widths in N. Finland which probably mainly reflect summer temperature. The shapes of Figures 9.2(A) and 9.2(B) are surprisingly similar with more power in Figure 9.2(B) at the 70-200 year time scale presumably because of the longer (497 year) data series. The 23 year peak, like the 76 year peak, is statistically significant (using an "F" test) and has sometimes been linked with the "double sunspot" cycle of magnetic activity on the sun. The double sunspot cycle is constructed from the sunspot series shown in Figure 3.6 (Lecture 3) by reversing the sign of the values in the sunspot series between alternate sunspot cycles, which have opposite magnetic polarity. Figure 8.2C (Folland (1983)) shows, however, that a band-pass filtered time series of annual CET whose filter function is centred on the 23 year time scale bears no consistent long-term phase relationship with the double sunspot cycle. Indeed the 23 year peak disappeared after 1880 whereas the double sunspot cycle increased slightly in amplitude. The inconstancy of the spectra of long temperature series (see also Figure 1.7 in Lecture 1) is not unexpected in view of the multiple causative factors. One physical forcing directly affecting air temperatures over islands is the sea surface temperature (SST), and the influence of North Atlantic SST on CET is considered in Section 9.4. Fluctuations of the atmospheric circulation are also a major influence on surface air temperature and are discussed in Section 9.6.

Figure 9.3 shows an attempt (Lamb (1972a)) to estimate Central England temperatures back to the beginning of the Medieval "climatic optimum" including assessments of their uncertainties. Prior to 1680, the temperatures have been derived from a mixture of botanical and documentary evidence. A clear minimum in mean annual and winter CET is suggested around 1600-1700 with winter temperatures in the period 1900-1950 similar to those during the "Medieval optimum".

The effects of urban heating were avoided as far as possible by Manley in his construction of the instrumentally-based CET series. However, other long temperature records have not always been as carefully quality-controlled, and we therefore devote the next section to a discussion of the effects of urbanisation.

9.2.3 Effects of urban heating on temperature records

The effects of urban heating on long time series of temperature are illustrated for Paris in Figure 9.4A (after Dettwiller (1978)). Central Paris has warmed by over 1°C since 1900 relative to the surrounding countryside; much of the warming has been in the minimum temperatures as is typical (Oke (1982)) of urban heating. Studies like that of Dettwiller can, however, only be used to correct urban data if long series of homogeneous rural data exist. The problem of the effects of urbanisation is serious as many of the longest temperature series have been kept in what are now large cities; and even in major parks as may, for example, surround old observatories, the urban heating effect, though reduced, is not eliminated (Oke (1982)). Figure 9.4B compares a 200-year series of annual mean temperature for Vienna with that for an observatory on a low mountain in S Germany (Hohenpeissenberg) 600 km to the west (Angell and Gruza (1984)). A relative warming of Vienna appears to have occurred since 1920. The higher frequency fluctuations tend too be in phase, however, and a very long period temperature fluctuation with a flat minimum around 1880-1890 is common to both series; the period around 1800 is relatively warm, in contrast to Central England (Figure 9.1).

Urban heating will, through its effects on individual local time series, affect estimates of regional and global temperature trends. Hansen and Lebedeff (1987) estimated the impact of urban heating on hemispheric and global land surface air temperatures by eliminating from their data set all stations associated with population centres which had more than 100,000 people in 1970. The number of stations was reduced by about one third and overall warming trends over the past century were reduced by about 0.1°C (Figure 9.5). Hansen and Lebedeff subjectively estimated that complete elimination of urban heating, by compensating for data from the smaller towns, would not reduce the trends by more than a further 0.1°C. The magnitude of urban heating may, however, even be significant in small towns in relation to century-time scale climatic trends: Figure 9.6, from Oke, (1982), shows that on individual occasions the heat-island in midlatitude towns of population 10,000 may reach 4°C. Tropical cities also undergo urban heating because the major underlying mechanisms in both cases are increased storage of sensible heat from the sun in buildings and roads, and decreased long-wave radiation loss as a result of reduced sky-view. Only in high-latitude settlements in winter is addition of heat from burning of fuels a major contributor (Oke (1982)).

9.2.4 <u>The effects of variations of coverage on estimates of the course of hemisphere land air temperatures</u>

The geographical coverage of land-based observing stations was far from complete before the early part of the 20th Century. For example, the coverage in the Northern Hemisphere was largely limited to Europe and eastern North America until the late 19th Century (Hansen and Lebedeff (1987); Jones et al (1986)). Because interdecadal changes of temperature over particular regions often differ from the hemispherically-averaged changes (Jones and Kelly (1983)), limited sampling is likely to produce biases in estimates of trends ascribed to the hemispheres or to the globe even when the computations include the essential initial step of converting data to anomalies from local climatologies. Jones et al (1986) assessed the effects of incomplete coverage for the Northern Hemisphere by means of "frozen grid" experiments in which the course of "hemispheric" temperature was computed firstly using all available acceptable data, and then using only locations having acceptable data for at least 80% of the time in the 1850's, 1860's etc. Figure 9.7A shows the differences between the resulting sequences. Even the restriction of coverage to that available in the 1850's appears to allow an adequate simulation of the subsequent course of the average temperature anomaly of the entire expanding network on time-scales longer than about two decades, though there are marked biases in individual years or groups of years, eg the early 1940's when Europe had a succession of severe winters, thus giving a very low "hemispheric" average anomaly on the basis of the networks of the 1850's, 1860's and 1870's. Figure 9.7B shows that subsequent interdecadal changes over the Southern Hemisphere land-based observing network (excluding the Antarctic) are well simulated by the networks for the 1860's onwards. These results strongly suggest that the coverage of land air temperature data in the late 19th Century was sufficient to yield a good representation of true hemispheric decadal average land air temperature anomalies. In the absence of full knowledge of any persistent changes of atmospheric circulation, however, they do not constitute absolute proof.

9.2.5 Summary of large-scale trends of land surface air temperature

Figures 9.8A and B show the hemispheric trends of land surface air temperature from 1852 to 1984, subject to the unavoidable limitations of coverage described in the previous section. In the Northern Hemisphere, the major feature was a warming of about 0.5°C in all seasons between the 1890's and the 1940's. This warming was greatest over the Arctic (Figure 9.9 and Hansen and Lebedeff (1987)). Much of the warming period was accompanied by stronger westerlies in the midlatitude N Atlantic especially in winter (Section 9.6). A subsequent cooling of about 0.2°C in spring, summer and autumn has recently been reversed, while winter temperatures have fluctuated interdecadally, at least partly reflecting temperature changes in central and northern Europe (Figure 9.8C) which are likely to have resulted from changes in atmospheric circulation (Section 9.6). In the mid and late 19th Century the Northern Hemisphere was generally cold over land, by about 0.5°C relative to 1951-80, with the notable exception of the summers which were warmer than the 1951-80 average before the 1880's, a feature again also particularly evident over central and northern Europe (Figure 9.8C) and to a lesser extent over other areas of the hemisphere. The coverage in the early part of the northern hemispheric record is somewhat dominated by Europe (Section 9.2.4). In the Southern Hemisphere (Figure 9.8B) there appears to have been a monotonic long-term warming trend over land with superimposed fluctuations on a 10 to 20 year time scale. The indication of warmth at the start of the record is based on very few data, and the improving coverage through the series probably caused the increasing agreement between the seasons.

The interannual fluctuations superimposed on the longer-term trends of land surface air temperature can be seen for part of the Northern Hemisphere record in Figure 9.9A. They are, as expected, much smaller than the local interannual variations (compare Figure 9.4B), whereas the longer-term trends in local and hemispheric series are of comparable magnitude. Because the original data are largely the same, different authors' assessments of the course of hemispheric land temperatures are very highly correlated. Most of the published series are for the Northern Hemisphere and correlate at over 0.95, with both interannual and longer-term changes agreeing very well (Ellsaesser et al (1986b)).

Groveman and Landsberg (1979) have constructed a continuous Northern Hemisphere land surface air temperature series extending back to 1579 (Figure 9.10). To do this, they used regression formulae relating a near-hemispheric series of Northern Hemisphere land surface air temperature for 1881-1975, which had been previously constructed by Borzenkova et al (1976), to temperature values constructed for a few very long-period stations. Their series had to be based on a mixture of botanical and documentary data in the pre-instrumental era. Confidence limits for the series are shown and are comparable with the magnitude of the climatic changes suggested by the series. The series must be regarded as very uncertain, in the light of the spatial variation of long-term trends (Figure 9.9 and Hansen and Lebedeff (1987)). A cold period around 1600-1700 is suggested in common with European series, with a hint of warmth in the 1730's. The large temperature fluctuation in the first half of the nineteenth century is less expected but the early twentieth century warming (based on instrumental data) is clearly visible in their series and is comparable in magnitude with that of Jones et al (1986).

9.3 CHANGES IN MARINE TEMPERATURES

Ships' observations have been systematically recorded since the mid-19th Century when Maury (1852) put into action his plan to "belt the earth with stations". Since that time, almost 100 million observations have been made, but only in the past decade or so, with the growth in computing technology, has it become possible to realise the potential of these data. Even now, about 20 million valuable early observations await digitization.

A major compilation of marine data, known as the Comprehensive Ocean-Atmosphere Data Set (COADS) is described by Woodruff et al (1987). This data set includes monthly summaries of air and sea surface temperatures, wind, pressure, humidity and cloudiness on 2° latitude x 2° longitude resolution. Quality controls made by the compilers included the elimination of duplicate observations; consistency checks which resulted in the removal of, for example, reports from locations which are land; and "trimming" to remove extreme values.

A further compilation of marine temperature data has been made using observations archived in the Meteorological Office Main Marine Data Bank (Bottomley et al (1988)). This data set has two advantages over the COADS compilation:

a) The quality controls were carried out on the observations after conversion to deviations or "anomalies" from a climatological background field on 1° latitude x 1° longitude and pentad (5-day) resolution. Monthly anomalies for 5° latitude x 5° longitude areas were then assembled from the quality-controlled high-resolution anomalies. The results will have been more precise than COADS in regions of strong climatological temperature gradients (eg the Gulf Stream) and at times of year of rapid climatological warming or cooling. In such cases low-resolution processing of sparse data could result in substantial errors in the computed anomalies.

b) Only night-time air temperature data were used, in order to avoid most of the effects of on-deck solar heating (Glahn (1933); Hayashi (1974); Folland, Parker and Kates (1984)).

The quality-controls applied to the COADS and the initial quality-controls carried out by Bottomley et al (1988) were designed to compensate for random errors in the data. Some of these errors are truly random, for example errors in computer-keying, or parallax errors in reading a thermometer: others, such as faulty instrumental calibration, may be systematic for a given ship for at least one passage, but can be taken to be random when considering the whole data set which is based on data from many ships.

In addition to random errors, however, spurious systematic changes, of instrumental or procedural origin, occur in the marine data. For sea surface temperature (SST), these have resulted from the change in usage from mainly uninsulated buckets to largely engine intakes or insulated buckets for the readings.

For air temperature, false systematic trends appear to have arisen from the gradual increase in the elevation of the observations above sea level as ships have become larger. In studies of climatic change, systematic errors are usually a greater hindrance than random errors: the following subsection is therefore devoted to a discussion of the instrumental corrections which need to be applied to SST and marine air temperature data. Another potential source of bias in estimating global and hemispheric trends from marine temperature data is the systematic change of geographical coverage during the long period of record. A further subsection therefore assesses the effects of this problem. Similar considerations, of course, apply to land-based data and were discussed in Section 9.2. Biases resulting from changes of marine observation times appear, however, to have been small (Bottomley et al (1988)).

9.3.1 <u>Instrumental Corrections</u>

9.3.1.1 <u>Sea Surface Temperature</u>

Engine-intake readings of SST largely replaced uninsulated bucket observations around the beginning of 1942 (Folland, Parker and Kates (1984)). The main evidence for the sudden change comes from the SST data themselves. Around 1942, SST worldwide became suddenly higher by several tenths °C relative to marine air temperature (Folland, Parker and Kates (1984)). Also, relative to the climatology for 1951 to 1980, spurious annual cycles of SST are visible in many extratropical data until about 1942. Wright (1986) has documented this effect for the North Pacific. The power spectra of hemispheric SST anomalies computed by Folland, Parker and Newman (1985) show a peak at the annual frequency (Figure 9.11) which is not evident in the corresponding marine air temperature (MAT) anomalies. Figure 9.12 demonstrates the spurious annual cycles for an area of the Gulf Stream where air-sea temperature contrasts are especially large in winter leading to excessive winter cooling of uninsulated buckets but a much smaller cooling in summer. Figure 9.12 also includes corrected data. The corrections were derived by Bottomley et al (1988) using versions of a physically-based model of an uninsulated bucket. The model assumes that the water in the bucket is kept well-mixed, and it takes account of the heat fluxes arising from the following causes, given climatlolgical temperatures, humidities, insolation and probability distributions of wind speed.

a) The difference between the external air temperature and the temperature of the water in the bucket;

b) The difference between the atmospheric vapour pressure and the saturation vapour pressure at the temperature of the water in the bucket;

c) The strength of the wind around the bucket, with allowance for typical ships' motion and for the estimated sheltering effects of ships' structures;

d) The influence of the mass of the thermometer, assumed to be initially at the air temperature, when plunged into the bucket;

e) The short and long-wave radiation incident on the bucket.

The combination of a), b) and c) and to some extent (d) makes midlatitude winter uninsulated bucket SST too cold; but (e) and to a small extent (d) can make midlatitude summer uninsulated bucket SST less cold or even a little too warm: hence the spurious annual cycles of pre-war SST anomalies relative to a 1951 to 1980 climatology.

A crucial unknown quantity relevant to the computation of the corrections is the typical length of time which elapsed between the extraction of the bucket from the sea and the reading of the thermometer. Instructions to mariners suggest a variety of times ranging from "two or three minutes (five)" (Maury (1958)) to "30 seconds" (Marine Observers' Handbook (Her Majesty's Stationery Office (1950))). This problem was circumvented by varying the period allowed in the model for heat transfer until the implied corrections, when applied to observed SST, minimised the spurious annual cycles. Figure 9.13A shows series of 15-year running values of the ratio of annual cycle variance to total variance, for monthly SST anomalies averaged over the belt 30°N to 40°N, without corrections and with corrections to pre-1942 data assuming 0.5, 1.5 and 3 minutes' heat transfer time. The corrections are based on a model version "D9" which is similar to those used by Bottomley et al (1988). It is necessary to minimise the variance ratio, rather than the annual cycle variance itself, because there will be real interannual variability of the strength of the annual cycle as a result of oceanic and meteorological fluctuations, as a result of which the annual cycle variance of true SST anomalies will not be zero, and can be assumed to be approximately proportional to the variance at other frequencies. Note in Figure 9.13A that the uncorrected data show generally much higher values of the variance ratio before the 1940's. Application to pre-1942 data of corrections assuming progressively longer heat transfer times reduces these values until a minimum is reached, in this case at around 1.5 minutes' heat transfer time. Eventually, lengthening the heat transfer time begins to increase the variance ratio, because the corrections are now making the data too warm in winter and too cold in summer. Figure 9.13B summarises this relationship between the variance ratio and the assumed heat-transfer time for the same zonal belt for the period 1881 to 1941 as a whole.

Figures 9.14A, B show the corrections as applied up to 1900 by Bottomley et al (1988). The corrections for 1901 to 1941 were more positive by 0.02°C to 0.04°C because it was assumed (Krummel (1907)) that buckets were more often exposed to direct insolation in the 19th Century, so different versions of the model, assuming respectively 100% and 25% of climatological direct insolation, were used in the earlier and later periods respectively. Corrections based on a variety of versions of the model (assuming, for example, different sizes of bucket or different degrees of reduction of the wind speed by the ship's structure) were found to be very similar. For example, a bigger bucket, holding more water, would cool more slowly than a small bucket, but the modelled exposure time would need to be greater if the spurious annual cycles were to be removed, so the resulting corrections would be similar. Additional versions of the model are still being assessed: for example, the effect of ship's speed is being investigated further, and it may become necessary to allow for the use of, for example, some wooden or metal buckets in the 19th Century (cf Maury (1958)).

As expected, Figures 9.14A, B show generally positive corrections, especially in midlatitude winter and in the tropics. The largest corrections are in winter over the Gulf stream and the Kuroshio where the sea is much warmer than the air. The effects of the corrections on time-series of regional SST anomalies can be assessed by comparing Figures 9.15A and B. As anticipated, the corrected anomalies are made less negative, or more positive, before 1942, and the climatic trends for the different seasons are brought into closer agreement. Clearly, the uncorrected data somewhat misrepresent climatic change.

9.3.1.2 Night Marine Air Temperature

Corrections for long-term systematic increases in deck elevation were derived by Bottomley et al (1988) on the basis of typical profiles of temperature in the marine boundary layer. Because these corrections were found to be insensitive to reasonable variations in the shape of the assumed boundary layer profile, corrections based on the same globally averaged profile were chosen irrespective of location and season. This profile is superadiabatic in the relevant height range, and the corrections applied were -0.15°C up to 1900; -0.09°C for 1901-15; -0.02°C for 1916-60; 0.01°C for 1971-5 and 0.02°C thereafter. These corrections are generally smaller than those made to SST (Figure 9.14), and much smaller than those which would be required to daytime marine air temperatures to compensate for solar heating on deck, which would be of the order of -1°C (Parker (1988)). However Bottomley et al (1988) did find the need to apply additional corrections as large as -0.9°C to night marine air temperatures observed between 1940 and 1945. These data showed discontinuities in time, not shared by the daytime data which were used as a reference: the cause was probably the wartime practice of carrying the thermometers indoors to be read, to avoid showing a light to the enemy.

Marine air temperature data for years before about 1880 appear to have been affected by positive biases in windy conditions (Parker (1988)). Possibly the thermometers were read under cover: investigations are continuing, and corrections have not yet been applied to compensate.

9.3.2 The effects of variations of coverage on estimates of the course of hemispheric marine temperatures

Incomplete geographical coverage could result in biases in estimating global and hemispheric trends from marine as well as from land (Section 9.2.4) temperature data. Figure 9.16 illustrates some of the changes in coverage of SST data since the 1860's. The coverage of marine air temperature data has followed virtually identical patterns. The coverage was temporarily diminished during the World Wars and has been affected by changes in patterns of international trading, due, for example, to the opening of the Suez Canal in 1869 and the Panama Canal in 1914, which resulted in a reduction of shipping traversing the Southern Ocean. In order to assess the effects of the changes in coverage, "frozen grid" experiments were carried out. The results of one of these are shown in Figure 9.17. Firstly, SST anomalies (SSTA) for each season in the record were averaged globally using all 5° latitude x 5° longitude boxes with data: the resulting seasonal time-series was smoothed using the filter illustrated in the inset of Figure 9.17, to give the continuous time-series curve in the main part of the diagram. The computations were then repeated, but using only the heavily hatched areas of Figure 9.16A, ie those with over 90% coverage in 1861-70, throughout the time-series. Comparison of the resulting dashed curve with the continuous curve in the main part of Figure 9.17 suggests that restriction of coverage to that available in the 1860's allows adequate simulation of the subsequent course of the longest-term changes of SST averaged over the entire expanding network. Similar experiments using hemispheric SST data, or global or hemispheric marine air temperature data, yielded estimates of long-term trends which were nearly as stable as those in Figure 9.17. The reason for this insensitivity to coverage is partly that the long-term trends appear to have occurred in unison over virtually the entire globe (Bottomley et al (1988)). This is shown by the correlation of 0.92 between seasonal time series of the coefficient of the rather geographically uniform first global all-seasons covariance eigenvector of SSTA defined for 1901-80 (Figure 9.18A) and the globally averaged SST anomaly, derived using all available data, for 1856 to 1987 (Figure 9.18B). Although the long-term trends have geographically varying amplitude (Figure 9.18A), this has apparently been rather well sampled by the time-varying coverage throughout the record. However, caution is needed because the region south of 45°S, which contains about 20% of the world's ocean, has never been adequately sampled (Figure 9.16). For this reason, and because we have not proved that the characteristic patterns of SST variations, represented by the eigenvectors, are entirely stable from epoch to epoch, the above results do not absolutely prove the adequacy of the coverage for assessments of global and hemispheric marine temperature trends.

9.3.3 Summary of large-scale trends of marine temperature

Figures 9.19A and B present the hemispheric trends of SST for 1856 to 1987, subject to the above mentioned unavoidable limitations of coverage. Instrumental corrections have been applied up to 1941 as in Bottomley et al (1988). The Northern Hemisphere curves are very similar to those for the Atlantic north of 35°N (Figure 9.15B, which has a different plotting scale), and the North Atlantic as a whole and the North Pacific have also undergone similar trends (Bottomley et al (1988)). Until about 1960 the Southern Hemisphere also cooled and warmed in unison with the Northern. The worldwide nature of the century time-scale fluctuation of SST is brought out by Figure 9.20A, which shows SSTA for 1903-12 which was on a global average the coldest decade. The geographical uniformity in long-term trends has already been noted in connection with the discussion of variations of data coverage in Section 9.3.2 and illustrated by means of the geographically rather uniform, first all-seasons eigenvector of global SSTA and the hightly-correlated time-series of its coefficient and of global SSTA in Figure 9.18. However, since about 1960 there has been substantial oceanic warming of the Southern Hemisphere relative to the Northern. This differential change has not, in fact, been exactly hemispheric: the Northern Indian Ocean has warmed in phase with the Southern Hemisphere, and the trends in much of the South Pacific have been weak (Figure 9.20B). The quasi-interhemispheric changes of SST since the 1950's are discussed in Lecture 5 in connection with the drought of the last two decades in sub-Saharan Africa.

Global, hemispheric and regional trends of night marine air temperature have, as would be expected on physical grounds, been very similar to those of SST (Bottomley et al (1988): see also Figure 9.21). This similarity confirms the reality of the trends, because the measurements have been made independently, and the instrumental corrections included no attempts to constrain the series to agree.

Shorter-term variations of both SST and night marine air temperature have been superimposed on the longer-term trends. As can be seen from the time-series in Figure 9.21, many of the shorter-term variations appear to be associated with the El Nino-Southern Oscillation (ENSO): see also Lecture 6. The variations on time-scales of 2 to 6 years indicated by the power-spectra in Figure 9.11 are likely, therefore, to be associated with ENSO, but the peak near 17 years in Southern Hemisphere SST and its equivalent near 20 years in night marine air temperature are as yet unexplained. The dominant peaks at about 70 years (Northern Hemisphere) and 100 years (Southern Hemisphere) represent the century time-scale fluctuations visible in Figure 9.19.

9.4 COMPARISON OF LAND AND MARINE TEMPERATURE TRENDS

Figures 9.8 and 9.19 reveal substantial similarities, but also some contrasts, between the changes of hemispheric anomalies of land surface air temperature and SST since the mid 19th Century. The similarities are, perhaps, surprising in view of the thermal inertia of the oceans. In the Northern Hemisphere, the general trends have been very similar since 1900 (note the different scales of the graphs), but in the mid-and late 19th Century the land surface air temperature anomalies were low relative to those of SST by about 0.5°C in winter and by about 0.25°C in spring and autumn. In the Southern Hemisphere the land surface air temperature anomalies were also low relative to those of SST in the 19th Century in autumn and winter, but to a lesser extent. In addition, the very recent rise of SST in the Southern Hemisphere has been more marked than that of land surface air temperature.

There are several possible reasons for the divergences between the indications of the early data:

a) The instrumental corrections to SST could have been inadequate, as a result of the use of different types of bucket or different procedures. The close agreement between the seasons in Figure 9.19A suggests, however, that this may not have been a serious problem.

b) The early land data could be too cold relative to the 1951-80 reference period as a result of increasing urban heating, changes of instrumentation, or changes in observing times. However, Jones et al (1986) eliminated stations showing evident urban heating and other discontinuities relative to neighbouring stations. The relative warmth over Northern Hemisphere land in summer may have resulted from the limited sampling (Section 9.2.4).

c) Atmospheric circulation anomalies could have made the oceans relatively warm and the continents relatively cold, or in the Northern Hemisphere, low latitudes (mainly oceanic) relatively warm and high latitudes (mainly continental) relatively cold. Jones and Kelly (1983) and Jones et al (1988) have documented substantial geographical variations in 20th Century temperature trends.

A test of the reliability of the data was made by comparing time-series of land surface air temperature over selected islands with corresponding series of SST and night marine air temperature from the surrounding ocean within 10° of latitude and longitude, instrumentally corrected as in Bottomley et al (1988). When averaged together over the hemispheres, the series for these locations were in better agreement than the series for the hemispheres as a whole after 1870 (see eg Figure 9.22 for the Northern Hemisphere), suggesting that anomalies of atmospheric circulation may have caused the divergences between Figures 9.8 and 9.19. The portion of Figure 9.22 before 1870 should be ignored because there were fewer than 5 sites available for the comparison. The relative warmth over the island stations between the 1890's and 1940 is, however, significant because about 30 well-scattered sites were used, and may indicate that slightly larger corrections are required to the SSTs after about 1900. If, in accord with known trends in ships' performance, a ships' speed of 7 m/sec were assumed after 1900, as opposed to 4 m/sec as used by Bottomley et al (1988), the corrections would be larger, though not in general by as much as 0.1°C. However, the SSTs in Figure 9.22 are supported by the night marine air temperatures, suggesting the need for investigation into the reliability of the land surface air temperatures also. Similar results were obtained for the Southern Hemisphere.

Climatic changes of island and coastal air temperature are, as Figure 9.22 suggests, often determined by regional climatic changes of SST. An example for the British Isles is shown in Figure 9.23, in which are compared the climatic changes of SST anomalies for the Atlantic north of 35°N, Central England Temperature, and Scilly Islands temperature, on days with westerly atmospheric circulation types defined by Lamb (1972b). Knowledge of local SST has been found to be useful in the interpretation of predicted patterns of atmospheric flow in terms of temperatures in the United Kingdom on weekly to monthly time-scales.

Figures 9.15B and 9.24 suggest a possible link between the long term changes of ocean surface temperatures and the fluctuations of some European glaciers, despite the complexity of the climatic factors that influence individual glacier advances and retreats. The advance of the Swiss glaciers in the early twentieth century seems to correspond with the cool period in the midlatitude N Atlantic (and over the globe) around 1900-1915; the subsequent retreat centred around 1950 coincides with highest SST. Most convincing is the recent advance that corresponds well with the fall in midlatitude N Atlantic SST up to about 1980. The changes in SST may not of course be the direct cause of the glacier fluctuations - both may be the result of a third common factor.

9.5 CHANGES IN RAINFALL

Long-term local, regional and Northern Hemispheric series of rainfall have been constructed on the basis of land-based observations, in a manner similar, but not identical, to that employed for land surface air temperature. However, we do not yet have reliable means of estimating rainfall at sea: for this, satellite-based techniques are being developed, partly under the aegis of the Global Precipitation Climatology Project (see Lecture 1).

The climatology of local rainfall can vary substantially over short distances, especially in mountainous terrain. Furthermore, the statistical distributions of local rainfalls are not Gaussian, even on monthly and seasonal time-scales. For these reasons, composite regional series cannot be formed by simply averaging anomalies over a set of stations. Often the data are first expressed as normalised deviations from the local average (eg Nicholson (1985)), or in terms of the parameters of a gamma-distribution (eg Bradley et al (1987)). If the rainfall climatology of the region is known in detail, the resulting series can be converted back into "dimensional" units, ie millimetres.

The best-attested climatic change in a regional rainfall series is the recent dessication of sub-Saharan Africa (Figure 9.25). The associated worldwide changes of SST (Figure 9.20B) and the mechanisms possibly involved in the generation of the drought are discussed in Lecture 5. There have, however, also been accompanying changes in atmospheric circulation in the extratropical N Atlantic sector, involving a tendency to increased anticyclonicity near the British Isles in high summer (see Section 9.6 below), and a resulting reduction of rainfall. The latter can be seen as a decrease in July and August rainfall over England and Wales since the 1950's in Figure 9.26.

The most significant long-term change in the England and Wales rainfall over the period of about 200 years covered by Figure 9.26 is an increase in January rainfall. December shows a much weaker increase and February shows no change. The annual totals have not changed systematically, so the increase in January is unlikely to have resulted from instrumental or procedural changes. The series was carefully adjusted for variations in observing locations. Figure 9.26 therefore suggests a change in atmospheric circulation in January, not affecting February. This explanation is supported by the relative constancy of February's Central England Temperature (Figure 9.1). Regressions relating monthly England and Wales rainfall (EWR) to monthly patterns of mean sea level pressure (MSLP) for the period 1901-80 were applied to earlier MSLP fields in order to simulate EWR. The results verified January EWR as far back as 1873, and to some extent for earlier years for which the pressure fields had been created by different techniques. The very dry conditions in January in the early 19th Century are in agreement with the pressure fields of Lamb and Johnson (1966).

Bradley et al (1987) created the first precipitation series for the Northern Hemisphere (Figure 9.27). However both their hemispheric and their regional series are likely to be revised when full account is taken of instrumental and procedural changes. For example, the Soviet Union has introduced gauges which are more efficient collectors of snow, and has also started to apply corrections for the fact that wetting of the collector funnel must occur before the water can begin to accumulate in the receiving bottle. These changes are likely to have contributed substantially to the recent increase in rainfall in the Soviet Union reported by Bradley et al (Figure 9.28).

9.6 FLUCTUATIONS OF THE ATMOSPHERIC CIRCULATION

9.6.1 North Atlantic sector

The chief evidence for fluctuations of atmospheric circulation in the last few hundred years years comes from the North Atlantic sector and is to be found in:

(a) diaries kept by careful observers of wind direction and weather;

(b) Many measurements of pressure at station level made since the eighteenth century.

One of the most interesting and lengthy series of type (a) was put together by Lamb (1972a), of necessity rather subjectively (Fig 9.29), and shows variations in the frequency of south westerly winds in S E England. A relatively low frequency during much of the seventeenth century and a peak in the 1730's is in accord with the variations in CET outside the summer season (Figure 9.1). In summer, the level of CET is not expected to be well-related to the frequency of south westerly winds. A minimum frequency of south westerly winds has been suggested for a few years in the late 18th century by Kington (1988) who has constructed daily weather maps for the period 1781-85. At this time, due to a briefly successful interlude of international cooperation, there was a well-distributed network of pressure observations in Europe. Lamb and Johnson (1966) have constructed monthly-mean MSL pressure charts for January and July since 1750 for the N Atlantic sector, and for later years for much of the Northern Hemisphere.

Strong evidence for the changing characteristics of the atmospheric circulation in winter in the N Atlantic sector over the last century is provided by the distributions of the Azores minus Iceland monthly pressure differences in Figure 9.30. The pressure data from the two stations used are of good quality and have been carefully scrutinised. Both stations are situated near sea level. The data provide an index of circulation reflecting the strength, or location, of the mid-latitude westerlies between the Azores and Iceland. Winters in the early twentieth century were characterised by persistently strong westerlies (middle panel) whereas those in the late nineteenth century and the period since 1940 have had a greater relative frequency of weak westerlies or even easterlies, probably reflecting an increased incidence of atmospheric blocking (see Section 2.5.3.1 in Lecture 2). Within the latter-period there has been a tendency for interdecadal fluctuations with more severe (blocked) winters in the 1940's, 1960's, and late 1970's to mid 1980's, and a notable succession of mild winters in the early to mid 1970's. Figure 9.31 shows variations in the frequency of Lamb's westerly types over the British Isles (see Lamb (1972b, 1977) and Lecture 1) for the year as a whole, and again indicates a greater prevalance of westerlies in the early twentieth century. Figure

9.32 shows differences in mean sea level pressure during January over the extratropical Northern Hemisphere between 1901-30 and 1951-70, and also indicates that the N Atlantic westerlies were substantially stronger in the earlier period, by perhaps 3 or 4 m/sec over Scotland. Scrutiny of Figure 9.1, where the 20 year running average of CET is plotted against the last year of the 20 year period, shows that between 1911-30, January CET averaged about 1.2°C higher than in the latter period. 1.2°C is a large change in mean temperature; e.g. during the recent 30 year period 1951-80 a month with an anomaly of 1.2°C from the mean was just enough to place that month into the top 20% of the January temperature probability distribution. The even larger warming in October between 1890 and 1975 in Figure 9.1 was also partly due to an increase in the frequency of south westerly winds in that month. The warming was so large that a very mild month (top 20% of the ranked distribution of October temperatures) in the period 1870-1900 could easily have had the same temperature as a rather cold month (bottom but one 20% of the 30 year ranked distribution of October temperature) in the period 1951-80. The sharp cooling in April since 1961 has been associated with a strong increase in blocking and thus in east-north-east winds in that month. So (mainly) as a result, there were no very warm Aprils in Central England after 1961 until 1987.

9.6.2 Evidence of circulation variations on the global scale

A comprehensive analysis of all available quality-controlled mean sea level (MSL) pressure data on land and at sea has yet to be carried out. However, the potential value of such analyses is suggested by Figure 9.33 taken from Tan and Yasunari (TY) (1982). TY analysed July MSL pressure over much of the globe using station, including island, data but excluding the Atlantic Ocean sector 0-60°W. The data were first analysed into a grid point format. Figure 9.33 shows the first two eigenvectors of the field of 11 year running mean MSL pressure; this averaging time-scale was chosen to highlight the longer-period variations. The first eigenvector (31% of the variance) is negative north of about 20°N and positive to the south; the time series suggests a progressive reduction of MSL pressure in the Southern Hemisphere relative to the extratropical Northern Hemisphere over the last century with a temporary halt to this tendency between about 1900 and 1930. These changes do not seem to be in accord with the elementary assumption that the warmer region (relative to climatology) will have the lower MSL pressure (again relative to climatology). Although the Southern Hemisphere with the N Indian Ocean has been relatively warm, by comparison with the rest of the Northern Hemisphere, in the most recent 20 years (Figures 9.8, 9.19, 9.20B), the same applied to a lesser extent at the beginning of the twentieth century, and the opposite was true around the 1940's and 1950's when Figure 9.33B indicates reduced MSL pressure on the Southern Hemisphere. The comparison is, however, hindered by the omission of the Atlantic by TY. The second eigenvector (19%) of the variance) represents a variation of MSL pressure between the Pacific and the Indian Ocean on the one hand and the surrounding continental areas on the other. Relatively low pressure over land and high pressure over the oceans is suggested in the late nineteenth century and mid-twentieth century, with a reversed pattern around 1900-1920. The century time-scale variations are in phase with those of hemispheric temperatures in Figures 9.8 and 9.19, but the physical connections are as yet unknown.

It must be emphasised that, away from the midlatitude N Atlantic sector, most existing grid point data sets of MSL pressure must be used with great caution. There have been unrealistic changes of derived MSL pressure over some mountainous regions and over the Arctic (Williams and Van Loon (1976)).

9.6.3 Links between Sahel rainfall and extratropical atmospheric circulation

The Sahel drought has been a special theme of these lectures, and we have already repeated at Figure 9.25 the time series of Sahel rainfall anomalies shown in Lectures 1 and 5. Figures 9.34A and B show, for the extratropical N Atlantic sector, July and August MSL pressure differences between the most recent dry Sahel period (1986-87) and the wet period (1950-59). The grid-point MSL pressure data set used has been corrected for a change of data time from 12 GMT to 00 GMT in 1966. The two maps are similar and indicate higher pressure centred near northern Britain in the later period, though only in August is this locally statistically significant. For the hemisphere north of 20N as a whole 8% (July) and 7% (August) of the area is locally statistically significant. Although this indicates that the field as a whole is probably not statistically significant (Livezey and Chen (1983)), the persistence of the anticyclonic anomaly, which was also very weakly apparent in June, suggests dynamical significance. The anticyclonic anomaly has not been consistently indicated by the atmospheric general circulation model experiments with SST anomalies appropriate to Sahel drought (Lecture 5). It has, however, been associated with a significant reduction of July and August England and Wales rainfall (Figures 9.26 and 9.35), and the summers affected include 4 of the 11 driest summers (June to August) in the England and Wales rainfall series which began in 1766. 1976 was the driest and 1983 the second driest.

Another feature of the MSL pressure differences between 1968-87 and 1950-59 has been a persistently deeper Aleutian low in the later period between December and March. The strengthened westerlies over the midlatitude N Pacific are likely to have contributed to the reduced SSTs there (Figure 9.20B), by southward Ekman drift, increased vertical mixing in the ocean, and increased fluxes of heat to the atmosphere. Despite increased anticyclonicity from April to June, the reduced SSTs in the later period have been evident throughout the year, possibly because the westerlies were strengthened slightly in most of the remaining months.

9.7 TEMPERATURE CHANGES ALOFT

Series of data based on radiosondes are generally too short to indicate much about climatic change; the series are at present much more useful for studying interannual variability, especially the effects of El Nino. Radiosonde data are unfortunately subject to severe problems of changing instrumental biases, which affect particularly upper atmospheric temperature measurements; biases vary between countries and therefore may be geographically variable. This problem results from a combination of changes in instrumentation and changes in correction procedures. The main difficulty has been the need to compensate adequately for solar heating of radiosonde thermometers; the problem is acute in the lower stratosphere. For example, Parker (1985a) found, in a study covering 1958 to 1982, that cooling of the lower stratosphere, an expected result of increasing atmospheric carbon dioxide, was only evident over stations using USA Weather Bureau radiosondes. Spurious changes in tropical tropospheric radiosonde data were eliminated as far as possible in a separate stucy by Parker (1985b) by checking the spatial consistency of interannual changes of the thicknesses of the 850 to 500 mb and 500 to 200 mb layers recorded over the stations. Those interannual changes which were regarded as reliable were used to construct series of thicknesses representing the entire tropics for 1950 to 1983. After adjustment for the phase of Southern Oscillation (see also Lecture 6) these series showed no trend (Figure 9.36).

Time series of tropospheric temperatures for 1958-87, derived by Angell (1988) from data from a global network of 63 well-distributed radiosonde stations, are presented in Figure 9.37, which also includes a series of SST for part of the eastern equatorial Pacific to show the influence of the El Nino-Southern Oscillation on the interannual changes of tropospheric temperature. The longer-term relative warming of the Southern Hemisphere is in agreement with hemispheric SST trends (Figure 9.19). Angell also found a recent marked cooling in the lower stratosphere over much of the globe: see Figure 10.10 in Lecture 10, and the associated discussion.

9.8 SEA LEVEL

A worldwide warming of climate might be expected to lead to a rise of sea level as a result of the thermal expansion of sea-water and the addition of water to the oceans from melting glaciers and ice-sheets. On the other hand, if a warmer climate were to entail increased precipitation of snow onto existing ice sheets, a fall of sea level could result.

Fairbridge (1987), however, drew attention to the non-climatic influences on sea-level. For time-scales shorter than a century these include:

i) Regional glacio-isostatic changes in response to loading and unloading of the Earth's crust by ice;

ii) Local and regional sedimental loading and compaction;

iii) Seismic displacement.

Fairbridge concluded that the averages of mean-sea-level change deduced from tide-gauge measurements during the 20th Century are grossly misrepresentative of changes of global ocean volume, because of clustering of gauges in northern midlatitudes (where glacio-isostatic changes may be important) and because of siting of stations at river mouths and on estuaries and deltas where crustal loading and sedimental compaction cause subsidence.

Barnett (1984) also discussed the difficulties inherent in the estimation of global mean sea level changes, and found that the existing data set was inadequate for this purpose. He warned that interpretation of long-term changes of sea level would be difficult because of glacio-isostatic changes. Nevertheless he found a coherent rise in mean sea level since the early 1900's except near Alaska, Scandinavia and southeast Asia, and, with the above caveats, computed a global rise of 23 cm/century since the early 1900's. This rate is greater than the consensus, 10 to 15 cm, of the estimates tabulated by Ellsaesser et al (1986), who not only reviewed the difficulties in assessing global sea level change, but also drew attention to problems in confirming such changes of sea level by means of changes in the Earth's rotation rate. The latter is affected not only by the increase of the Earth's moment of inertia when polar land-ice melts, but also by Earth-moon interactions and, maybe, by rearrangements of material in the Earth's core.

Wigley and Raper (1987) used an energy-balance climate model, with separate boxes for land and ocean for each hemisphere and with oceanic upwelling and diffusion, to deduce that the greenhouse-gas-induced thermal expansion contribution to sea-level rise between 1880 and 1985 was between

2 and 5 cm. The range in their values resulted from the fact that a variety of combinations of oceanic diffusivity and equilibrium climate sensitivity to carbon dioxide increases could be inserted in the model and still give global mean sea surface temperature changes consistent with those observed: the different combinations of parameters gave different vertical profiles of sea temperature changes, and therefore different estimates of thermal expansion.

9.9 CAUSES OF CLIMATIC CHANGES ON DECADAL TO CENTURY TIMESCALES

We conclude by drawing attention to some likely reasons for the climatic changes described in this Lecture. Much of the relevant discussion of these mechanisms has already been presented in other Lectures, to which the reader is referred where necessary.

9.9.1 Variations in solar output

The most recent finding is that total solar irradiance appears to vary in phase with the 11-year sunspot cycle (Section 3.1.2 and Figure 3.5 in Lecture 3). If this relationship also holds for the longer-period changes in the number of sunspots (Figure 3.6), then the minimum in worldwide temperatures shortly after the beginning of the present century may have at least part of its origin in a reduction of the solar output; and the peak of warmth around the 1940's to 1950's may have been partly caused by increased solar irradiance. Similar considerations would apply to the climax of the "Little Ice Age" around the time of the Maunder minimum of sunspots in the 17th Century: see also Lecture 8.

9.9.2 Oceanic circulations

Changes in the thermohaline circulation of the oceans have been proposed as mechanisms of past climatic change (Section 7.5.2 in Lecture 7; Section 8.4.3 in Lecture 8). Interactions between winds and ocean currents may also be important in maintaining the present relative warmth of the Southern Hemisphere (Section 5.4.5 in Lecture 5).

9.9.3 Volcanic eruptions

Section 3.3 (Lecture 3) discusses the possibility that injections of volcanic aerosols into the stratosphere cause temporary coolings of climate. Most of the observational evidence and modelling results suggest, however, that the residence times of the aerosols are only of the order of a few years: thus, to force the sustained interdecadal climatic changes observed in the last century would require sequences of several decades with many and few powerful eruptions respectively. The volcanic indices and Antarctic sulphuric acid profile shown in Figure 3.16 do not show this and certainly do not match the observed decadal to century time-scale temperature changes. In particular, the marked early 20th century warming began about 20 years after Santa Maria (1902) and the subsequent cooling began befor Agung which was not followed by other major eruptions until El Chichon, which may not (Section 3.3.3) have interrupted the recent warming.

9.9.4 Greenhouse gases

The reader is referred to Lecture 10 for an assessment of the evidence for the influence of increasing carbon dioxide and other greenhouse gases in the atmosphere on the climate of the Earth in recent decades. The rôle of carbon dioxide in the climatic changes in the late Pleistocene is discussed in Section 7.5.3 (Lecture 7) and Section 8.4.1 (Lecture 8).

REFERENCES TO ADVANCED LECTURE NO 9

ANGELL, J K (1988) Variations and trends in tropospheric and stratospheric global temperature, 1958-1987. Submitted to J Climate.

ANGELL, J K and GRUZA, G V (1984) Climate Variability as estimated from atmospheric observations. In "The Global Climate" Ed: J T Houghton, pp 25-36. Cambridge University Press.

BARNETT, T P (1984) The estimation of "global" sea level change: a problem of uniqueness. J Geophys. Res., 89, C5 7980-7988.

BORZENKOVA, I I, VINNIKOV, K Ya SPIRINA, L P and STECHNOVSKII, P I (1976) Variations of Northern Hemisphere air temperature from 1881 to 1975. Met i Gid, 7, 27-35.

BOTTOMLEY, M, FOLLAND, C K, HSIUNG, J, NEWELL, R E and PARKER, D E (1988). Global Ocean Surface Temperature Atlas (GOSTA). Meteorological Office/Massachusetts Institute of Technology. In press.

BRADLEY, R S, DIAZ, H F, EISCHEID, J K, JONES, P D, KELLY, P M and GOODESS, C M (1987) Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th Century. Science, 237, 171-175.

DETTWILLER, J (1978) L'evolution seculaire de la temperature à Paris. La Meteorologie, VI, 13, 95-130.

ELLSAESSER, H W, MacCRACKEN, M C, WALTON, J J and GROTCH, S L (1986) Global climatic trends as revealed by the recorded data. Rev Geophys, 24, 745-792.

FAIRBRIDGE, R W (1987) The spectra of sea level in a Holocene time frame. In "Climate. History, Periodicity, and Predictability", Eds. M R Rampino, J E Sanders, W S Newman and L K Königsson. Van Nostrand Reinhold Co. New York. pp 127-143.

FOLLAND, C K (1983) Regional-scale interannual variability of climate - a north-west European perspective. Met. Mag., 112, 163-183.

FOLLAND, C K, PARKER, D E and KATES, F E (1984) Worldwide marine temperature fluctuations 1856-1981. Nature 310, 670-673.

FOLLAND, C K, PARKER, D E and NEWMAN, M (1985) Worldwide marine temperature variations on the season to century timescale. Proc 9th Climate Diagnostics Conf., Corvallis, Oregon 22-26 Oct. 1984. Amer. Met. Soc., pp 70-85.

GLAHN, W (1933) False measurements of air temperatures on ships. Hamburg, D Seewarte, Der Seewart, 2, H6, 250-256. In German but English translation available in National Meteorological Library, Bracknell, UK.

GROVEMAN, B S and LANDSBERG, H E (1979) Reconstruction of Northern Hemisphere temperature: 1579-1980. Univ. Maryland Met. Program, Publ. 79-181. Data appendices in separate volume.

HANSEN J and LEBEDEFF, S (1987) Global trends of measured surface air temperature. J. Geophys. Res., 92, D11, 13345-13372.

HAYASHI, S (1974) Some problems in marine meteorological observations, particularly of pressure and temperature. Tokyo, Japan Met. Agency, J. Met. Res. 26, 84-87. In Japanese but English translation available in National Meteorological Library, Bracknell, UK.

HER MAJESTY'S STATIONERY OFFICE (1950) Marine Observers' Handbook, 7th Edition. London.

JONES, D E (1987) Daily Centrel England Temperature: recently constructed series. Weather, 42, 130-133.

JONES, P D and KELLY, P M (1983) The spatial and temporal characteristics of Northern Hemisphere surface air temperature variations. J. Climatology, 3, 243-252.

JONES, P D, RAPER, S C B, BRADLEY, R S, DIAZ, H F, KELLY P M and WIGLEY, T M L (1986) Northern Hemisphere surface air temperature variations: 1851-1984. J. Clim. Appl. Met., 25, 161-179.

JONES, P D, RAPER, S C B and WIGLEY, T M L (1986) Southern Hemisphere surface air temperature variations: 1851-1984. J. Clim. Appl. Met., 25, 1213-1230.

JONES, P D, WIGLEY, T M L, FOLLAND, C K and PARKER, D E (1988) Spatial patterns in recent worldwide temperature trends. Submitted to Nature.

KASSER, P and AELLEN, M (1981) Switzerland and her Glaciers. Swiss National Tourist Office, Kummerly and Fry, Bern, 191 pp.

KINGTON, J (1988) The weather of the 1780's over Europe. Cambridge University Press, 166 pp.

KRÜMMEL, O (1907) Handbuch der Oceanographie, Vol 1, Stuttgart, 373 pp.

LAMB, H H (1965) The early mediaeval warm epoch and its sequel. Paleogeography, Palaeoclimatology, Palaeoecology, 1, 13-37. Amsterdam (Elsevier).

LAMB, H H (1972a) Climate Present, Past and Future. Vol 1, Methuen.

LAMB, H H (1972b) British Isles weather types and register of the daily sequence of circulation patterns 1861-1971. Geophysical Memoirs No 116 (SECOND NUMBER, VOLUME XVI). London, Her Majesty's Stationery Office, 85 pp.

LAMB, H H (1977) Climate Present, Past and Future. Vol. 2, Methuen.

LAMB, H H and JOHNSON, A I (1966) Secular variations of the atmospheric circulation since 1750. Geophysical Memoirs No. 110. (FIFTH NUMBER VOLUME XIV). London, Her Majesty's Stationery Office, 125 pp..

LANDSBERG, H E (1979) Atmospheric changes in a growing community. Urban Ecology, 4, 53-82.

LIVEZEY, R E and CHEN, W Y (1983) Statistical field significance and its determination by Monte Carlo techniques. Mon. Weath. Rev., 111, 46-59.

MANLEY, G (1974) Central England temperatures: monthly means 1659-1973. Quart. J. Roy. Met. Soc., 100, 389-405.

MAURY, M F (1852) Correspondence with J Glaisher, in the Report of the Council of the British Meteorological Society, 25 May 1852, pp. 6-10. Available in National Meteorological Library, Bracknell, UK.

MAURY, M F (1858) Explanations and Sailing Directions to accompany the wind and Current Charts. Vol. 1. 383 pp + 51 plates. Printed by W A Harris, Washington D C.

NICHOLSON, S E (1985) Sub-Saharan rainfall 1981-84. J. Clim. Appl. Met., 24, 1388-1391.

OKE, T R (1982) The energetic basis of the urban heat island. Quart J Roy. Met. Soc., 108, 1-24.

PARKER, D E (1985a) On the detection of temperature changes induced by increasing atmospheric carbon dioxide. Quart. J. Roy. Met. Soc, 111, 587-601.

PARKER, D E (1985b) The influence of the Southern Oscillation and volcanic eruptions on temperature in the tropical troposphere. J. Climatology, 5, 273-282.

PARKER, D E (1988) A note on the use of voluntary observing fleet data to estimate air-sea fluxes. Long-Range Forecasting and Climate Research LRFC 17, Meteorological Office, Bracknell.

PARKER, D E and FOLLAND, C K (1988) The nature of climatic variability. Met. Mag., 117, 201-210.

SIREN, G (1961) Skogsgranstallen som indikator for klimatfluktuationerna i norra Fennoskandien under historisk tid. Communicationes Inst. Forest. Fenniae, 54 (2), Helsingfors.

TAN, C and YASUNARI, T (1982) Fluctuations of global surface pressure patterns during the past 100 years and their relation to the Asian monsoon. Part I. Northern Summer (July). J. Met. Soc. Japan, 60, 1132-1142.

UNTERSTEINER (1984) The cryosphere. In "The Global Climate" Ed: J T Houghton, pp 121-140. Cambridge Univ. Press.

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. J. Climatology, 4, 1-25.

WIGLEY, T M L and RAPER, S C B (1987) Thermal expansion of sea water associated with global warming. Nature, 330, 127-131.

WILLIAMS, J and VAN LOON, H (1976). An examination of the Northern Hemisphere sea level pressure data set. Mon. Weath. Rev, 104, 1354-1361.

WOODRUFF, S D, SLUTZ, R J, JENNE, R L and STEURER, P M (1987) A Comprehensive Ocean-Atmosphere Data Set. Bull. Amer. Met. Soc., 68, 1239-1250.

WRIGHT, P B (1986) Problems in the use of ship observations for the study of interdecadal climate changes. Mon. Weath. Rev., 114, 1028-1034.

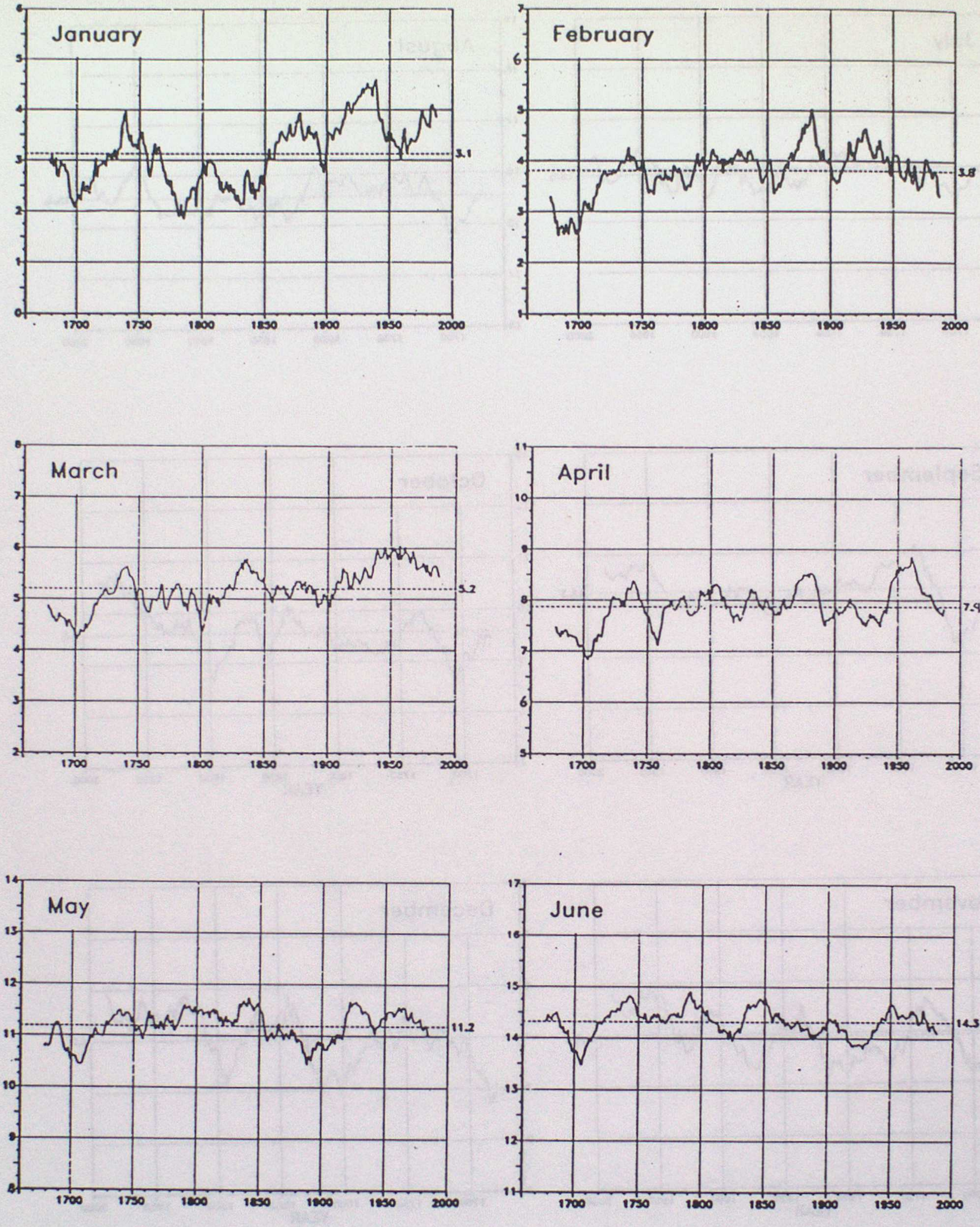


Figure 9.1. Central England Temperature (°C), 1659 to 1987. Values are 20-year running averages ending at the plotted date. Dashed horizontal lines are whole-period means.

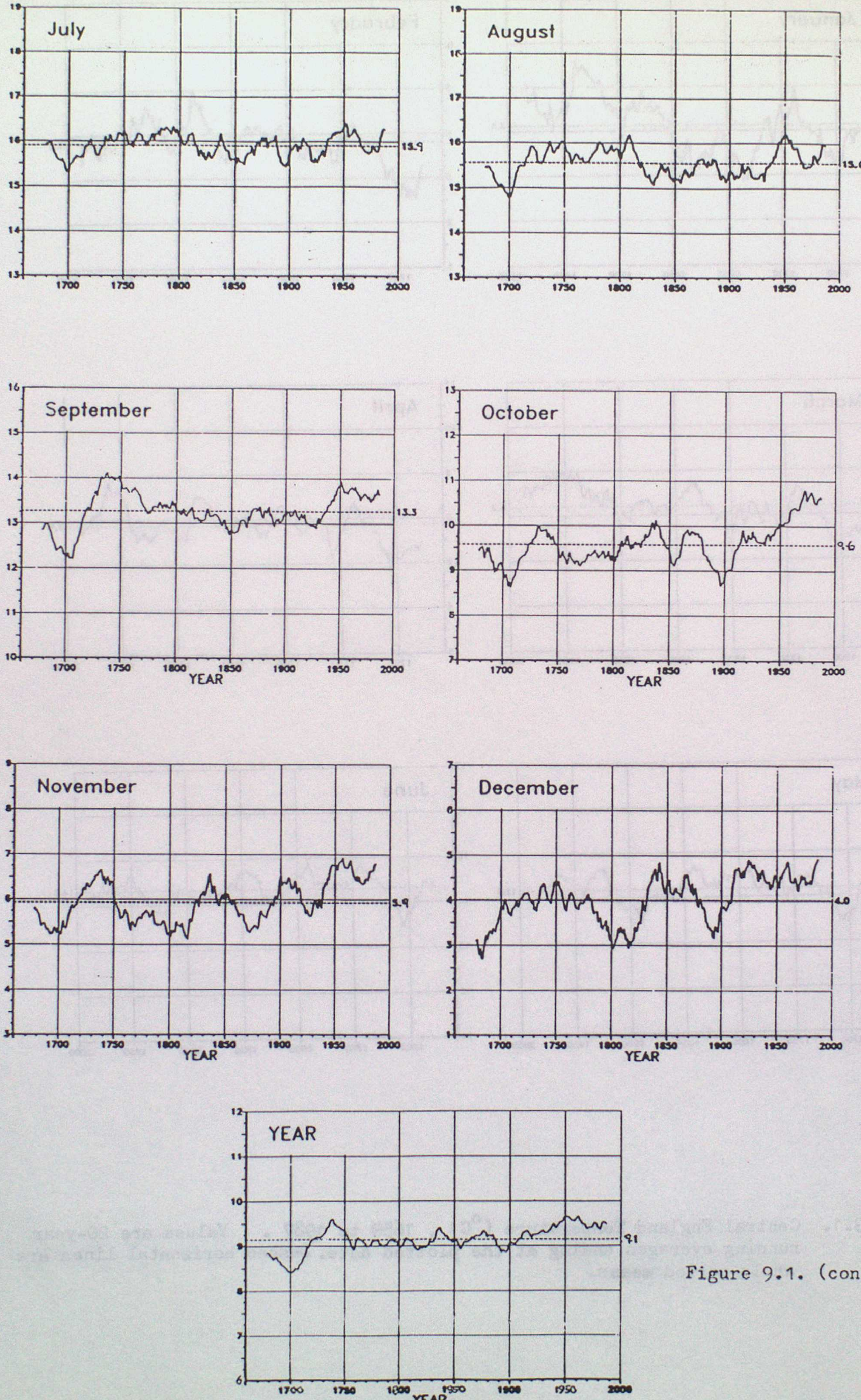
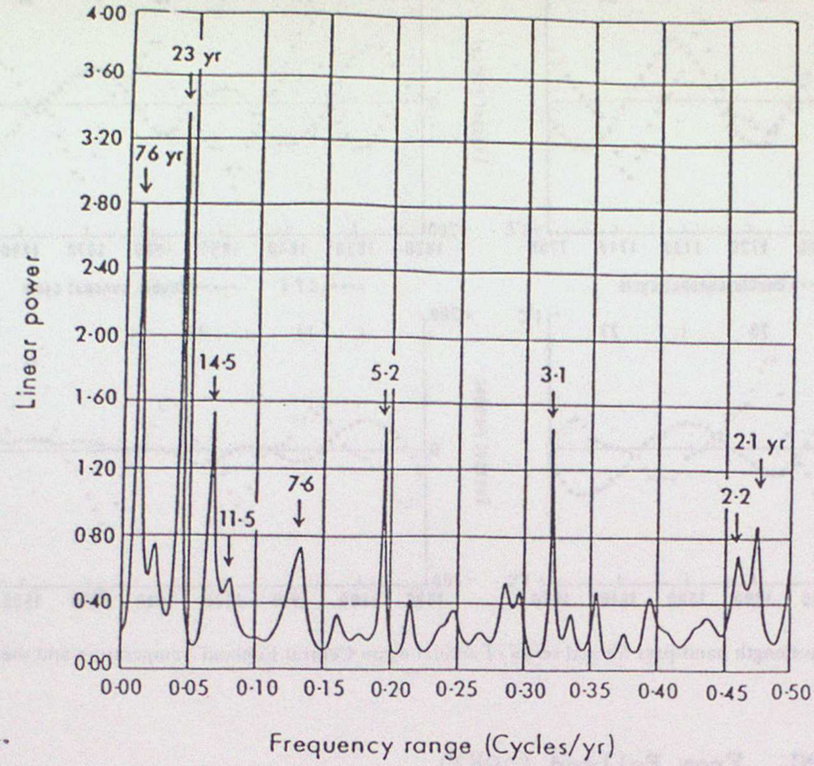
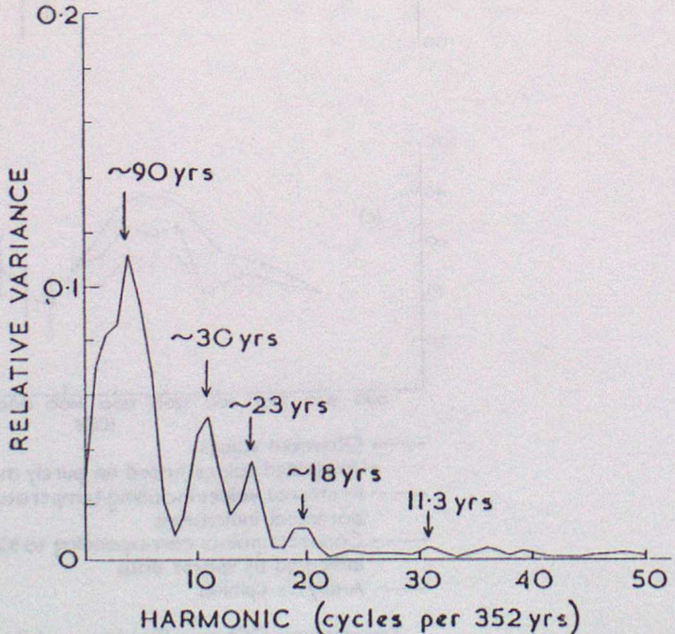


Figure 9.1. (continued)



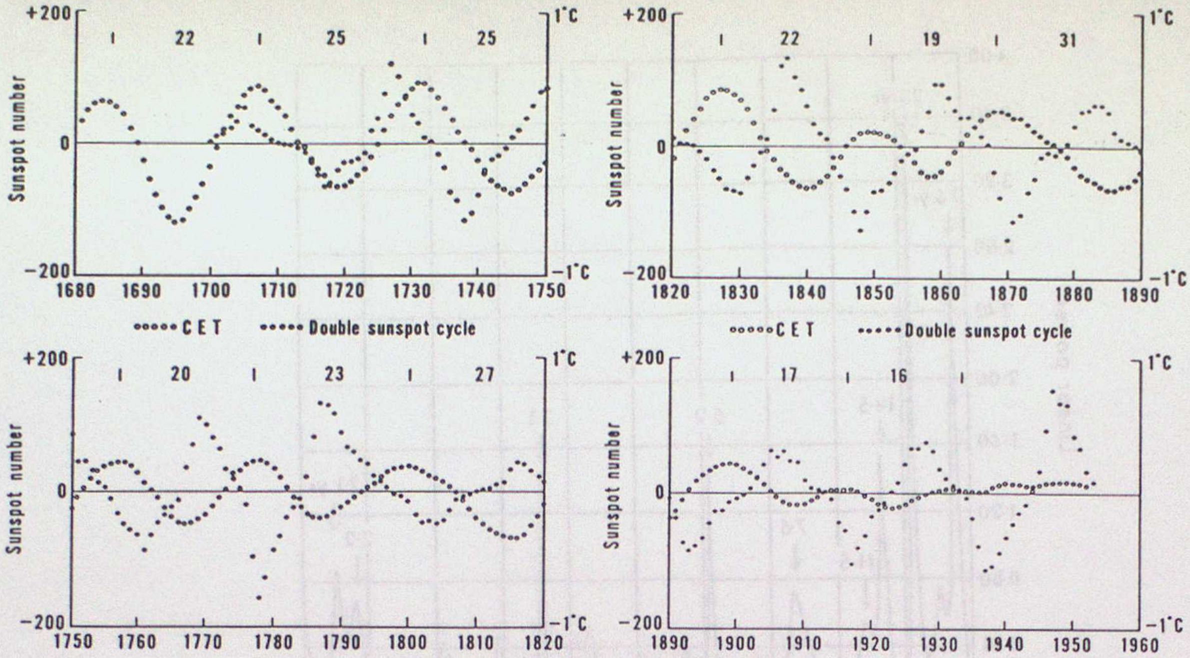
Power spectrum of the Manley record of Central England temperatures with the long-term trend removed.

Figure 9.2A.



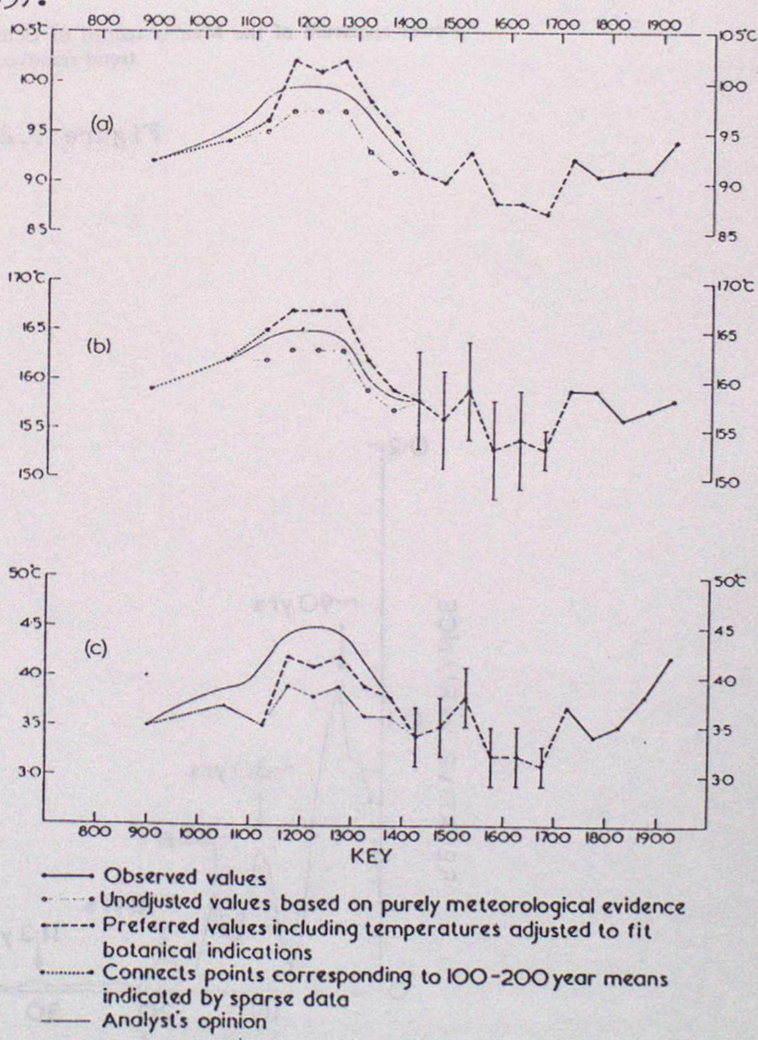
Power spectrum of Sirén's (1961) Lapland tree-ring index from 1463 to 1960, which is believed to register mean temperatures of the high summer period in northern Finland. (*Kindly supplied to the author by* J. M. Mitchell *and reproduced by permission.*)

Figure 9.2B. From Lamb (1972a).



The '23-year' wavelength band-pass filtered series of annual mean Central England Temperature and the 'Hale' or double-sunspot cycle.

Figure 9.2C. From Folland (1983).



Temperatures (°C) prevailing in central England, 50-year averages:

(*a*) Year

(*b*) High summer (July and August)

(*c*) Winter (December, January and February).

Observed values from 1680, as standardized by MANLEY. Values for earlier periods as derived by LAMB (1965). The ranges indicated by the vertical bars are three times the standard error of the estimates.

Figure 9.3. From Lamb (1972a).

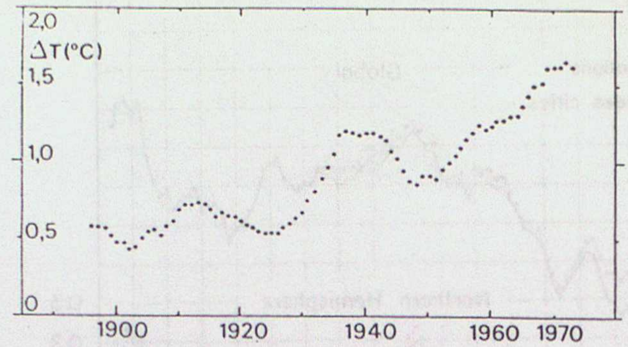


Figure 9.4A. 10-year running mean temperature difference, Paris (Montsouris) minus Besançon. The data are for 1891 to 1977 and the values are plotted at the centre of the averaging interval.

After Dettwiller (1978).

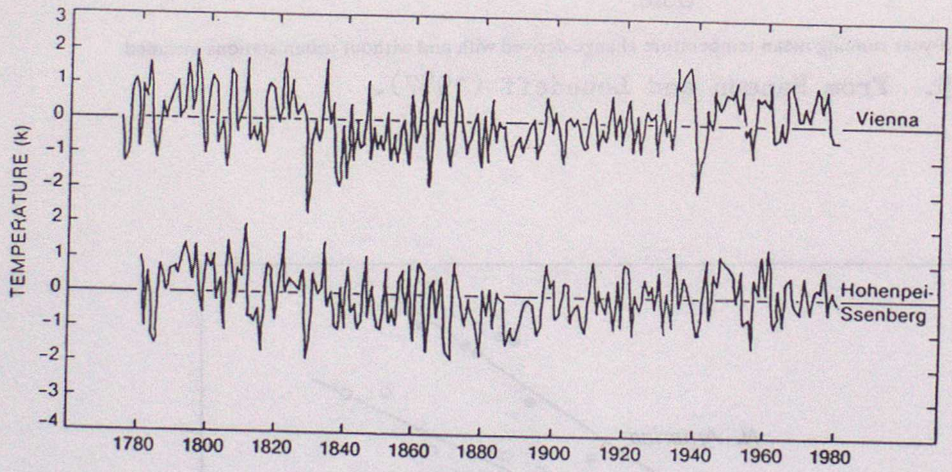
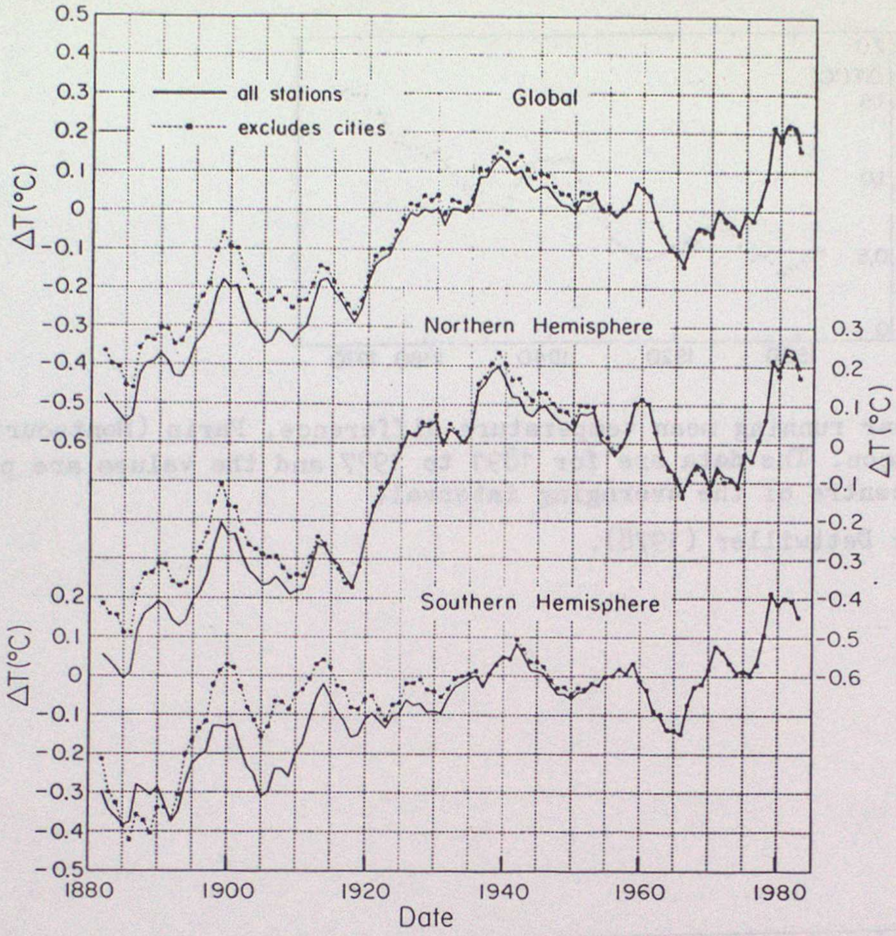


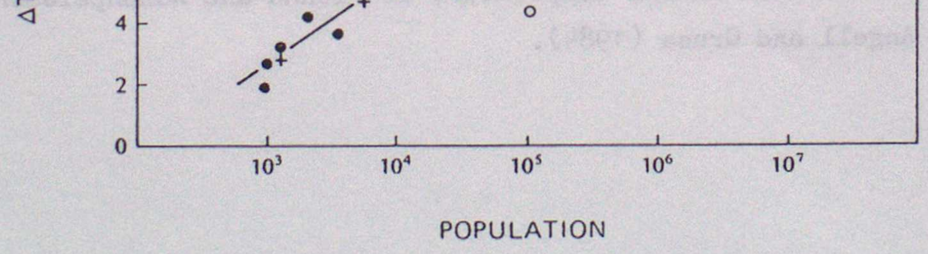
Figure 9.4B. Variation in mean annual temperature at Vienna and Hohenpeissenberg.

After Angell and Gruza (1984).



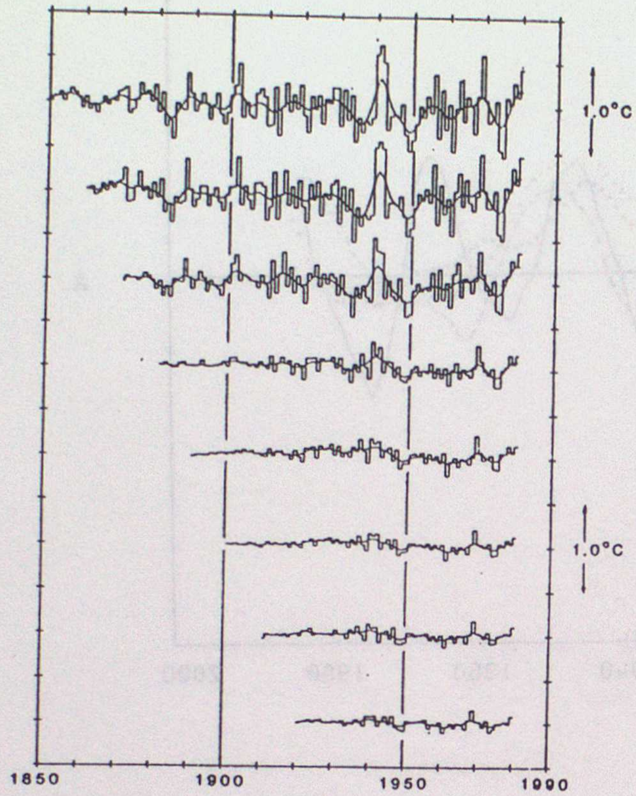
Comparison of 5-year running mean temperature change derived with and without urban stations included.

Figure 9.5. From Hansen and Lebedeff (1987).



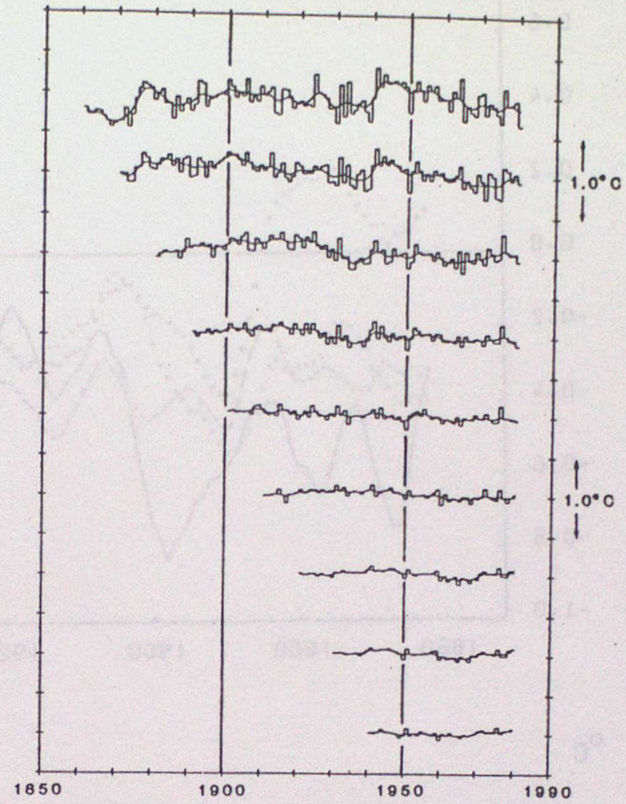
Relation between maximum heat island intensity ($\Delta T_{u-r(max)}$) and population (P) for European and North American settlements. The crosses are for the growing new town of Columbia, Maryland reported by Landsberg (1979).

Figure 9.6. From Oke (1982).



. Estimating the effect of incomplete coverage during the early years. Each curve shows the difference between the result from the time-varying grid and Northern Hemisphere averages based only on grid points with data during at least 80% of the decades (top to bottom): 1850s, 1860s, 1870s, 1880s, 1890s, 1900s, 1910s and 1920s. The filtered curve is a 13-term Gaussian filter designed to suppress variations on time scales less than 10 years. In order to estimate filtered values at the ends of each curve, six extra years are used at each end with values equal to the mean of the six years at the beginning/end of each curve.

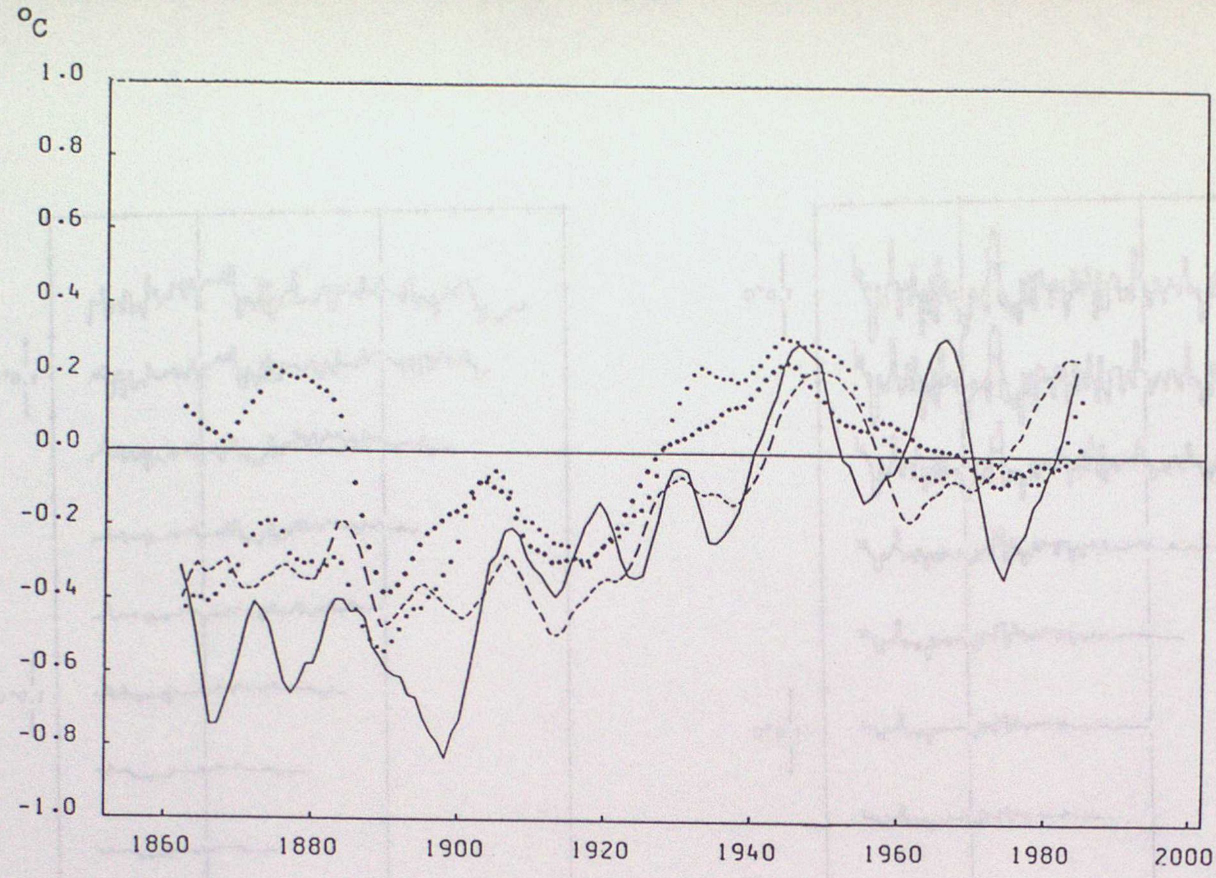
Figure 9.7A. After Jones et al (1986)



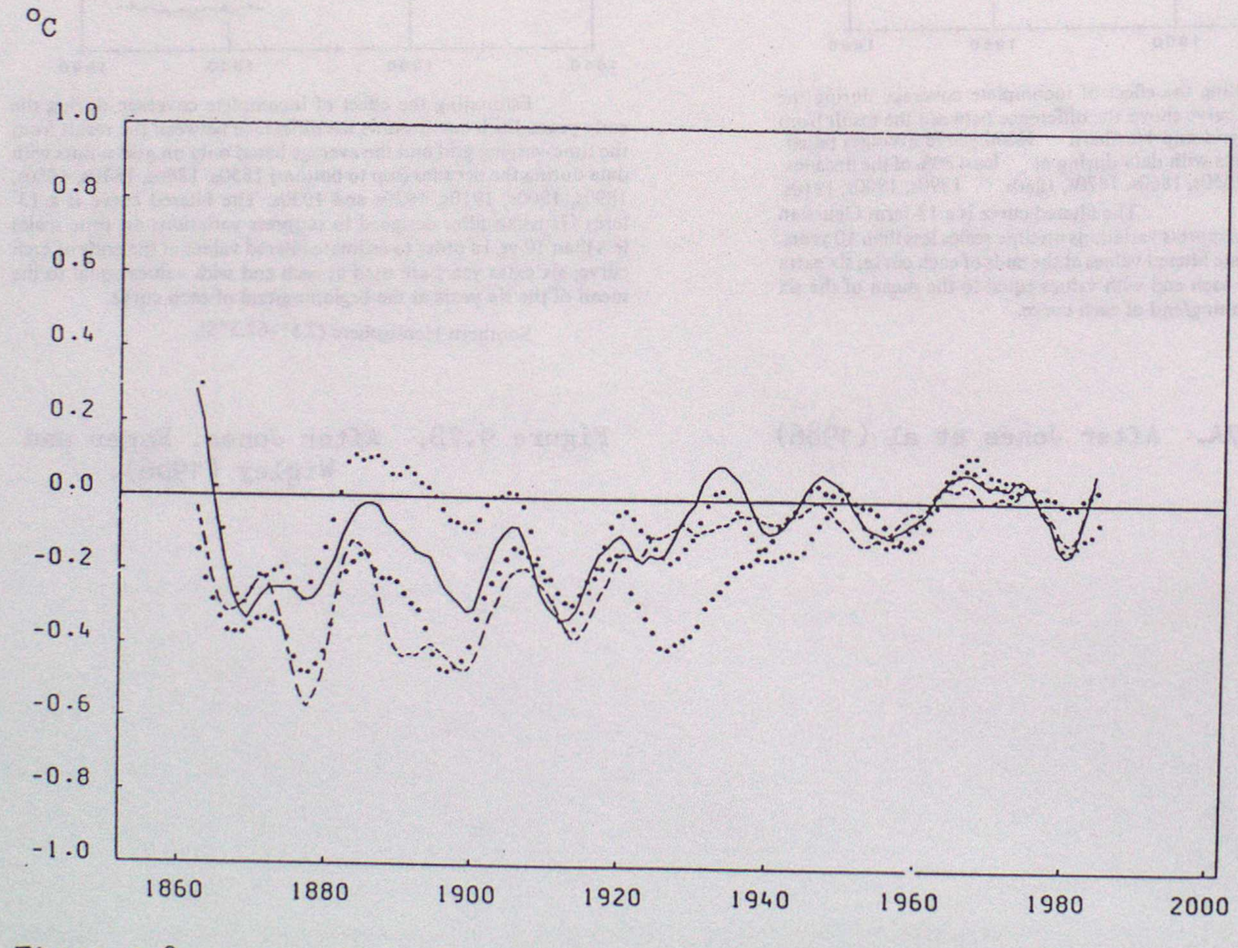
Estimating the effect of incomplete coverage during the early years. Each curve shows the difference between the result from the time-varying grid and the average based only on grid points with data during the decades (top to bottom) 1850s, 1860s, 1870s, 1880s, 1890s, 1900s, 1910s, 1920s and 1930s. The filtered curve is a 13-term Gaussian filter designed to suppress variations on time scales less than 10 yr. In order to estimate filtered values at the ends of each curve, six extra years are used at each end with values equal to the mean of the six years at the beginning/end of each curve.

Southern Hemisphere (2.5°–62.5°S).

Figure 9.7B. After Jones, Raper and Wigley (1986).



A



B

Figure 9.8. Land surface air temperature anomalies (w.r.t. 1951-80) for 1852 to 1984 averaged over the Northern Hemisphere (A), the Southern Hemisphere north of $62\frac{1}{2}^{\circ}$S (B), and central and northern Europe (45°-65°N, 25°W-60°E) (C; on next page), plotted against the end-date of an 11-year triangular smoothing filter. Dec-Feb, Mar-May, June-Aug, Sept-Nov are solid line, dashed line, round dots, square dots. Data from P.D.Jones, University of East Anglia.

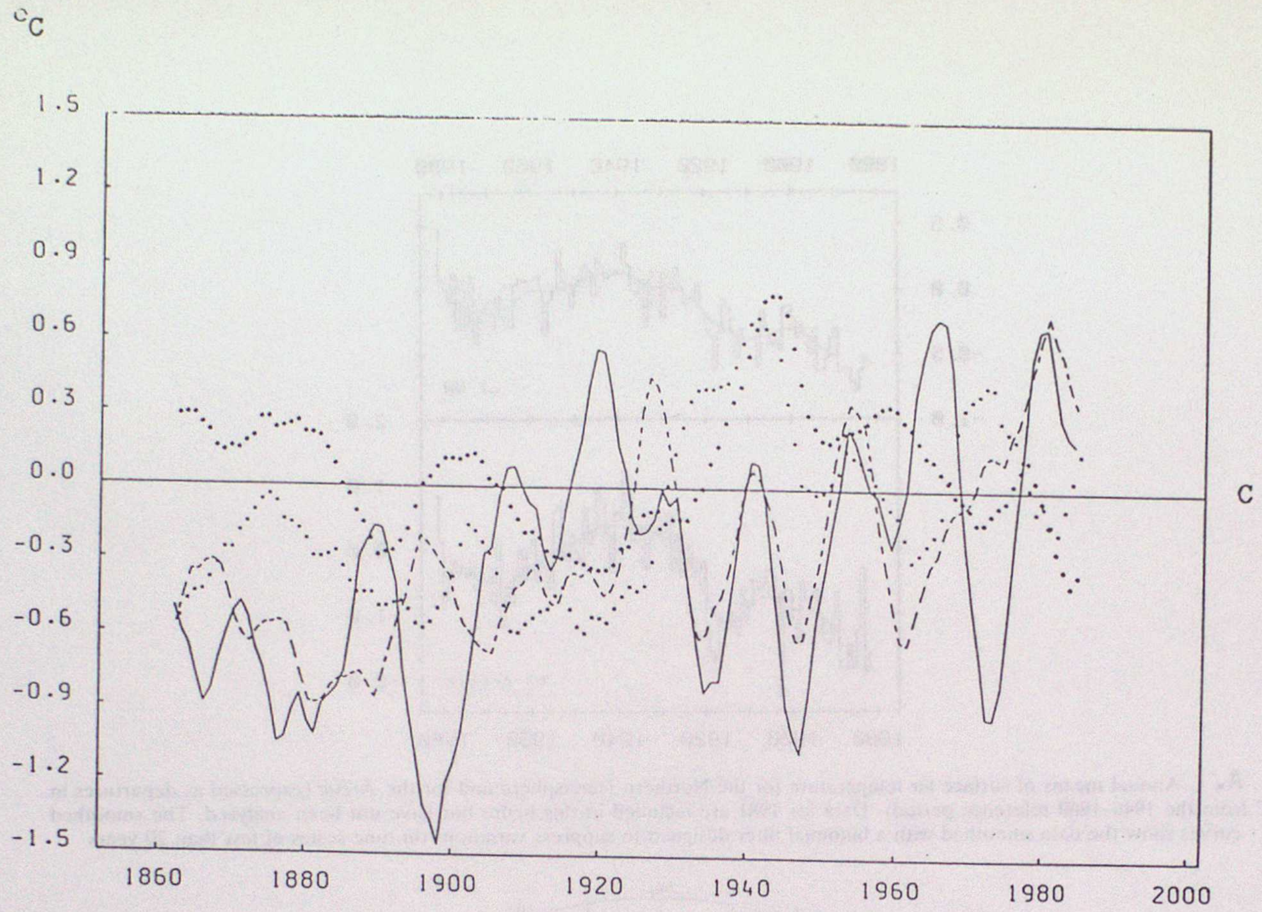
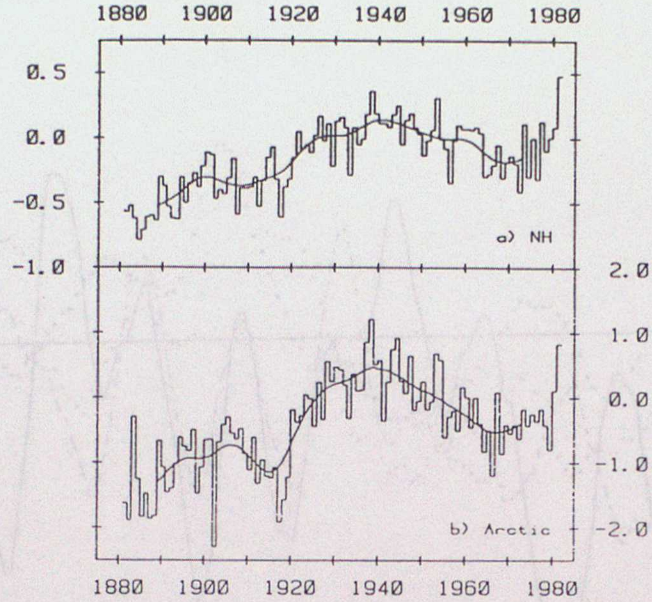
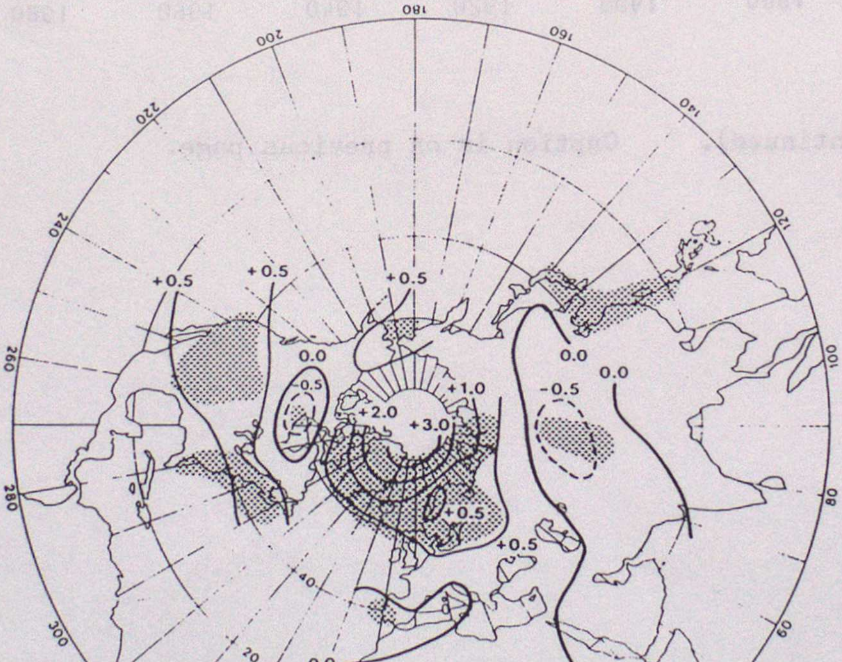


Figure 9.8. (continued). Caption is on previous page.



A. Annual means of surface air temperature for the Northern Hemisphere and for the Arctic (expressed as departures in °C from the 1946–1960 reference period). Data for 1981 are included in this figure but have not been analyzed. The smoothed curves show the data smoothed with a binomial filter designed to suppress variations on time scales of less than 20 years



B. Linear trend of gridpoint temperatures over the period 1917–1939 (°C/y×10⁻¹). Shaded areas are significant at the 5 per cent level

Figure 9.9. From Jones and Kelly (1983).

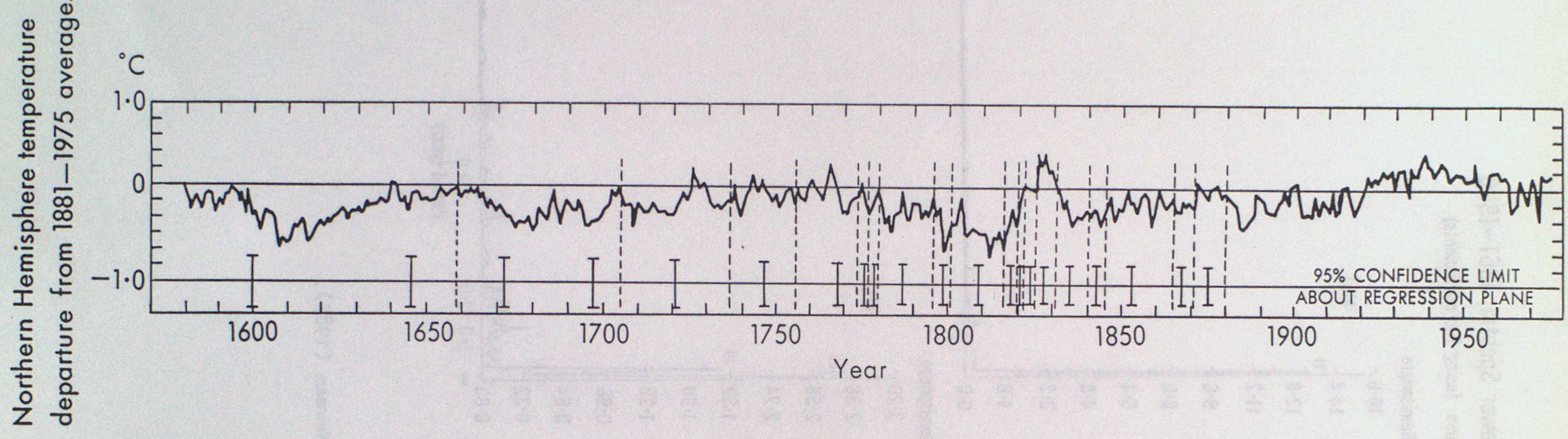


FIGURE 9.10 RECONSTRUCTED ANNUAL TEMPERATURE DEPARTURES (1579—1880) FOR THE NORTHERN HEMISPHERE FOLLOWED BY DATA OF BORZENKOVA et al., (1976). AFTER GROVEMAN AND LANDSBERG (1979). Confidence limits of regressions at bottom of graph.

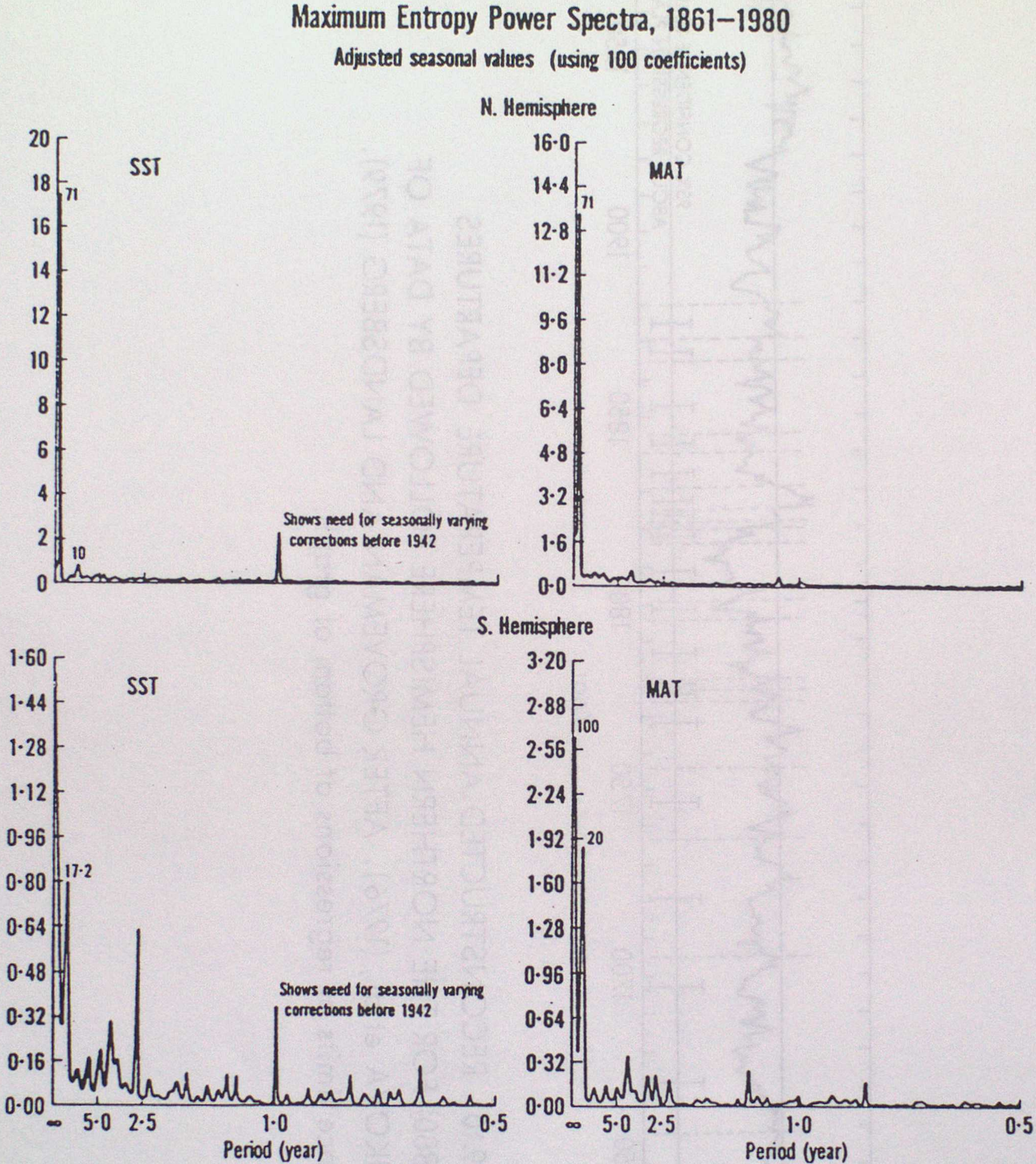
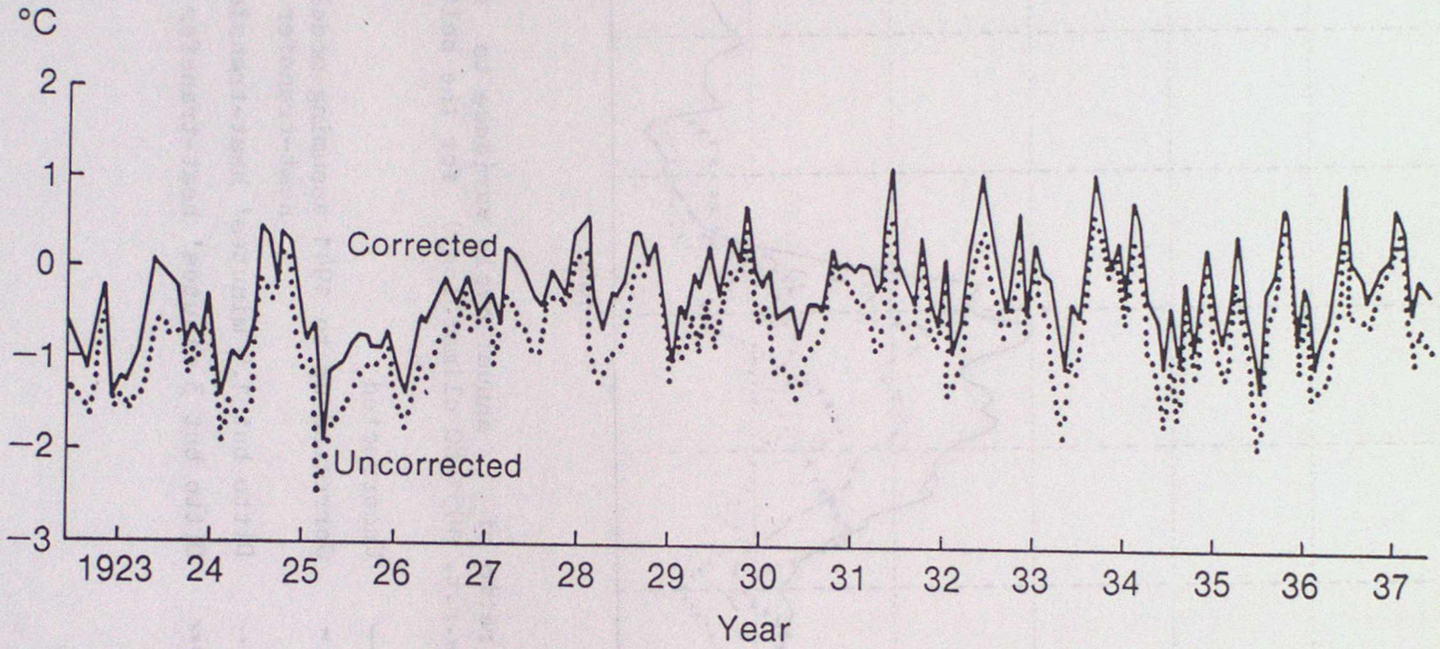


Figure 9.11. From Folland, Parker and Newman (1985).



Monthly SST anomalies (relative to 1951–80) for 1923–1937, 35°–45° N; 60°–70° W, with and without corrections for the use of uninsulated buckets. Tick marks are in July of each year.

Figure 9.12. From Bottomley et al (1988).

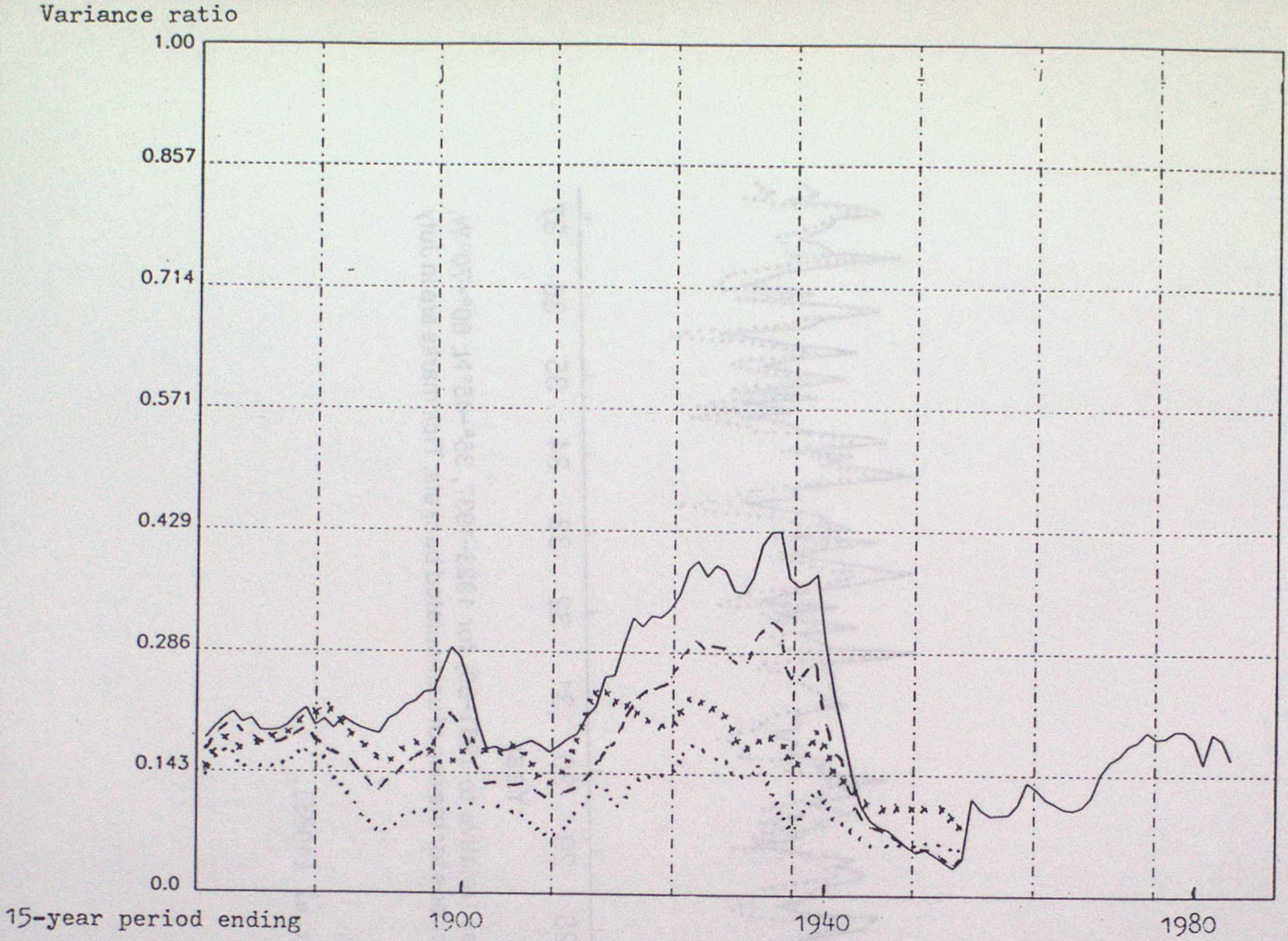


Figure 9.13A. 15-year running ratio of annual cycle variance to total variance of monthly SST anomalies (w.r.t. 1951-80 climatology) for the belt 30°N to 40°N.

KEY

	————	Uncorrected
	- - - - -	Corrected up to 1941 assuming model D9 with 0.5 minutes heat-transfer time.
	·········	Ditto but 1.5 minutes' heat-transfer time.
	×××××××××	Ditto but 3 minutes' heat-transfer time.

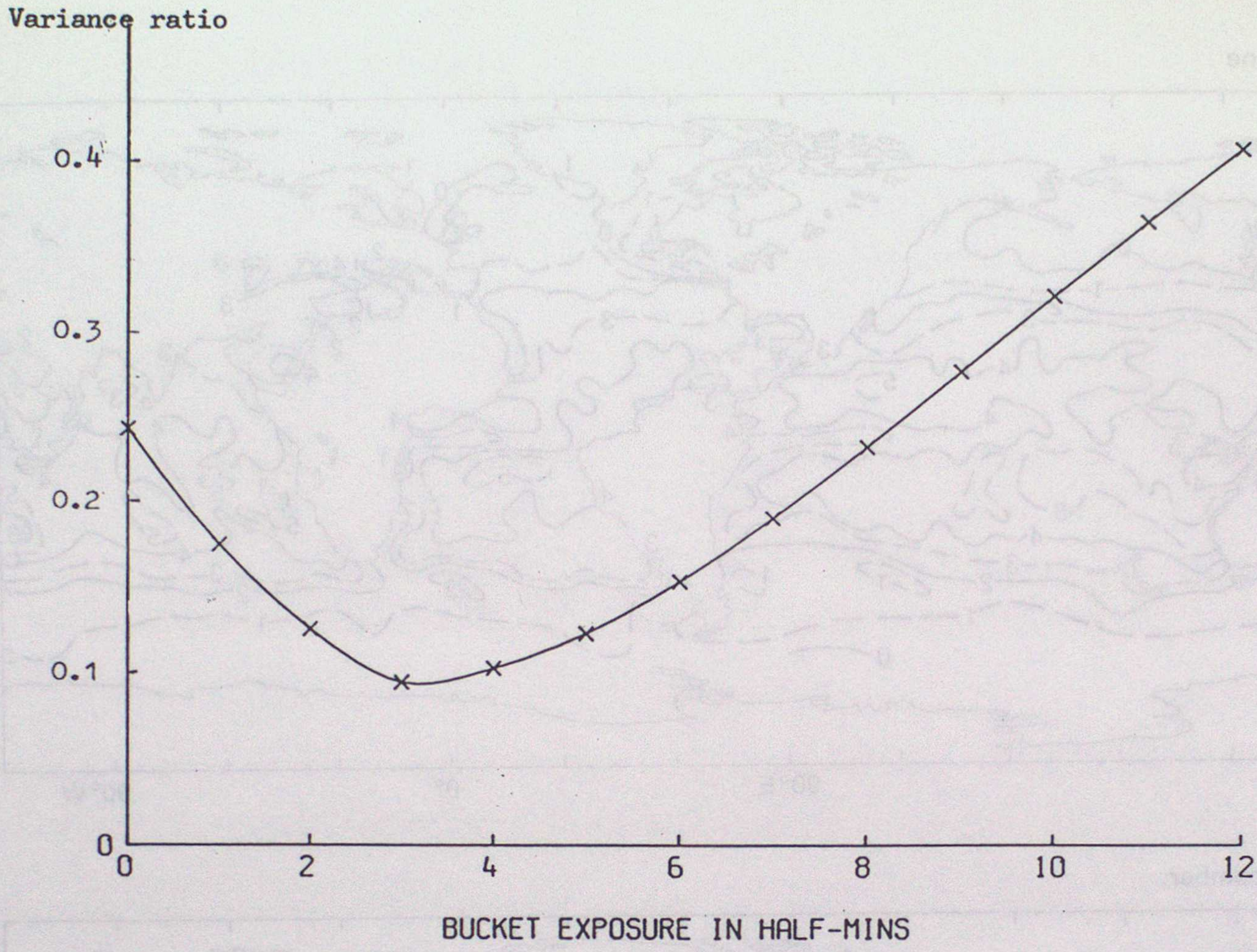
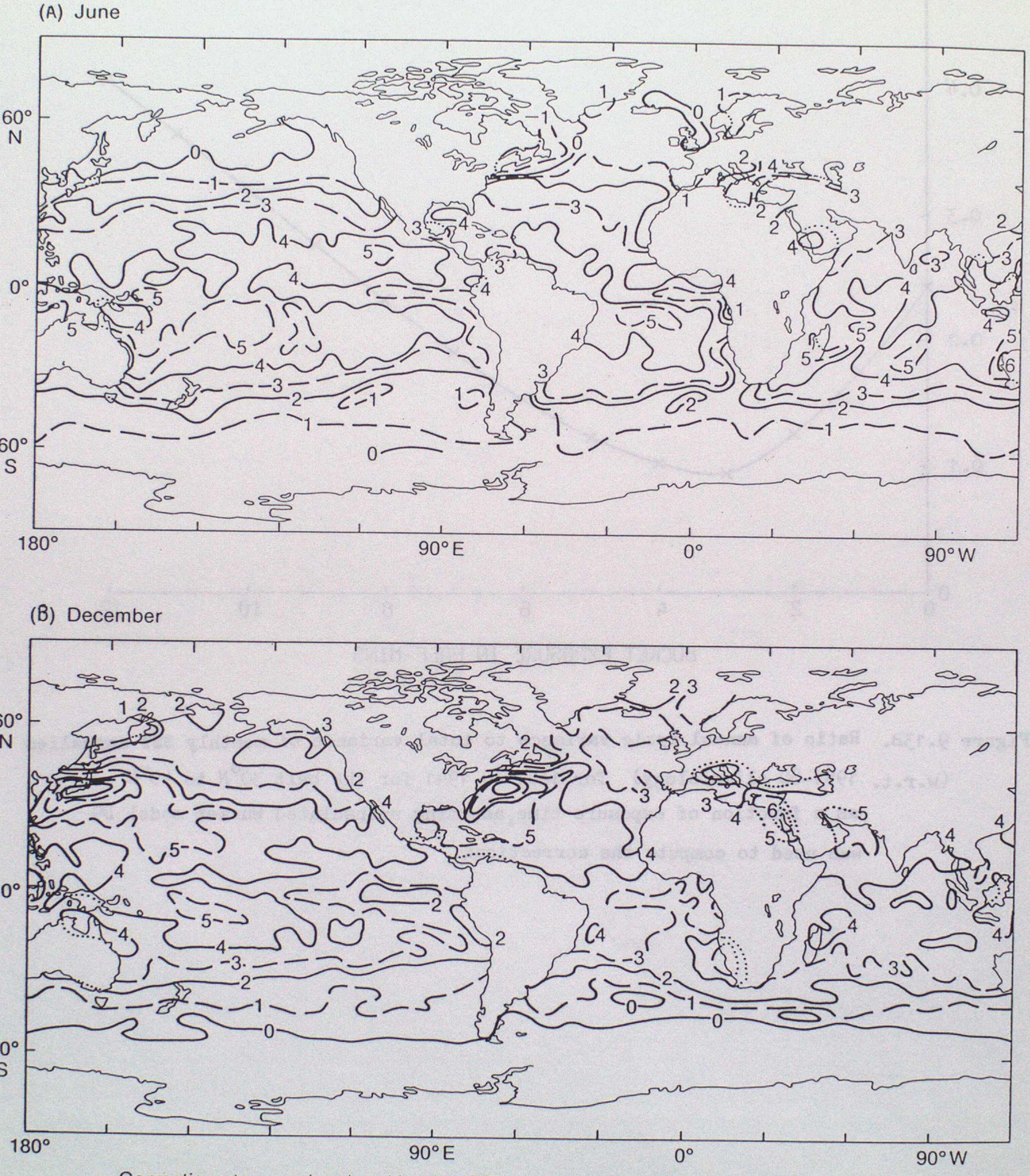


Figure 9.13B. Ratio of annual cycle variance to total variance of monthly SST anomalies (w.r.t. 1951-80 climatology) for 1881 to 1941 for the belt 30°N to 40°N, as a function of exposure time, assuming uninsulated bucket model D9 was used to compute the corrections.



Corrections to uninsulated bucket SST applied up to 1900 (tenths °C)

Figure 9.14. From Bottomley et al (1988).

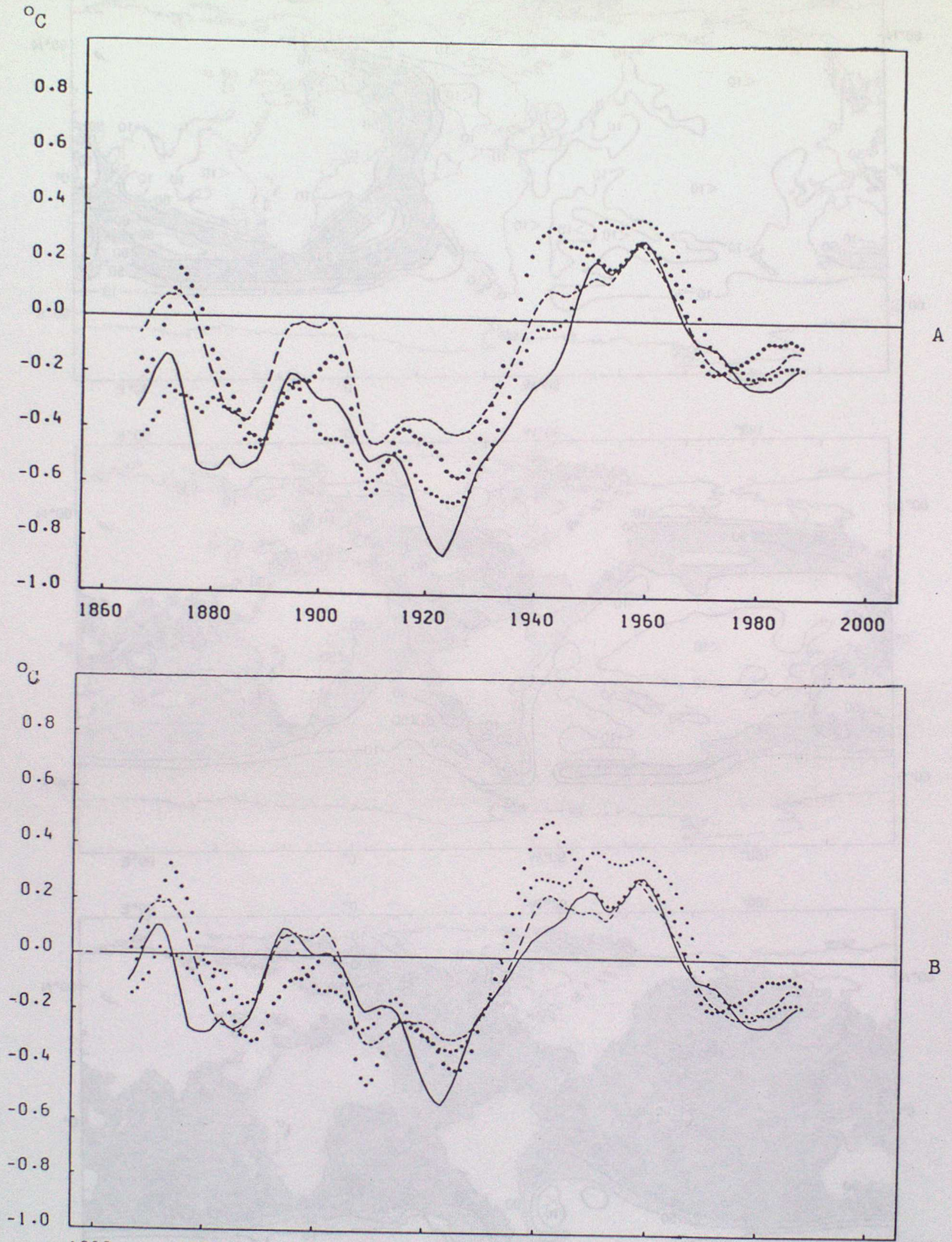
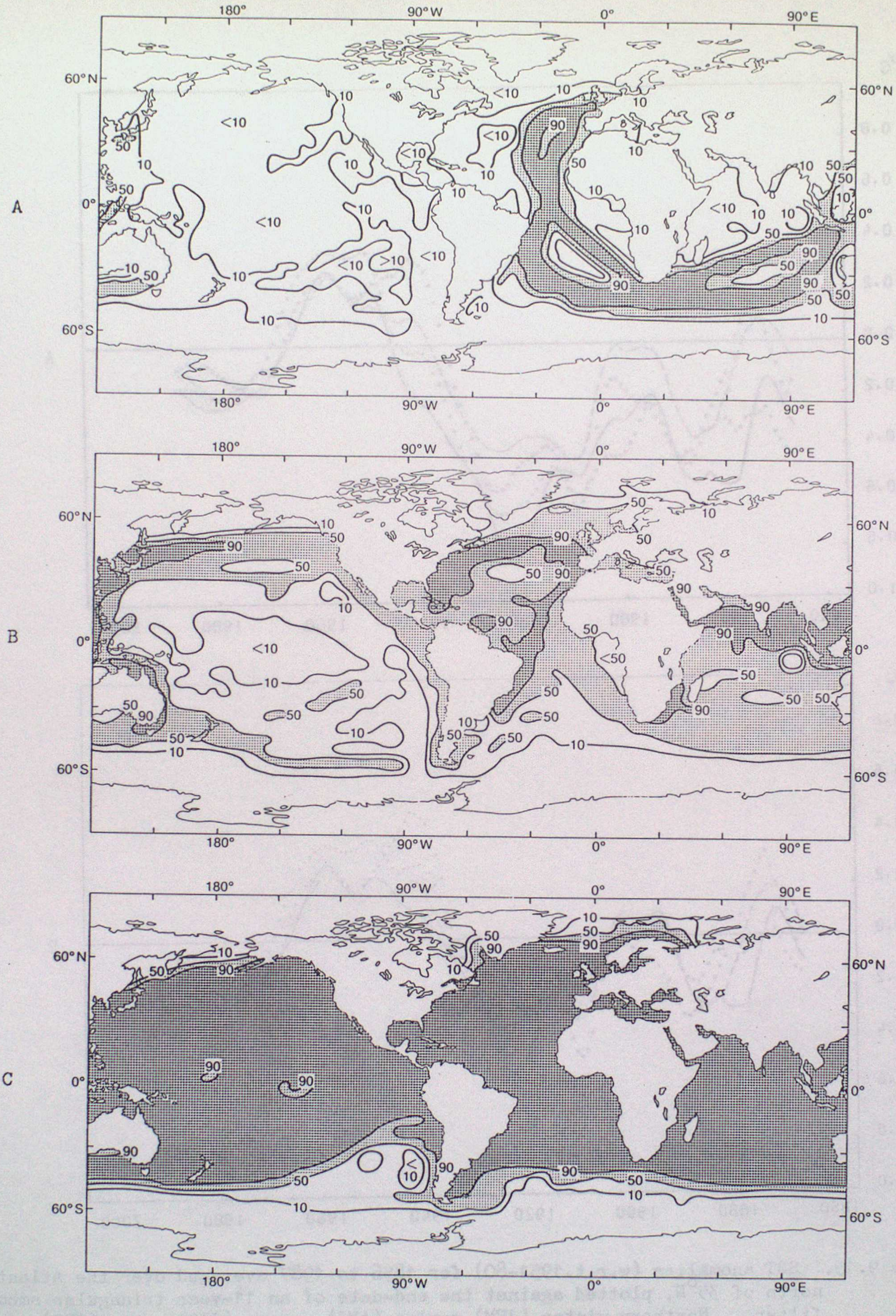


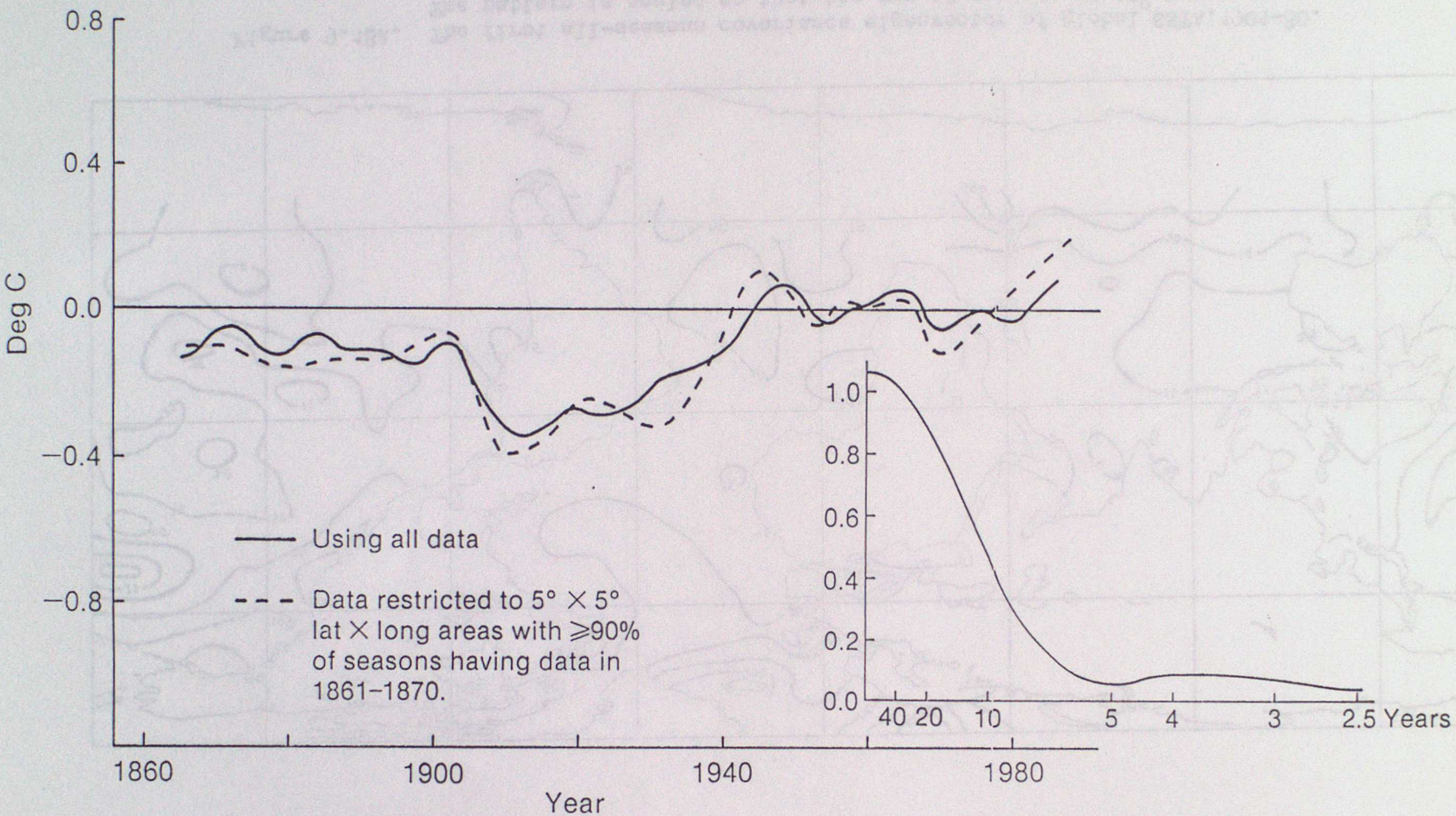
Figure 9.15. SST anomalies (w.r.t.1951-80) for 1856 to 1987 averaged over the Atlantic north of 35°N, plotted against the end-date of an 11-year triangular smoothing filter. Northern winter (JFM), spring (AMJ), summer (JAS), autumn (OND) are solid line, dashed line, round dots, square dots.
A. No instrumental corrections. B. Instrumental corrections as in Bottomley et al (1988).



Percentage of seasons with SST data (on a 5° × 5° space scale).
A) 1861-70; B) 1911-20; C) 1971-80.

>90%   50-90%

Figure 9.16. From Bottomley et al (1988).



Global SST w.r.t. 1951–80. Values plotted at end date of 10.25 year triangular filter (magnification function given in inset). Bucket corrections applied to SST up to 1941.

Figure 9.17. From Bottomley et al (1988).

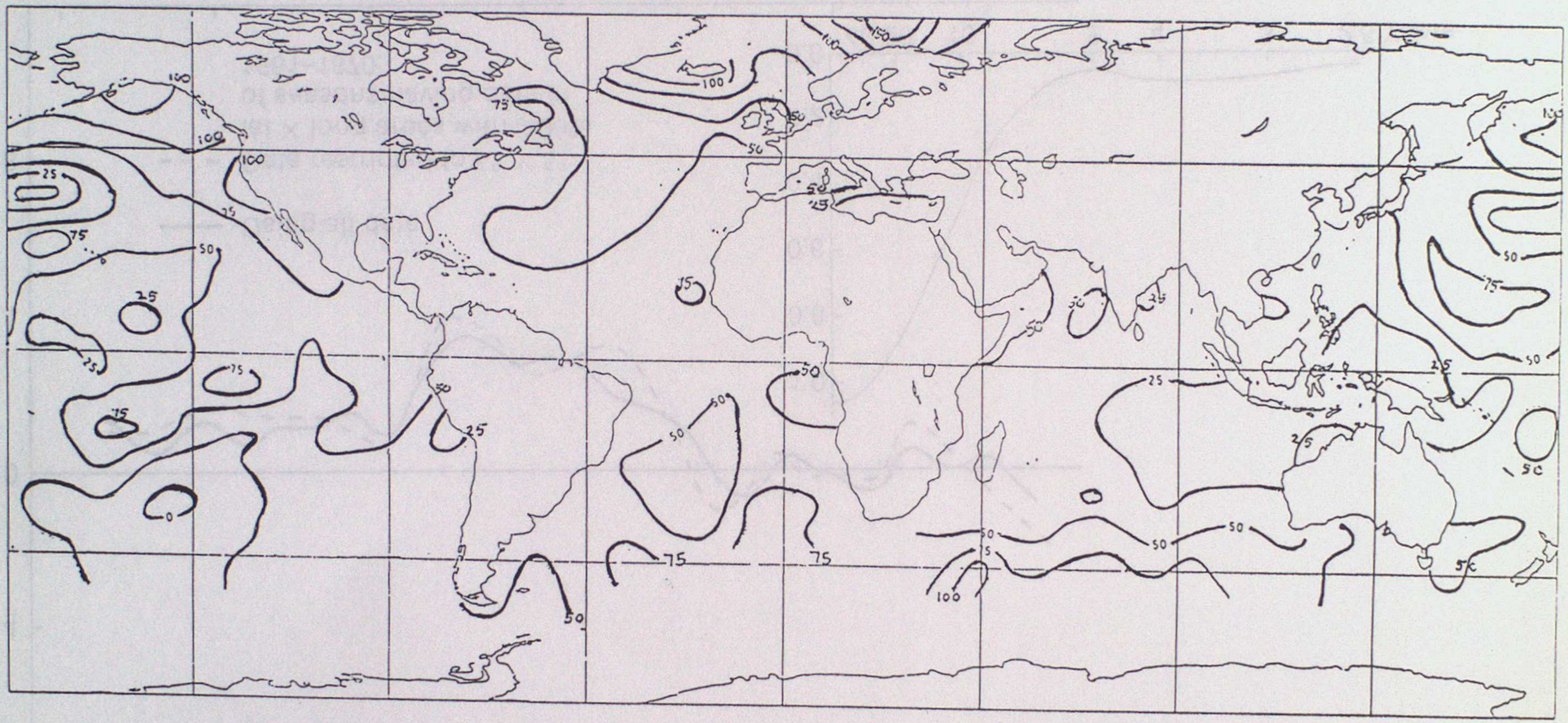


Figure 9.18A. The first all-seasons covariance eigenvector of global SSTA, 1901-80. The pattern is scaled so that the sum of squares of 10^o latitude x longitude values equals 10^6. Instrumental corrections as in Bottomley et al (1988).

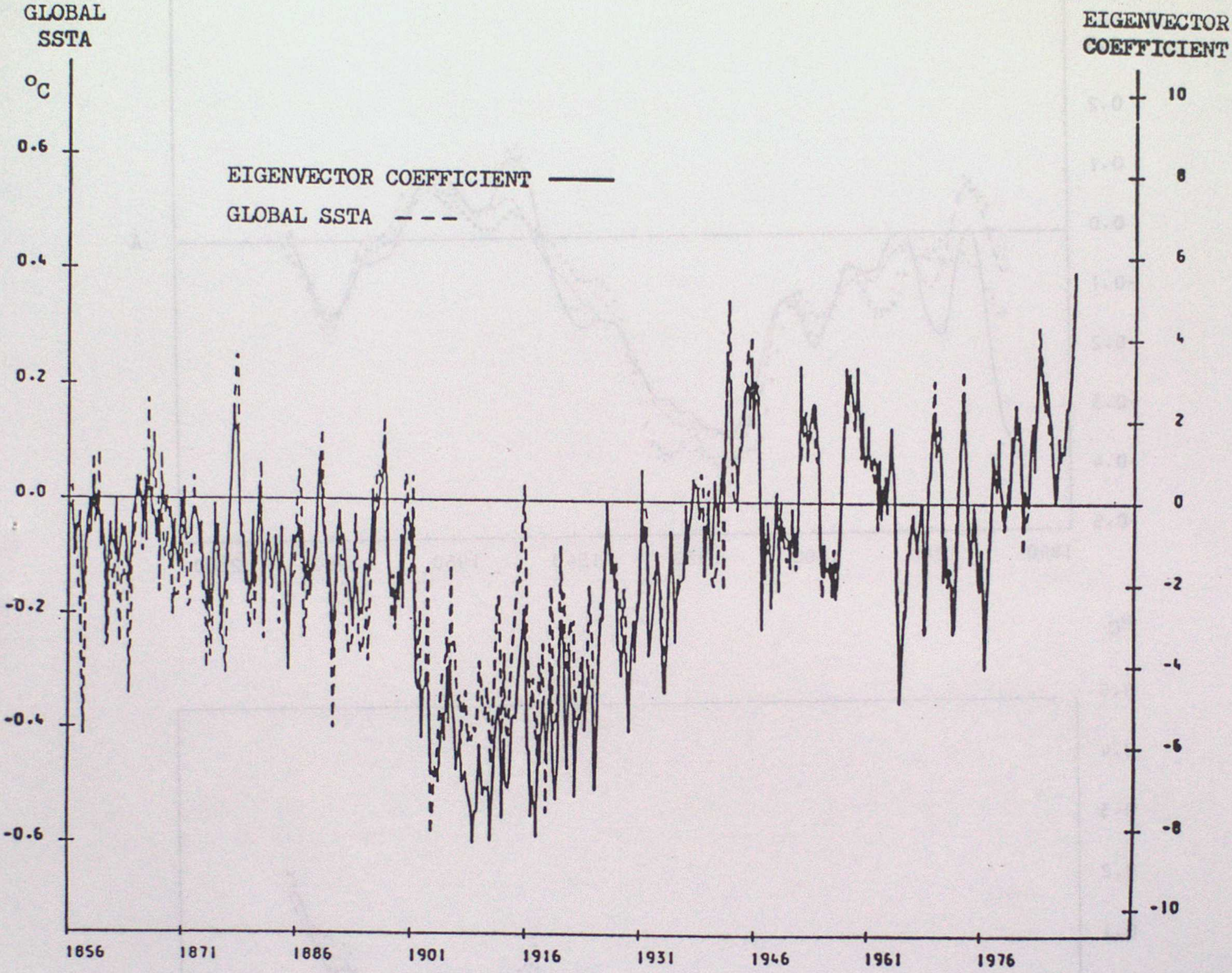
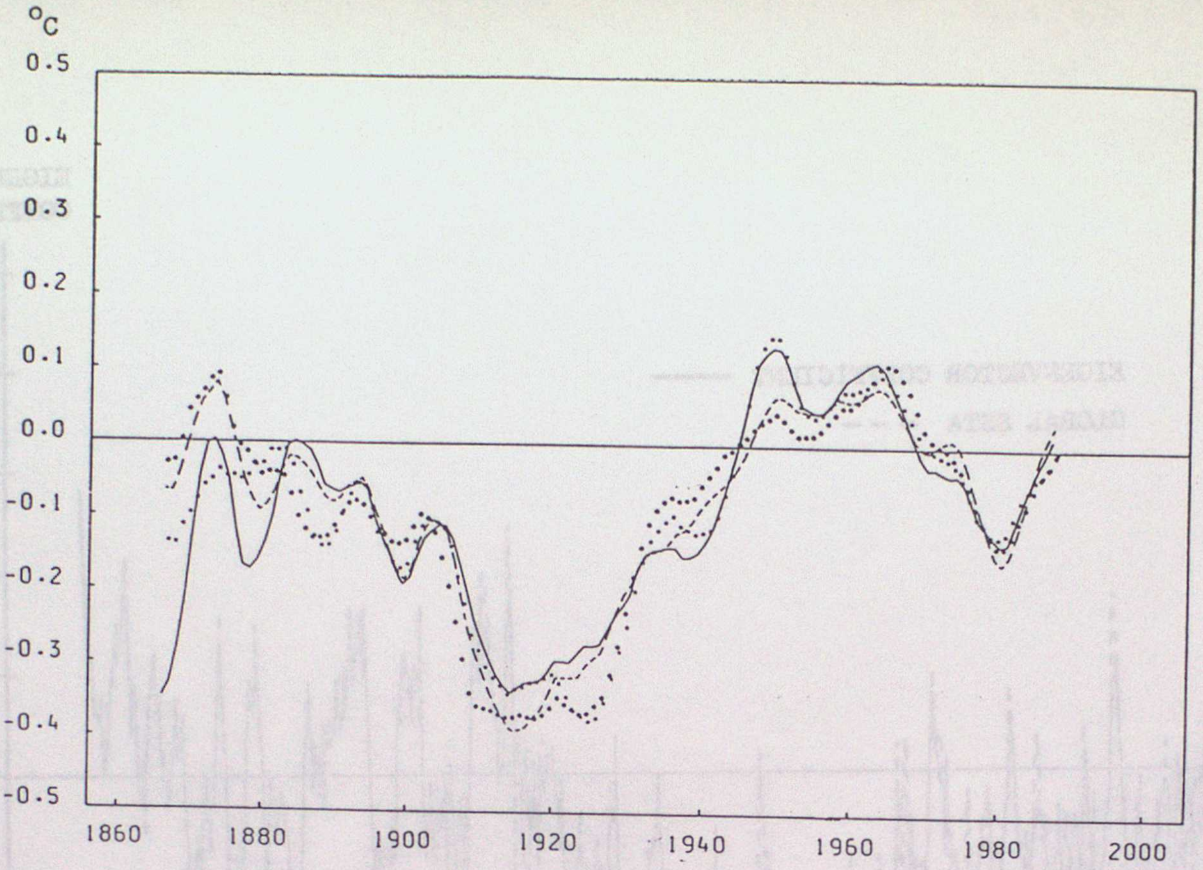


Figure 9.18B. Seasonal time series for 1856 to 1987 of the coefficient of the first all-seasons covariance eigenvector of global SSTA weighted according to the area of the appropriate 10° latitude x 10° longitude square, along with seasonal time series of global SSTA. Instrumental corrections as in Bottomley et al (1988).



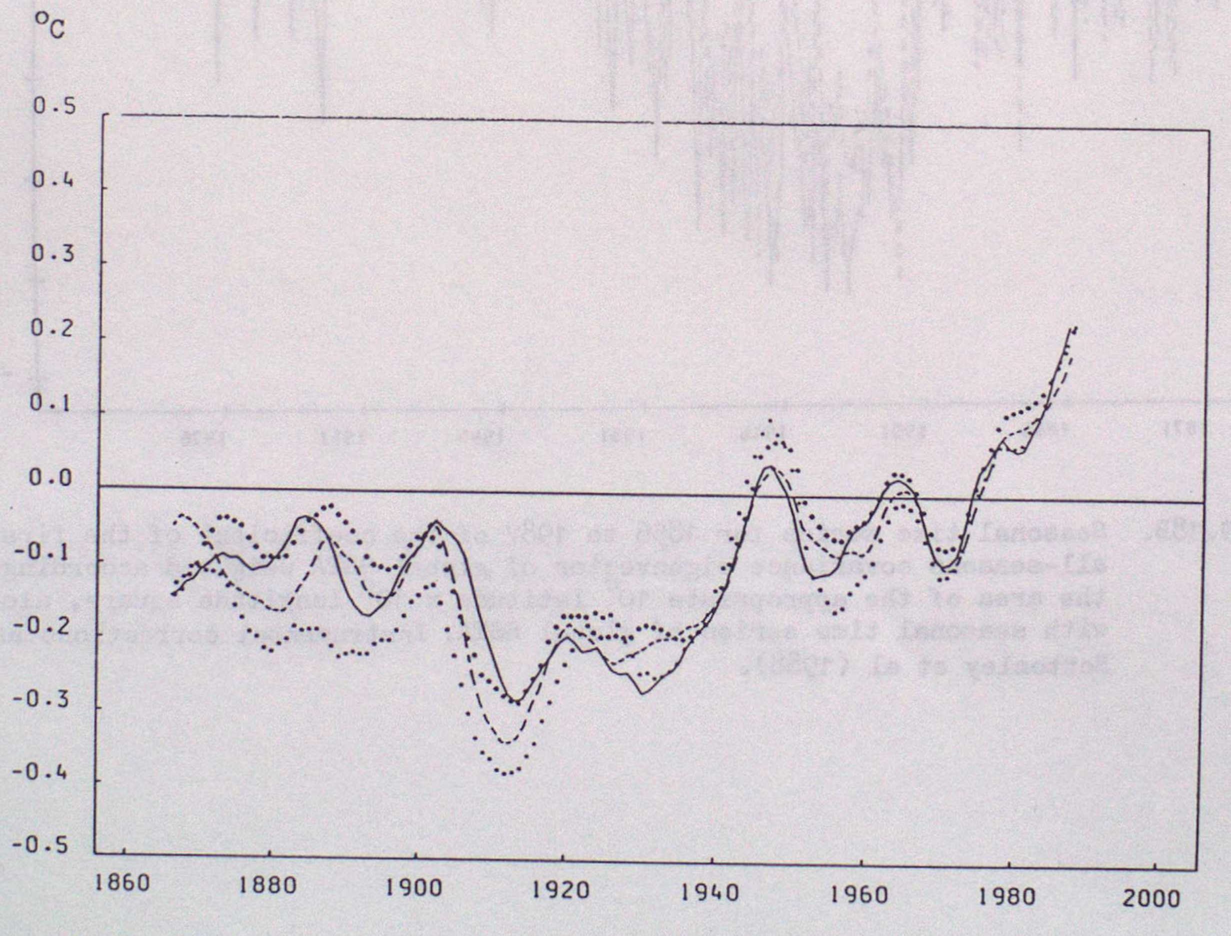


Figure 9.19. SST anomalies (w.r.t. 1951-80) for 1856 to 1987 averaged over the Northern Hemisphere (A) and the Southern Hemisphere (B) , plotted against the end-date of an 11-year triangular smoothing filter. Jan-Mar, Apr-Jun, Jul-Sept, Oct-Dec are solid line, dashed line, round dots, square dots. Instrumental corrections as in Bottomley et al (1988).

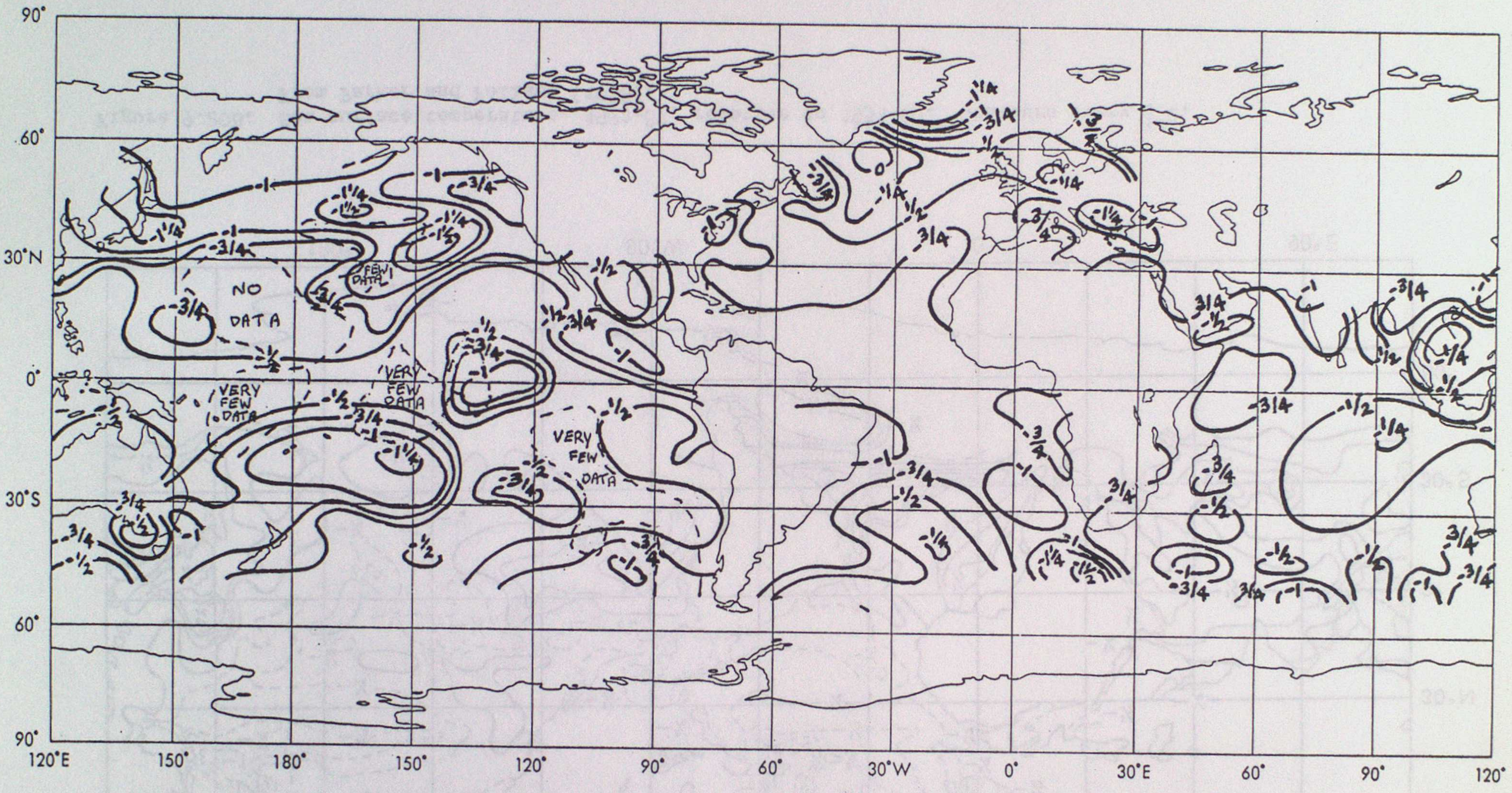


Figure 9.20A. Sea surface temperature, 1903-12, relative to 1951-80. Contours every $\frac{1}{4}$°C. Instrumental corrections as in Bottomley et al (1988).

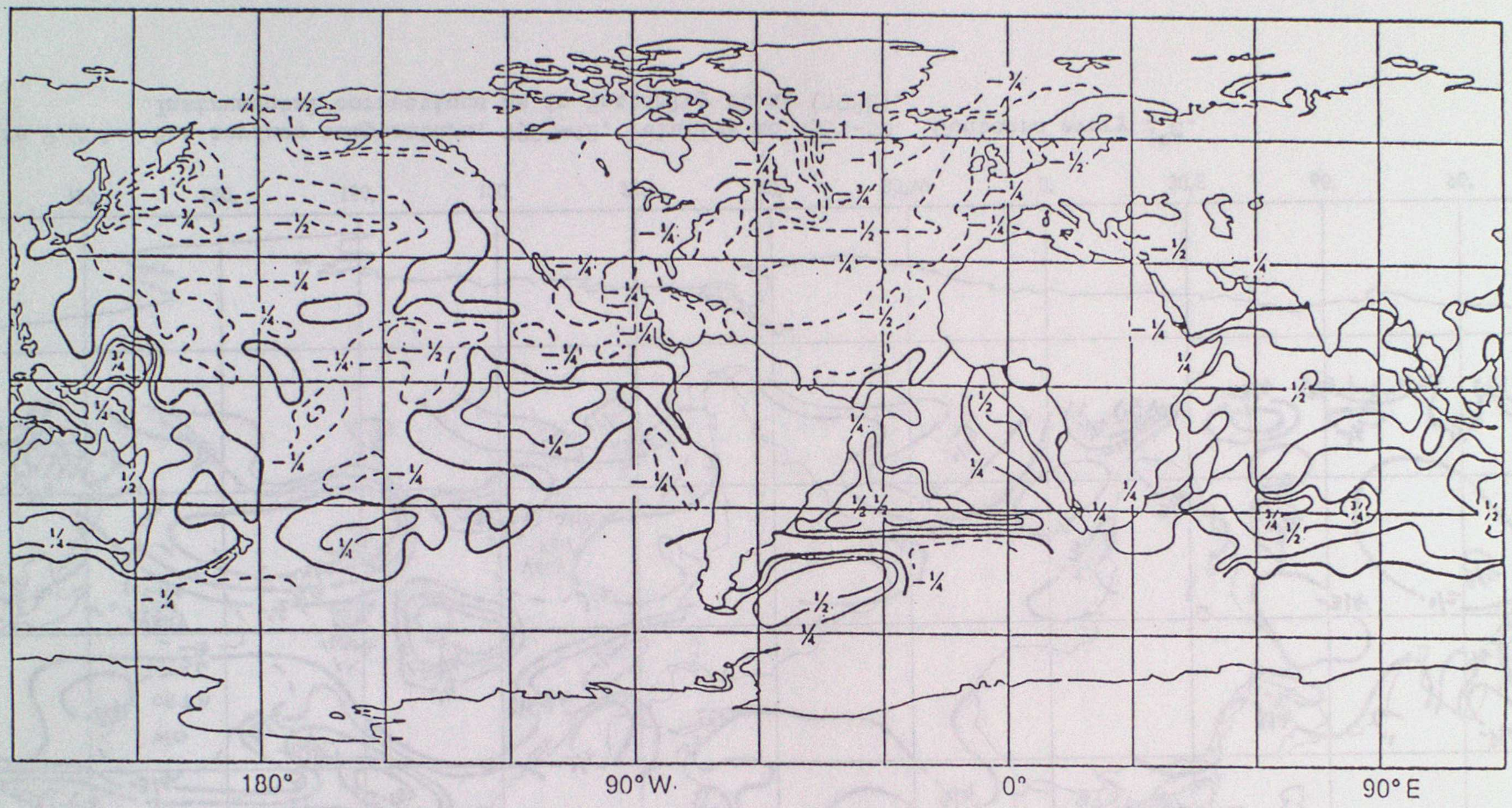


Figure 9.20B. Sea surface temperature, 1971-87, relative to 1951-60. Contours every $\frac{1}{4}$°C. From Parker and Folland (1988).

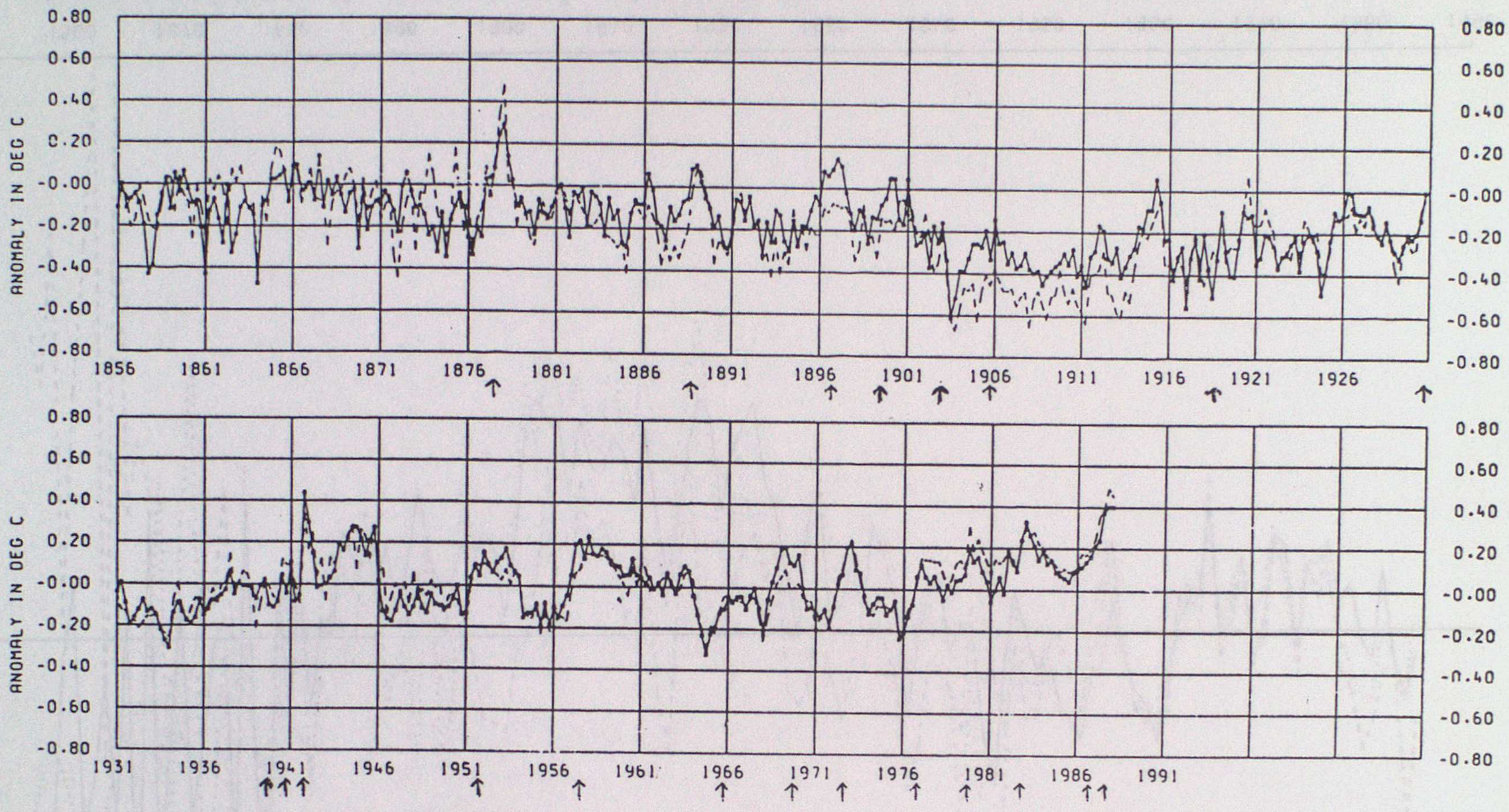


Figure 9.21. Seasonal sea surface temperature (solid) and night marine air temperature (dashed) anomalies (w.r.t. 1951-80) averaged over the globe , 1856 to 1987. Instrumental corrections as in Bottomley et al (1988). Arrows mark Oct to Dec of El Nino years.

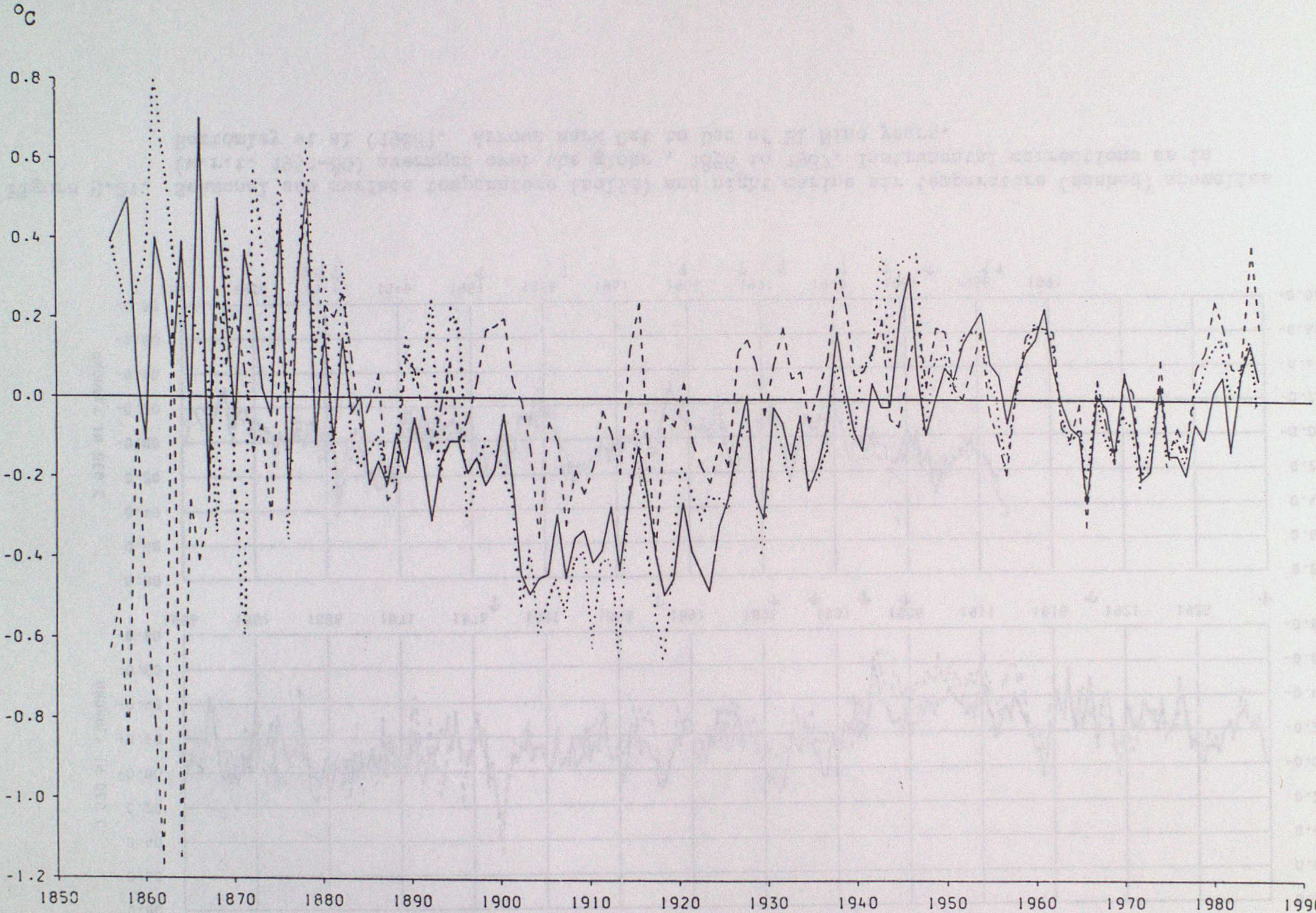


Figure 9.22. Annual land surface air temperature (----), ships' SST (——) and ships' night marine air temperature (....), w.r.t. 1951-80, averaged over selected islands in the Northern Hemisphere.

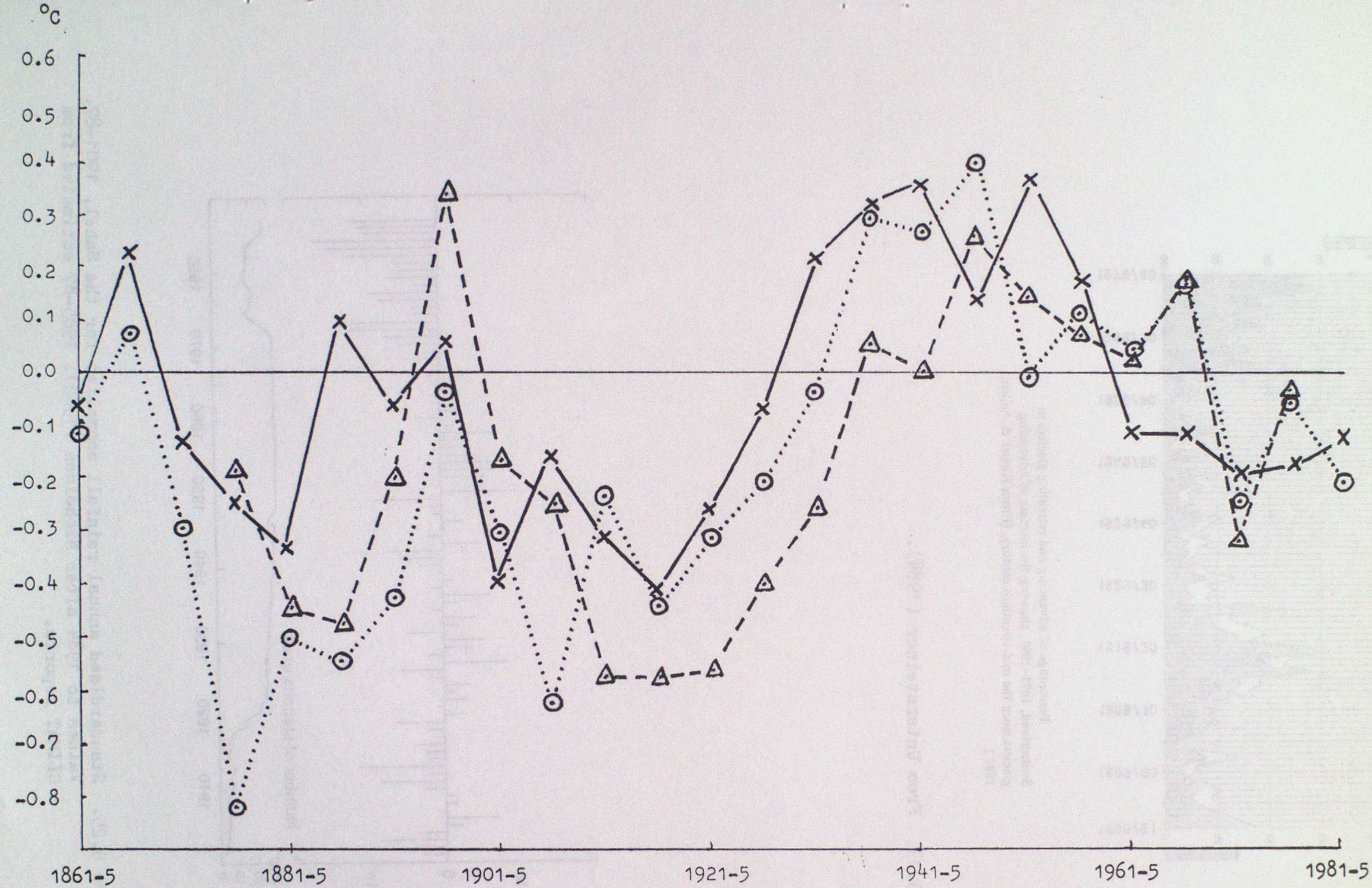
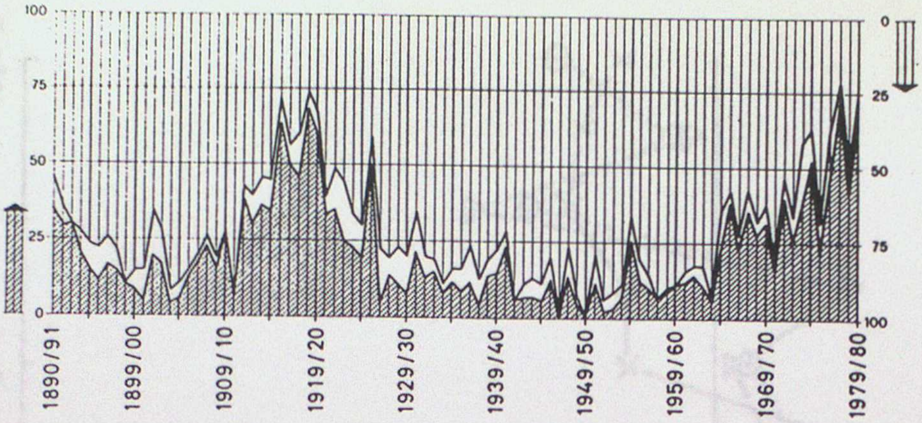


Figure 9.23. Solid line: Averages of seasonal SST anomalies w.r.t. 1951-80 for the Atlantic north of 35°N, weighted by the frequency of Lamb's circulation types NW,SW,CSW,W,CW (Lamb (1972b)), excluding isolated days and first days of spells.

Dashed line: Average temperature anomalies w.r.t. 1951-80 for the Scilly Is. on days with Lamb's circulation types NW,SW,CSW,W,CW, excluding isolated days and first days of spells.

Dotted line: Ditto but for Central England Temperature.



Percentage of advancing and retreating glaciers in Switzerland, 1891–1980, showing the increase of advancing glaciers since the mid-twentieth century. (From Kasser & Aellen, 1981.)

Figure 9.24. From Untersteiner (1984).

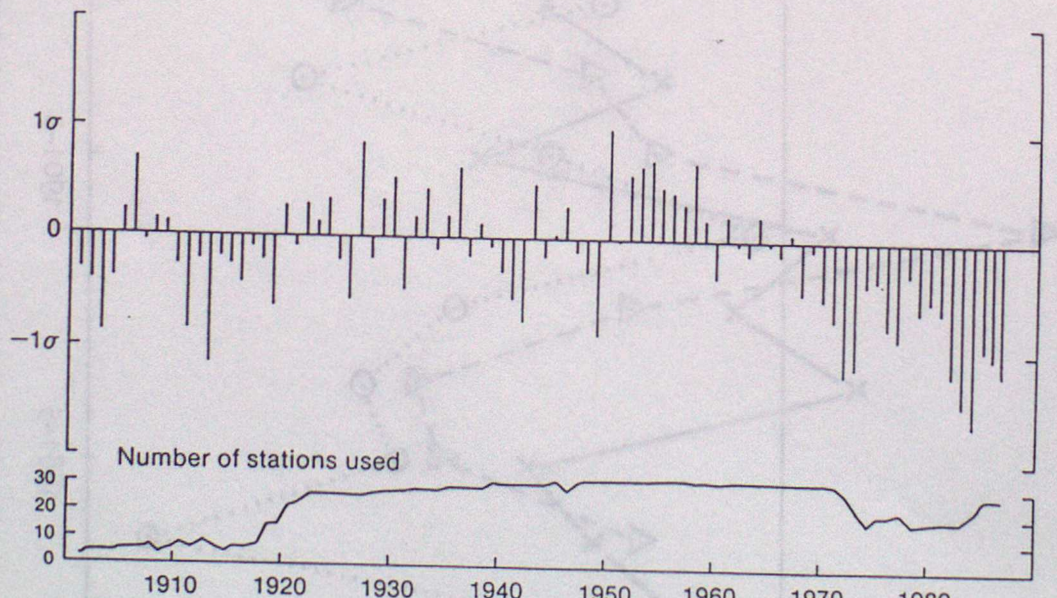


Figure 9.25. Standardised annual rainfall anomalies for the Sahel, 1901–87. Values to 1984 after Nicholson (1985): 1985–87 estimated from CLIMAT reports.

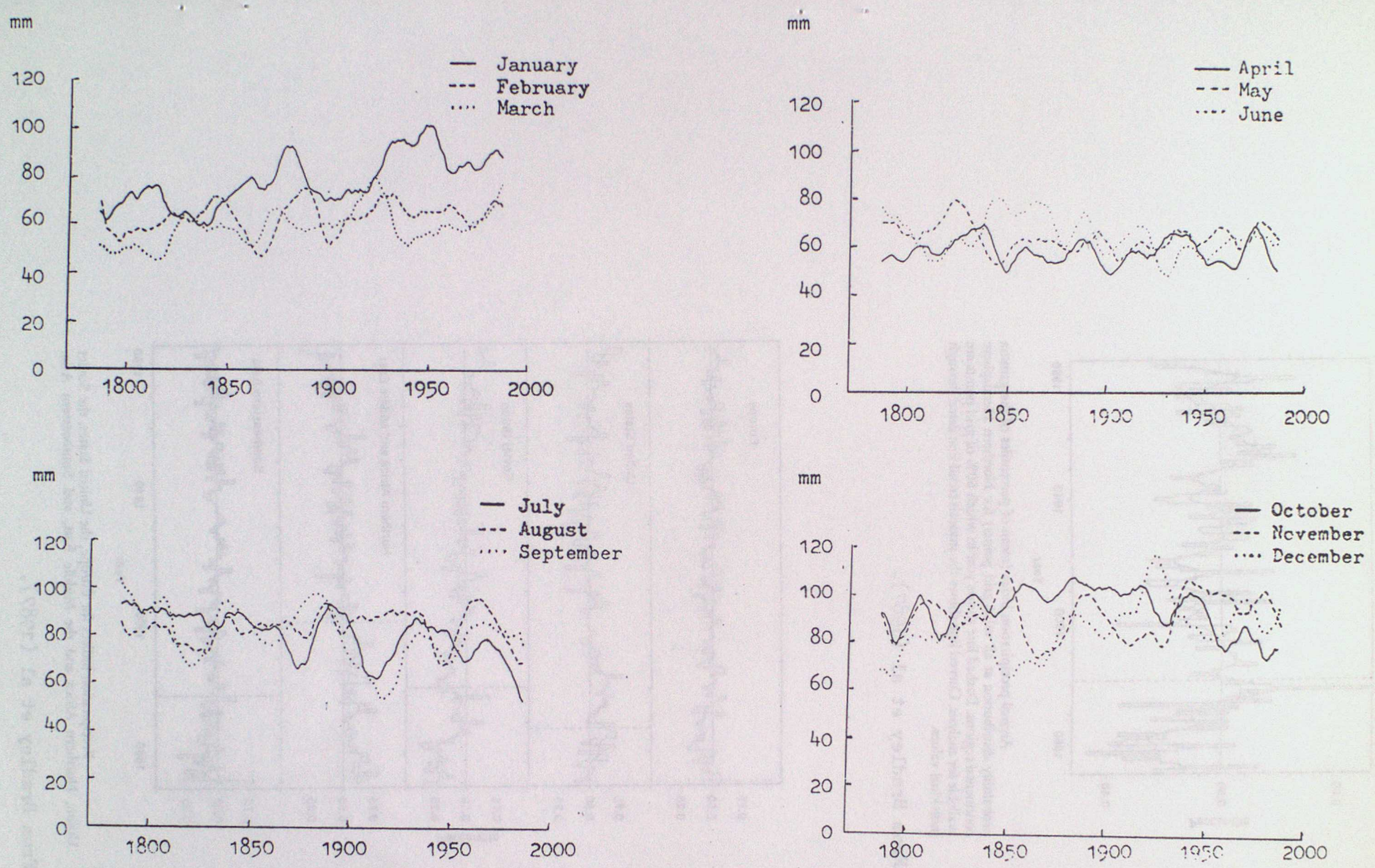
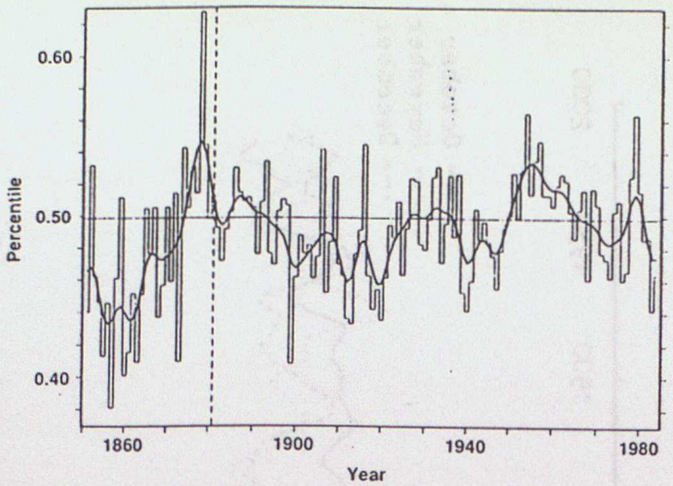
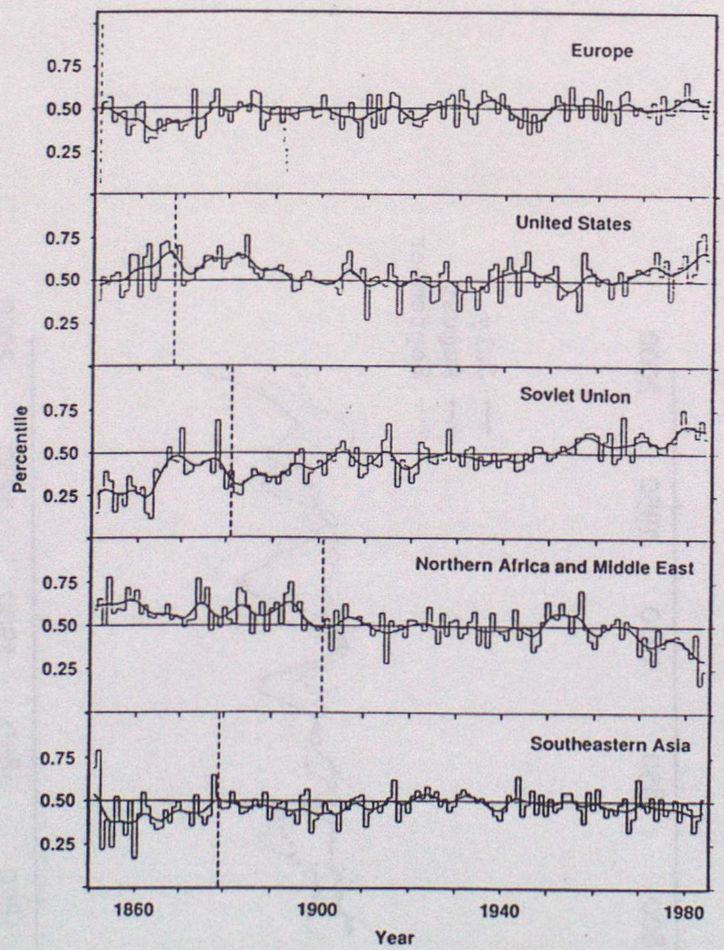


Figure 9.26. England and Wales rainfall, 1766 to 1987, plotted at the end date of a 20-year triangular smoothing filter. Data up to 1980 are from Wigley et al (1984).



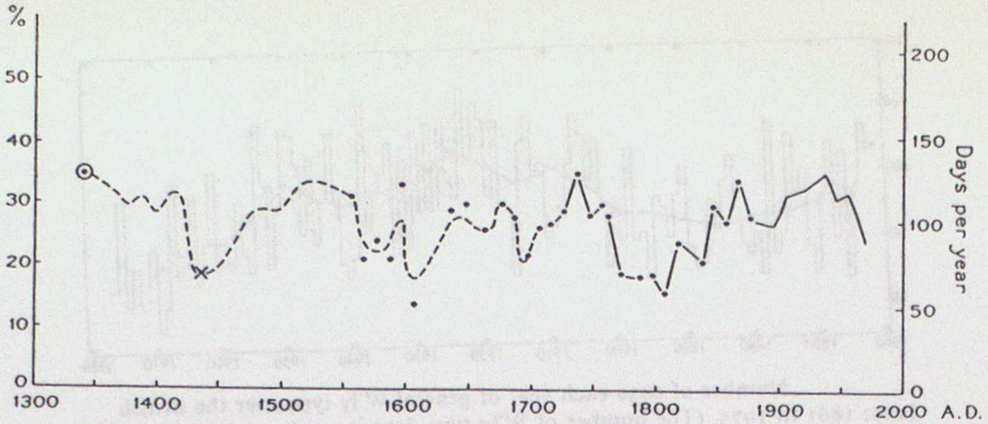
Annual precipitation index (mean of percentiles of the gamma probability distribution at all valid grid points) for Northern Hemisphere continental regions. Dashed line shows year in which 50% of grid points are available for analysis. Curved line shows the smooth trend line fitted through individual values.

Figure 9.27. From Bradley et al (1987).



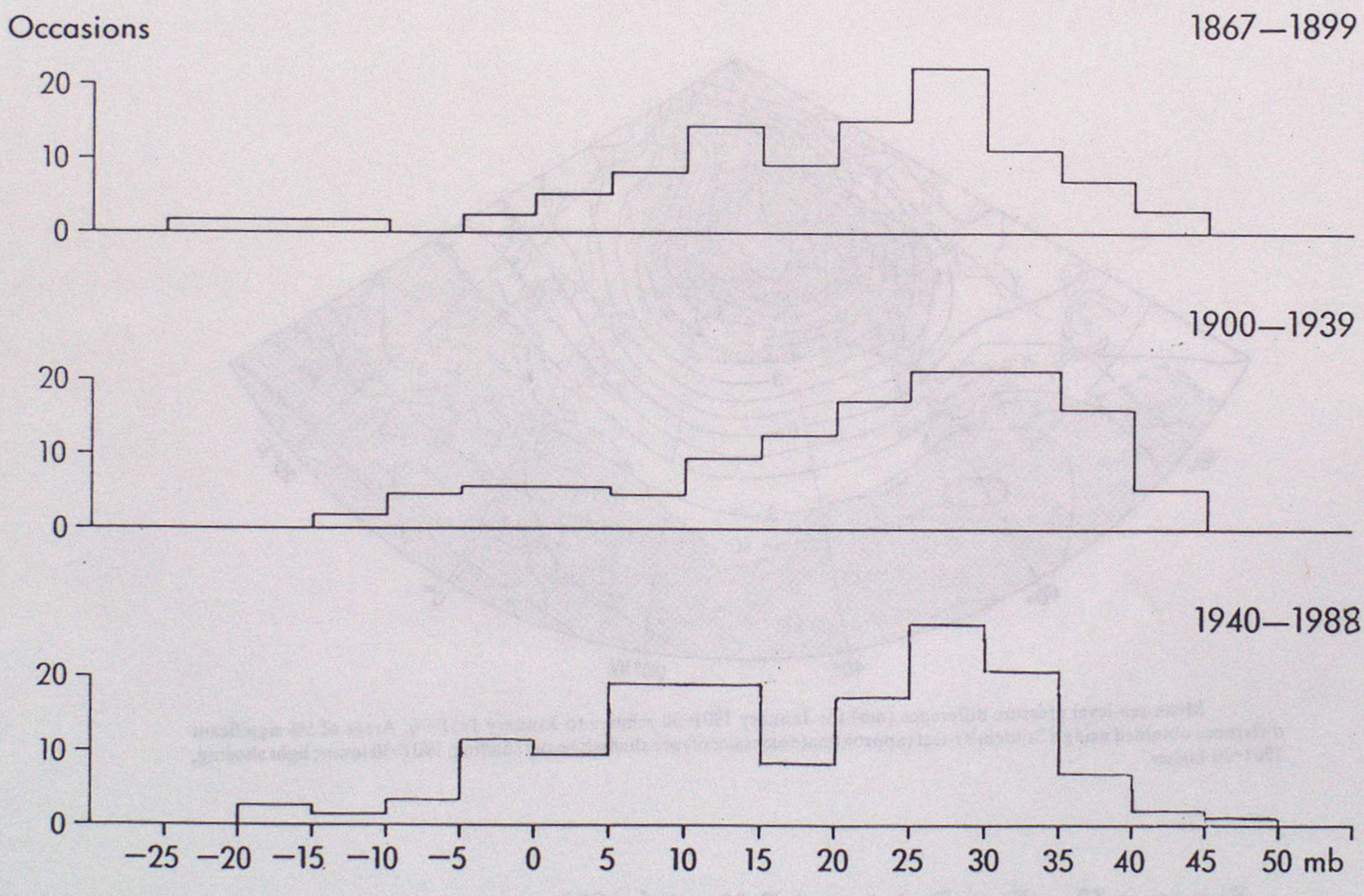
Precipitation indices for Europe, the United States, the Soviet Union, Northern Africa and the Middle East, and Southeastern Asia.

Figure 9.28. From Bradley et al (1987).



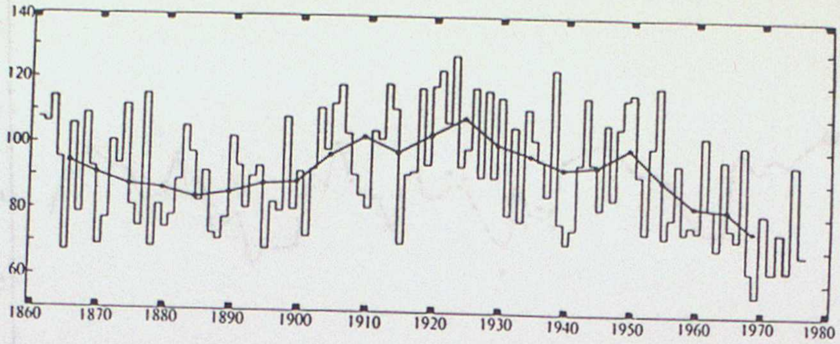
Frequency of SW'ly surface winds in southeastern England since A.D. 1340.
Approximately 10-year average values and estimates.
Composite record derived directly from daily observations near London since 1670 (the earlier part worked up from manuscript sources by MANLEY, the later part since 1811 from observations in the archives of the Meteorological Office). Estimates for periods before 1670 provisionally derived from indirect evidence including weather diaries kept in various parts of England and neighbouring parts of Europe.

Figure 9.29. From Lamb (1972a).



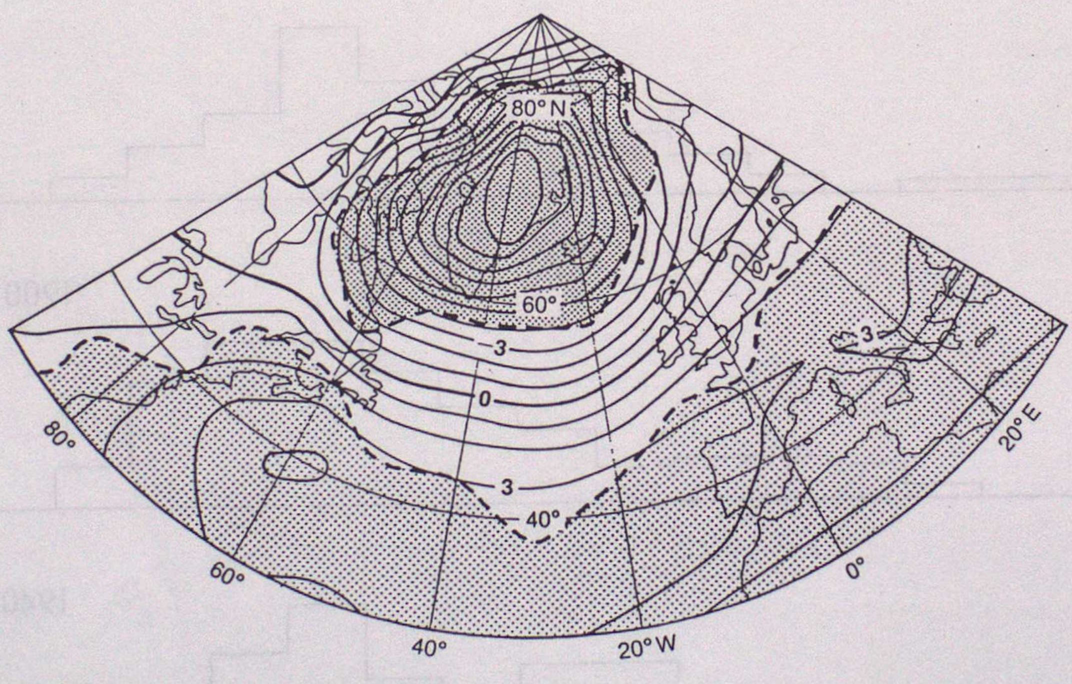
Ponta Delgada (Azores) minus Stykkisholmur (Iceland) mean sea level pressure, winter months (up to Feb. 1988).

Figure 9.30.



Number of days each year of general W'ly type over the British Isles: 1861 to 1975. (The number of W'ly type days in 1976 was 59.) Individual years and 10-year means at 5-year intervals.

Figure 9.31. From Lamb (1977).



Mean-sea-level pressure difference (mb) for January 1901–30 relative to January 1951–70. Areas of 5% significant difference obtained using a Student's *t*-test (approximate assessment) are shaded: heavy shading, 1901–30 lower; light shading, 1901–30 higher.

Figure 9.32. From Parker and Folland (1988).

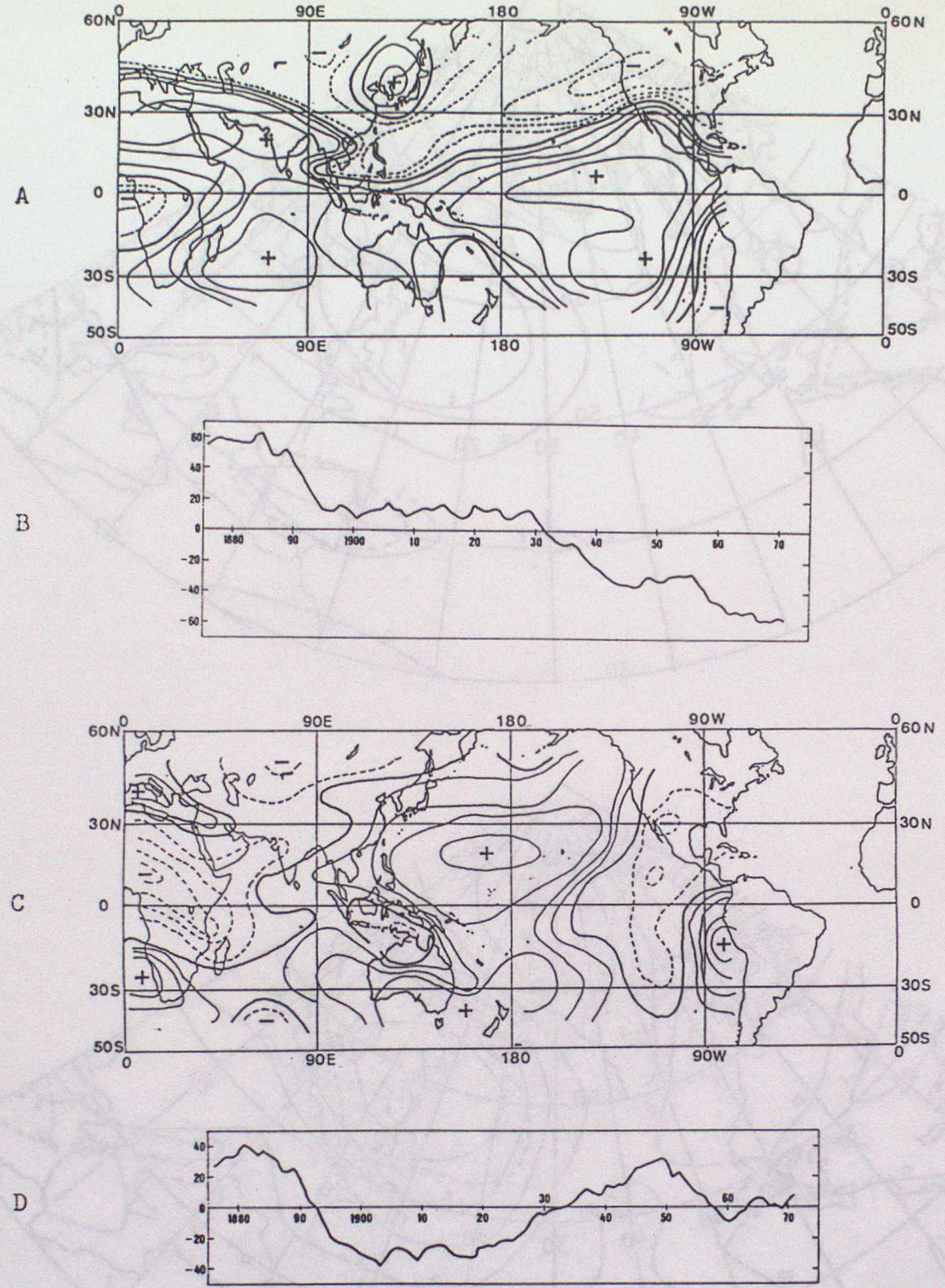


Figure 9.33. A. First eigenvector of the field of 11-year running mean MSL pressure. Dashed contours are negative values. Units are 0.2.
B. Time coefficients of the first eigenvector.
C. As A but for the second eigenvector.
D. As B but for the second eigenvector.

Data base : 1871 to 1976.

After Tan and Yasunari (1982).

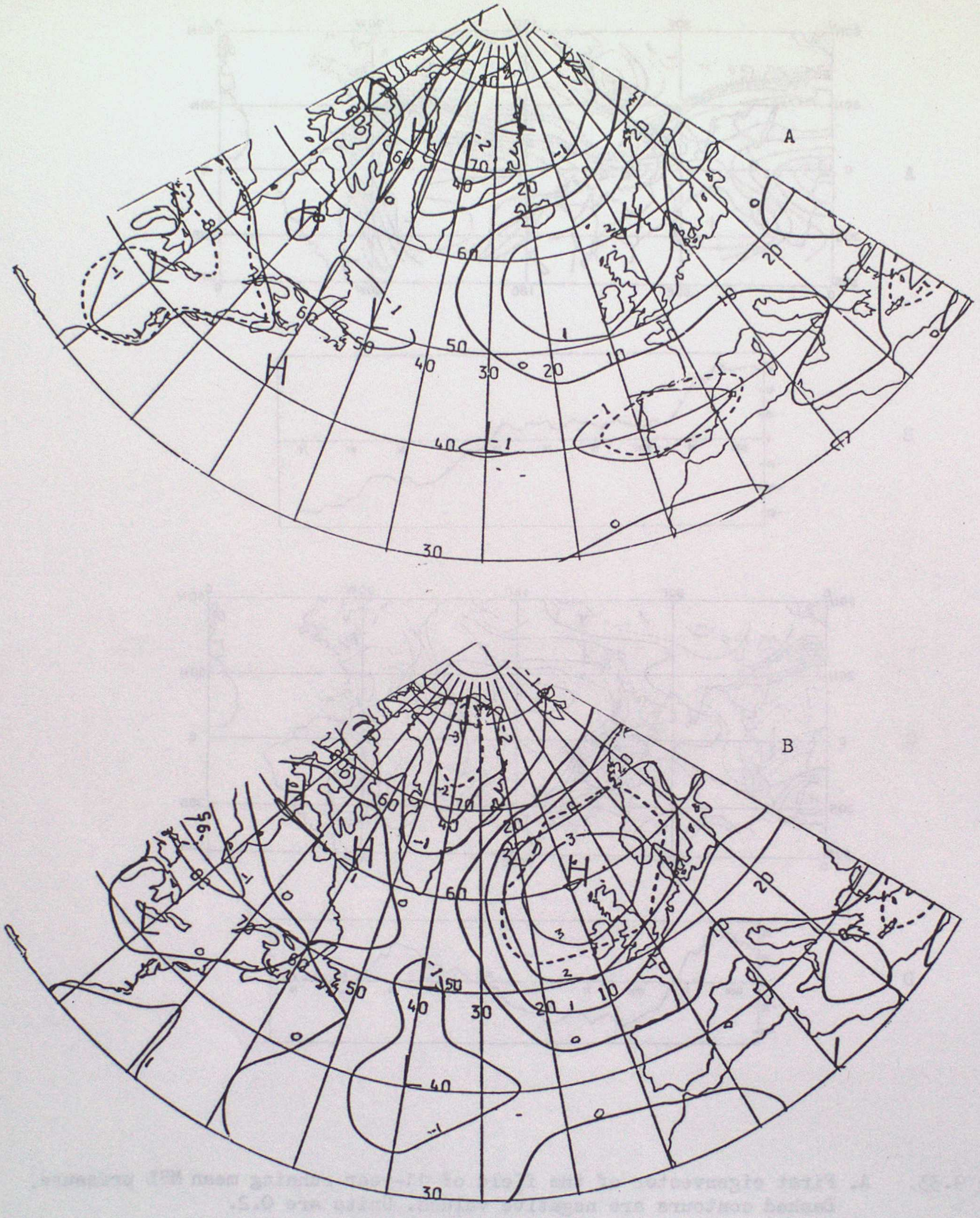
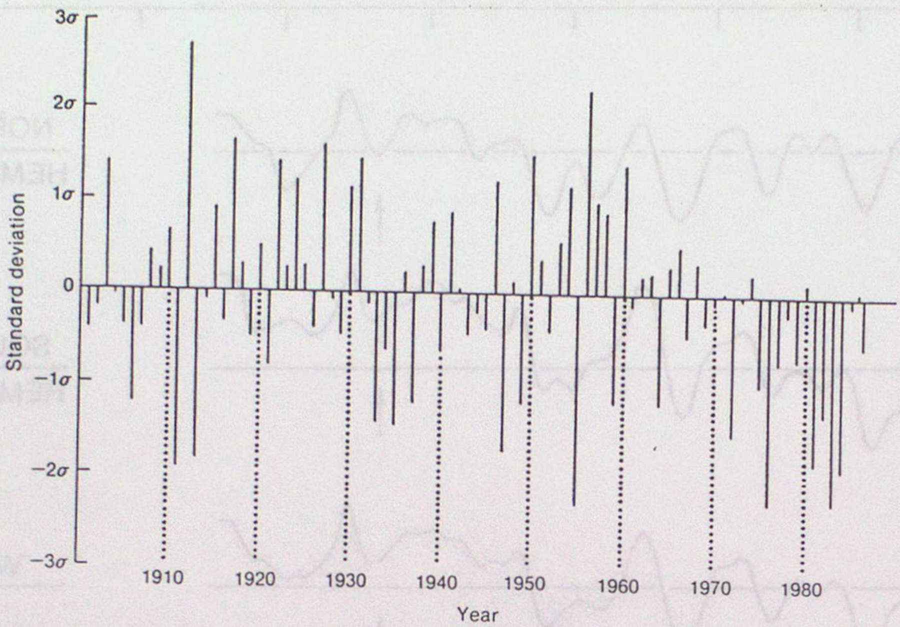
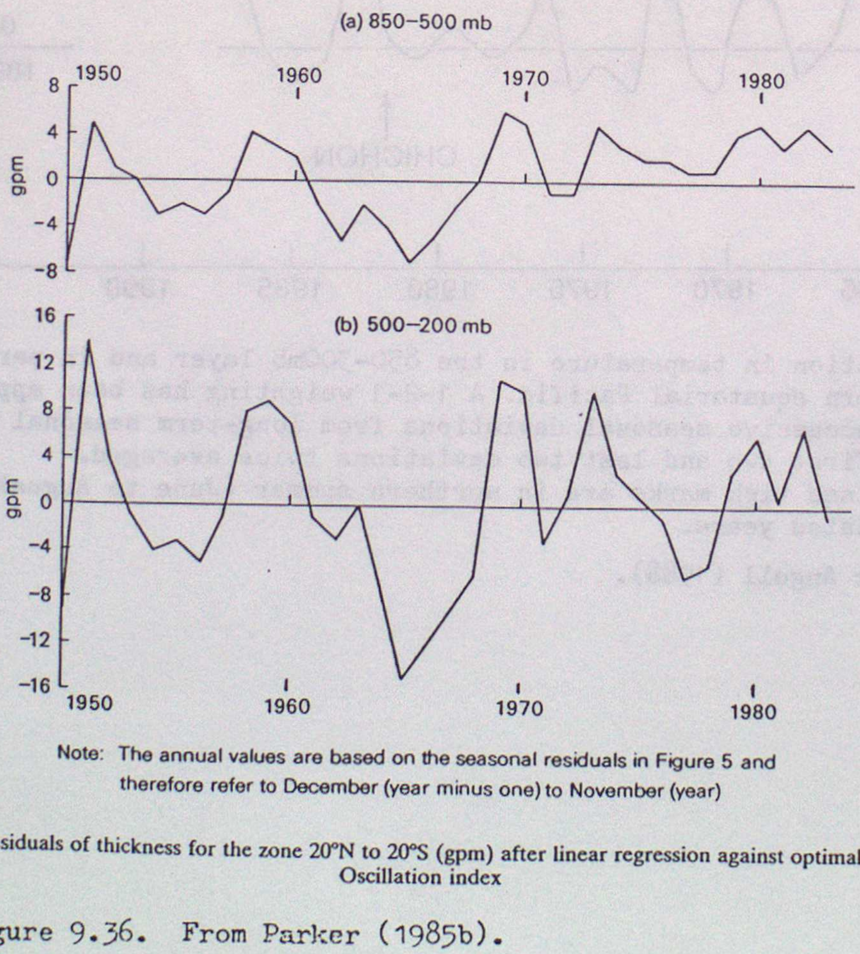


Figure 9.34. MSL pressure (mb), 1968-87 relative to 1950-59.
A, July. B, August.
Areas of 5% significant difference obtained using a Student's t-test (approximate assessment) are enclosed by the dashed lines.



Standardized July and August total rainfall for England and Wales, 1901–87, based on the period 1901–80.

Figure 9.35. From Parker and Folland (1988). Data up to 1980 are from Wigley et al (1984)



Note: The annual values are based on the seasonal residuals in Figure 5 and therefore refer to December (year minus one) to November (year)

Annual residuals of thickness for the zone 20°N to 20°S (gpm) after linear regression against optimally lagged Southern Oscillation index

Figure 9.36. From Parker (1985b).

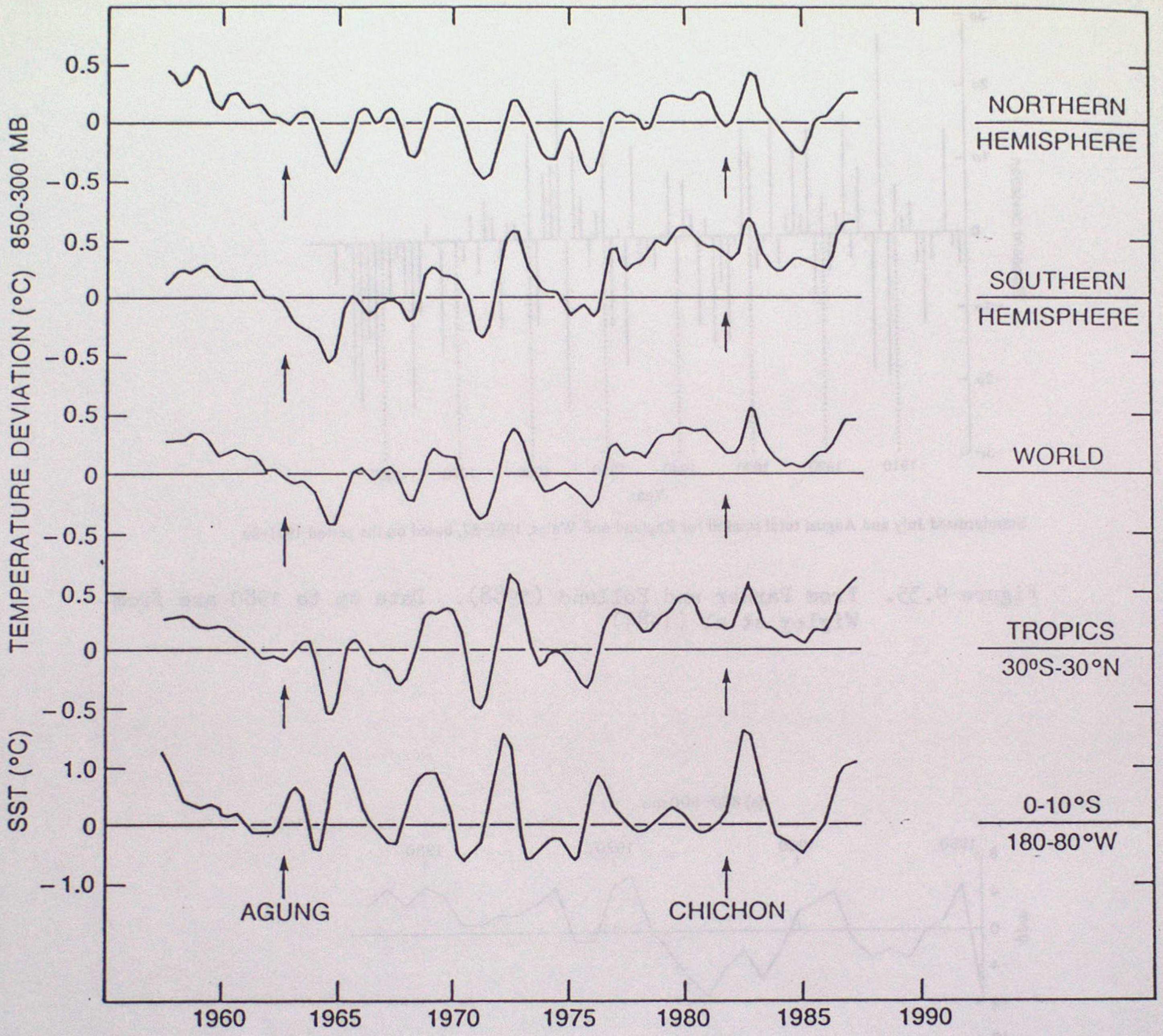


Figure 9.37. Variation in temperature in the 850-300mb layer and in part of the eastern equatorial Pacific. A 1-2-1 weighting has been applied twice to successive seasonal deviations from long-term seasonal means, with the first two and last two deviations twice averaged. Abscissa tick marks are in northern summer (June to August) of the indicated years.

After Angell (1988).

INDEX TO LONG-RANGE FORECASTING AND CLIMATE RESEARCH SERIES

1) THE CLIMATE OF THE WORLD - Introduction and description of world climate.
by C K Folland (March 1986)

2) THE CLIMATE OF THE WORLD - Forcing and feedback processess.
by C K Folland (March 1986)

3) THE CLIMATE OF THE WORLD - El Nino/Southern Oscillation and the Quasi-biennial Oscillation.
by C K Folland (March 1986)

4) THE CLIMATE OF THE WORLD - Climate change: the ancient earth to the 'Little Ice Age'.
by C K Folland

5) THE CLIMATE OF THE WORLD - Climate change: the instumental period.
by C K Folland (March 1986)

6) THE CLIMATE OF THE WORLD - Carbon dioxide and climate (with appendix on simple climate models).
by C K Folland (March 1986)

7a) Sahel rainfall, Northern Hempishere circulation anomalies and worldwide sea temperature changes, (To be published in the Proceedings of the "Pontifical Academy of Sciences Study Week", Vatican, 23-27 September 1986).
by C K Folland, D E Parker, M N Ward and A W Colman (September 1986)
(Amended July 1987)

8) Lagged-average forecast experiments with a 5-level general circulation model.
by J M Murphy (March 1986)

9) Statistical Aspects of Ensemble Forecasts.
by J M Murphy (July 1986)

10) The impact of El Nino on an Ensemble of Extended-Range Forecasts.
(Submitted to Monthly Weather Review)
by J A Owen and T N Palmer (December 1986)

11) An experimental forecast of the 1987 rainfall in the Northern Nordeste region of Brazil.
by M N Ward, S Brooks and C K Folland (March 1987)

12) The sensitivity of Estimates of Trends of Global and Hemispheric Marine Temperature to Limitations in Geographical Coverage.
by D E Parker (April 1987)

13) General circulation model simulations using cloud distributions from the GAPOD satellite data archive and other sources.
by R Swinbank (May 1987)

14) Similation of the Madden and Julian Oscillation in GCM Experiments.
by R Swinbank (May 1987)

15) Numerical simulation of seasonal Sahel rainfall in four past years using observed sea surface temperatures.
by J A Owen, C K Folland and M Bottomley (April 1988)

16) Not used

17) A note on the use of Voluntary Observing Fleet Data to estimate air-sea fluxes.
by D E Parker (April 1988)

18) Extended-range prediction experiments using an 11-level GCM
by J M Murphy and A Dickinson (April 1988)

19) Numerical models of the Raingauge Exposure problems - field experiments and an improved collector design.
by C K Folland (May 1988)

20) An interim analysis of the leading covariance eigenvectors of worldwide sea surface temperature anomalies for 1901-80.
by C K Folland and A Colman (April 1988)

21) Prospects for long range forecasting for the United Kingdom.
by A Dickinson and C K Folland (July 1988)

22) CLIMATE OF THE WORLD (Restricted Issue)
1. Introduction to world climate
2. Description of world climate
by C K Folland and D E Parker (July 1988)

23) CLIMATE OF THE WORLD (Restricted issue)
3. Climatic forcing and feedback processes.
I. Forcing from above.
4. Climatic forcing and feedback processes.
II. Interactions with land surface
by C K Folland and D E Parker (July 1988)

24) CLIMATE OF THE WORLD (Restricted Issue)
5. Ocean-atmosphere interaction
by D E Parker and C K Folland (July 1988)

25) CLIMATE OF THE WORLD (Restricted Issue)
6. The El Nino/Southern Oscillation, the Quasi-Biennial Oscillation, and the 30-60 day variations.
by C K Folland and D E Parker (July 1988)

26) CLIMATE OF THE WORLD (Restricted Issue)
7. A review of palaeoclimate from the early Earth to the Pleistocene ice ages
8. Climate from the late glacial to the "Little ice age"
by C K Folland and D E Parker (July 1988)

27) CLIMATE OF THE WORLD 9. Climatic change in the instrumental period
(Restricted Issue) by D E Parker and C K Folland (July 1988)

28) CLIMATE OF THE WORLD 10. Carbon dioxide and other greenhouse gases, and climatic variation
(Restricted Issue)
(with appendix on simple climate models).
by D E Parker, C K Folland and D J Carson
(July 1988)