HADLEY CENTRE
FOR CLIMATE PREDICTION AND RESEARCH

# A new daily Central England Temperature Series, 1772 - 1991.

by

D. E. Parker, T. P. Legg and C. K. Folland

CRTN 11

June 1991

CLIMATE
RESEARCH
TECHNICAL
NOTE

Hadley Centre
Meteorological Office
London Road
Bracknell
Berkshire RG12 2SY

CLIMATE RESEARCH TECHNICAL NOTE NO. 11

# A NEW DAILY CENTRAL ENGLAND TEMPERATURE SERIES, 1772-1991

by

D E PARKER, T P LEGG and C K FOLLAND

Hadley Centre for Climate Prediction and Research
Meteorological Office
London Road
Bracknell
Berkshire RG12 2SY
U. K.

# A NEW DAILY CENTRAL ENGLAND TEMPERATURE SERIES, 1772-1991

D E Parker, T P Legg and C K Folland

June 1991

ABSTRACT

Manley (1974) produced a time series of monthly average temperatures representative of Central England for 1659 to 1973. The present paper describes how a series of homogenised daily values has been formed. This series starts in 1772, and is consistent with Manley's monthly average values. Between 1772 and 1876 the daily series is based on a sequence of single stations whose variance has been reduced to counter the artificial increase that results from sampling single locations. For subsequent years, the series has been produced from combinations of as few stations as can reliably represent Central England in the manner defined by Manley. We have used the daily series to update Manley's published monthly series in a consistent way.

We have evaluated recent urban warming influences at the chosen stations by comparison with nearby rural stations, and have corrected the series from 1974 onwards. The corrections do not (yet) exceed 0.1°C.

We present all the monthly data from 1974, along with averages and standard deviations for 1961 to 1990. The daily data are available on request.

## 1. INTRODUCTION

Manley (1953) published a time series of monthly mean temperatures representative of Central England for 1698 to 1952, followed (Manley 1974) by an extended and revised series for 1659 to 1973. Up to 1814 his data are based mainly on overlapping sequences of observations from a variety of carefully chosen and documented locations. Up to 1722, available instrumental records fail to overlap, and Manley needed to use non-instrumental weather diaries, and to refer to the instrumental series for Utrecht compiled by Labrijn (1945), in order to make the monthly Central England Temperature (CET) series complete. Between 1723 and the 1760's there are no gaps in the composite instrumental record, but the observations were generally taken in unheated rooms rather than with a truly outdoor exposure. Manley (1952) used a few outdoor temperatures, observations of snow or sleet, and likely temperatures given the wind direction, to establish relationships between the unheated room and outdoor temperatures: these relationships were used to adjust the monthly unheated room data. Daily temperatures in unheated rooms are, however, not reliably convertible to daily outdoor values, because of the slow thermal response of the rooms. For this reason, no daily series truly representative of CET can begin before about 1770. In this paper we present a daily CET series from 1772 to the present. The series from 1800 to 1877 is based on an unpublished compilation by Jenkinson et al (JCS) (1979); for earlier and later years we choose stations as described in Section 2. A preliminary, unpublished, version of the present paper is that of Storey et al (1985), which has been summarised by Jones (1987).

Our series represents only a very small portion of the globe, but it offers valuable support to wider studies of European climate because it is very sensitive to atmospheric circulation variations over the North Atlantic. A long, homogeneous daily series is also of particular value to climatic and long-range forecasting studies because it allows the analysis of relationships between sea surface temperature anomalies in the North Atlantic Ocean and anomalies of surface temperature over the UK within given atmospheric circulation types (Storey, 1982; Parker and Folland, 1988). Such a series is also valuable for long-range forecasting because it aids the study of spells of surface weather anomalies in which the long-range forecaster is particularly interested. These spells can vary in length from a few days to months and are linked to larger scale atmospheric processes. Regular updating of the daily series has the additional advantage that homogeneous monthly averages can be updated in near-real-time. Finally, the statistical characteristics of a reliable daily CET series can be used to verify general circulation model simulations of observed UK climate, e.g. to support model-based assessments of future UK climate resulting from increased concentrations of "greenhouse" gases in the atmosphere. Here, we include the statistical character of day-to-day variability within the concept of climate (Wilson and Mitchell, 1987).

The chosen stations, and reasons for choosing them, are documented in Section 2.

In Section 3 we present the methods used to combine the stations' daily data, within the constraints of maintaining Manley's monthly averages and ensuring the historical homogeneity of the variance of the resulting daily CET series. It was found necessary to scale the variance of the daily series, according to the varying number of constituent stations and the mean correlation between their daily temperatures. After 1973, we have applied compensation for recent urban warming, which is calculated using comparisons with rural stations, and given qualified support by radiosonde data.

Before presenting the daily CET series, we review various non-climatic influences on temperature observations (Section 4). Our series is, on a monthly basis, anchored to that of Manley (1974) who took account of all these influences. But his adjustments were designed for monthly data, so they are less accurate for daily data, because non-climatic influences, depending on the balance between radiative and advective heat fluxes, vary from day to day.

The final daily CET series is used to update Manley's monthly series to 1991 and to derive climatological statistics for 1961-90 (Section 5). The daily series is too extensive to be printed, but is available on disk or microfiche.

In an Appendix we discuss the uncertainties in the daily CET series due to urban warming, and some incompatibilities in the statistics of climate between the stations used.

## 2. CHOICE OF STATIONS

### a) Selected stations

The stations chosen to represent Central England are listed in Table 1 which also shows those used by Manley (1974). Ideally, to fit Manley's concept of Central England (which is not the same as the English Midlands), the stations should be located in and between the two stippled areas in Figure 1 - Central Lancashire and a region from the southern border of the Midlands to western East Anglia. This could be achieved by having one station representing the Lancashire Plain and one each near the western and eastern extremities of the south Midlands. However, there are other constraints, also in keeping with Manley's approach, to be taken into account, viz:

i) avoidance of severely urbanised stations;
ii) avoidance of geographically unrepresentative stations, e.g. those in frost-hollows, on the coast, or in upland locations;
iii) choice of stations with long, unbroken records, to optimise the homogeneity of the series.

Ideally, the entire late 18th Century portion of the daily series would have been based on the excellent records kept by Thomas Barker at Lyndon Hall in County Rutland (see Manley, 1952; Kington, 1988). However, we have only located his daily records for 1777 to June 1789, with a gap in December 1786 because of a broken thermometer. These have been used, with occasional adjustments to compensate for irregular observing hours (Appendix 1); for the remainder of the late 18th Century we used the Royal Society's record in London whenever it was available, otherwise Hoy's London record. Our preference for the Royal Society's record, in contrast to that of Hoy, was based on Manley's (1953, 1960) assessments, and confirmed by correlations calculated for each month of overlap between Barker's record and the Royal Society's and between Barker's and Hoy's. The former correlations exceeded the latter for 67 out of 85 months, and the converse only applied to 13 months. In this choice of the Royal Society's record, and in our access to Barker's records, our series is an improvement on JCS's preliminary compilation. Other contemporary observations such as W. Cary's in the Strand (London) (1786-1846) were made in rather over-sheltered sites (Manley, 1960). We did, however, use Cary's readings to further confirm our choice of the Royal Society's record rather than Hoy's between 1789 and 1799, and to estimate amendments to the former where necessary (Appendix 1), in view of Manley's (1964) remark that the Royal Society's record contains mis-read temperatures between 1794 and 1799. Of 467 disagreements between the Royal Society's and Hoy's records, which would have affected a single day's Central England Temperature estimate by at least 1.5°C, Cary's record favoured the Royal Society's on 345 occasions.

The daily series for 1800-1852 is based on three London records: Royal Society; Greenwich (J. Belville's series); and Royal Horticultural Society (Table 1) which are well-attested by Manley (1960). During this period the London series have substantial overlaps and the choice of station appears, from Manley's comments, not to be critical. Any urban influence in the city-centre Royal Society record will, on a monthly basis, have been removed from our series by our adjustment of the monthly mean to agree with Manley's (1974) series. However our transition to the less urban Greenwich record as soon as it began in 1812, and then to the Royal Horticultural Society record at Chiswick when that began in 1826, will have avoided any subsequent residual urban effects in the Royal Society record.

The Oxford temperature record began in 1815, but the temperatures are less reliable before 1840 owing to lack of knowledge of the index errors of the thermometers (Knox-Shaw and Balk, 1932). In 1849 the shielding from radiation was improved (Johnson, 1851, page x). We use the daily Oxford record from 1853, the first year when daily, as opposed to monthly, values were published (Johnson, 1842-1855).

We could be criticised for our choices of single stations up to 1877 (Table 1), and for sometimes using London stations on the southeastern fringe of Manley's "Central England" (Figure 1). Other possible records are discussed by Manley (1953). Of these, Hughes' at Stroud (Gloucestershire) (1771-1813) and a series for South Kyme (near Sleaford, Lincolnshire)

(1800-1869) would appear to be the best candidates, but the Stroud record suffers from the "prevailing omission of one or two days each month" (Manley, 1953), and the South Kyme record is not well documented, e.g. Manley (1953) cites the observing time as "apparently" 8 a.m. Observations at Cambridge Botanical Gardens began only in July 1873 and at Ross on Wye only in March 1877. Manley (1946)'s "Lancashire" series is based on a wide range of overlapping but mainly short-term (<20 years' duration) stations. The best of these (before 1877) are Dalton's records for Kendal (1788-1809) and Manchester (1794-1840) but only his published monthly averages exist, because the original manuscripts of the daily data were largely destroyed by fire in the Second World War (Manley, 1946). Also, Marshall's record (1823-1860) at Kendal is only available as monthly means plus a few other fragments of information. There are thus substantial periods before the mid-1840's when there are no known reliable daily data for Lancashire: see Fig 2 of Manley (1946). Manley also had only monthly means for Liverpool (1846-1866) and nearby Bidston (1865 onwards), and he described the thermometer shelters at these two stations as "not perfect". Although observations began at Stonyhurst, Lancashire, in 1848, daily values appear not to be available until 1868, the year after the station was chosen as one of the seven meteorological observatories of the Board of Trade (Perry, 1872; Meteorological Office, 1874).

We chose 1878 for the change to three stations, the combination of Stonyhurst, Cambridge and Ross on Wye, this being the first complete year for which daily data for all three are readily available. It may be possible in future to use more than one station back to the 1840's and even, with meticulous scrutiny, to extend one or more extra stations back to 1800. However the substantial effort involved is not considered worthwhile at present in view of the generally high correlation of daily variations between the south Midlands and south Lancashire (Table 4). We could have used Oxford and Stonyhurst for 1868 to 1877, but use of a single transition from one to three stations in 1877-8 made homogenization of the variance of the daily series (Section 3e) simpler.

While retaining three stations, we replaced the Cambridge station by Rothamsted Observatory in 1931 because of evidence of urban warming at the former by that time. Stonyhurst closed in 1978 and its records had an increasing number of missing days from 1960, so we used an average of Squires Gate and Ringway airport to replace it from 1959. Thus our third station from 1959 is a composite of two stations in the northwest of Central England. Other possible single stations, such as Preston and Macclesfield, were rejected owing to urban influences, and Slaidburn (192m) was not used because of its upland location. The relationship between Stonyhurst and ½ (Ringway + Squires Gate) is discussed in Appendix 3. Squires Gate could not be used on its own because of its proximity to the coast, and Ringway could not be used alone because it is too far south to truly represent the Lancashire plain. Recent evidence for urban warming at Ringway is assessed in Table 8 and Section 3f.

Ross on Wye was closed from 1975 to 1985. We replaced it by Malvern in 1959, to minimise the number of discontinuities. Note that the Ross on Wye station is within a small urban area.

The two single stations and the composite station chosen for the period 1959 to date (Table 1) will be used to continue the daily CET series for as long as possible; they were chosen partly because they are likely to continue to provide temperature observations for some time to come. Squires Gate and Malvern have been designated as 'reference climatological stations' by WMO and the Meteorological Office, while Rothamsted is a very prominent agricultural research station co-operating with the Meteorological Office. Ringway (Manchester) is sited at an international airport, and its site is not ideal. Appendix 2 gives details of all the sites used since 1878 in our series.

b) <u>Comparions with the choices of JCS after 1877</u>

We did not use JCS's stations after 1877 (see also Jones, 1987) because they inadequately represent Manley's Central England. JCS chose the following sequence (see Figure 1 for locations):

1878-1882: Oxford, Ross on Wye;

1883-1973: Oxford, Ross on Wye; Sheffield;

1974 onwards: Ringway, Finningley, Wittering, Cardington, Shawbury, Birmingham (Elmdon).

This sequence does not cover Manley's "Lancashire" area until 1974, and throughout it represents a smaller area than that spanned by Manley's concept of Central England (Figure 1). Even after 1973, the daily variance of JCS's series appears to be slightly too great, despite the use of six stations, because of the smaller area represented (Section 3e). To yield a homogeneous variance, the mean simultaneous correlation of daily temperatures between stations needs to be kept as constant as possible (Section 3e), and this demands that the area represented should stay as constant as possible. For the earlier part of our new CET series when only one station could be used, we adjusted the daily variance (Section 3e), to represent that of the "Central England" area. Our replacement of Stonyhurst by ½(Squires Gate + Ringway) in 1959 did not affect the variance of the new CET series (Appendix 3).

3. CONSTRUCTION OF THE DAILY SERIES

a) Introduction

Construction of the daily series was carried out in five steps. First, maximum and minimum temperatures, or values at fixed hours, at individual stations were averaged into daily values. Second, where more than one station was used, the stations' daily values were combined into a composite daily temperature. Third, all daily temperatures in a given month were adjusted by a single common factor so that their average equalled the monthly CET given by Manley (1974). Fourth, the daily temperatures from single stations up to 1877 were adjusted to reduce their variance expressed relative to the averages for individual months in individual years, without changing these averages. Finally, corrections for urban warming were made from 1974 onwards.

b) Calculation of daily values for individual stations

The daily value for station s was calculated as

$$t_s = \frac{\sum_{h=1}^{m} W_h t_h}{\sum_{h=1}^{m} W_h} \qquad (3.1)$$

where $t_h$ denotes a temperature observation and $W_h$ is a weight. In general $W_h$ was unity, except for a few cases noted in Appendix 1 for the late 18th Century data. The number m of temperatures averaged was generally 2, again with a few exceptions given in Appendix 1. Up to 1877, the temperatures were generally morning and afternoon values: thereafter, they were 24-hour maxima and minima read at 9 am.

c) Combination of stations

Composite daily values were calculated from:

$$t_c = \frac{\sum_{s=1}^{n} W_s t_s}{\sum_{s=1}^{n} W_s} \quad . \qquad (3.2)$$

where $n = 1$ and $W_s = 1$ before 1878

$n = 3$ and $W_s = 1$ from 1878 to 1958

$n = 4$, $W_1 = W_2 = 1$, $W_3 = W_4 = 0.5$ from 1959. $W_3$ and $W_4$ were applied to Squires Gate and Ringway (Table 1).

d) Adjustments to daily values for compatibility with Manley's monthly series

Small corrections were needed to ensure that the daily values of CET yielded monthly averages identical with those in Manley's (1974) homogeneous series. The adjustments are consistent with Manley's own approach: he made small, seasonally dependent, corrections to calculated mean temperatures to allow for inevitable variations in the climatic mean when one station had to be replaced by another. The limitations of this procedure for providing homogeneous daily temperatures are discussed in Section 4.

The method of correcting $t_c$ is best shown by an example:

i) for March 1973 Manley's monthly mean is 6.2°C;

ii) the monthly mean for March 1973 of all the daily combined-station means is 6.32°C;

iii) the value 6.2 - 6.32 = -0.12°C is used as a fixed daily correction for March 1973 and is added to each value of $t_c$.

In general

$$\text{Daily CET} = t_d = t_c + C \qquad (3.3)$$

where C = (Manley's monthly mean) - (monthly mean of daily means from Equation 3.2). C was calculated separately for all 2424 months between 1772 and 1973.

All corrections for 1878-1973 are shown in Table 2. Small systematic variations took place in the size of the corrections as stations changed. The calculations revealed an error in Manley's monthly series as published in 1974. Our originally calculated correction for February 1898 was 1.31°C, a considerably larger value than the others. This suggested a fault with the station data or with Manley's value. Investigation confirmed that Manley's published monthly mean of 5.8°C for February 1898 was 1 degree C too high; Manley's earlier, 1953, paper gives a value of 40.6°F (4.8°C), which was accepted. This results in a more typical correction of 0.31°C.

This method of deriving monthly corrections cannot be applied to daily values after the end of Manley's series in 1973. However, because the same combination of stations was used from 1974 onwards as for 1959-1973, we considered it adequate to apply the average of previous corrections for this combination of stations, separately in each calendar month. Average corrections for 1944, 1948, 1949 and 1953 to 1973 (24 years) were used to calculate the post-1973 corrections to maximise sample size, other years being incomplete. A statistic described by Cramer (1946) was applied to the monthly mean corrections to determine whether they varied significantly through the calendar year (Table 3 and Mitchell et al (1966)). The statistic $t_i$ is defined by

$$t_i = \frac{[\,n(N-2)\,]^{1/2}}{[\,N-n(1+T_i^2)\,]^{1/2}}\, T_i \;, \quad i = 1, 12 \qquad (3.4)$$

$$T_i = \frac{\bar{x}_i - \bar{\bar{x}}}{s}$$

where

and s is the standard deviation of all N correction values

This was calculated for each calendar month i to test the null hypothesis that the mean $\bar{x}_i$ of the n(=24) correction values for calendar month i equalled the mean $\bar{\bar{x}}$ of all N (=24 x 12=288) individual monthly corrections.

Cramer's test showed that the mean corrections in January, August, September and December differed from the annual mean correction at the 99% significance level (Table 3). Therefore the corrections were allowed to vary through the year, with some smoothing to reduce sampling error (final column of Table 3).

e) Adjustment of variance of pre-1878 data

The variance of a composite daily temperature series depends on the number and geographical distribution of stations used. It was therefore necessary to adjust the variance of the pre-1878 single-station data to make it homogeneous with that of the subsequent 3-station data. The variance of the mean of n' independent variables, assumed to have equal individual variances $S_o^2$, is

$$S^2 = S_o^2/n' \qquad (3.5)$$

From 1878, n' is considerably less than the number n(= 3) of stations used, because day-to-day variations of temperature at the stations are strongly positively correlated. The effective number n' of stations is shown by Yevjevich (1972) to be

$$n' = \frac{n}{1 + \bar{r}(n-1)} \qquad (3.6)$$

where $\bar{r}$ is the average of the correlation coefficients between daily values measured simultaneously at each of the n different stations, all possible combinations being taken. In Central England, $\bar{r}$ depends mainly on the mean distance between the stations.

Table 4 gives correlation coefficients between the mean daily temperatures at the stations used for our daily series from 1878 onwards. The correlations had to be calculated using anomalies from the mean of the individual month in a given year at the given station, to remove the large common inter-annual variations. The effects of autocorrelation of the daily data were minimised by correlating simultaneous daily anomalies measured at five-day intervals. The average of Squires Gate and Ringway was treated as a single station (see Appendix 3).

Table 4 shows that, for January, n' = 1.08, 1.08 and 1.06 for the three successive combinations of stations used in our series since 1878. Corresponding values of n' for July are 1.22, 1.16 and 1.15. Comparison of August with July suggests that estimates of n' are subject to sampling variations: nevertheless the daily series appears to be homoscedastic to within about 5% from 1878. Note that JCS's increase from three stations to six in 1974 (Section 2) entailed (unexpectedly) a reduction in n' (from 1.10 to 1.04 in January; and from 1.15 to 1.12 in July), and therefore an increase in variance. Despite the increase in n, n' decreased because of the greater $\bar{r}$ over the slightly smaller area covered by their six stations than by their previous three (Figure 1). Because daily mean temperatures read at the same time in Central England are highly correlated, little new information is gained about CET (considered as a single entity) by increasing the number of stations beyond about three.

Before 1878, our series is based on a sequence of single stations and so represents a much smaller area than Central England. With n = n' = 1, the original data showed significantly more daily variance than the later three-station combination (Table 5 and Figure 2). Accordingly, adjustments were applied to reduce the variance of this early part of the series while ensuring that the monthly averages of the daily values remained equal to Manley's values.

Consider daily temperature values $x_d$ (d = 1, 2 ..... N) having mean $\bar{x}$ and variance $\sigma^2_x$. The series $bx_d$ has mean $b\bar{x}$ and variance $b^2\sigma^2_x$. Thus if the series for the period 1772-1877 is multiplied by a factor b, where $0 < b < 1$, the variance is reduced, as required, but its mean is also reduced, to $b\bar{x}$. Because the mean is required to stay constant, we must multiply temperature <u>anomalies</u>, calculated from a suitable mean, by b. Choice of the appropriate mean is not straightforward. The daily values of CET derive from statistical populations which vary with atmospheric circulation as well as with season of the year. Both factors are of comparable importance; each circulation type has its own seasonal thermal characteristics in Central England (Storey (1982)). Thus the structure of the underlying population of daily temperature changes continually. To allow for this as far as possible, daily anomalies were calculated from the individual monthly means for each month in each year. These anomalies were then multiplied by b. Finally, Manley's monthly mean value was added to the revised daily anomalies.

A single value of b was required for each calendar month. The data used to calculate b were chosen by assuming that two 30-year sections of the <u>daily series</u> should have similar variance in a given calendar month if Manley's corresponding <u>monthly</u> mean series also has similar variance for the same two periods. On this assumption, the two most appropriate 30-year periods corresponding to our use of one and three stations, were conveniently the consecutive periods 1848 to 1877 and 1878 to 1907 respectively. Table 6 shows the means and the variances of the <u>monthly means</u> for these two periods for each calendar month, together with F-tests on the variance ratios. In all months, except October, there is no significant difference at the 5% level between the variances of the monthly values; even the October variance ratio only just exceeds the 5% F-value. Accordingly, the variances $\sigma_{3i}{}^2$ of daily anomalies as defined above for 1878 to 1907 were divided separately for each calendar month i by corresponding variances $\sigma_{1i}{}^2$ for 1848 to 1877 to yield provisional values of $b_i{}^2$:

$$b_{1i}{}^2 = \sigma_{3i}{}^2/\sigma_{1i}{}^2 \qquad (3.7)$$

$b_{1i}$ is based on sample estimates of variance and so its calendar monthly values do not vary smoothly through the year (Table 7). Only the annual mean $\bar{b}_1$, being based on a larger sample, is likely to be reliable. Therefore a second estimate, $b_{2i}$, was calculated for each calendar month using Equations 3.5 and 3.6 with n = 3 to give

$$b_{2i}^2 = \frac{1}{n'} = \frac{1+2\bar{r}_i}{3} \qquad (3.8)$$

$\bar{r}_i$ was calculated for 1878-1907 from Table 4. $b_{2i}$ was found to change more smoothly through the year than $b_{1i}$ (Table 7), mainly because the statistic $\bar{r}$ is less affected by geographically coherent sampling errors than are the variances in Equation 3.7.

Finally, we chose b to have an annual mean $\bar{b}_1$, to reflect the overall observed discontinuity in variance, but to have a seasonal variation determined by the more reliable seasonal variation of $b_2$. Thus for calendar month i we took:

$$b_i = \frac{\bar{b}_1}{\bar{b}_2} b_{2i} \qquad (3.9)$$

Table 7 gives the values of $b_i$. Note that there appears to be a systematic difference between $\bar{b}_1$ and $\bar{b}_2$. The mean value of $\frac{\bar{b}_1}{\bar{b}_2}$, 0.94, could be interpreted to mean that earlier instrumental practices etc yielded greater apparent day-to-day variance, since 1877 was close to the time of a general change from Glaisher to Stevenson screens. The value for $\bar{b}_1$ will automatically include the effects of such changes, but the estimate of $\bar{b}_2$ assumes that the change of variance around 1878 is solely a result of the change of the number of stations. Thus our retention of $\bar{b}_1$ allows both for changes in the number of stations and for any systematic changes in instrumental practice between the two 30 year periods.

b varies seasonally, being slightly smaller in summer, because the daily temperatures have a slightly lower spatial correlation then than in winter

(Table 7). Thus the variance of the daily series up to 1877 has been reduced in summer by a greater proportion than in winter.

Figure 3 shows histograms of daily temperature values before and after transformation for (a) a particularly warm month (June 1846), and (b) a particularly cold month (January 1838). As expected, the distributions retain a similar shape after transformation but the more extreme values are closer to the monthly mean.

Figure 4 shows 10-year running mean variances of the adjusted daily data, calculated from anomalies from individual monthly averages. F-tests comparing the unsmoothed variances for 1772-1877 with those for 1878-1990, i.e. much longer periods than those used to calculate the adjustments to the variances, showed no significant differences at the 5% level for any calendar month.

f) Adjustment for recent urbanization

Of the stations used since the end of Manley's series, all apart from Rothamsted and perhaps Squires Gate are situated in locations liable to progressive urban warming (Figure 5). We therefore compared the temperatures at each station used since 1974 with those at nearby, relatively rural, sites over approximately the last thirty years. Relative warming trends were found at some of the stations, so corrections have been made to the CET series from 1974 for each calendar month to compensate for progressive urban warming since that time. Calculation of a set of reliable corrections which varied from day to day with changes in atmospheric circulation type was found to be impracticable, because the sample sizes for many circulation types were too small.

The following stations were used in the urban-rural comparisons (Figure 6). See Table 1b for exact locations and altitudes.

a) Rural stations for comparison with Malvern: -

(i) Luddington, (ii) Lyonshall,

(iii) Pershore, (iv) Preston Wynne.

b) Stations for comparison with Squires Gate: -

(i) Preston (not truly rural), (ii) Slaidburn.

c) Station for comparison with Ringway: -

(i) Macclesfield (not truly rural).

Digitised daily data for most of these stations begin in 1959, giving approximately thirty years' data from which to derive relative temperature trends. For (c), data for the nearer station at Knutsford (Figure 6) were found to be too incomplete. Trends in the difference between a CET station and its rural counterparts were calculated using a least-squares linear regression of differences in temperature anomalies against time. Separate regressions were performed for each calendar month and for the year as a whole. The statistical significance of the computed linear trends was assessed by an F-test on the regression slopes (Draper and Smith, 1966).

No significant relative trend between Squires Gate and either Preston or Slaidburn was found. The environments of these stations are not very comparable: Squires Gate is very near the coast; Preston (an urban station) and Slaidburn are much further inland; Slaidburn, moreover, is an upland site (192m above MSL). Nevertheless, the lack of relative warming at Squires Gate, especially compared with Slaidburn, suggests that the urban influence at Squires Gate has not increased. Squires Gate is just outside the built-up area of Blackpool and is a relatively small airport (Figure 5 and Appendix 2).

Malvern warmed relative to Luddington considerably more strongly than relative to Preston Wynne, Lyonshall, and Pershore (Table 8), suggesting that these latter three stations may also have undergone slight urban warming. Site maps (not shown), however, do not support this. Alternatively, trends in atmospheric circulation may, fortuitously, have favoured relative cooling at Luddington.

Ringway warmed significantly relative to Macclesfield over the year as a whole (Table 8). The screen at Ringway is exposed to airport activities; nearby building work in the mid-1980's (Appendix 2) may have affected the observations; a change of site in January 1988 is too recent to assess any improvement. Thus Ringway is only marginally suitable and its use must be kept under review. Although Macclesfield is a town of area about 10km², its station has not warmed relative to stations in smaller settlements (e.g. Shawbury, Stone) in recent decades. The climatological site is west, i.e. climatologically upwind, of the town centre, in a park district.

We did not replace Malvern and Ringway in our CET series by any of their "rural" equivalents, because of occasional missing days' data at the latter stations. However, on the basis of Table 8 a-c, we constructed a parallel series of daily values, starting in January 1959, replacing Malvern with ½ (Luddington + Preston Wynne) and replacing Ringway with Macclesfield, whenever these alternative stations had data. Monthly means of the CET and parallel series were compared by linearly regressing their differences for each calendar month against time over the period 1959 to 1989. The relative warming trend of the original series was statistically significant according to t-tests on the slope of the trend line in all calendar months, as shown in Table 8. The trends were strongest in April to July, equivalent to about 0.08 deg C per 10 years. In order to obtain a smooth seasonal cycle of urbanisation corrections to CET, the calendar monthly slopes m of the regression lines were smoothed 1:2:1 in time. Corrections equal to m(1973-year), rounded to the nearest 0.1 deg C, have been applied to the monthly CET values from 1974 onwards, and the daily CET values within a month altered by the same amount.

Table 9a shows the urbanisation corrections. No corrections are applied until 1979 or later. At present all urbanisation corrections are -0.1 °C, but from 1992 corrections will reach -0.2 °C in June and July. Urban warming trends may change, so future corrections will need to be kept under review.

g) Test of urban warming corrections using radiosonde data

The urban warming corrections have been assessed by comparing the corrected CET series with radiosonde data for 1979 to 1990 for Crawley (south of London, Table 1b and Fig 6) and Aughton, near Liverpool. Earlier radiosonde temperatures may have been inconsistent with those for 1979 onwards because of a change from Kew MK IIb to Kew MK III sondes in 1978. The MK II sondes used a bimetallic strip, but the MK III sondes were radically different, using thin tungsten wires as a temperature-dependent electrical resistor (Pettifer, 1983).

Average temperatures for the 850mb level for each year were converted to anomalies from their 1979-90 means for each radiosonde station, and the averages of the anomalies for the two radiosonde stations were regressed linearly against the corresponding annual CET anomalies. The regression correlation coefficient was 0.91. The residuals had an insignificant trend regression correlation of 0.12 and the estimated relative warming of CET was 0.10 °C. Without the corrections for urban warming of CET, the trend regression correlation of the residuals was 0.20, which is still insignificant, and the estimated relative warming of CET was 0.17°C. In 1990, Vaisala radiosondes were introduced, but regressions for 1979-89 also yielded insignificant relative trends. These results give qualified support to the validity of the corrections for urban warming in CET so far, but 1979-90 is too short a period to give reliable statistical comparisons.

h) Total corrections

For clarity Table 9b shows the total corrections applied in 1991 to calendar monthly data for urbanisation and for compatibility with Manley's series.

4. NON-CLIMATIC INFLUENCES ON TEMPERATURE OBSERVATIONS

Long climatic time-series must be homogeneous if they are to be of benefit in studies of climatic change (Mitchell et al, 1966). Non-meteorological effects, including changes in the daily variance, resulting from changes in instruments, in observing sites or surroundings of sites, and in times of measurement, etc. should be reduced as much as possible, since even quite small artificial signals in a time series could be mistaken for real climatic changes. This is why we constrained our daily CET series up to 1973 to yield values consistent with Manley's homogenized monthly series (Section 3d), and why from 1974 we made adjustments for urban warming trends (Section 3f). However, we only made minor within-month compensations for non-meteorological effects (Appendix 1). To the extent that non-meteorological effects vary from day to day, our individual daily values are, consequently, less reliable than Manley's monthly values. Remaining non-climatic influences on our daily CET series are therefore discussed.

a) Changes in instrumentation and exposure

Manley's (1974) careful adjustments to overlapping records from different sites will have compensated his monthly series for changes in instrumentation and exposure to a considerable extent. The major changes included that from an assortment of instruments and exposures to the use of Glaisher stands (Glaisher, 1868) in the mid-19th century, followed by Stevenson screens in the 1870's. These changes, in general, improved the shielding of the thermometer from radiation. Thus earlier records were more prone to high values on sunny days (Laing, 1977) and low values on clear nights, so that the apparent day-to-day variability would have been enhanced, giving a greater frequency of extremely high summer values and extremely low winter values in our series. Table 10 is an average of the results of several investigations of temperature differences between Glaisher stands and Stevenson screens, in southern England, as a function of time of year. Our adjustments to the variance of our series up to 1877 (Section 3e) will have slightly reduced this excess day-to-day variability.

b) Changes of site

Manley carefully compensated his monthly series for changes of site. We have included his compensation factors by constraining the monthly averages of our daily series to be equal to Manley's (Section 3d). However, day-to-day variations in our series will still be affected by the choice of site in two ways. First, some sites are more prone than others to hot days and cold nights. We have therefore followed Manley in avoiding frost-hollows as far as possible. The unavoidable use of the Lancashire station Squires Gate in recent years is a weakness here, but its frost-hollow characteristics are partly compensated by its coastal location and its 1/6 weighting in the daily series (Section 2). Second, the geographical location of the single sites available in the early years will have biased the daily values in different ways depending on the synoptic weather situation. In the severe January of 1795, for example, anticyclonic easterlies prevailed (Lamb and Johnson, 1966); to compensate, the daily data, being only from London (Section 2), were all adjusted in that month by +0.2 °C to yield an average of -3.1°C to agree with Manley (1974). This adjustment will have offset the relative coldness of southeastern England in the anticyclonic easterly situation dominating January 1795, as well as implicitly compensating for unknown local siting characteristics. However, on individual days in that month the particular synoptic situation will have made the "true" offset different from its monthly mean for January 1795. Thus the Royal Society's (1774-1843) and Hoy's (1771-1822) London records show a single mild day on 27 January with a mean temperature of about 7 °C, SSW wind and pressure 988mb, implying that the centre of a depression passed northwest of London. We assess conditions elsewhere on that date as follows. Although we have not been able to find Barker's daily register for Lyndon, Rutland (about 150 km to the north-northwest of London) for 1795, we do have his monthly abstract (Barker, 1796) which gives extremes for morning and afternoon temperatures. Assuming that the highest values for January 1795 took place on the 27th, and converting them to daily Central England temperature by the methods described in Section 3, yields 3.7 °C for that date. Hughes at Stroud, Gloucestershire (about 150 km to the west of London) reported a violent flood from the sudden thaw, but the 8 am temperature was below 1 °C. Withering, who made a brief record near Birmingham (Giles, 1991), reported a daily mean temperature between 3 °C and 4 °C. Pennant reported a day's mean of 5.9 °C at Holywell, a climatologically slightly milder location near the Dee estuary in N Wales, about 300 km northwest of London. So our estimate of CET from the London data is probably a little too high. The converse would naturally apply to any days when cold air was confined to the southeast.

c) Urbanisation

Manley (1974) took reasonable care to avoid urban sites or to compensate for recent urban warming in his monthly series which ended in 1973. Our series is also largely compensated for urbanisation, on a monthly average, by being anchored to Manley's up to 1973 and by our own adjustments (Section 3f) thereafter. The urban heat island is formed mainly by retention of solar heat in building fabrics and roads by night, and by the "canyon-effect" obstruction of nocturnal outgoing longwave radiation by buildings (Oke, 1982). So relative urban warmth is most intense on nights when long-wave radiation loss, as opposed to advection, dominates the heat balance. The parts of our series which use observations made in London, and in recent decades, Malvern and Ringway airport (near Manchester) (Table 1 and Section 3f) may thus be a little too warm on individual dates with calm clear nights, when urban warming exceeds its monthly average, and a little too cold on dates with cloudy or windy nights.

d) Changes of observing-time

Manley took considerable care to compensate his monthly series for changes of observing time. Much of this compensation was implicit, through his use of overlaps between stations to make adjustments for changes of site. Our daily series, by adhering to Manley's monthly averages, incorporates his compensation on the monthly time-scale. But, because our daily values up to 1877 are based on observations for a variety of hours rather than the standard $t_a$ = ½ (24-hour maximum + 24-hour minimum) used thereafter, there will be some day-to-day scatter caused by variability in the warmth of particular observing hours relative to the individual day's true $t_a$.

Table 11 uses the early records of Hoy and the Royal Society in London to illustrate the composite effects of differences in observing time, urban environment, siting, exposure, instrumentation, and probably also observers' errors, on daily temperature variations relative to individual months' means. These factors (e.g. Hoy's observing hours were generally 8 am, 3 pm; the Royal Society's 7 am (8 am in winter), 2 pm) contributed to a > 1.5°C root-mean-square difference in the 1770's and 1780's, falling to typically 1°C after Hoy's move to Syon House and the Royal Society's move to Somerset House. In October 1774 and July 1775, when the correlations were low, Hoy's reports of wind and weather conditions tended to support the Royal Society's temperatures rather than Hoy's in cases of disagreement.

Appendix 3 contains a discussion of some of the remaining uncertainties in the corrected daily CET series.

## 5. TABULATION OF MONTHLY SERIES WITH REVISED NORMALS

Table 12 updates Manley (1974)'s monthly CET series to 1990 using the daily series reported in this paper. The table includes averages and standard deviations of monthly values for 1961-1990, the current World Meteorological Organisation standard climatological period. The averages are also compared with those given by Manley (1974) for 1931-1960. Only January and October have warmed, and the 1961-1990 annual average is 0.13°C cooler than that for 1931-60. These changes are placed in a long-term context by Figure 7, which shows 30-year running means from 1659, when Manley's series commenced, to the present. There are some substantial seasonally specific climatic variations on a variety of timescales. These will be discussed elsewhere.

Because of day-to-day persistence, the standard deviation $\sigma_m$ of the monthly values in 1961-1990 greatly exceeds $\sigma_d / n^{1/2}$, where $\sigma_d$ is a standard deviation of daily values and n is the number of days in the month. $\sigma_d$ was calculated using anomalies from (daily mean climatology for 1961-1990 + individual months' anomalies) to avoid enhancement of variance by the annual cycle in spring and autumn and by interannual variability. $\sigma_m$ also exceeds $\sigma_d/(n/5)^{1/2}$, especially in winter. Thus even every fifth day is not completely independent.

Manley (1974) gave monthly and annual extremes. Our extension to his series provides two new record warm months: July 1983 (19.5°C) and August 1975 (18.7°C). December 1974 (8.1°C) equalled the previous record for warmth set in 1934. 1990 was, marginally, the warmest year after 1949. The annual value for 1989 fell short of that for 1949 by 0.1°C, the amount of our urban warming adjustment. No new monthly mean low-temperature CET records have been set since Manley's record ended.

Table 12 also includes extreme daily values of CET for 1961-1990 and for the record as a whole. The period 1961-1990 includes the highest daily mean values for August and October in the entire series, but no corresponding record low daily values. However the record daily minimum temperature for England (-26.1 °C) was recorded on 10 January 1982 at

Newport, Shropshire, 20 km east of Shawbury and well within the Central England area (Fig 1).

## 6. CONCLUSION

We have used a rather diverse set of stations to build on Manley's work and create a daily mean CET series for 1772 to date. Our daily series is one of the longest available, but it cannot at present be based on an entirely satisfactory set of stations. This is unfortunate since the monthly CET record is the longest available instrumental temperature record in the world. The uncertainties involved in the replacement of Stonyhurst, and the evidence for urban warming at several of our stations, lead us to stress the importance of the establishment of guaranteed reference-stations for monitoring climatic variability and change. The stations should be "guaranteed" by according them special protection from closure or from serious local disturbances such as major building within a few hundred metres. If the stations are in areas where progressive urbanisation is unavoidable, rural stations should be established as cross-checks. If the site is to be moved, even by a short distance, observations should be made in parallel at both sites for at least one year, preferably longer.

Acknowledgements

Special thanks are due to Ann Storey who carried out extensive preliminary calculations in the early 1980's to provide a more homogeneous daily series, and with whom the third author collaborated.

Thanks are also due to Walter Shackleton who extracted large amounts of manuscript data from the Meteorological Office Archive.

REFERENCES

Barker, T. 1777-1789. Meteorological Register made at Lyndon Hall, Rutland. 371 pp.

Barker, T. 1796. Abstract of a Register of the Barometer, Thermometer and Rain at Lyndon in Rutland, 1795. Communicated by Thomas White, Esq. FRS. Phil. Trans. Roy. Soc. London, 86, 483-485. Reproduced in Kington (1988).

Cary, W. 1786-1846. Observations made at the Strand, London. Published regularly in the Gentlemans Magazine.

Cramer, H. 1946. Mathematical methods of statistics. Princeton University Press. 575 pp.

Draper, N R, and Smith, H. 1966. Applied Regression Analysis. Wiley. 407 pp.

Ellis, W. 1891. On the comparison of thermometrical observations made in a Stevenson screen with corresponding observations made on the revolving stand at the Royal Observatory, Greenwich. QJR Meteorol Soc, 17, 240-249.

Giles, B.D. 1991. Late eighteenth century temperatures in Birmingham, England. J. Meteorology (Trowbridge), 16, 40-45.

Glaisher, J. 1868. Description of thermometer stand. Symons's Monthly Meteorol Mag, 33, 155-157.

Hoy, T. 1771-1822. Meteorological records made at Barn Elms, Kennington, Muswell Hill and Sion House.

Hughes, T. 1771-1813. Meteorological records made at Stroud, Glos.

Jenkinson, A F, and Carr, D with Shackleton, W. 1979. A daily catalogue of Central England Temperatures, 1814 to 1978. Meteorological Office Synoptic Climatology Branch Memorandum No. 71. (Unpublished work: copy held in National Meteorological Library, Meteorological Office, Bracknell, UK.)

Johnson, M J. 1842-1855. Astronomical observations made at the Radcliffe Observatory, Oxford, in the years 1840-1853.

Jones, D E. 1987. Daily Central England temperature: recently constructed series. Weather, 42, 130-133.

Kington, J. 1988. The weather journals of a Rutland squire: Thomas Barker of Lyndon Hall. Rutland Record Series Vol.2. General Editor Bryan Waites. Rutland Record Society, Oakham, UK. xiv+217 pp.

Knox-Shaw, H and Balk, J G. 1932. Radcliffe Observations, 55, Appendix. Oxford.

Labrijn, A. 1945. The climate of the Netherlands during the last two and a half centuries. Mededeelingen en Verhandelingen 49, KNMI No 102, 14pp.

Laing, J. 1977. Maximum summer temperatures recorded in Glaisher stands and Stevenson screens. Meteorol Mag, 106, 220-228.

Lamb, H H. 1972. British Isles weather types and a register of the daily sequence of circulation patterns 1861-1971. Met Office Geophys Mem 116, 85pp.

Lamb, H H and Johnson, A I. 1966. Secular variations of the atmospheric circulation since 1750. Meteorological Office Geophys Mem. 110. HMSO, 125 pp.

Manley, G. 1946. Temperature trend in Lancashire, 1753-1945. QJR Meteorol Soc, 72, 1-31.

Manley, G. 1952. Thomas Barker's meteorological journals, 1748-1763 and 1777-1789. QJR Meteorol Soc, 78, 255-259.

Manley, G. 1953. The mean temperature of Central England, 1698 to 1952. QJR Meteorol Soc, 79, 242-261.

Manley, G. 1960. Bibliography of the principal sources of daily meteorological observations for the London area. (Unpublished work: copy held in National Meteorological Library.)

Manley, G. 1964. London Weather Diary. (Unpublished work: copy held in National Meteorological Library.)

Manley, G. 1974. Central England Temperatures: monthly means 1659 to 1973. QJR Meteorol Soc, 100, 389-405.

Margary, I D. 1924. A comparison of forty years' observations of maximum and minimum temperature as recorded in both screens at Camden Square, London. QJR Meteorol Soc, 50, 209-226 and 363.

Mawley, E. 1897. Shade temperature. QJR Meteorol Soc, 23, 69-87.

Meteorological Office. 1874. Hourly readings from the self-recording instruments at the seven observatories in connection with the Meteorological Office, 1874.

Mitchell, J M, Dzerdeevskii, B, Flohn, H, Hofmeyr, W L, Lamb, H H, Rao, K N and Wallén, C C. 1966. Climate change. WMO Tech Note No 79. WMO No 195, TP 100. 79pp.

Oke, T R. 1982. The energetic basis of the urban heat island. QJR Meteorol Soc, 108, 1-24.

Parker, D E and Folland, C K. 1988. The nature of climatic variability. Meteorol Mag, 117, 201-210.

Pennant, D. 1793-1835. Meteorological record made at Holywell, Flintshire.

Perry, S J. 1872. Results of meteorological and magnetical observations at Stonyhurst College Observatory, 1871, pp 34-37. J Robinson, Preston.

Pettifer, R E W. 1983. A brief introduction to the United Kingdom Mark 3 Radiosonde System. Meteorological Office.

Royal Society. 1774-1780, 1787-1843 Daily weather observations, Royal Society, London. Published in Phil. Trans. Roy. Soc. London.

Six, J. 1782. Account of an improved thermometer. Phil. Trans. R. Soc. London, 72, 10 pp.

Storey, A M. 1982. A study of the relationship between isobaric patterns over the UK and Central England temperature and England - Wales rainfall. Weather, 37, 2-11.

Storey, A M, Folland, C K and Parker D E. 1985. A homogeneous archive of daily Central England temperature 1772 to 1985 and new monthly average values 1974 to 1985. Synoptic Climatology Branch Memo. No. 107. Unpublished: available in National Meteorological Library, Meteorological Office, Bracknell, UK.

Wilson, C A and Mitchell, J F B. 1987. Simulated climate and $CO_2$-induced climate change over Western Europe. Climatic Change, 10, 11-42.

Yevjevich, V. 1972. Probability and statistics in hydrology. Water Resources Publications, Fort Collins, Colorado, USA. 302 pp.

TABLE 1a Stations chosen to represent Central England
(* indicates that Manley (1953, 1974) also used the station)

| Period | Station |
|---|---|
| 1772-1773 | London (Kennington) (Hoy's record) |
| 1774-1776 | London (Royal Society, Crane Court)* |
| Jan 1777-June 1789 (except Dec 1786) | Lyndon Hall, Rutland* (Barker's record) |
| Dec 1786 | London (Syon House, Kew) (Hoy's record) |
| July 1789-Dec 1811 | London (Royal Society, Somerset House)* |
| 1812-1825 | Greenwich Observatory (London) |
| 1826-1852 | London (Royal Horticultural Society, Chiswick) |
| 1853-1877 | Oxford (Radcliffe Observatory)* |
| 1878-1930 | Stonyhurst* (Lancashire), Cambridge (Botanical Gardens) and Ross-on-Wye, equally weighted |
| 1931-1958 | Stonyhurst*, Rothamsted (Herts) and Ross-on-Wye, equally weighted |
| 1959 onwards | Rothamsted, Malvern, Squires Gate (Lancs) and Ringway, with weights 1:1:0.5:0.5 |

TABLE 1b Locations of stations

Stations used in our daily CET series, in JCS's series, and in our urban-rural comparisons are listed.

| Station | Latitude | Longitude | Elevation (m) |
|---|---|---|---|
| Aughton | 53°33'N | 2°55'W | 56 |
| Birmingham (Elmdon) | 52°27'N | 1°44'W | 99 |
| Cambridge (Botanical Gardens) | 52°12'N | 0°08'E | 12 |
| Cardington | 52°06'N | 0°25'W | 70 |
| Crawley | 51°05'N | 0°13'W | 144 |
| Finningley | 53°29'N | 1°00'W | 17 |
| London: Chiswick (Roy.Hort.Soc) | 51°29'N | 0°16'W | 5 |
| Crane Court | 51°31'N | 0°06'W | 10 |
| Greenwich Observatory | 51°29'N | 0°00'W | 48 |
| Kennington | 51°29'N | 0°07'W | 7 |
| Syon House, Kew | 51°28'N | 0°19'W | 5 |
| Somerset House | 51°31'N | 0°07'W | 12 |
| Luddington | 52°10'N | 1°45'W | 56 |
| Lyndon Hall, Rutland | 52°38'N | 0°40'W | 102 (approx) |
| Lyonshall | 52°13'N | 2°58'W | 155 |
| Macclesfield | 53°16'N | 2°08'W | 143 |
| Malvern | 52°07'N | 2°19'W | 62 |
| Oxford (Radcliffe Observatory) | 51°46'N | 1°16'W | 63 |
| Pershore | 52°06'N | 2°03'W | 40 |
| Preston Wynne | 52°07'N | 2°30'W | 84 |
| Preston (Moor Park) (Lancs) | 53°46'N | 2°42'W | 33 |
| Ringway Airport | 53°21'N | 2°16'W | 75 |
| Ross on Wye | 51°55'N | 2°35'W | 67 |
| Rothamsted | 51°48'N | 0°21'W | 128 |
| Shawbury | 52°48'N | 2°40'W | 76 |
| Sheffield (Weston Park) | 53°23'N | 1°29'W | 146 |
| Slaidburn | 53°59'N | 2°26'W | 192 |
| Squires Gate | 53°46'N | 3°02'W | 10 |
| Stonyhurst | 53°51'N | 2°28'W | 115 |
| Wittering | 52°37'N | 0°28'W | 84 |

TABLE 2 Monthly corrections applied during the period 1878-1973 (Deg C)

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1878 | -0.25 | 0.12 | -0.38 | -0.28 | -0.39 | -0.21 | -0.10 | -0.34 | -0.23 | -0.25 | -0.17 | -0.15 |
| 1879 | -0.19 | -0.05 | -0.42 | -0.48 | -0.19 | -0.46 | -0.67 | -0.47 | 0.12 | -0.19 | 0.02 | 0.63 |
| 1880 | -0.29 | 0.13 | -0.19 | -0.20 | -0.14 | 0.02 | -0.37 | -0.57 | -0.40 | -0.08 | 0.23 | -0.02 |
| 1881 | 0.15 | 0.21 | 0.13 | 0.01 | -0.03 | 0.04 | -0.26 | -0.22 | -0.15 | -0.07 | 0.20 | 0.22 |
| 1882 | 0.30 | 0.67 | 0.25 | -0.08 | 0.03 | -0.02 | -0.06 | -0.35 | 0.22 | 0.22 | -0.02 | 0.38 |
| 1883 | 0.12 | 0.13 | -0.33 | -0.17 | -0.17 | -0.22 | -0.08 | -0.14 | -0.23 | -0.08 | -0.00 | -0.02 |
| 1884 | 0.13 | 0.18 | 0.11 | 0.10 | -0.02 | -0.07 | -0.00 | 0.11 | 0.01 | 0.23 | -0.21 | 0.08 |
| 1885 | 0.19 | -0.04 | -0.18 | 0.05 | -0.13 | -0.30 | -0.18 | -0.44 | -0.03 | 0.19 | 0.37 | 0.37 |
| 1886 | 0.32 | 0.33 | 0.11 | -0.16 | -0.25 | 0.01 | -0.18 | -0.23 | 0.04 | 0.21 | 0.20 | -0.10 |
| 1887 | 0.60 | -0.01 | -0.12 | -0.17 | -0.33 | -0.38 | -0.41 | -0.09 | -0.08 | 0.05 | 0.03 | -0.01 |
| 1888 | 0.16 | 0.11 | -0.26 | -0.29 | -0.32 | -0.32 | -0.27 | -0.33 | -0.16 | 0.11 | -0.03 | 0.18 |
| 1889 | 0.68 | -0.05 | 0.03 | -0.10 | -0.12 | -0.25 | 0.02 | -0.14 | 0.05 | -0.07 | 0.10 | 0.38 |
| 1890 | 0.04 | 0.24 | 0.07 | -0.06 | -0.35 | -0.62 | -0.27 | -0.52 | -0.36 | -0.23 | -0.20 | 0.33 |
| 1891 | 0.24 | -0.81 | -0.47 | -0.09 | -0.26 | -0.39 | -0.10 | -0.35 | -0.13 | -0.30 | 0.08 | 0.11 |
| 1892 | 0.45 | 0.25 | -0.12 | -0.28 | -0.15 | -0.12 | -0.13 | -0.21 | -0.01 | 0.11 | 0.20 | 0.26 |
| 1893 | 0.33 | -0.10 | -0.48 | -0.29 | -0.14 | -0.30 | -0.40 | -0.24 | -0.25 | -0.06 | 0.21 | 0.22 |
| 1894 | 0.41 | 0.28 | 0.03 | -0.12 | -0.04 | -0.37 | -0.21 | -0.15 | -0.04 | 0.12 | 0.18 | 0.29 |
| 1895 | 0.27 | 0.12 | -0.25 | -0.24 | -0.14 | 0.03 | -0.31 | 0.06 | -0.06 | 0.11 | 0.12 | 0.29 |
| 1896 | 0.24 | 0.31 | -0.07 | 0.25 | -0.25 | -0.25 | -0.45 | -0.19 | -0.08 | -0.07 | 0.34 | 0.27 |
| 1897 | 0.35 | 0.32 | -0.11 | -0.14 | -0.29 | -0.30 | -0.12 | -0.15 | 0.01 | 0.09 | 0.41 | 0.03 |
| 1898 | 0.41 | 0.31 | 0.12 | 0.11 | -0.12 | -0.18 | -0.17 | -0.14 | -0.20 | 0.06 | 0.09 | 0.25 |
| 1899 | 0.03 | 0.01 | 0.11 | -0.29 | -0.27 | 0.02 | -0.23 | -0.41 | -0.39 | -0.11 | 0.11 | 0.19 |
| 1900 | 0.22 | -0.04 | 0.08 | -0.10 | -0.22 | -0.28 | -0.43 | -0.41 | -0.21 | 0.13 | 0.17 | 0.21 |
| 1901 | 0.19 | 0.27 | -0.01 | -0.12 | -0.42 | -0.30 | -0.29 | -0.67 | -0.27 | 0.15 | 0.23 | 0.08 |
| 1902 | -0.06 | 0.04 | -0.21 | -0.18 | -0.14 | -0.18 | -0.27 | -0.25 | -0.28 | 0.05 | 0.11 | 0.06 |
| 1903 | 0.25 | 0.29 | -0.12 | -0.21 | -0.29 | -0.15 | -0.14 | -0.08 | -0.25 | -0.07 | 0.05 | 0.10 |
| 1904 | 0.28 | -0.04 | 0.06 | -0.21 | -0.09 | -0.30 | -0.38 | -0.11 | -0.11 | 0.16 | 0.11 | 0.17 |
| 1905 | 0.33 | 0.07 | -0.07 | -0.07 | -0.09 | -0.31 | -0.32 | -0.17 | -0.06 | -0.00 | 0.10 | 0.41 |
| 1906 | 0.27 | 0.05 | -0.02 | 0.03 | -0.23 | 0.17 | -0.06 | -0.37 | -0.05 | -0.03 | 0.11 | 0.07 |
| 1907 | 0.27 | 0.14 | 0.08 | -0.13 | -0.25 | -0.26 | -0.20 | -0.11 | -0.17 | 0.09 | 0.04 | 0.17 |
| 1908 | 0.18 | 0.17 | 0.03 | -0.24 | -0.23 | -0.22 | -0.34 | -0.13 | -0.04 | -0.14 | 0.12 | -0.08 |
| 1909 | 0.30 | -0.02 | 0.14 | -0.17 | 0.20 | -0.29 | -0.33 | -0.22 | -0.10 | -0.08 | -0.10 | 0.12 |
| 1910 | 0.17 | 0.06 | 0.20 | -0.06 | -0.36 | -0.22 | -0.49 | 0.03 | -0.18 | -0.10 | -0.16 | 0.13 |
| 1911 | 0.16 | 0.28 | -0.00 | -0.19 | -0.28 | -0.22 | -0.07 | -0.36 | -0.17 | -0.14 | 0.06 | 0.12 |
| 1912 | 0.25 | -0.09 | -0.11 | -0.17 | -0.04 | -0.22 | -0.35 | -0.34 | -0.15 | 0.06 | 0.12 | 0.06 |
| 1913 | 0.19 | 0.14 | 0.09 | 0.28 | -0.39 | -0.14 | -0.35 | -0.17 | -0.15 | -0.15 | 0.18 | 0.19 |
| 1914 | 0.21 | 0.07 | -0.11 | 0.12 | 0.04 | -0.11 | -0.35 | -0.15 | -0.04 | 0.00 | 0.33 | 0.04 |
| 1915 | 0.09 | 0.19 | -0.00 | 0.05 | -0.18 | -0.03 | -0.16 | 0.02 | 0.25 | 0.22 | -0.23 | 0.02 |
| 1916 | 0.36 | 0.05 | -0.21 | 0.01 | 0.10 | -0.04 | -0.06 | -0.02 | 0.00 | -0.07 | 0.17 | 0.04 |
| 1917 | -0.10 | 0.14 | -0.17 | -0.05 | -0.22 | 0.08 | -0.01 | -0.39 | -0.20 | -0.09 | -0.01 | 0.21 |
| 1918 | 0.10 | 0.01 | -0.23 | -0.23 | -0.04 | 0.14 | -0.30 | -0.18 | -0.33 | 0.00 | 0.08 | -0.13 |
| 1919 | -0.00 | 0.34 | 0.01 | 0.08 | 0.40 | 0.05 | -0.28 | -0.23 | -0.22 | -0.04 | -0.08 | 0.16 |
| 1920 | 0.09 | 0.06 | -0.04 | -0.29 | -0.15 | -0.08 | -0.22 | -0.19 | 0.02 | -0.06 | 0.22 | -0.02 |
| 1921 | 0.04 | -0.05 | 0.12 | -0.20 | -0.12 | 0.00 | -0.07 | -0.30 | -0.04 | -0.06 | -0.13 | 0.04 |
| 1922 | -0.12 | -0.23 | -0.24 | -0.08 | -0.15 | -0.07 | -0.13 | -0.01 | -0.06 | -0.30 | 0.24 | 0.08 |
| 1923 | 0.32 | 0.19 | 0.20 | -0.04 | -0.11 | 0.05 | -0.09 | -0.05 | 0.24 | -0.03 | -0.14 | 0.24 |
| 1924 | 0.20 | 0.19 | -0.02 | -0.20 | -0.05 | -0.00 | 0.14 | -0.01 | -0.14 | 0.01 | 0.09 | 0.11 |
| 1925 | 0.07 | 0.13 | -0.04 | -0.07 | -0.21 | 0.08 | -0.22 | -0.19 | -0.04 | -0.08 | -0.16 | -0.00 |
| 1926 | 0.13 | -0.04 | -0.04 | 0.02 | -0.02 | 0.01 | 0.15 | -0.08 | -0.21 | 0.05 | -0.25 | 0.05 |
| 1927 | -0.03 | -0.16 | 0.06 | 0.08 | 0.00 | 0.00 | 0.05 | -0.07 | -0.16 | 0.22 | 0.08 | 0.24 |
| 1928 | 0.22 | -0.02 | 0.17 | 0.08 | 0.14 | -0.10 | -0.07 | -0.07 | 0.14 | -0.06 | -0.05 | 0.15 |
| 1929 | -0.28 | 0.33 | 0.16 | 0.12 | 0.13 | 0.16 | 0.12 | 0.08 | -0.21 | 0.22 | -0.01 | -0.06 |
| 1930 | 0.04 | -0.33 | -0.01 | -0.04 | -0.12 | -0.06 | -0.11 | -0.06 | -0.14 | 0.05 | -0.08 | 0.13 |
| 1931 | 0.12 | 0.45 | 0.44 | 0.29 | 0.42 | 0.28 | 0.30 | 0.30 | 0.07 | 0.28 | 0.36 | 0.12 |

TABLE 2 (Continued) Monthly corrections applied during the period 1878-1973 (Deg C)

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1932 | 0.51 | 0.08 | 0.35 | 0.50 | 0.40 | 0.22 | 0.22 | 0.16 | 0.14 | 0.44 | 0.32 | 0.40 |
| 1933 | 0.18 | 0.53 | 0.27 | 0.38 | 0.37 | 0.43 | 0.31 | 0.36 | 0.17 | 0.42 | 0.25 | 0.45 |
| 1934 | 0.28 | 0.49 | 0.18 | 0.35 | 0.31 | 0.14 | 0.30 | 0.36 | 0.51 | 0.56 | 0.27 | 0.37 |
| 1935 | 0.10 | 0.26 | 0.36 | 0.38 | 0.09 | 0.28 | 0.24 | 0.25 | 0.33 | 0.42 | 0.50 | -0.01 |
| 1936 | 0.35 | 0.71 | 0.47 | 0.31 | 0.18 | 0.33 | 0.40 | 0.45 | 0.41 | 0.45 | 0.31 | 0.30 |
| 1937 | 0.30 | 0.36 | 0.42 | 0.50 | 0.41 | 0.43 | 0.37 | 0.47 | 0.55 | 0.49 | 0.31 | 0.38 |
| 1938 | 0.25 | 0.41 | 0.63 | 0.36 | 0.36 | 0.31 | 0.37 | 0.63 | 0.53 | 0.54 | 0.60 | 0.53 |
| 1939 | 0.27 | 0.55 | 0.33 | 0.58 | 0.42 | 0.25 | 0.50 | 0.24 | 0.24 | 0.43 | 0.31 | 0.44 |
| 1940 | 0.26 | 0.62 | 0.41 | 0.42 | 0.24 | 0.29 | 0.46 | 0.42 | 0.30 | 0.34 | 0.32 | 0.16 |
| 1941 | 0.21 | 0.35 | 0.38 | 0.20 | 0.50 | 0.30 | 0.24 | 0.35 | 0.28 | 0.44 | 0.36 | 0.43 |
| 1942 | 0.27 | 0.23 | 0.44 | 0.29 | 0.28 | 0.30 | 0.35 | 0.50 | 0.39 | 0.23 | 0.16 | 0.29 |
| 1943 | 0.26 | 0.09 | 0.29 | 0.35 | 0.13 | 0.41 | 0.39 | 0.54 | 0.55 | 0.25 | 0.30 | 0.05 |
| 1944 | 0.30 | 0.29 | 0.38 | 0.53 | 0.37 | 0.32 | 0.32 | 0.21 | 0.45 | 0.31 | 0.15 | 0.21 |
| 1945 | 0.24 | 0.29 | 0.30 | 0.21 | 0.23 | 0.38 | 0.36 | 0.29 | 0.38 | 0.42 | 0.12 | 0.11 |
| 1946 | 0.03 | 0.11 | 0.96 | 0.29 | 0.29 | 0.32 | 0.29 | 0.41 | 0.33 | 0.25 | 0.22 | 0.38 |
| 1947 | 0.29 | 0.21 | 0.22 | 0.31 | 0.30 | 0.28 | 0.33 | 0.28 | 0.21 | 0.31 | 0.26 | 0.05 |
| 1948 | 0.11 | 0.19 | 0.30 | 0.29 | 0.28 | 0.13 | 0.25 | 0.22 | 0.18 | 0.32 | 0.36 | 0.18 |
| 1949 | 0.28 | 0.42 | 0.24 | 0.27 | 0.26 | 0.34 | 0.18 | 0.04 | 0.14 | 0.10 | 0.25 | 0.23 |
| 1950 | 0.22 | 0.15 | 0.26 | 0.20 | 0.24 | 0.37 | 0.34 | 0.34 | 0.12 | -0.01 | 0.21 | 0.20 |
| 1951 | 0.24 | 0.28 | 0.31 | 0.10 | 0.22 | 0.18 | 0.26 | 0.21 | 0.22 | 0.07 | 0.41 | 0.13 |
| 1952 | 0.14 | 0.47 | 0.15 | 0.26 | 0.27 | 0.32 | 0.29 | 0.04 | -0.01 | 0.03 | 0.28 | 0.09 |
| 1953 | 0.18 | 0.43 | 0.32 | 0.10 | 0.08 | 0.40 | 0.21 | 0.23 | 0.14 | 0.30 | 0.44 | 0.18 |
| 1954 | 0.24 | 0.16 | 0.17 | 0.11 | 0.02 | 0.07 | 0.28 | 0.22 | 0.05 | 0.13 | 0.15 | 0.40 |
| 1955 | 0.32 | 0.08 | 0.19 | 0.09 | -0.05 | 0.12 | 0.30 | 0.31 | 0.14 | 0.31 | 0.24 | 0.04 |
| 1956 | 0.15 | 0.41 | 0.17 | 0.24 | 0.12 | 0.13 | 0.17 | 0.15 | 0.13 | 0.29 | 0.24 | 0.30 |
| 1957 | 0.26 | 0.22 | 0.11 | 0.37 | 0.00 | 0.10 | 0.02 | 0.01 | 0.05 | 0.24 | 0.31 | 0.47 |
| 1958 | 0.10 | 0.17 | 0.14 | 0.19 | -0.05 | 0.37 | 0.23 | 0.06 | 0.23 | 0.17 | 0.37 | 0.19 |
| 1959 | 0.08 | 0.38 | 0.26 | 0.13 | 0.18 | 0.10 | 0.09 | -0.10 | -0.27 | -0.06 | 0.30 | 0.40 |
| 1960 | -0.07 | 0.15 | 0.19 | 0.19 | 0.05 | 0.16 | -0.20 | -0.05 | -0.06 | 0.09 | 0.23 | 0.04 |
| 1961 | 0.52 | 0.12 | 0.07 | 0.10 | 0.07 | -0.16 | -0.24 | -0.38 | -0.13 | 0.10 | -0.12 | 0.01 |
| 1962 | 0.18 | 0.02 | 0.05 | 0.15 | 0.07 | 0.20 | 0.08 | -0.31 | -0.23 | 0.07 | 0.10 | 0.04 |
| 1963 | 0.18 | 0.06 | 0.28 | 0.09 | 0.03 | -0.04 | 0.06 | -0.15 | -0.14 | 0.09 | 0.35 | 0.27 |
| 1964 | 0.52 | 0.11 | 0.16 | 0.07 | -0.02 | -0.01 | -0.09 | -0.15 | -0.19 | 0.03 | 0.06 | 0.45 |
| 1965 | -0.12 | -0.16 | 0.08 | -0.05 | 0.17 | 0.45 | -0.08 | -0.21 | -0.04 | 0.27 | -0.15 | 0.12 |
| 1966 | 0.38 | 0.20 | 0.07 | 0.03 | -0.01 | 0.10 | -0.15 | -0.17 | -0.27 | -0.10 | -0.07 | -0.16 |
| 1967 | -0.01 | -0.01 | -0.29 | -0.18 | 0.00 | -0.22 | -0.11 | -0.05 | -0.20 | -0.21 | -0.13 | -0.09 |
| 1968 | 0.10 | -0.02 | -0.23 | 0.08 | -0.16 | -0.02 | -0.15 | -0.22 | -0.13 | -0.12 | 0.21 | 0.09 |
| 1969 | 0.07 | -0.03 | -0.21 | -0.26 | -0.07 | 0.14 | 0.01 | -0.04 | -0.17 | -0.07 | -0.24 | 0.09 |
| 1970 | 0.10 | -0.22 | -0.06 | -0.07 | -0.04 | 0.03 | -0.01 | -0.10 | -0.19 | -0.16 | -0.03 | 0.02 |
| 1971 | 0.22 | -0.17 | -0.31 | 0.07 | -0.09 | -0.19 | -0.03 | -0.22 | -0.19 | -0.06 | -0.18 | 0.15 |
| 1972 | 0.12 | 0.03 | -0.09 | -0.27 | -0.09 | -0.20 | -0.10 | -0.13 | -0.17 | -0.09 | -0.19 | 0.29 |
| 1973 | 0.03 | -0.31 | -0.12 | -0.33 | -0.26 | -0.17 | -0.10 | -0.33 | -0.32 | -0.32 | -0.29 | -0.17 |

TABLE 3 Establishment of the annual cycle in adjustments required for making our series from 1958-73 consistent with Manley's series: results of t-test described by Cramer and corrections applied from 1974 onwards

| MONTH | MEAN CORRECTION (DEG C) $\bar{x}_i$ | $t_i$ | $P(\lvert t \rvert > t_i)$ (DEGS OF FREEDOM N-2 = 286) (2-tailed) | FINAL CORRECTION (DEG C) |
|---|---|---|---|---|
| JAN | 0.15 | 4.33 | <0.01 | + 0.1 |
| FEB | 0.01 | 1.15 | >0.1 | 0.0 |
| MAR | -0.01 | 0.71 | >0.1 | 0.0 |
| APR | -0.07 | -0.78 | >0.1 | - 0.1 |
| MAY | -0.09 | -1.23 | >0.1 | - 0.1 |
| JUN | -0.07 | -0.78 | >0.1 | - 0.1 |
| JUL | -0.12 | -1.83 | <0.1 | - 0.1 |
| AUG | -0.20 | -3.73 | <0.01 | - 0.2 |
| SEP | -0.21 | -4.07 | <0.01 | - 0.1 |
| OCT | -0.03 | 0.26 | >0.1 | 0.0 |
| NOV | 0.06 | 2.22 | <0.05 | + 0.1 |
| DEC | 0.13 | 3.82 | <0.01 | + 0.1 |

TABLE 4 Correlation coefficients between mean daily temperatures at stations used for the daily series for 1878 onwards.

(a) Stonyhurst (S), Cambridge Botanical Gardens (C) and Ross-on-Wye (R) 1878-1907

JANUARY

| | C | R |
|---|---|---|
| S | 0.86 | 0.88 |
| C | 1.00 | 0.92 |

FEBRUARY

| | C | R |
|---|---|---|
| S | 0.84 | 0.86 |
| C | 1.00 | 0.90 |

MARCH

| | C | R |
|---|---|---|
| S | 0.85 | 0.87 |
| C | 1.00 | 0.90 |

APRIL

| | C | R |
|---|---|---|
| S | 0.84 | 0.89 |
| C | 1.00 | 0.85 |

MAY

| | C | R |
|---|---|---|
| S | 0.81 | 0.85 |
| C | 1.00 | 0.85 |

JUNE

| | C | R |
|---|---|---|
| S | 0.73 | 0.76 |
| C | 1.00 | 0.80 |

JULY

| | C | R |
|---|---|---|
| S | 0.65 | 0.76 |
| C | 1.00 | 0.78 |

AUGUST

| | C | R |
|---|---|---|
| S | 0.78 | 0.72 |
| C | 1.00 | 0.82 |

SEPTEMBER

| | C | R |
|---|---|---|
| S | 0.87 | 0.81 |
| C | 1.00 | 0.87 |

OCTOBER

| | C | R |
|---|---|---|
| S | 0.86 | 0.83 |
| C | 1.00 | 0.88 |

NOVEMBER

| | C | R |
|---|---|---|
| S | 0.82 | 0.84 |
| C | 1.00 | 0.88 |

DECEMBER

| | C | R |
|---|---|---|
| S | 0.85 | 0.86 |
| C | 1.00 | 0.91 |

(b) Stonyhurst (S), Ross-on-Wye (RS) and Rothamsted (RT) 1931-1958

JANUARY

| | RS | RT |
|---|---|---|
| S | 0.86 | 0.89 |
| RS | 1.00 | 0.91 |

FEBRUARY

| | RS | RT |
|---|---|---|
| S | 0.87 | 0.91 |
| RS | 1.00 | 0.92 |

MARCH

| | RS | RT |
|---|---|---|
| S | 0.80 | 0.84 |
| RS | 1.00 | 0.92 |

APRIL

| | RS | RT |
|---|---|---|
| S | 0.83 | 0.84 |
| RS | 1.00 | 0.92 |

MAY

| | RS | RT |
|---|---|---|
| S | 0.82 | 0.89 |
| RS | 1.00 | 0.90 |

JUNE

| | RS | RT |
|---|---|---|
| S | 0.82 | 0.86 |
| RS | 1.00 | 0.87 |

JULY

| | RS | RT |
|---|---|---|
| S | 0.76 | 0.77 |
| RS | 1.00 | 0.85 |

AUGUST

| | RS | RT |
|---|---|---|
| S | 0.73 | 0.74 |
| RS | 1.00 | 0.83 |

SEPTEMBER

| | RS | RT |
|---|---|---|
| S | 0.86 | 0.89 |
| RS | 1.00 | 0.90 |

OCTOBER

| | RS | RT |
|---|---|---|
| S | 0.87 | 0.88 |
| RS | 1.00 | 0.92 |

NOVEMBER

| | RS | RT |
|---|---|---|
| S | 0.83 | 0.84 |
| RS | 1.00 | 0.89 |

DECEMBER

| | RS | RT |
|---|---|---|
| S | 0.88 | 0.91 |
| RS | 1.00 | 0.93 |

Table 4 (continued)

(c) 0.5 X (Squires Gate + Ringway) (S), Rothamsted (R) and Malvern (M) 1959-1981

JANUARY

| | R | M |
|---|---|---|
| S | 0.88 | 0.92 |
| R | 1.00 | 0.93 |

FEBRUARY

| | R | M |
|---|---|---|
| S | 0.90 | 0.89 |
| R | 1.00 | 0.91 |

MARCH

| | R | M |
|---|---|---|
| S | 0.86 | 0.89 |
| R | 1.00 | 0.91 |

APRIL

| | R | M |
|---|---|---|
| S | 0.87 | 0.87 |
| R | 1.00 | 0.91 |

MAY

| | R | M |
|---|---|---|
| S | 0.87 | 0.89 |
| R | 1.00 | 0.86 |

JUNE

| | R | M |
|---|---|---|
| S | 0.86 | 0.85 |
| R | 1.00 | 0.89 |

JULY

| | R | M |
|---|---|---|
| S | 0.80 | 0.74 |
| R | 1.00 | 0.88 |

AUGUST

| | R | M |
|---|---|---|
| S | 0.77 | 0.84 |
| R | 1.00 | 0.81 |

SEPTEMBER

| | R | M |
|---|---|---|
| S | 0.85 | 0.87 |
| R | 1.00 | 0.88 |

OCTOBER

| | R | M |
|---|---|---|
| S | 0.89 | 0.88 |
| R | 1.00 | 0.88 |

NOVEMBER

| | R | M |
|---|---|---|
| S | 0.89 | 0.90 |
| R | 1.00 | 0.91 |

DECEMBER

| | R | M |
|---|---|---|
| S | 0.88 | 0.92 |
| R | 1.00 | 0.93 |

TABLE 5 F-tests of variances of unadjusted daily Central England Temperatures

The variances were calculated using deviations from individual months' averages.

| | Variance ratio F (1772-1877 vs 1878-1990) | Significance (see footnote) |
|---|---|---|
| Jan | 1.41 | 5% |
| Feb | 1.42 | 5% |
| Mar | 1.44 | 5% |
| Apr | 1.66 | 1% |
| May | 1.35 | - |
| Jun | 1.26 | - |
| Jul | 1.33 | - |
| Aug | 1.39 | 5% |
| Sep | 1.25 | - |
| Oct | 1.37 | 5% |
| Nov | 1.32 | - |
| Dec | 1.43 | 5% |

Note: The significances were assessed assuming one degree of freedom per year, because the lag-one-year correlations of the variances for given calendar months ranged between +0.15 and -0.07 and can therefore be neglected.

TABLE 6 F-test of variances of monthly Central England temperature for the periods 1848-1877 and 1878-1907 used for the calculation of scaling factors

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1848-77 MEAN TEMP (°C) | 3.72 | 4.33 | 5.25 | 8.27 | 10.94 | 14.26 | 15.98 | 15.52 | 13.17 | 9.71 | 5.56 | 4.33 |
| VARIANCE OF MONTHLY MEAN $(°C)^2$ | 2.71 | 4.63 | 1.52 | 1.11 | 1.64 | 1.11 | 1.59 | 0.88 | 1.27 | 0.92 | 1.67 | 4.05 |
| 1878-1907 MEAN TEMP (°C) | 3.34 | 3.92 | 5.19 | 7.71 | 10.75 | 14.14 | 15.77 | 15.27 | 13.21 | 9.04 | 6.18 | 3.68 |
| VARIANCE OF MONTHLY MEAN $(°C)^2$ | 3.92 | 3.28 | 2.16 | 1.12 | 1.31 | 0.89 | 1.38 | 1.28 | 0.99 | 1.83 | 1.82 | 3.24 |
| F-VALUE | 1.45 | 1.41 | 1.42 | 1.00 | 1.25 | 1.23 | 1.15 | 1.45 | 1.28 | 1.99 | 1.09 | 1.25 |

$F(0.05;\ 29,\ 29) = 1.9$ $F(0.01;\ 29,\ 29) = 2.5$

TABLE 7 SCALING OF VARIANCES: CALCULATION OF SCALING FACTORS b

| MONTH | DAILY ANOMALY VARIANCE 1848-1877 $\sigma_1^2$ $(°C)^2$ | DAILY ANOMALY VARIANCE 1878-1907 $\sigma_3^2$ $(°C)^2$ | FIRST ESTIMATE OF b $(=b_1)$ | MEAN CORRELATION $\bar{r}$ 1878-1907 | EFFECTIVE NUMBER OF STATIONS (=n') | SECOND ESTIMATE OF b $(=b_2)$ | FINAL b VALUE |
|---|---|---|---|---|---|---|---|
| JAN | 10.63 | 8.61 | 0.90 | 0.89 | 1.08 | 0.96 | 0.90 |
| FEB | 8.37 | 6.69 | 0.89 | 0.87 | 1.09 | 0.96 | 0.90 |
| MAR | 8.39 | 6.89 | 0.91 | 0.87 | 1.09 | 0.96 | 0.90 |
| APR | 7.69 | 5.47 | 0.84 | 0.86 | 1.10 | 0.95 | 0.89 |
| MAY | 9.32 | 6.10 | 0.81 | 0.84 | 1.12 | 0.94 | 0.88 |
| JUN | 6.30 | 5.11 | 0.90 | 0.76 | 1.19 | 0.92 | 0.86 |
| JUL | 5.07 | 3.67 | 0.85 | 0.73 | 1.22 | 0.91 | 0.86 |
| AUG | 5.46 | 3.70 | 0.82 | 0.78 | 1.17 | 0.92 | 0.86 |
| SEP | 5.55 | 5.40 | 0.98 | 0.85 | 1.11 | 0.95 | 0.89 |
| OCT | 9.38 | 6.31 | 0.82 | 0.86 | 1.10 | 0.95 | 0.89 |
| NOV | 9.28 | 7.48 | 0.90 | 0.85 | 1.11 | 0.95 | 0.89 |
| DEC | 11.12 | 9.55 | 0.93 | 0.88 | 1.09 | 0.96 | 0.90 |
| ANNUAL MEAN | | | 0.88 | | | 0.94 | |

Table 8

Linear trend regressions diagnosing urban warming. Monthly mean data, first named minus second named station or composite, are used.

(a) Malvern vs Luddington

| | Number of years data N | Equation (Y=year minus 1958) | Trend Correlation coefficient r | t-value | Significance (one-tailed test) |
|---|---|---|---|---|---|
| January | 28 | T = -0.12 + 0.024Y | 0.66 | 4.49 | 0.1% |
| February | 28 | T = -0.01 + 0.018Y | 0.57 | 3.57 | 0.1% |
| March | 29 | T = 0.01 + 0.018Y | 0.51 | 3.07 | 1% |
| April | 29 | T = -0.26 + 0.029Y | 0.70 | 5.07 | 0.1% |
| May | 28 | T = -0.19 + 0.026Y | 0.60 | 3.80 | 0.1% |
| June | 28 | T = -0.16 + 0.025Y | 0.60 | 3.82 | 0.1% |
| July | 29 | T = -0.08 + 0.023Y | 0.62 | 4.09 | 0.1% |
| August | 29 | T = 0.04 + 0.019Y | 0.53 | 3.24 | 1% |
| September | 29 | T = 0.18 + 0.012Y | 0.35 | 1.92 | 5% |
| October | 27 | T = 0.07 + 0.012Y | 0.39 | 2.10 | 5% |
| November | 29 | T = 0.37 + 0.011Y | 0.34 | 1.86 | 5% |
| December | 28 | T = 0.38 + 0.012Y | 0.38 | 2.09 | 5% |
| Year | 29 | T = 0.03 + 0.019Y | 0.85 | 8.25 | 0.1% |

(b) Malvern vs Preston Wynne

| | N | | r | t-value | Significance (one-tailed test) |
|---|---|---|---|---|---|
| January | 27 | T = 0.45 + 0.009Y | 0.29 | 1.50 | - |
| February | 27 | T = 0.65 + 0.001Y | 0.01 | 0.03 | - |
| March | 27 | T = 0.85 - 0.003Y | -0.08 | -0.41 | - |
| April | 29 | T = 0.60 + 0.013Y | 0.31 | 1.73 | 5% |
| May | 29 | T = 0.67 + 0.014Y | 0.44 | 2.53 | 1% |
| June | 29 | T = 0.97 + 0.010Y | 0.30 | 1.61 | - |
| July | 28 | T = 0.71 + 0.021Y | 0.52 | 3.14 | 1% |
| August | 29 | T = 0.77 + 0.015Y | 0.38 | 3.31 | 1% |
| September | 29 | T = 0.83 + 0.010Y | 0.32 | 1.77 | 5% |
| October | 27 | T = 0.65 + 0.009Y | 0.31 | 1.62 | - |
| November | 29 | T = 0.52 + 0.011Y | 0.42 | 2.38 | 5% |
| December | 28 | T = 0.55 + 0.008Y | 0.27 | 1.45 | - |
| Year | 29 | T = 0.69 + 0.010Y | 0.62 | 4.16 | 0.1% |

Table 8 (continued)

(c) Ringway vs Macclesfield

| | N | | r | t-value | Significance (one-tailed test) |
|---|---|---|---|---|---|
| January | 29 | T = 0.29 + 0.010Y | 0.44 | 2.53 | 1% |
| February | 29 | T = 0.50 + 0.005Y | 0.18 | 0.97 | - |
| March | 29 | T = 0.32 + 0.006Y | 0.32 | 1.74 | 5% |
| April | 27 | T = 0.26 + 0.009Y | 0.49 | 2.80 | 1% |
| May | 28 | T = 0.17 + 0.009Y | 0.37 | 2.05 | 5% |
| June | 27 | T = 0.12 + 0.019Y | 0.65 | 4.34 | 0.1% |
| July | 29 | T = 0.19 + 0.010Y | 0.44 | 2.58 | 1% |
| August | 29 | T = 0.38 + 0.004Y | 0.19 | 1.02 | - |
| September | 29 | T = 0.29 + 0.007Y | 0.32 | 1.74 | 5% |
| October | 26 | T = 0.08 + 0.014Y | 0.62 | 3.83 | 0.1% |
| November | 28 | T = 0.29 + 0.009Y | 0.38 | 2.08 | 5% |
| December | 29 | T = 0.35 + 0.007Y | 0.30 | 1.63 | - |
| Year | 29 | T = 0.25 + 0.009Y | 0.72 | 5.37 | 0.1% |

(d) Series A vs Series B

where

Series A is [Rothamsted + Malvern + ½(Squires Gate + Ringway)]/3

and

Series B is [Rothamsted + ½(Luddington + Preston Wynne) + + ½(Squires Gate + Macclesfield)]/3

| Month | Trend equation (Y is year) | Trend correlation r | Smoothed trend coefficient m |
|---|---|---|---|
| January | T = 0.33 + 0.0075(Y-1973) | 0.67 | 0.0059 |
| February | T = 0.31 + 0.0042(Y-1973) | 0.44 | 0.0051 |
| March | T = 0.32 + 0.0043(Y-1973) | 0.41 | 0.0054 |
| April | T = 0.37 + 0.0087(Y-1973) | 0.66 | 0.0071 |
| May | T = 0.36 + 0.0068(Y-1973) | 0.54 | 0.0076 |
| June | T = 0.40 + 0.0083(Y-1973) | 0.63 | 0.0081 |
| July | T = 0.43 + 0.0093(Y-1973) | 0.72 | 0.0083 |
| August | T = 0.40 + 0.0062(Y-1973) | 0.53 | 0.0066 |
| September | T = 0.37 + 0.0048(Y-1973) | 0.44 | 0.0056 |
| October | T = 0.33 + 0.0066(Y-1973) | 0.53 | 0.0059 |
| November | T = 0.36 + 0.0054(Y-1973) | 0.54 | 0.0055 |
| december | T = 0.36 + 0.0045(Y-1973) | 0.40 | 0.0055 |
| [Year | T = 0.37 + 0.0077(Y-1973) | 0.78] | |

Table 9a Corrections to Central England Temperature based on $^1/_3$ (Rothamsted + Malvern + ½ (Ringway + Squires Gate)) to compensate for urban warming.

| Month | No correction necessary | Correction -0.1 °C | Correction -0.2 °C |
|---|---|---|---|
| January | until 1981 | 1982-1998 | 1999-2015 |
| February | until 1982 | 1983-2002 | 2003-2022 |
| March | until 1982 | 1983-2000 | 2001-2019 |
| April | until 1980 | 1981-1994 | 1995-2008 |
| May | until 1979 | 1980-1992 | 1993-2005 |
| June | until 1979 | 1980-1991 | 1992-2003 |
| July | until 1979 | 1980-1991 | 1992-2003 |
| August | until 1980 | 1981-1995 | 1996-2010 |
| September | until 1981 | 1982-1999 | 2000-2017 |
| October | until 1981 | 1982-1998 | 1999-2015 |
| November | until 1982 | 1983-2000 | 2001-2018 |
| December | until 1982 | 1983-2000 | 2001-2018 |
| (Year | until 1979 | 1980-1992 | 1993-2005) |

Table 9b Total corrections applied to Central England Temperatures for 1991

These corrections are the sum of the final column of Table 3 and the urbanization correction of -0.1 °C from Table 9a.

| Month | Correction (°C) |
|---|---|
| January | 0.0 |
| February | -0.1 |
| March | -0.1 |
| April | -0.2 |
| May | -0.2 |
| June | -0.2 |
| July | -0.2 |
| August | -0.3 |
| September | -0.2 |
| October | -0.1 |
| November | 0.0 |
| December | 0.0 |

TABLE 10 Deviations of temperatures in Glaisher stands from those in Stevenson screens. Values are averages of results reported by Ellis (1891), Mawley (1897) and Margary (1924) °C

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max | -0.01 | 0.01 | 0.19 | 0.53 | 0.67 | 0.87 | 0.91 | 0.77 | 0.49 | 0.25 | 0.00 | -0.08 |
| Min | -0.33 | -0.36 | -0.40 | -0.43 | -0.43 | -0.38 | -0.43 | -0.40 | -0.45 | -0.45 | -0.35 | -0.32 |
| Mean | -0.17 | -0.17 | -0.10 | 0.05 | 0.12 | 0.25 | 0.24 | 0.18 | 0.02 | -0.10 | -0.17 | -0.20 |

TABLE 11 Comparison of Hoy's and the Royal Society's record

| Month | Standard deviation of Hoy's daily means (°C) | Standard deviation of Royal Society's daily means (°C) | Correlation r between daily means | Root mean square difference of daily anomalies (relative to individual stations' monthly averages) (°C) |
|---|---|---|---|---|
| January 1774[a, b] | 4.1 | 3.3 | 0.96 | 1.4 |
| April 1774 | 2.8 | 2.4 | 0.86 | 1.4 |
| July 1774 | 1.9 | 1.9 | 0.75 | 1.3 |
| October 1774 | 2.6 | 2.3 | 0.52 | 2.5 |
| January 1775 | 4.4 | 3.7 | 0.91 | 1.8 |
| April 1775 | 4.3 | 4.0 | 0.93 | 1.6 |
| July 1775 | 1.4 | 1.9 | 0.59 | 1.6 |
| October 1775 | 3.6 | 3.7 | 0.83 | 2.1 |
| January 1781 | 2.6 | 3.2 | 0.94 | 1.1 |
| April 1781 | 3.1 | 3.2 | 0.86 | 1.6 |
| July 1781[c] | 2.2 | 2.1 | 0.70 | 1.7 |
| January 1787[c] | 3.4 | 2.9 | 0.94 | 1.2 |
| April 1787 | 2.2 | 1.5 | 0.64 | 1.7 |
| July 1787 | 2.7 | 2.3 | 0.83 | 1.5 |
| October 1787 | 3.3 | 2.7 | 0.96 | 1.1 |
| January 1795 | 3.7 | 3.5 | 0.95 | 1.1 |
| April 1795 | 3.1 | 2.6 | 0.95 | 1.0 |
| July 1795 | 2.4 | 2.1 | 0.84 | 1.3 |
| October 1795 | 2.3 | 2.1 | 0.95 | 0.8 |
| January 1800 | 3.1 | 2.8 | 0.97 | 0.8 |
| April 1800 | 1.8 | 1.6 | 0.79 | 1.1 |
| July 1800 | 1.7 | 1.8 | 0.82 | 1.1 |
| October 1800 | 2.5 | 2.3 | 0.96 | 0.7 |
| January 1805 | 2.9 | 2.7 | 0.95 | 0.9 |
| April 1805 | 2.5 | 2.2 | 0.89 | 1.2 |
| July 1805 | 1.9 | 1.3 | 0.82 | 1.1 |
| October 1805 | 3.3 | 2.8 | 0.98 | 0.8 |

Notes: a January 1774 is the first month with Royal Society data. These were at Crane Court until 1781 and at Somerset House from 1787.

b Hoy's site was in Kennington until the end of August 1774, then at Muswell Hill until the end of June 1782, then at Syon House, Kew.

c There are no Royal Society data from September 1781 to December 1786.

Table 12. Monthly and annual Central England temperatures (°C), 1974-1991, compensated for urban warming.

| | | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | YEAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1974 | | 5.9 | 5.4 | 5.8 | 8.2 | 11.0 | 13.9 | 15.2 | 15.2 | 12.1 | 7.8 | 6.8 | 8.1 | 9.6 |
| 1975 | | 6.8 | 4.4 | 4.8 | 8.3 | 9.9 | 14.7 | 17.4 | 18.7 | 13.5 | 9.9 | 6.3 | 5.3 | 10.0 |
| 1976 | | 5.9 | 4.5 | 4.8 | 8.1 | 12.1 | 17.0 | 18.7 | 17.6 | 13.4 | 10.6 | 6.3 | 2.0 | 10.1 |
| 1977 | | 2.8 | 5.2 | 6.9 | 7.2 | 10.6 | 12.2 | 15.9 | 15.2 | 13.3 | 11.8 | 6.6 | 6.1 | 9.5 |
| 1978 | | 3.4 | 2.8 | 6.7 | 6.5 | 11.7 | 13.7 | 14.8 | 15.0 | 14.2 | 11.9 | 8.5 | 3.9 | 9.4 |
| 1979 | | -0.4 | 1.2 | 4.7 | 7.8 | 10.0 | 13.9 | 16.2 | 14.9 | 13.5 | 11.3 | 6.8 | 5.8 | 8.8 |
| 1980 | | 2.3 | 5.7 | 4.7 | 8.8 | 11.2 | 13.8 | 14.7 | 15.9 | 14.7 | 9.0 | 6.6 | 5.6 | 9.4 |
| 1981 | | 4.9 | 3.0 | 7.9 | 7.8 | 11.2 | 13.2 | 15.5 | 16.2 | 14.5 | 8.6 | 7.8 | 0.3 | 9.2 |
| 1982 | | 2.6 | 4.8 | 6.1 | 8.6 | 11.6 | 15.5 | 16.5 | 15.7 | 14.2 | 10.1 | 8.0 | 4.4 | 9.8 |
| 1983 | | 6.7 | 1.7 | 6.4 | 6.8 | 10.3 | 14.4 | 19.5 | 17.3 | 13.7 | 10.5 | 7.5 | 5.6 | 10.0 |
| 1984 | | 3.8 | 3.3 | 4.7 | 8.1 | 9.9 | 14.5 | 16.9 | 17.6 | 13.7 | 11.1 | 8.0 | 5.2 | 9.7 |
| 1985 | | 0.8 | 2.1 | 4.7 | 8.3 | 10.9 | 12.7 | 16.2 | 14.6 | 14.6 | 11.0 | 4.1 | 6.3 | 8.9 |
| 1986 | | 3.5 | -1.1 | 4.9 | 5.8 | 11.1 | 14.8 | 15.9 | 13.7 | 11.3 | 11.0 | 7.8 | 6.2 | 8.7 |
| 1987 | | 0.8 | 3.6 | 4.1 | 10.3 | 10.1 | 12.8 | 15.9 | 15.6 | 13.6 | 9.7 | 6.5 | 5.6 | 9.1 |
| 1988 | | 5.3 | 4.9 | 6.4 | 8.2 | 11.9 | 14.4 | 14.7 | 15.2 | 13.2 | 10.4 | 5.2 | 7.5 | 9.8 |
| 1989 | | 6.1 | 5.9 | 7.5 | 6.6 | 13.0 | 14.6 | 18.2 | 16.6 | 14.7 | 11.7 | 6.2 | 4.9 | 10.5 |
| 1990 | | 6.5 | 7.3 | 8.3 | 8.0 | 12.6 | 13.6 | 16.9 | 18.0 | 13.2 | 11.9 | 6.9 | 4.3 | 10.6 |
| 1991 | | 3.3 | 1.5 | | | | | | | | | | | |
| 1961-1990 | average | 3.8 | 3.8 | 5.7 | 7.9 | 11.2 | 14.2 | 16.1 | 15.8 | 13.6 | 10.6 | 6.5 | 4.7 | 9.47 |
| Difference | from 1931-1960 average | 0.3 | -0.1 | -0.2 | -0.6 | -0.2 | -0.4 | -0.1 | -0.2 | -0.1 | 0.5 | -0.3 | 0.0 | -0.13 |
| 1961-1990 | standard deviations $\sigma_m$ | 2.1 | 2.0 | 1.4 | 1.0 | 1.0 | 1.1 | 1.2 | 1.2 | 0.9 | 1.2 | 1.1 | 1.8 | 0.5 |
| 1961-1990 | standard deviation $\sigma_d$ of daily values (using anomalies from a daily climatology + individual months' anomalies) | 2.8 | 2.4 | 2.2 | 2.2 | 2.1 | 2.2 | 1.9 | 1.8 | 1.9 | 2.0 | 2.7 | 2.9 | |
| 1961-1990 | Highest daily | 10.8 | 11.5 | 14.1 | 15.5 | 19.4 | 22.6 | 24.7 | 24.4 | 21.4 | 20.2 | 13.5 | 12.2 | |
| 1772-1990 | Highest daily | 11.6 | 12.0 | 14.8 | 19.6 | 21.2 | 23.0 | 25.2 | 24.4 | 22.6 | 20.2 | 15.4 | 12.6 | |
| 1961-1990 | Lowest daily | - 8.4 | -4.6 | -3.9 | 0.5 | 3.8 | 7.7 | 10.0 | 10.4 | 7.0 | 3.5 | -2.1 | - 8.5 | |
| 1772-1990 | Lowest daily | -11.9 | -8.8 | -6.5 | -0.5 | 2.9 | 7.3 | 8.7 | 8.8 | 4.9 | 0.3 | -4.6 | -10.8 | |


Figure 1 Locations of stations used in our daily series (without brackets), and other places mentioned in the text (bracketed). The two stippled areas and intermediate regions represent Manley's "Central England".

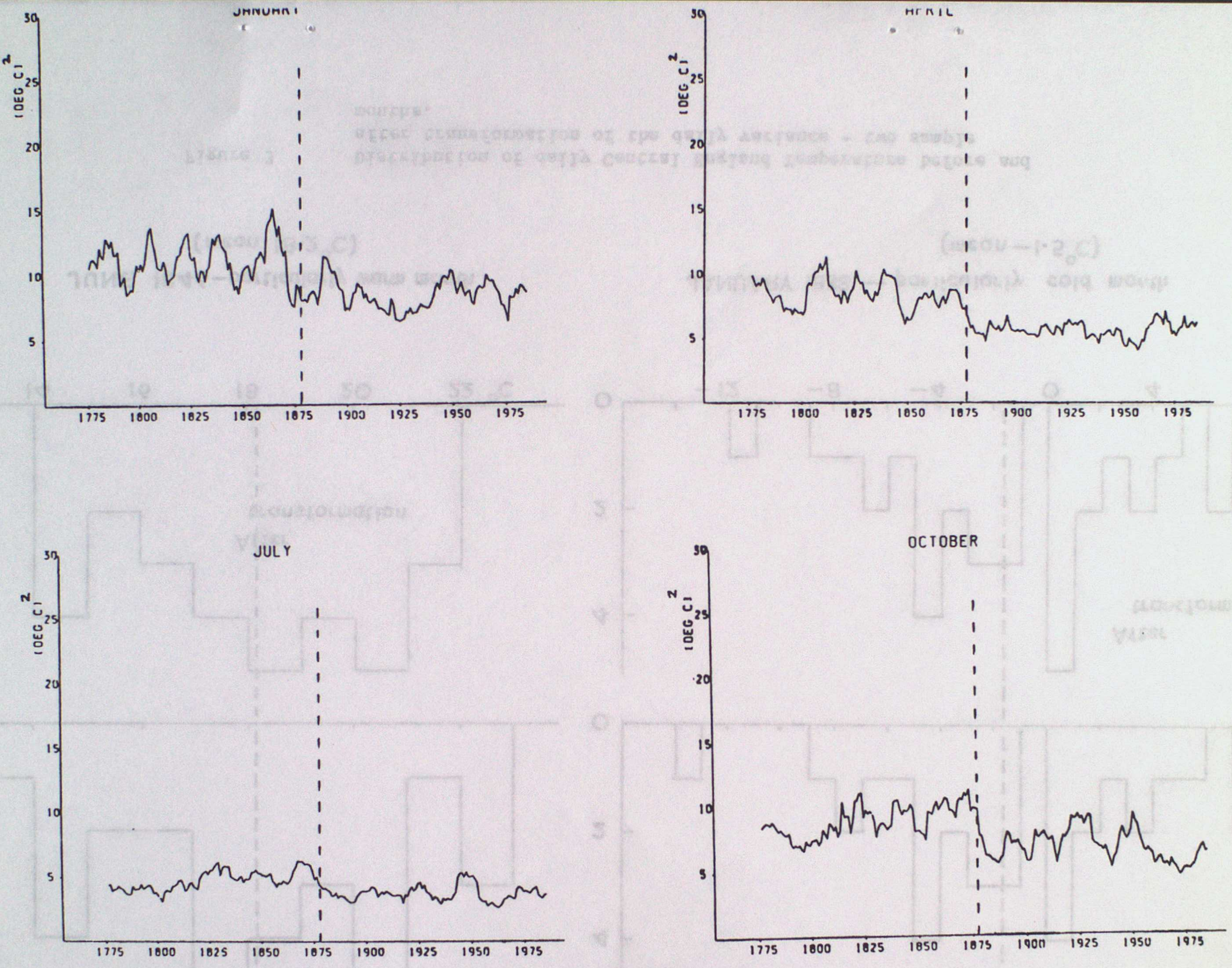



Figure 2 10-year running mean unadjusted variances of the daily series for January, April, July and October. Variances were calculated using anomalies from the mean of each individual month and year. Values are plotted at the centre of each 10-year interval.

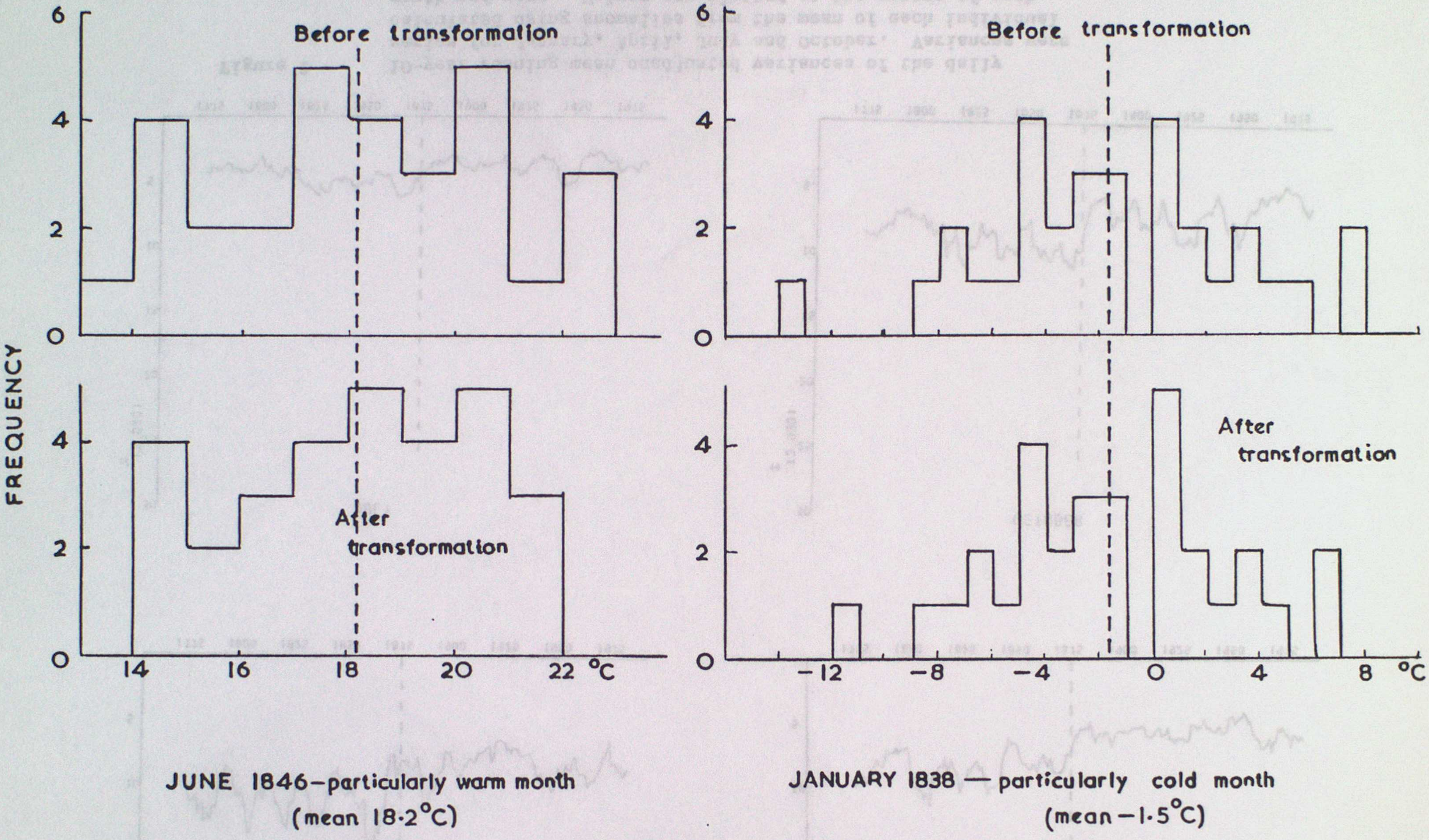



Figure 3 Distribution of daily Central England Temperature before and after transformation of the daily variance - two sample months.

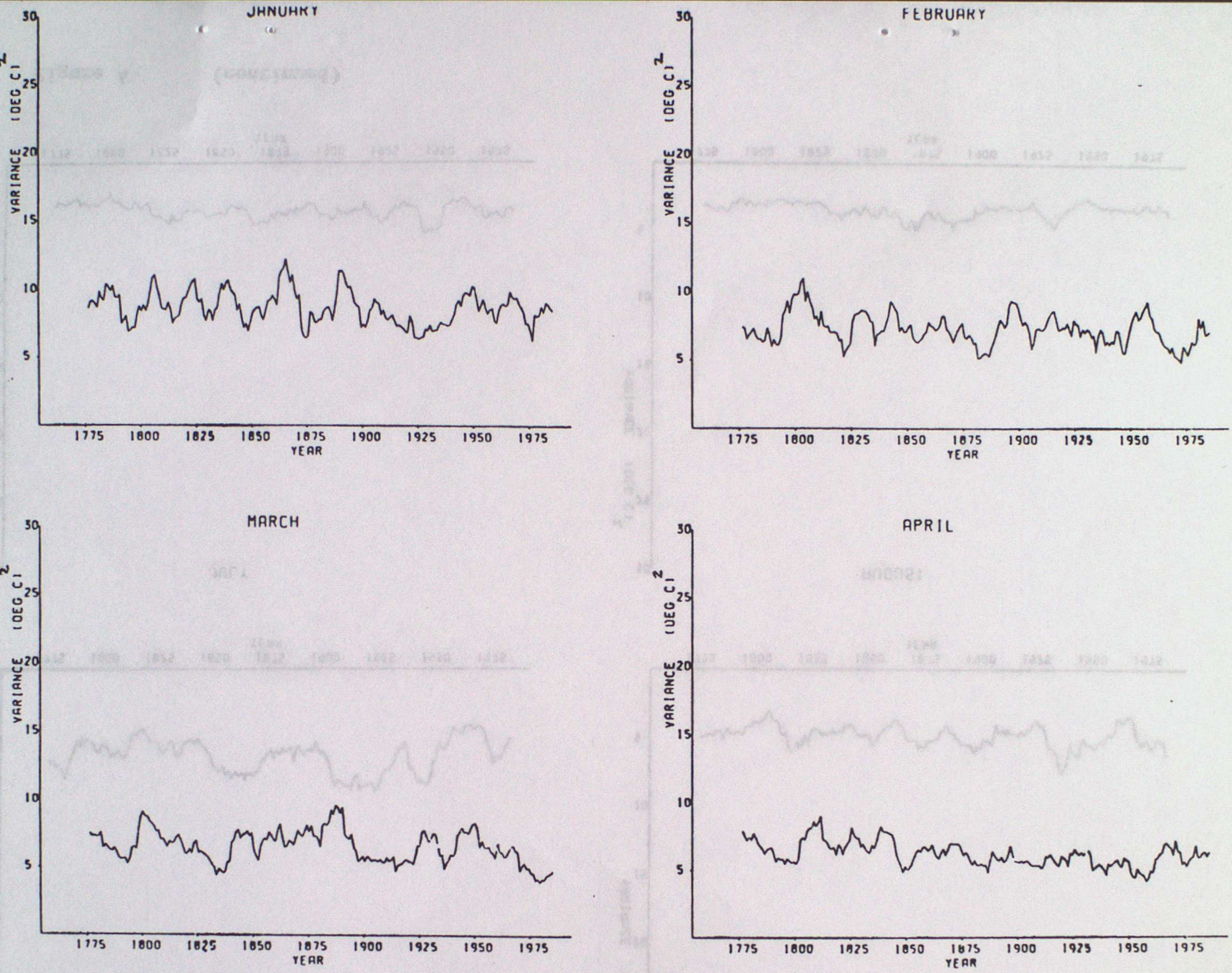



Figure 4 10-year running mean adjusted variances of the daily series for each calendar month. Variances were calculated using anomalies from the mean of each individual month and year. Plotting convention is as in Figure 2.

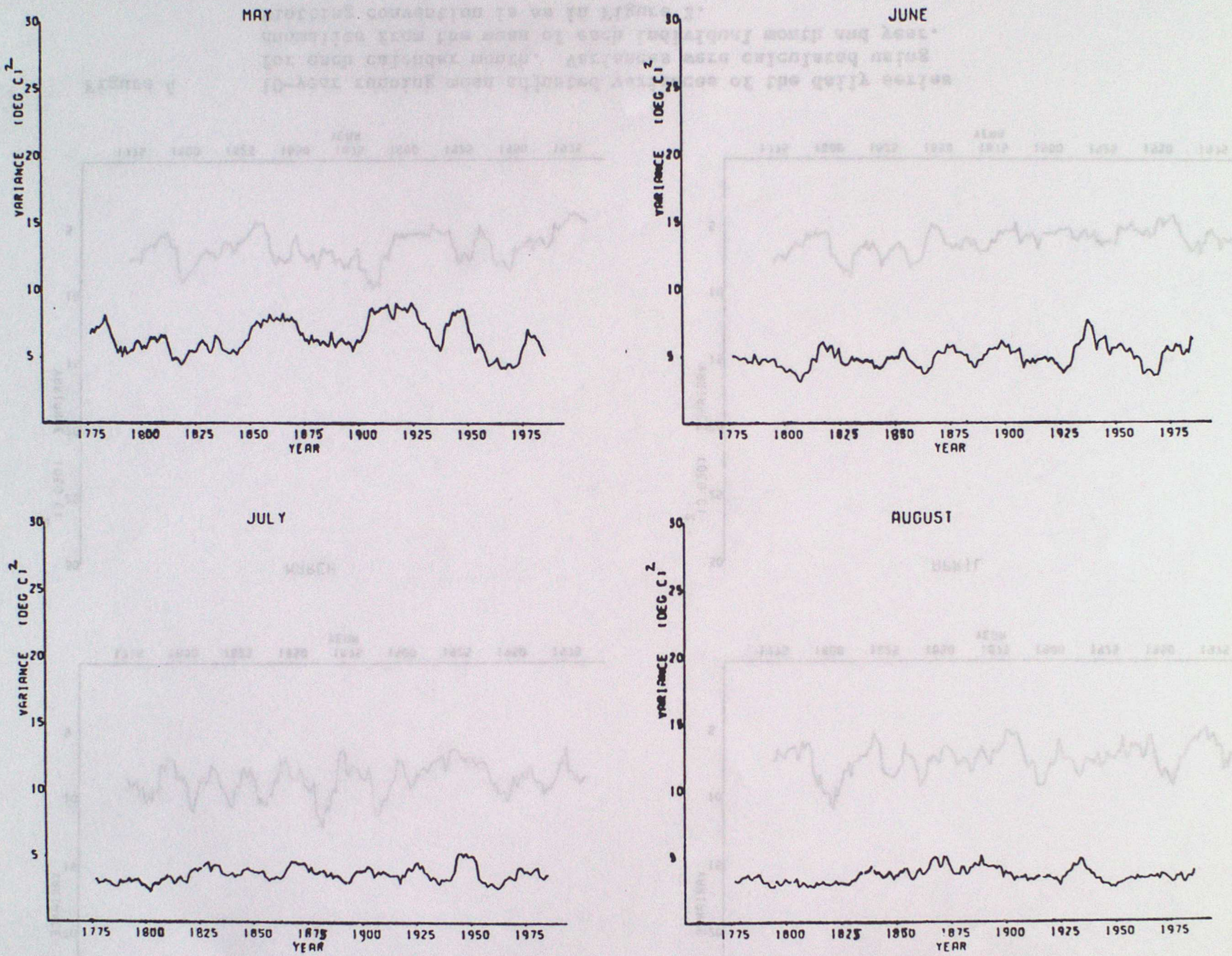



Figure 4 (continued)

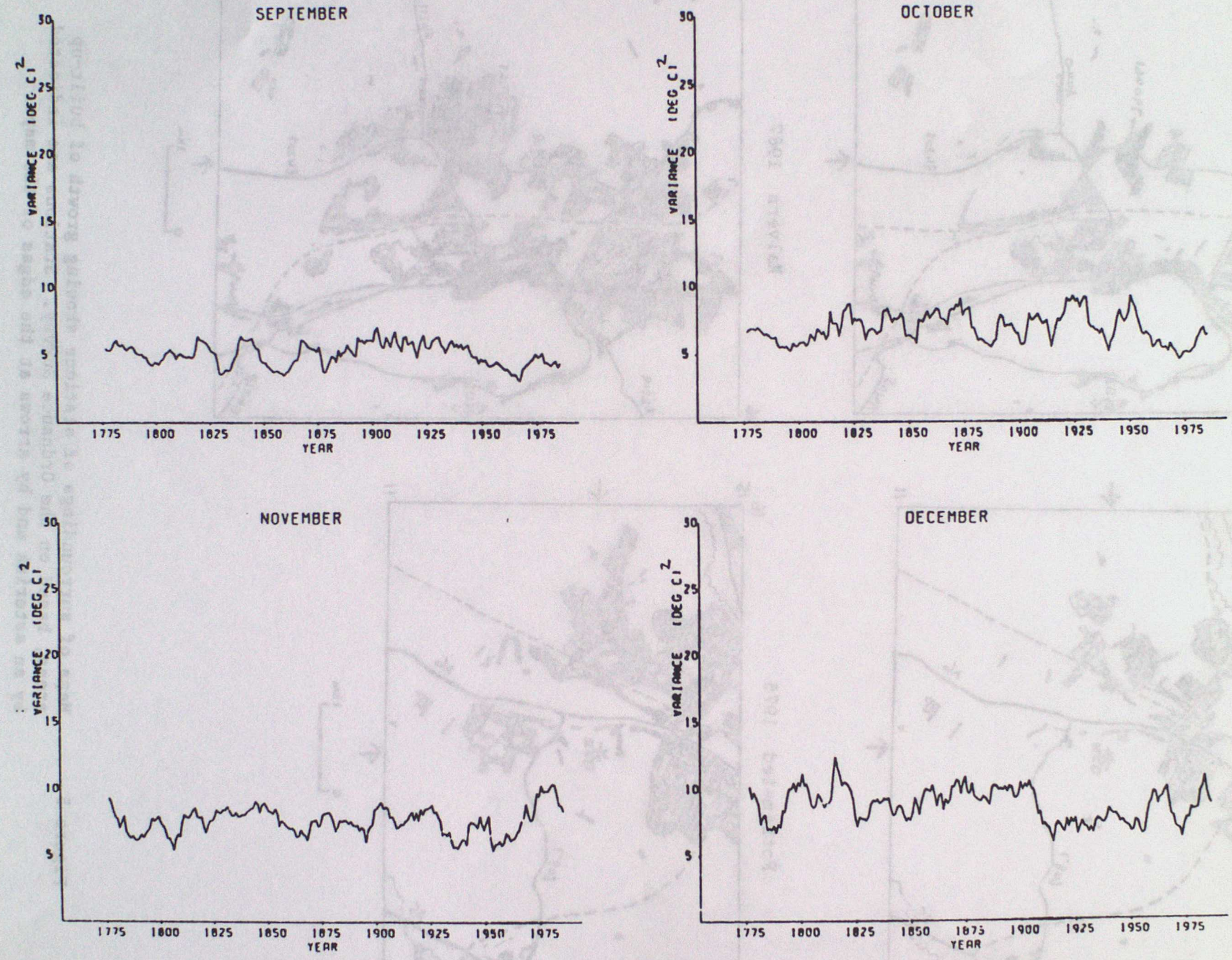



Figure 4 (continued)

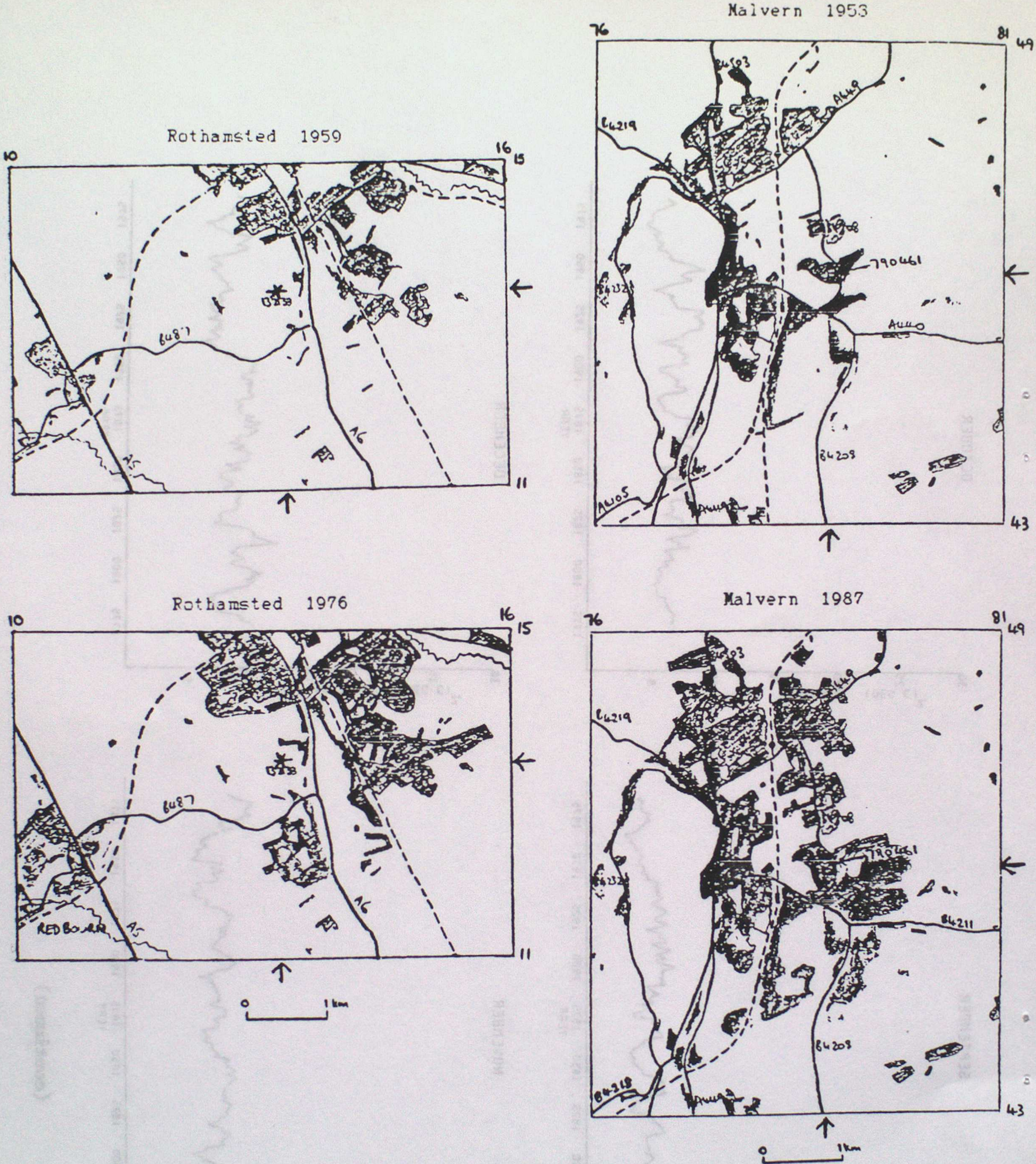
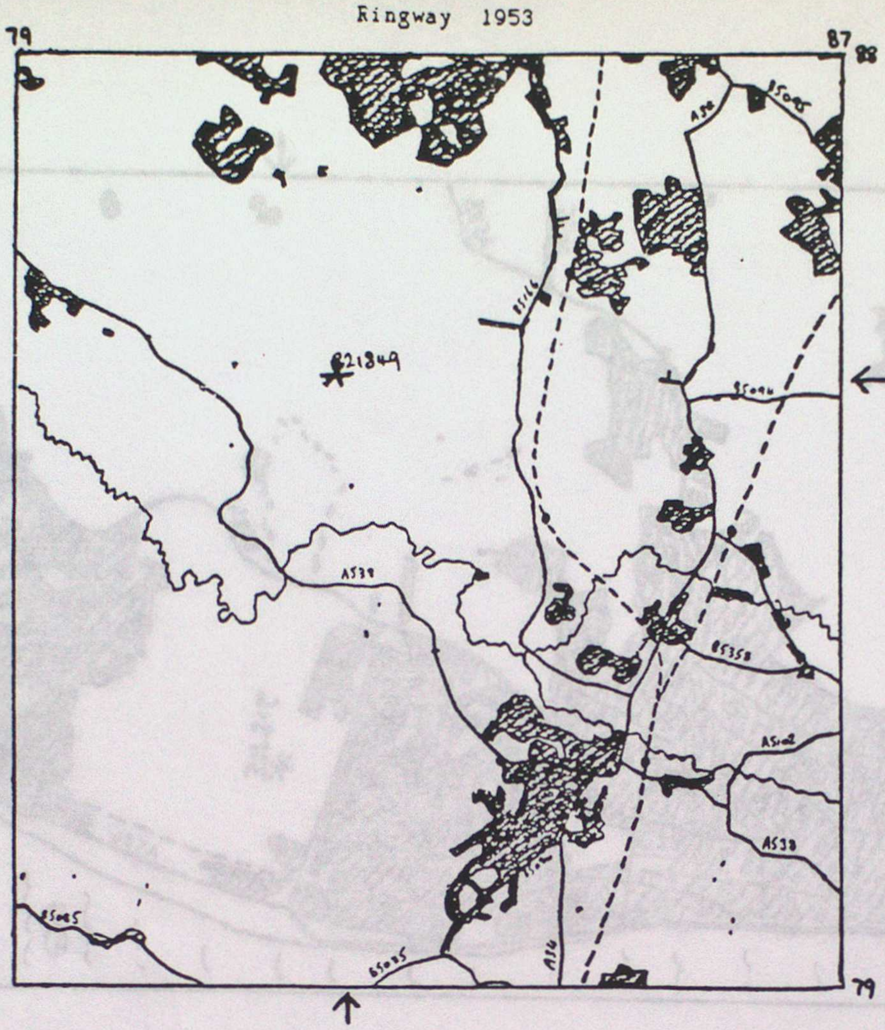



Figure 5 Maps of surroundings of stations showing growth of built-up areas, based on the Ordnance Survey. Stations are indicated by an asterisk and by arrows at the edges of the maps.

Ringway 1953




Ringway 1983


**Figure 5** (continued)

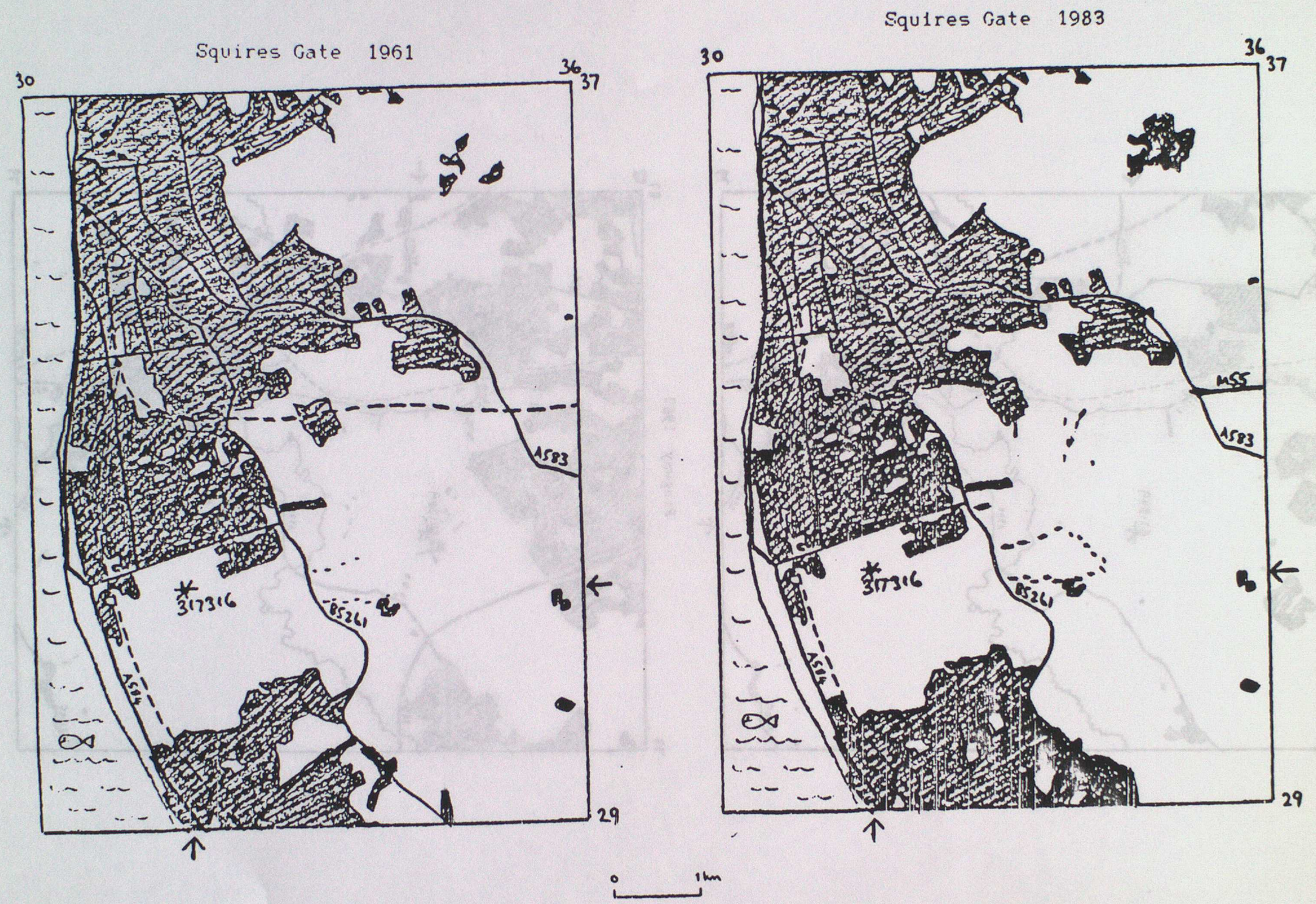



**Figure 5** **(continued)**

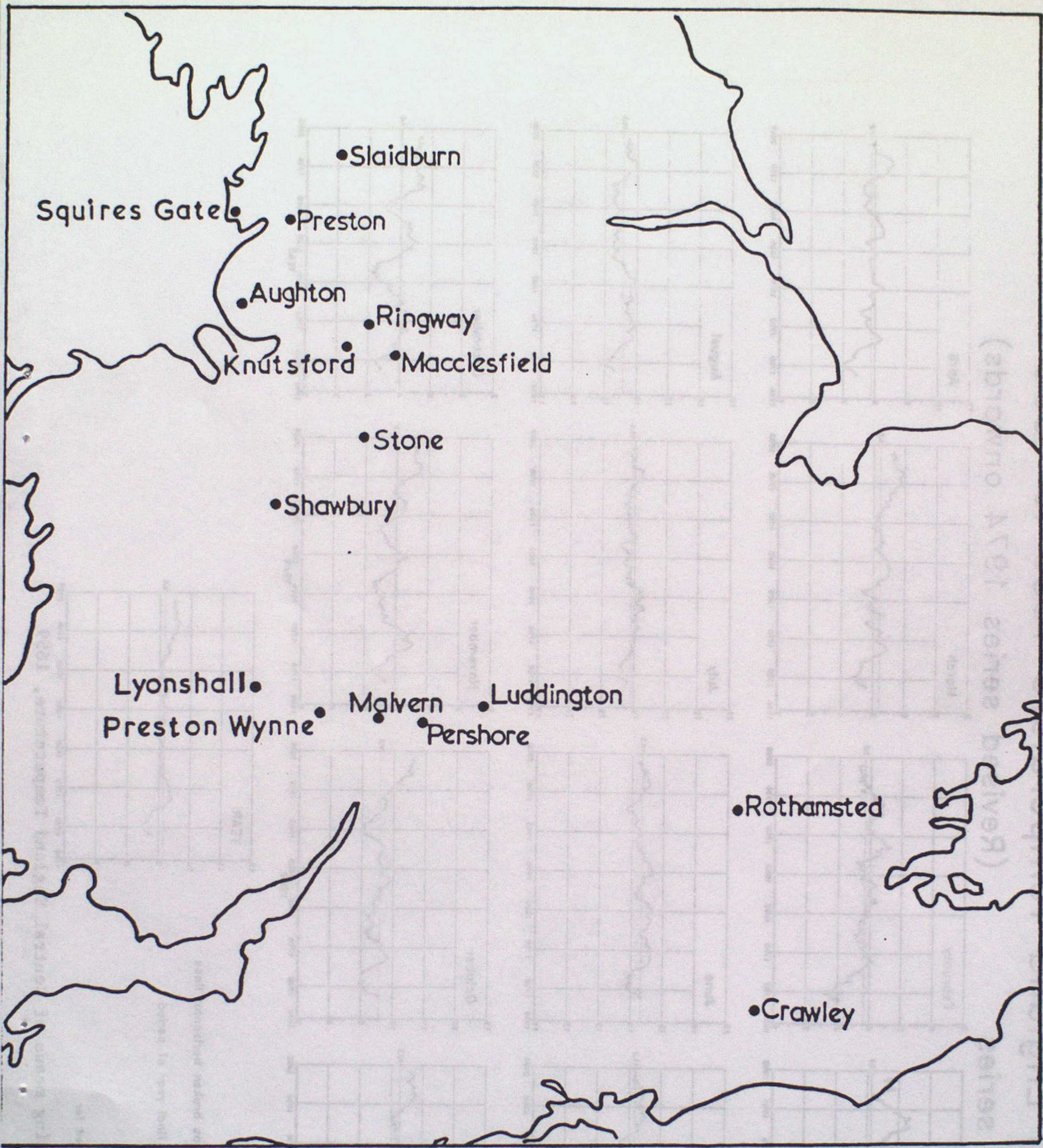



Figure 6 Locations of stations used to assess recent urban warming.

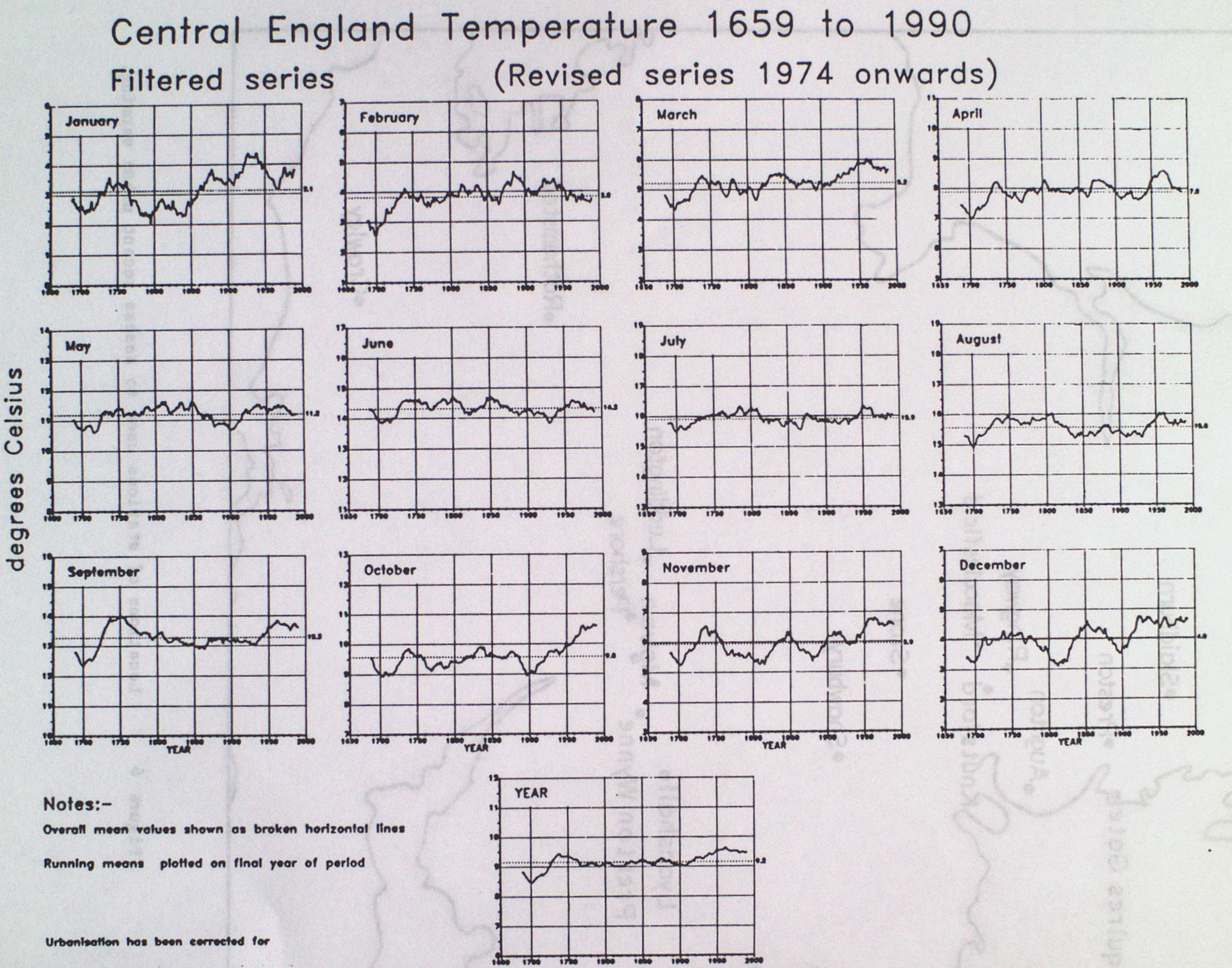



Figure 7 30-year running means of Central England Temperature, 1659 to 1990.

APPENDIX 1 Adjustments to daily temperatures for 1777 to 1799

A1. Treatment of Thomas Barker's temperatures for Lyndon Hall, Rutland, January 1777 to November 1786 and January 1787 to June 1789

Barker usually recorded morning and afternoon temperatures for each day, the time of observation being given to the nearest 5 minutes. Barker did not have a registering thermometer (James Six invented these in 1782), but on a significant minority of occasions, untimed estimates of maximum or occasionally minimum temperatures were recorded. Occasionally two maxima were reported. Barker was an alert observer and probably noticed, for example, prolonged sunny intervals on showery days and took extra readings at appropriate moments. Clearly, however, he may often have missed the extremes. In general (93.9% of total days) we simply averaged the timed morning and afternoon values, and did not use the untimed maxima: otherwise the day-to-day variance would have been artificially slightly enhanced in our series.

The recorded hours of observations varied somewhat from day to day and the morning hour varied systematically with the season, ranging from typically 0730-0800 in midwinter to 0615-0645 in midsummer. The afternoon hour was typically 1330-1500. Our subsequent adjustment of the daily temperatures in each month, so that their average equalled Manley's (see main text), will have largely compensated for the annual cycle in the morning observing hour. On a few days (2.8% of the total) with observing hours markedly different from those prevailing in the particular month, compensating adjustments were made to the average of the recorded temperatures for the day. In estimating these adjustments, account was taken of the weather and wind as recorded in detail by Barker: temperatures on adjacent days were also taken into account if the weather and wind and pressure data indicated continuity of air-mass.

On 1.7% of days, there was only a single observation of temperature, usually in the morning: a representative daily average was then estimated from this and from the weather, wind and if appropriate, surrounding days' temperatures. On a further 0.5% of days there was only a morning observation and an estimated maximum: these were averaged.

On 1.0% of days, an average was taken of the morning temperature and the mean of a timed afternoon temperature and one or two maximum temperatures, because the timed afternoon temperature appeared to be unrepresentative of prevailing conditions, e.g. it was taken during a thunderstorm.

Finally, on 0.1% of days Barker's record had no outdoor temperatures: daily values were then estimated using Hoy's London readings along with Barker's weather and wind observations.

A2. <u>Adjustments to the Royal Society temperatures for London for July 1789 to December 1799</u>

Manley (1964) noted that the Royal Society's London record appeared to contain mis-readings between 1794 and 1799. We therefore used Hoy's and Cary's London records to detect and remove probable errors from the Royal Society series in the entire period July 1789 to December 1799, as described below. We could not treat the Royal Society's record for 1774 to 1776 in this way, because Cary's record, which we used as arbiter for the later years, had not commenced.

The Royal Society's record and Hoy's record were both converted to daily variance-reduced CET as described in the main text. When the resulting estimates differed by 1.5°C or more, Cary's record was consulted. This threshold was passed on 12.3% of days and was chosen to capture all major errors. On nearly three-quarters of these days, Cary's record favoured the Royal Society rather than Hoy, and we used the Royal Society's value. On a very few days, Cary's record appeared to be in serious error and we then also used the Royal Society's value. On the remaining days (3.2% of the total number of days in the 10½-year period) we amended the Royal Society's value (by an integral number of °F, in which the original data are recorded) so that the resulting daily CET approximated to the daily CET implied by averaging Hoy's and Cary's records.

APPENDIX 2 Sites used since 1878

Figures A2.1 (a) - (g) show the detailed environment of each station used since 1878, based on recent maps only.

i) Stonyhurst Observatory

The site, which closed in 1978, was in the grounds of Stonyhurst College for boys. The screen was in an unfenced area of a large lawn about 350 m SSE of the main school buildings. The ground was practically level in the vicinity of the site but beyond the ground rose to the north and north-west and fell to the east and south; the slope to the north-west was steep. The surrounding land was well wooded. Elevation of station: 114m above MSL.

ii) Squires Gate Observatory

The enclosure is surrounded by chain link fencing 1.3m high and is near the centre of the airport. There are no trees, and the nearest hills are some 25km east and rise to 450m. The Ribble estuary is 5km south and the land to the west slopes gently down to sand dunes on the coast. The high-water mark is about 1.25km from the enclosure. From a point due west of the site a sea wall (5-9m high) runs to the north. Elevation of station: 10.1m above MSL.

iii Ringway Observatory

Until 8 January 1988, the enclosure was adjacent to the airfield apron on a busy roadside on Manchester airport. There was much tarmac close by, and a road traffic security post was built around 1985 only about 6 metres north of the screens. Screen A (see diagram) was used for climatological records; screen B contained a platinum resistance thermometer not used for computation of CET. The nearest major building was a store (once a terminal building) 30 metres to the southeast. The present terminal building and control tower were about 100 metres to the west-north-west.

Elevation of station: 75m above MSL.

On 8 January 1988 the enclosure was moved 765m to the WSW (Figure A2.1c), to a site where the nearest major building is the airport fire station, 40 metres to the north-north-east.

iv) Ross-on-Wye Observatory

The site was near the edge of the town in a public park area on a small ridge surrounded by a fence on two sides and a hedge. The park is partly surrounded by trees and there are a few low buildings nearby.

Elevation of station: 69m above MSL.

v) Malvern Observatory

The site is in a built up area of Malvern situated near a council yard in a slightly elevated position. The enclosure is surrounded by railings topped with barbed wire about 2m high, with small trees and shrubs around the outside of these. The Malvern Hills, which rise to over 400m, are about 2km to the west.

Elevation of station: 62m above MSL.

vi) Cambridge Botanical Gardens Observatory

Cambridge Botanical Gardens are near the southern edge of the town, about 2km from its centre. The observatory is sited in the garden with hedges (one hedge is particularly close). Some of the surrounding land is cultivated but none of the crops are tall.

Elevation of station: 12m above MSL.

vii) Rothamsted Observatory

The site is in gently undulating countryside at the top of a rise on a slight NE-facing slope. There are trees around the site approximately 400m away, but in general the surroundings consist of fields with the odd low building. The site is not fenced and the instruments are somewhat dispersed.

Elevation of station: 128m above MSL.

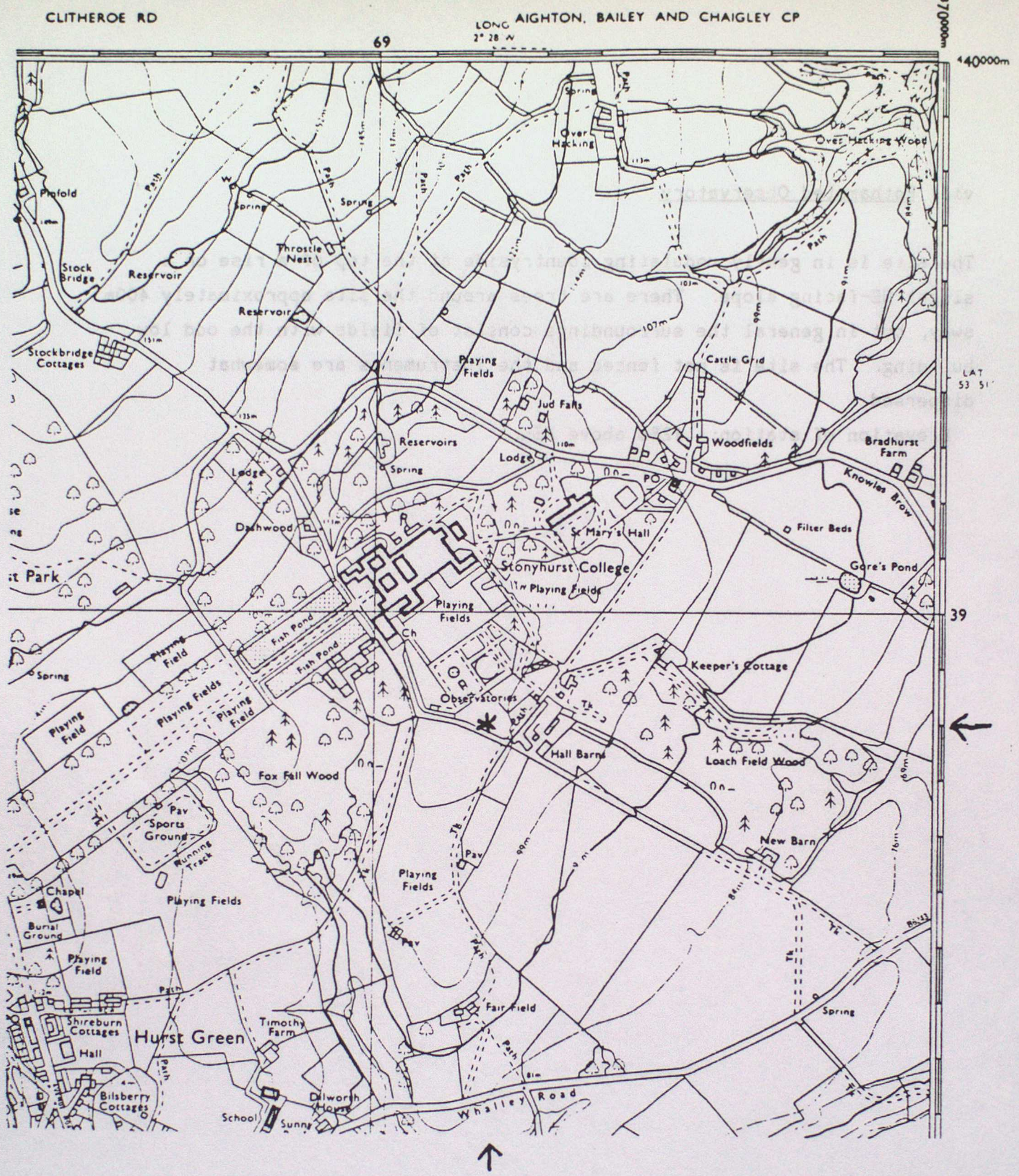



Figure A2.1 (a) **Stonyhurst**
The site is marked * at grid reference 6920/3880 and by arrows at the edges of the map. From Ordnance Survey 1:10,000 map SD 63 NE (1972).

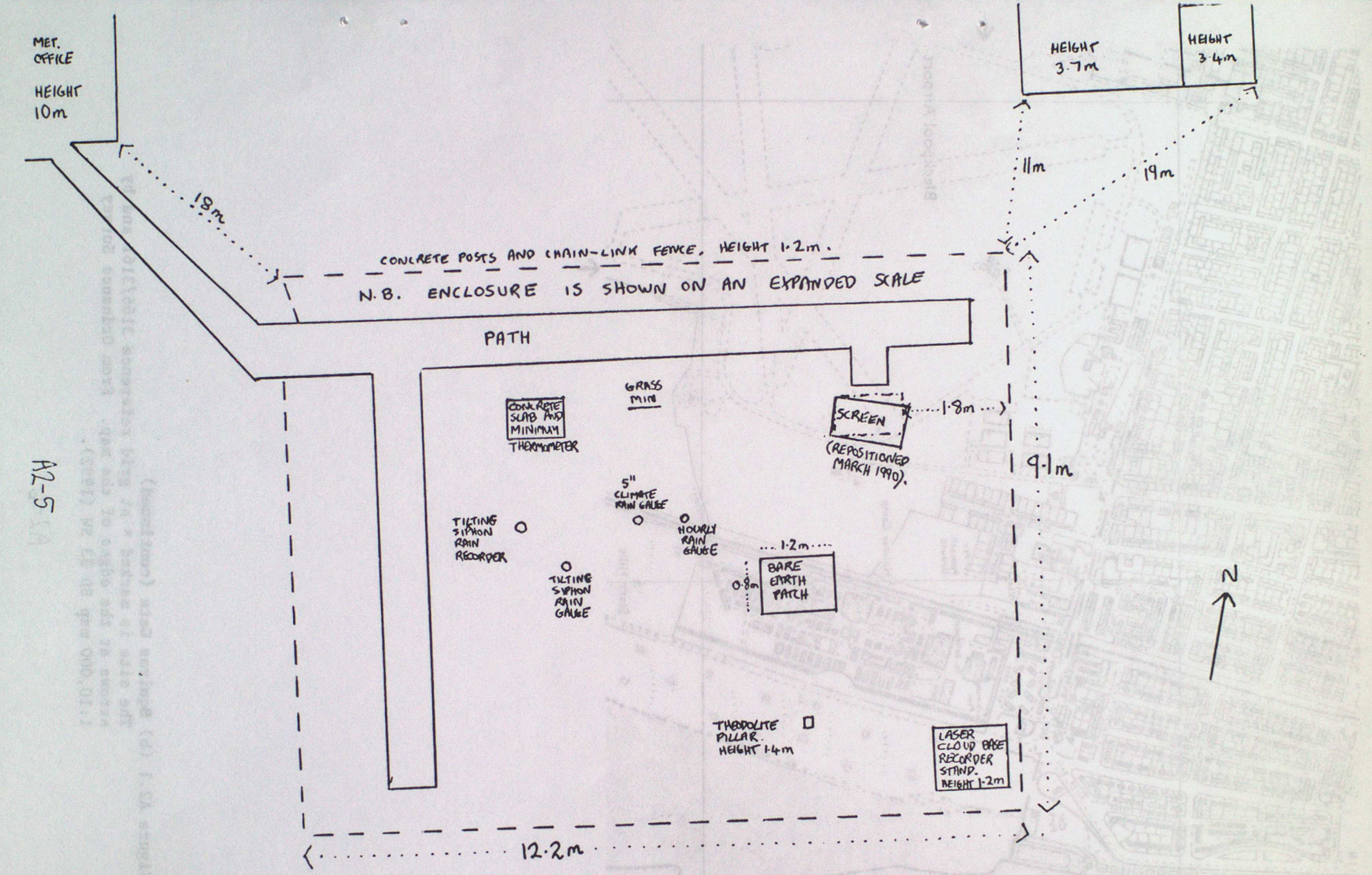



Figure A2·1 (b) **Squires Gate**
Site diagram. The enclosure is shown enlarged relative to its surroundings.

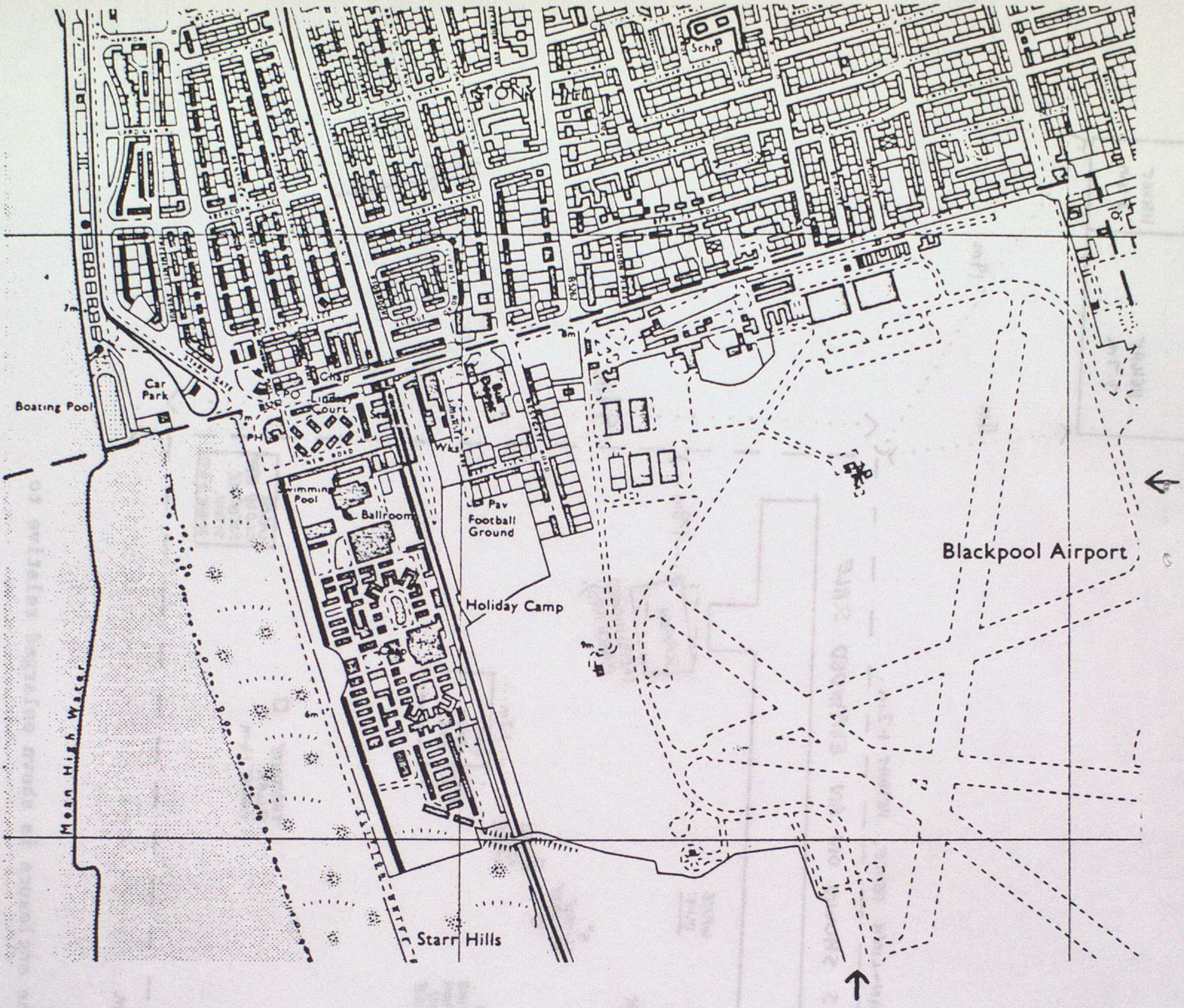



Figure A2.1 (b) **Squires Gate (continued)**
The site is marked * at grid reference 3166/3161 and by arrows at the edges of the map. From Ordnance Survey 1:10,000 map SD 33 SW (1982).

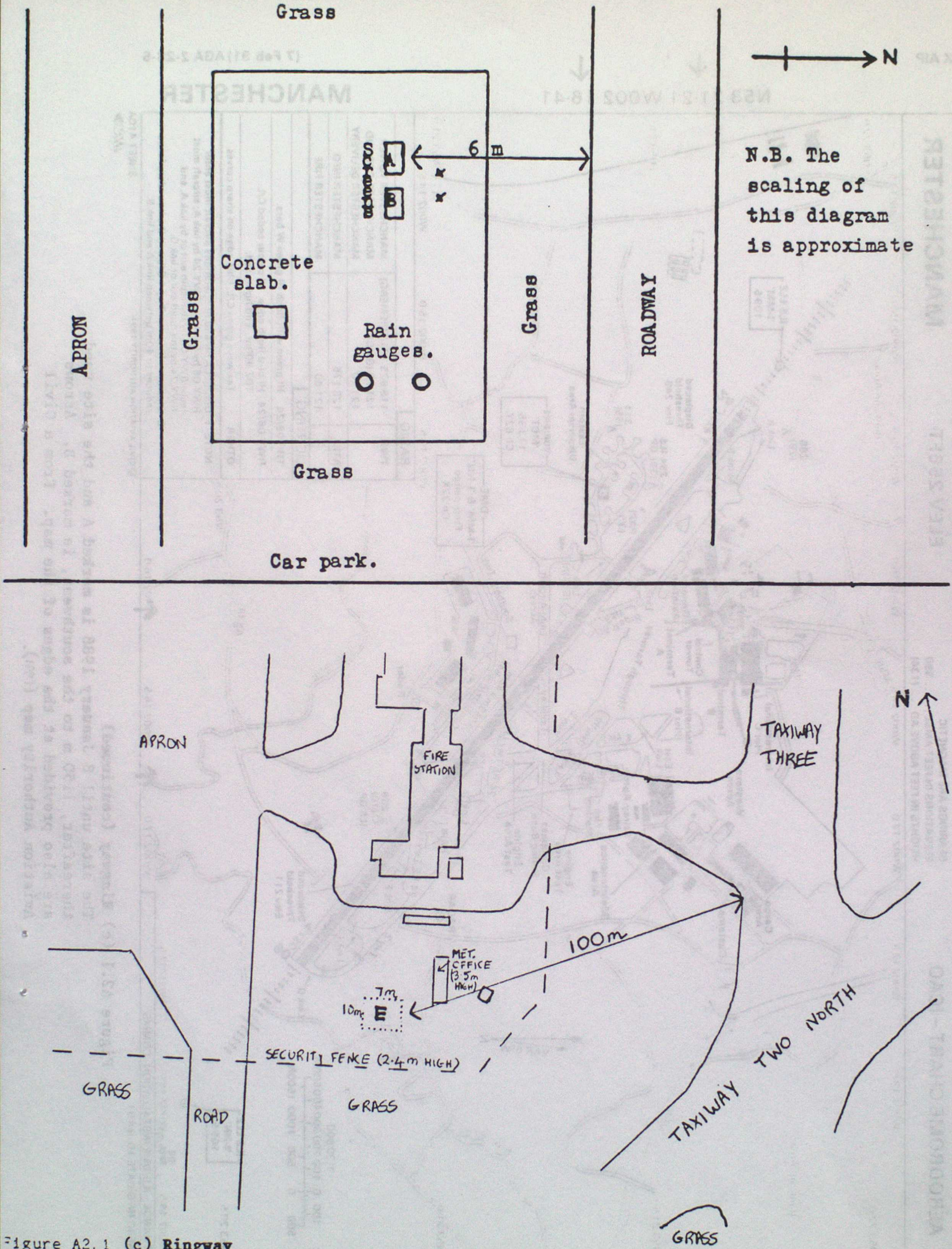
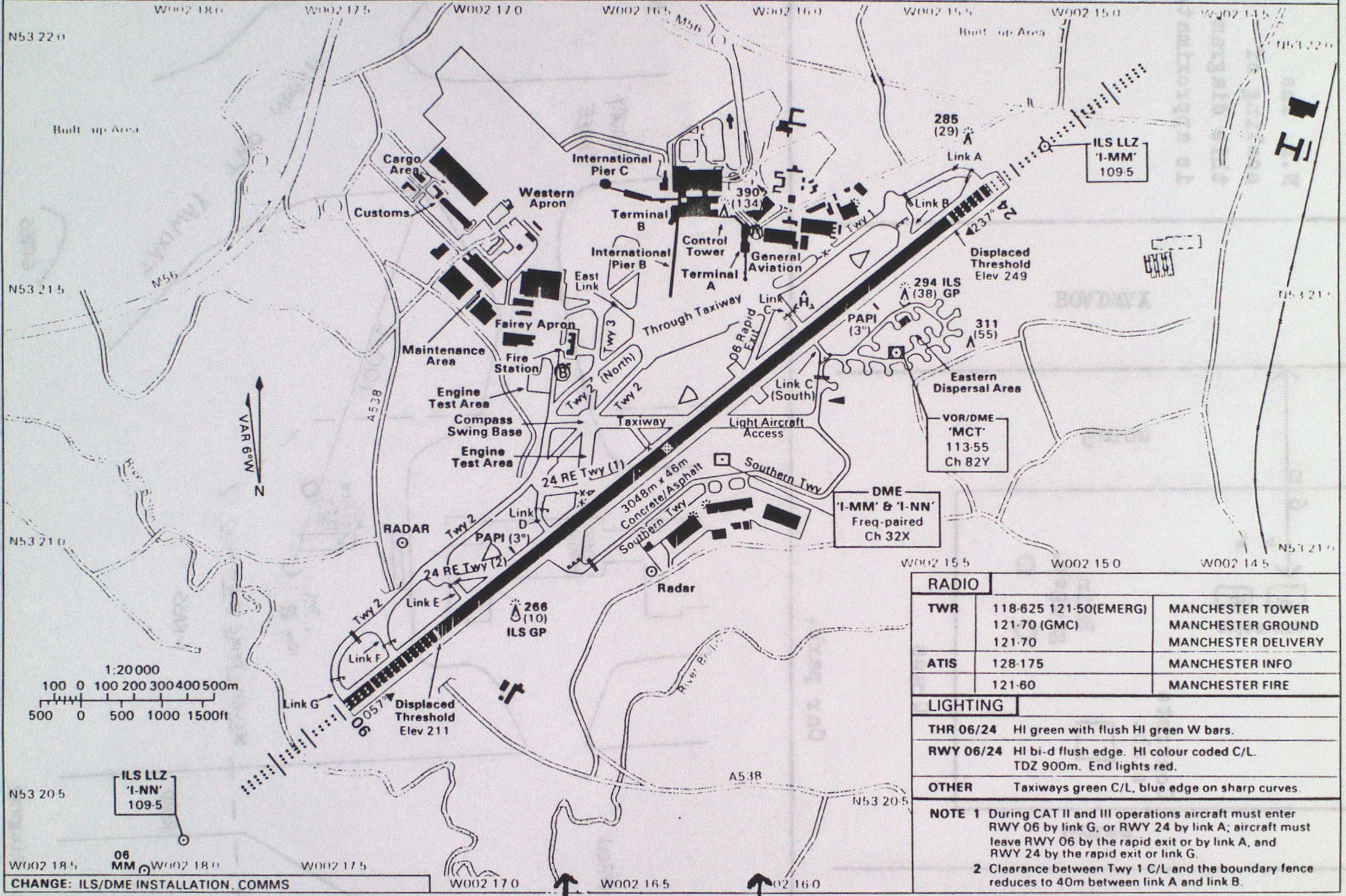



Figure A2.1 (c) **Ringway**
Top, site of Ringway until 8 January 1988.
Bottom, site of Ringway from 8 January 1988. The enclosure is marked E and is raised approximately 0.5 m above the surrounding ground owing to the high water table.

# MANCHESTER

N53 21·21 W002 16·41




**RADIO**

| | | |
|---|---|---|
| TWR | 118·625 121·50(EMERG)<br>121·70 (GMC)<br>121·70 | MANCHESTER TOWER<br>MANCHESTER GROUND<br>MANCHESTER DELIVERY |
| ATIS | 128·175 | MANCHESTER INFO |
| | 121·60 | MANCHESTER FIRE |

**LIGHTING**

| | |
|---|---|
| THR 06/24 | HI green with flush HI green W bars. |
| RWY 06/24 | HI bi-d flush edge. HI colour coded C/L. TDZ 900m. End lights red. |
| OTHER | Taxiways green C/L, blue edge on sharp curves. |

NOTE 1 During CAT II and III operations aircraft must enter RWY 06 by link G, or RWY 24 by link A; aircraft must leave RWY 06 by the rapid exit or by link A, and RWY 24 by the rapid exit or link G.

2 Clearance between Twy 1 C/L and the boundary fence reduces to 40m between link A and link B.



SHEET 410A

Figure A2.1 (c) **Ringway (continued)**
The site until 8 January 1988 is marked A and the site used thereafter, 1150 m to the southwest, is marked B. Arrows are also provided at the edges of the map. From a Civil Aviation Authority map (1991).

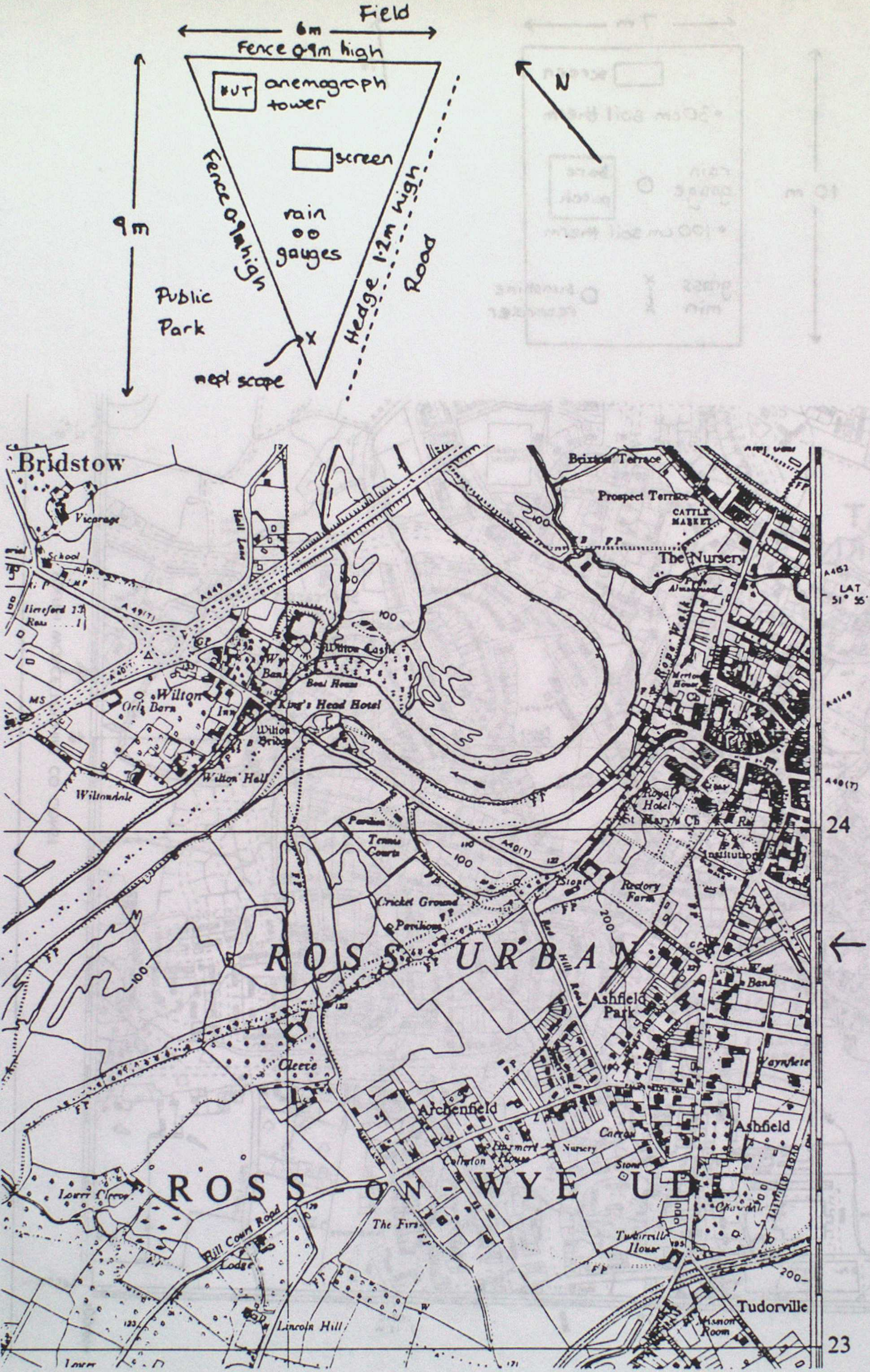
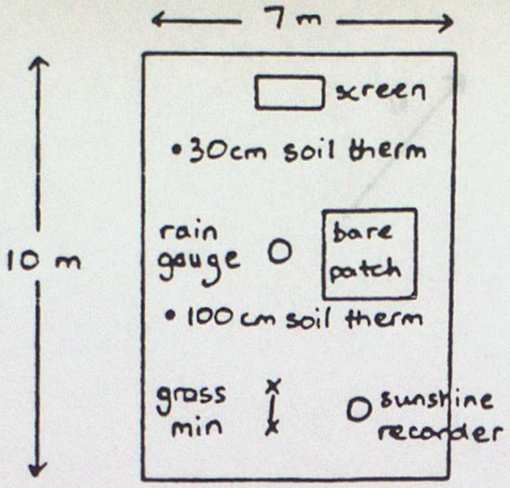



Figure A2.1 (d) **Ross on Wye**

Top, site.

Bottom, environs: the site is marked * at grid reference 5981/2377 and by arrows at the edges of the map. From Ordnance Survey 1:10,560 map SO 52 SE (1964).



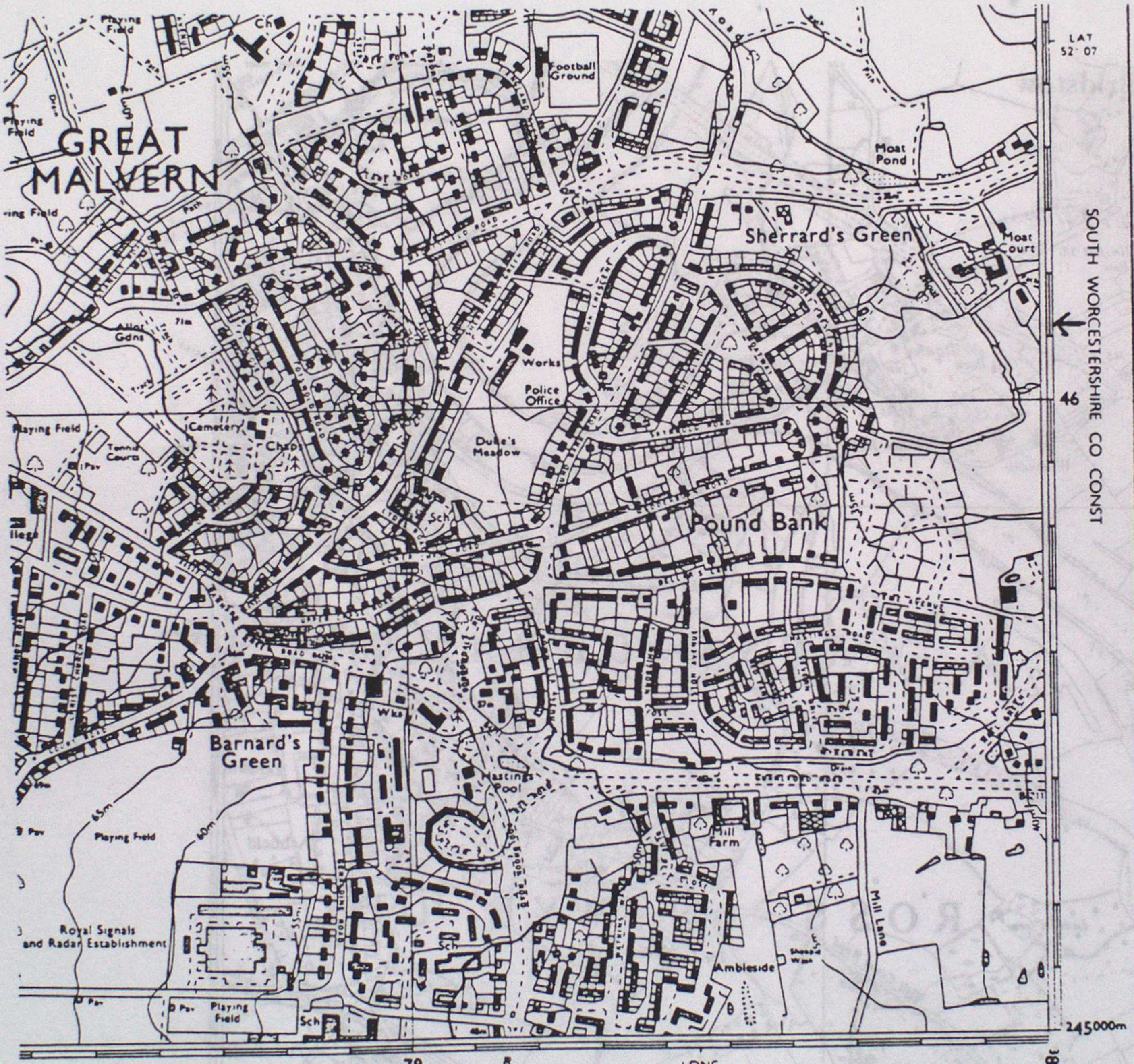




Figure A2.1 (e) **Malvern**
Top, site.
Bottom, environs: the site is marked * at grid reference 7898/4612 and by arrows at the edges of the map. From Ordnance Survey 1:10,000 map SO 74 NE (1978).

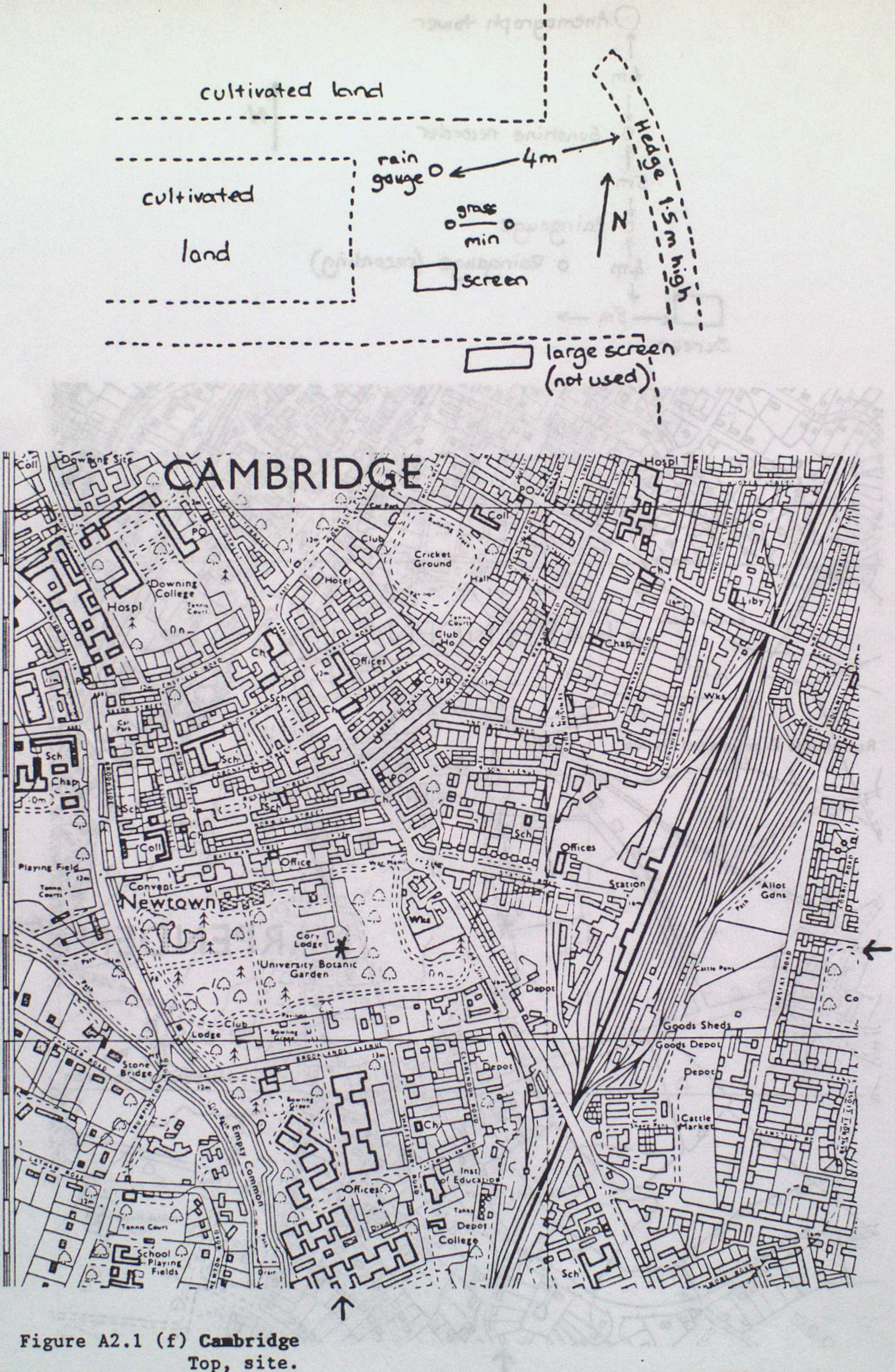



Figure A2.1 (f) **Cambridge**
Top, site.
Bottom, environs: the site is marked * at grid reference 4562/5717 and by arrows at the edges of the map. From Ordnance Survey 1:10,000 map TL 45 NE (1973).

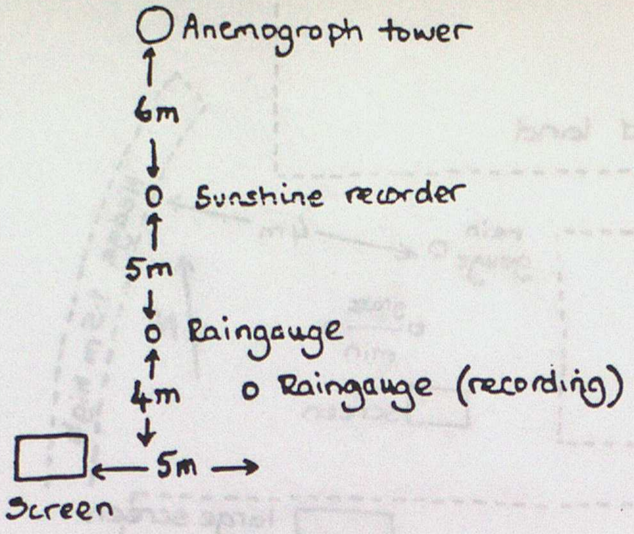




Figure A2.1 (g) **Rothamsted**
Top, site.
Bottom, environs: the site is marked * at grid reference 1316/1332 and by arrows at the edges of the map. From Ordnance Survey 1:10,000 map TL 11 SW (1981).

## APPENDIX 3 Some uncertainties in the corrected daily CET series

### a) Uncertainties in the single-station segment of the daily series

The uncertainties of the earliest, and probably least reliable, parts of our series can be estimated from Table A3.1. This provides root-mean square differences and correlations between our CET series, where derived from Thomas Barker's data, and a corresponding series derived from the Royal Society's data, for each month of the periods of overlap. The latter had been amended, according to the technique described in Appendix 1, for 1787 onwards, but not for 1777-81 which predates Cary's record. Examination of the data, along with Hoy's, suggests errors in the Royal Society record in March 1779 and possibly November 1779: thus the values for 1777-81 in Table A3.1 are likely to be representative of levels of uncertainties in our series for 1774-6, when unamended Royal Society data were used, whereas the values for 1787-89 may be more representative of uncertainties in our series for 1789-99. The uncertainties are a combination of genuine errors in the data, and a root-mean square 'error' or difference $\sigma_g = (\Sigma(LTA-CETA)^2/N)^{1/2}$ resulting from the location of London on the periphery of 'Central England'. Here, LTA are daily temperature anomalies (relative to individual months' means) for London and N is number of data. If the variances of daily LTA and CETA are equal then

$$\sigma_g = 2^{1/2}\sigma_d(1-r_g)^{1/2} \qquad \text{(A3.1)}$$

where $\sigma_d$ is the corrected standard deviation of daily CETA. $\sigma_d$ ranges from 2.9°C in winter to 1.8°C in summer (Figure 4 and Table 12). $r_g$ is the true correlation between daily temperatures in London and in Central England calculated using anomalies from individual months' averages. $r_g$ is estimated to range from 0.93 in winter to 0.86 in summer (Figure A3.1), using correlations $r_{150}$ between daily temperatures 150 km apart. The value of $r_g$ is adjusted for random errors and siting irregularities, which cause imperfect zero-distance correlation $r_0$, by using $r_{adj} = r_{150}/r_0$ (Appendix 4), with $r_0$ estimated from Figure A3.1. So the geographical component of the scatter in the daily values will be approximately 1.0°C in both winter and summer, and accounts for most of the uncertainties implied by Table A3.1. The use of Hoy's data for 1772-3 will have made our series somewhat less reliable again for those years, as suggested by the comparison of Hoy's record with that for the Royal Society in Table 10, and the generally lower correlations between Barker and Hoy than between Barker and the Royal Society for the months of overlap (Section 2).

Up to 1852, the geographical daily scatter of 1.0°C will have persisted in our series because we used single London stations. A slight decrease should have accompanied the change to Oxford data in 1853 (Table 1), and the geographical scatter should have been very small from 1878 onwards when we used three stations closely representative of Manley's 'Central England' area (Table 1 and Figure 1).

b) Replacement of Stonyhurst by Squires Gate and Ringway in 1959

We discuss here the suitability of (Squires Gate + Ringway)/2 as a replacement for Stonyhurst. The problems anticipated are:-

i) Urbanization at Ringway. Our series has been compensated for recent urban warming on a calendar-monthly basis (Section 3f), and the remaining uncertainties in this regard, affecting the daily values, are discussed in Section 4c. Note that if the urbanisation at Ringway becomes much more marked, it will be necessary to find a replacement station in the future.

ii) The relatively southerly location of Ringway, a little outside Manley's 'Lancashire Plain' area (Figure 1).

iii) The near-coastal location of Squires Gate (Appendix 2), and its proneness to low temperatures on clear nights as a result of sandy soil and a flat terrain separated from the sea by dunes.

We used daily data for 1957-1966 at the three stations to determine whether the variances of daily maximum, minimum and mean temperature at Squires Gate, at Ringway and for (Squires Gate + Ringway)/2 were the same as those at Stonyhurst in each month and for the year as a whole; and whether the mean difference in daily maximum, minimum and mean temperature anomaly between these stations was a function of atmospheric circulation type. As in Section 3e, we used anomalies from the individual monthly averages (e.g. January 1960) at each station to carry out the analysis. To minimise autocorrelation in the anomalies, we sampled every fifth day. The following dates were excluded by gaps in the Stonyhurst record: 29 Feb 1960, 7 Apr and 30 June 1963, and much of Nov 1966.

Table A3.2 presents the variances of the daily temperature anomalies for Stonyhurst, Squires Gate, Ringway and (Squires Gate + Ringway)/2, for each calendar month and for the year as a whole. Table A3.3 lists the significant F ratios between these variances, estimated according to

$$F = \frac{\text{Var (A)}}{\text{Var (B)}} \geq C \qquad \text{(A3.2)}$$

where the critical value C is applicable to a two-tailed F test with 59 degrees of freedom (10 years x 6 days = 60 independent days) for the calendar monthly tests (C = 1.55, 1.67 for significance at the 90%, 95% levels respectively) and 719 degrees of freedom for the annual tests (C = 1.13, 1.16 for significance at the 90%, 95% levels respectively).

As anticipated, Squires Gate shows enhanced variability at night relative to the other two stations, being prone to low temperatures on clear nights. Squires Gate also shows reduced variability by day, especially relative to Ringway. In the diurnal mean, these two opposing characteristics largely cancel. Furthermore, the variance of (Squires Gate + Ringway)/2 never differs significantly from that of Stonyhurst. The variance of (Squires Gate + Ringway)/2 tends to be greater than that of Stonyhurst at night (Table A3.2), by an insignificant amount, but the converse applies by day, with partial cancellation of even these small differences when the diurnal mean is analysed.

A similar analysis for the influence of atmospheric circulation types in different seasons was based on a classification of these into 'very warm' and 'very cold' types, according to the occurrence of mean corrected daily CET anomaly in the top or bottom quints of its probability distribution in the given 3-month season (Storey, 1982). We excluded days falling into the other CET quints. The seasons used were December to February, etc. The circulation types implicitly identified by this procedure differed between the four seasons. The differences of the daily maximum, minimum and mean temperature data between the stations were then analysed for very warm and very cold days. We used a one-way analysis of variance to test the null hypothesis that the temperature differences between stations did not change systematically between temperature classes in given seasons; and a two-way analysis of variance to test the hypothesis that there was no systematic change in these mean temperature differences between temperature classes for all seasons taken together, or between seasons for both temperature classes taken together.

Table A3.4 shows the results of the one-way analysis of variance for Stonyhurst versus (Squires Gate + Ringway)/2. The only systematic change of temperature difference with temperature class was in summer, when daily maxima were relatively higher, and daily minima were relatively lower, in very warm conditions at the combined stations. For daily mean temperatures, these opposing biases cancelled, to give no significant overall effect. Comparisons of individual stations (not shown) showed Ringway to be less suitable than Squires Gate as an individual replacement for Stonyhurst, because Ringway was always relatively warmer than Stonyhurst in very warm conditions by day and in the daily mean. Squires Gate was generally relatively colder than Stonyhurst in very warm conditions, but this was only significant for maxima in spring and minima and daily means in summer. The results confirm the bias of Squires Gate to cold nights in summer in very warm conditions when the wind is often from inland and the humidity is low. When Ringway and Squires Gate were combined, their opposing differences from Stonyhurst tended to cancel. Thus one-way analysis of variance confirms that (Squires Gate + Ringway)/2 is the most suitable replacement for Stonyhurst, with Ringway on its own the least suitable.

The two-way analysis of variance for Stonyhurst versus (Squires Gate + Ringway)/2 confirmed that the temperature differences between them did not vary systematically between very warm and very cold conditions when all seasons were considered together. There was a significant variation with season of the temperature difference between Stonyhurst and (Squires Gate + Ringway)/2 when very warm and very cold days were combined. However the seasonally-varying overall climatic difference between these stations will have been removed in the final daily series by our adjustment of the monthly averages to be consistent with Manley's (Section 3d).

c) <u>Extent of climatic heterogeneity of the 'Central England' area</u>

We confirmed above that (Squires Gate + Ringway)/2 is a satisfactory substitute for Stonyhurst, but noted some systematic differences in day-to-day variability amongst these stations taken individually. Here we place these differences in the context of the extent to which "Central England" shows climatic heterogeneity.

The variance of daily maximum temperatures was found in Section A3b) to be smaller at Squires Gate than at Ringway or Stonyhurst. Figure A3.2 supports this result by showing that Ringway's standard deviation is similar to that at several Midland stations, while Squires Gate's is much smaller. These results are based on data for 1961 to 1990, and are calculated by averaging individual months' variances. Other Lancashire stations' standard deviations of maximum temperature are also smaller than those of Ringway, though not as small as those of Squires Gate (Figure A3.2). This is mainly because Lancashire is more maritime than the Midlands.

Corresponding standard deviations of daily minimum temperatures (not shown) confirm the greater variability at Squires Gate than at Ringway, but there are no systematic differences between Lancashire and the Midlands.

Figure A3.3 shows greater positive skewness in daily maxima in summer at the northwestern stations, especially Squires Gate, than at the Midland stations. Lancashire, especially near the coast, is generally cooler by day than the Midlands in summer, but can be as warm on occasional days with southeasterly (offshore) winds (e.g. 33°C at Squires Gate, 2 August 1990).

Figure A3.4 shows the expected enhanced negative skewness of Squires Gate's daily minima, reflecting very low values on clear nights in a frost-prone location. However, the other Lancashire stations show the same tendency to a lesser extent, suggesting a regional climatological characteristic of rarer very cool nights than very warm ones.

To summarize, Manley combined two climatologically slightly different areas into his 'Central England' (Figure 1). These differences may be as important as differences between sites within Lancashire, or within the Midlands, and must be borne in mind in any analysis of the data.

TABLE A3.1 a) Root-mean square differences between daily Central England Temperatures as derived from Barker's data and as would have been derived if the Royal Society's data had been used. b) Correlations corresponding to a). The Royal Society data for 1787-9 had been amended as described in Appendix 1.

a)

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1777 | 0.97 | 1.42 | 0.91 | 1.35 | 1.25 | 1.41 | 1.49 | 1.02 | 1.22 | 0.99 | 1.30 | 0.80 |
| 1778 | 1.22 | 1.12 | 0.95 | 0.77 | 1.05 | 1.05 | 1.33 | 0.94 | 1.17 | 1.02 | 0.75 | 1.09 |
| 1779 | 1.32 | 1.13 | 2.45 | 1.04 | 1.18 | 1.23 | 1.35 | 1.11 | 1.19 | 0.79 | 1.81 | 1.16 |
| 1780 | 0.90 | 1.07 | 1.03 | 1.12 | 1.28 | 0.93 | 1.22 | 1.45 | 0.92 | 1.12 | 1.14 | 1.09 |
| 1781 | 1.47 | 1.00 | 1.51 | 1.66 | 1.47 | 0.94 | 1.13 | 1.18 | ---- | ---- | ---- | ---- |
| | | | | | | | | | | | | |
| 1787 | 1.11 | 0.93 | 0.99 | 0.91 | 1.07 | 1.15 | 0.80 | 0.85 | 0.65 | 0.69 | 1.06 | 1.03 |
| 1788 | 1.01 | 0.88 | 1.09 | 1.52 | 1.57 | 1.38 | 1.59 | 1.23 | 1.05 | 1.18 | 1.14 | 1.00 |
| 1789 | 1.51 | 0.72 | 1.07 | 0.83 | 0.99 | 0.98 | ---- | ---- | ---- | ---- | ---- | ---- |

b)

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1777 | 0.96 | 0.92 | 0.97 | 0.89 | 0.76 | 0.79 | 0.84 | 0.83 | 0.86 | 0.94 | 0.89 | 0.92 |
| 1778 | 0.86 | 0.90 | 0.95 | 0.97 | 0.74 | 0.92 | 0.85 | 0.90 | 0.89 | 0.94 | 0.94 | 0.91 |
| 1779 | 0.87 | 0.81 | 0.31 | 0.93 | 0.95 | 0.55 | 0.79 | 0.82 | 0.80 | 0.94 | 0.89 | 0.96 |
| 1780 | 0.94 | 0.92 | 0.88 | 0.93 | 0.89 | 0.93 | 0.71 | 0.48 | 0.93 | 0.88 | 0.93 | 0.91 |
| 1781 | 0.86 | 0.87 | 0.78 | 0.82 | 0.90 | 0.92 | 0.78 | 0.82 | ---- | ---- | ---- | ---- |
| | | | | | | | | | | | | |
| 1787 | 0.91 | 0.92 | 0.85 | 0.83 | 0.88 | 0.85 | 0.91 | 0.93 | 0.90 | 0.96 | 0.95 | 0.94 |
| 1788 | 0.88 | 0.90 | 0.95 | 0.84 | 0.84 | 0.69 | 0.65 | 0.65 | 0.91 | 0.91 | 0.95 | 0.94 |
| 1789 | 0.95 | 0.93 | 0.75 | 0.94 | 0.87 | 0.86 | ---- | ---- | ---- | ---- | ---- | ---- |

TABLE A3.2 Variances (°C)$^2$ of daily temperature anomalies from individual monthly averages at the same station for Stonyhurst, Squires Gate, Ringway and (Squires Gate + Ringway)/2 for 1957-1966

| | STONYHURST | | | SQUIRES GATE | | | RINGWAY | | | (SQUIRES GATE + RINGWAY)/2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 24-hour maximum ($T_x$) | 24-hour minimum ($T_n$) | $\frac{1}{2}(T_x+T_n)$ | 24-hour maximum ($T_x$) | 24-hour minimum ($T_n$) | $\frac{1}{2}(T_x+T_n)$ | 24-hour maximum ($T_x$) | 24-hour minimum ($T_n$) | $\frac{1}{2}(T_x+T_n)$ | 24-hour maximum ($T_x$) | 24-hour minimum ($T_n$) | $\frac{1}{2}(T_x+T_n)$ |
| Jan | 6.61 | 10.53 | 6.96 | 5.68 | 16.09 | 8.46 | 8.78 | 10.34 | 7.56 | 6.82 | 12.11 | 7.61 |
| Feb | 7.35 | 8.59 | 6.45 | 5.81 | 10.99 | 6.21 | 8.35 | 8.91 | 7.02 | 6.71 | 9.08 | 6.33 |
| Mar | 7.49 | 6.70 | 5.07 | 6.27 | 10.35 | 4.65 | 7.77 | 8.88 | 6.11 | 6.59 | 8.66 | 5.08 |
| Apr | 6.72 | 5.85 | 4.01 | 5.71 | 7.47 | 3.37 | 7.69 | 6.44 | 5.05 | 6.03 | 6.11 | 3.91 |
| May | 10.75 | 5.83 | 5.89 | 9.75 | 7.04 | 5.12 | 12.25 | 6.79 | 7.11 | 10.44 | 5.88 | 5.67 |
| Jun | 10.19 | 4.93 | 4.91 | 9.94 | 8.15 | 4.90 | 11.47 | 4.36 | 5.39 | 9.92 | 5.14 | 4.59 |
| Jul | 6.61 | 3.84 | 3.36 | 4.78 | 4.79 | 2.47 | 6.19 | 4.13 | 3.41 | 4.92 | 3.33 | 2.53 |
| Aug | 6.21 | 4.71 | 3.25 | 5.00 | 5.96 | 2.43 | 6.87 | 4.89 | 3.97 | 5.46 | 4.53 | 2.85 |
| Sep | 6.02 | 9.34 | 5.46 | 5.90 | 12.98 | 5.01 | 8.24 | 9.72 | 6.44 | 6.71 | 10.31 | 5.39 |
| Oct | 5.79 | 7.25 | 4.87 | 5.14 | 6.91 | 3.78 | 6.49 | 6.48 | 4.97 | 5.54 | 5.79 | 4.04 |
| Nov | 6.88 | 11.90 | 7.43 | 5.22 | 15.49 | 7.43 | 7.53 | 11.61 | 7.51 | 6.05 | 12.54 | 7.15 |
| Dec | 7.89 | 11.94 | 8.64 | 5.37 | 16.42 | 8.81 | 7.05 | 12.14 | 7.96 | 5.83 | 13.40 | 8.02 |
| "Annual" (months weighted by numbers of days' data) | 7.37 | 7.61 | 5.52 | 6.21 | 10.21 | 5.21 | 8.22 | 7.88 | 6.03 | 6.75 | 8.06 | 5.25 |

TABLE A3.3 Significant ratios between the variances of daily temperature anomalies from individual monthly averages for Stonyhurst, Squires Gate, Ringway and (Squires Gate + Ringway)/2 for 1957-1966

| Stations | Parameter | Month/year | Variance ratio | Significance level |
|---|---|---|---|---|
| Stonyhurst (S) and Squires Gate (SG) | Maximum temperature | Whole year | S/SG : 1.19 | 95% |
| | Minimum temperature | March | SG/S : 1.55 | 90% |
| | | June | SG/S : 1.65 | 90% |
| | | Whole year | SG/S : 1.34 | 95% |
| Stonyhurst (S) and Ringway (R) | No significant ratios | | | |
| Squires Gate (SG) and Ringway (R) | Maximum temperature | January | R/SG : 1.55 | 90% |
| | | Whole year | R/SG : 1.32 | 95% |
| | Minimum temperature | January | SG/R : 1.56 | 90% |
| | | June | SG/R : 1.87 | 95% |
| | | Whole year | SG/R : 1.29 | 95% |
| | (Max + min)/2 | August | R/SG : 1.64 | 90% |
| | | Whole year | R/SG : 1.16 | 90% |
| Stonyhurst (S) and (Squires Gate + Ringway)/2 (SR) | No significant ratios | | | |

TABLE A3.4 One-way analysis of variance of daily temperature differences for warm and cold circulation types : (Squires Gate + Ringway)/2 - Stonyhurst

| MAXIMUM TEMPERATURE | SPRING | SUMMER | AUTUMN | WINTER |
|---|---|---|---|---|
| Warm circulation mean difference | 0.87 | 1.29 | 0.91 | 0.65 |
| Cold circulation mean difference | 0.78 | 0.45 | 0.61 | 0.30 |
| F-Ratio | 0.25 | 6.3 | 2.01 | 2.47 |
| Significance* | 0.62 | 0.014 | 0.16 | 0.12 |
| No. of warm cases $N_w$ | 102 | 35 | 85 | 85 |
| No. of cold cases $N_c$ | 68 | 52 | 56 | 76 |

| MINIMUM TEMPERATURE | SPRING | SUMMER | AUTUMN | WINTER |
|---|---|---|---|---|
| Warm circulation mean difference | 0.53 | -0.01 | 0.37 | 0.33 |
| Cold circulation mean difference | 0.28 | 1.12 | 0.33 | 0.19 |
| F-Ratio | 2.38 | 25.72 | 0.02 | 0.83 |
| Significance* | 0.13 | <0.001 | 0.88 | 0.37 |
| No. of warm cases $N_w$ | 102 | 35 | 84 | 85 |
| No. of cold cases $N_c$ | 68 | 52 | 55 | 76 |

| MEAN TEMPERATURE | SPRING | SUMMER | AUTUMN | WINTER |
|---|---|---|---|---|
| Warm circulation mean difference | 0.70 | 0.64 | 0.64 | 0.49 |
| Cold circulation mean difference | 0.53 | 0.78 | 0.48 | 0.24 |
| F-Ratio | 2.4 | 0.47 | 1.28 | 3.46 |
| Significance* | 0.15 | 0.50 | 0.26 | 0.07 |
| No. of warm cases $N_w$ | 102 | 35 | 84 | 85 |
| No. of cold cases $N_c$ | 68 | 52 | 55 | 76 |

* Note: The analysis of variance assumes (number of classes -1) i.e. 1 degree of freedom in the numerator, and $(N_w + N_c - 1)$ degrees of freedom in the denominator.

Figure A3.1a.

Correlations between daily temperature anomalies from stations' individual monthly averages, as a function of distance between stations, for January.

Based on:

Oxford, Ross-on-Wye and (boxed points) Sheffield for 1883-1912;
Ringway, Finningley, Wittering, Cardington, Shawbury and Birmingham (Elmdon) for 1974-1979;
Stonyhurst, Cambridge and Ross-on-Wye for 1878-1907;
Stonyhurst, Rothamsted and Ross-on-Wye for 1931-1958;
Rothamsted and Malvern for 1959-1981.

Solid line: r=0.996-0.000467*distance. Regression correlation = -0.83.
This regression excludes Sheffield (131m above MSL).

Dashed line: r=0.998-0.000517*distance. Regression correlation = -0.73.
This regression includes Sheffield.

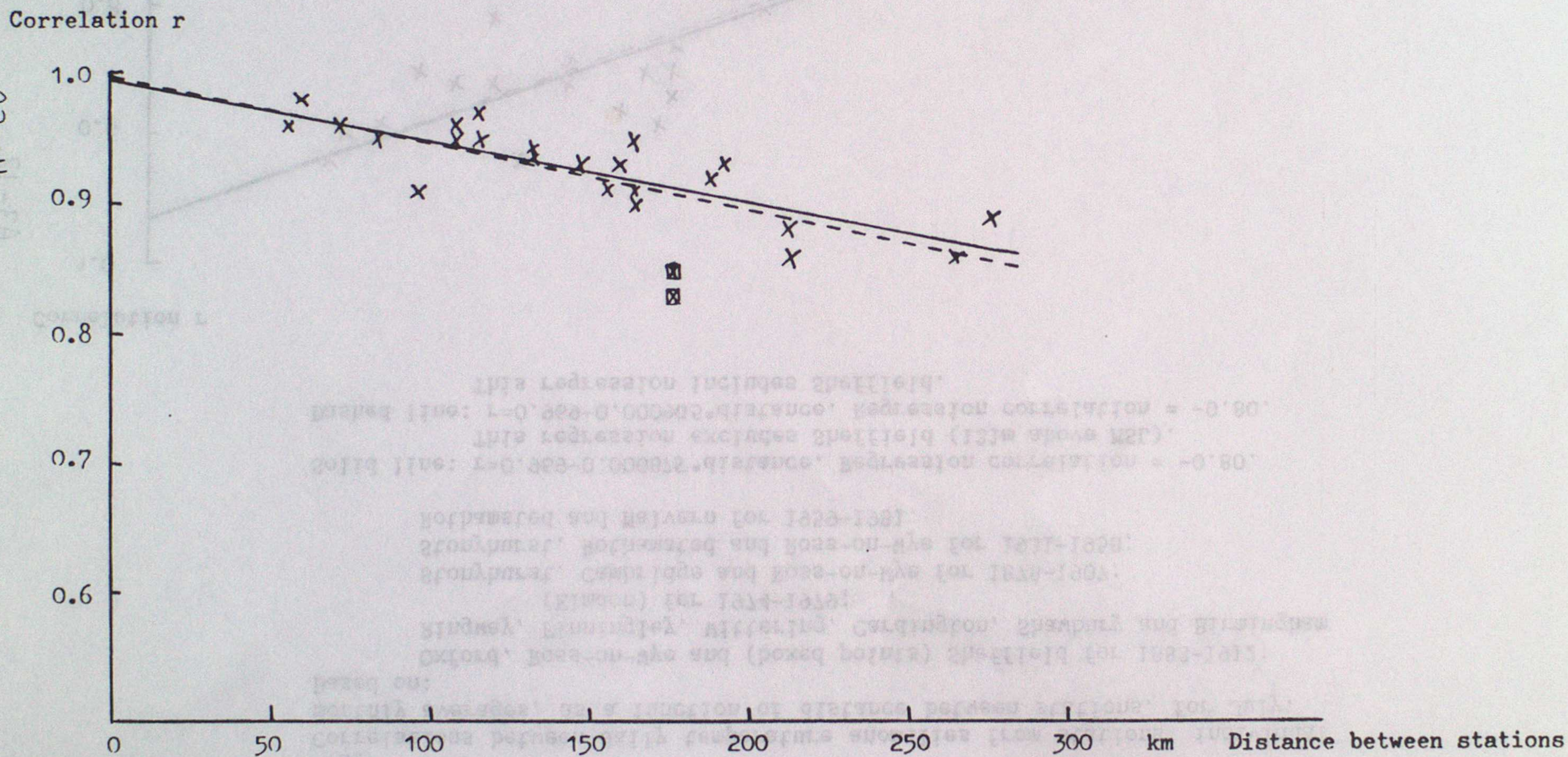
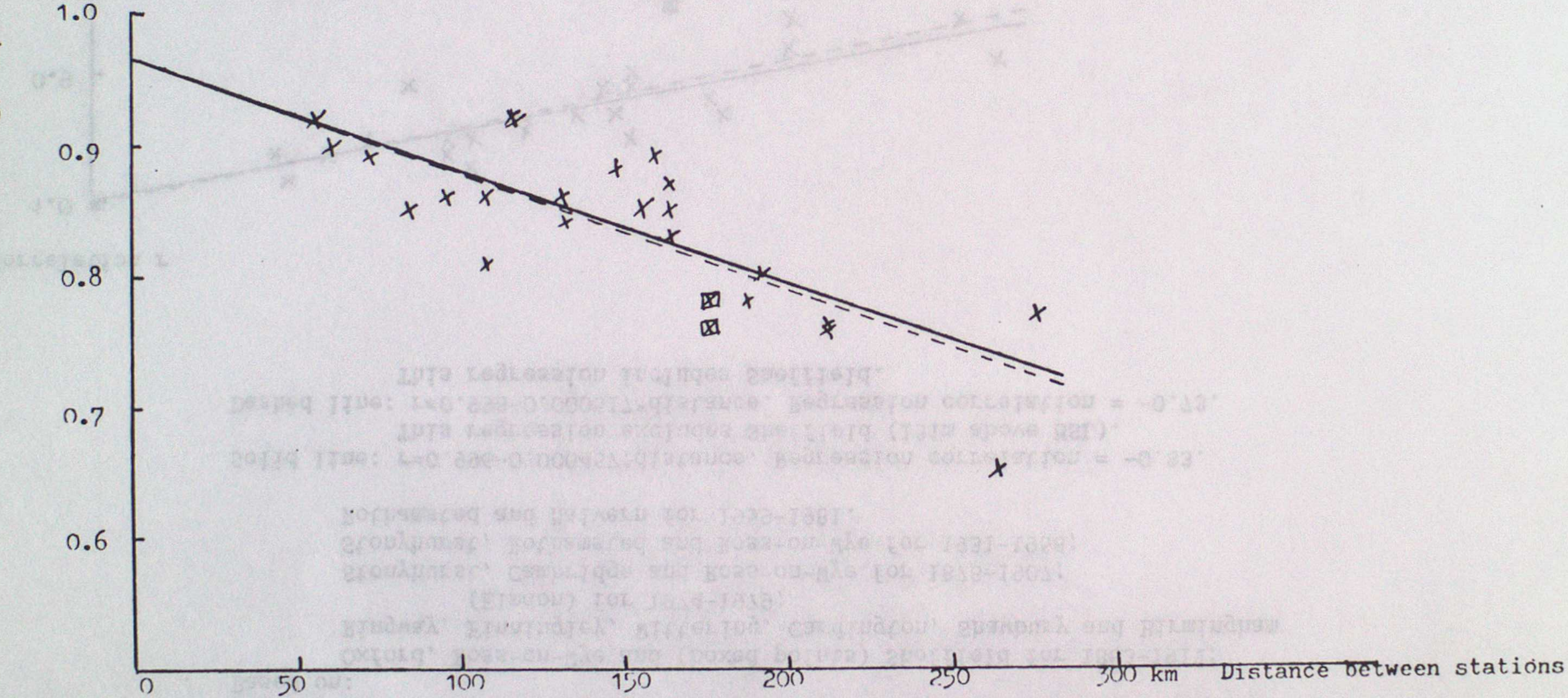


Figure A3.1b.
Correlations between daily temperature anomalies from stations' individual monthly averages, as a function of distance between stations, for July.
Based on:

Oxford, Ross-on-Wye and (boxed points) Sheffield for 1883-1912;
Ringway, Finningley, Wittering, Cardington, Shawbury and Birmingham (Elmdon) for 1974-1979;
Stonyhurst, Cambridge and Ross-on-Wye for 1878-1907;
Stonyhurst, Rothamsted and Ross-on-Wye for 1931-1958;
Rothamsted and Malvern for 1959-1981.

Solid line: r=0.969-0.000875*distance. Regression correlation = -0.80.
This regression excludes Sheffield (131m above MSL).
Dashed line: r=0.969-0.000905*distance. Regression correlation = -0.80.
This regression includes Sheffield.



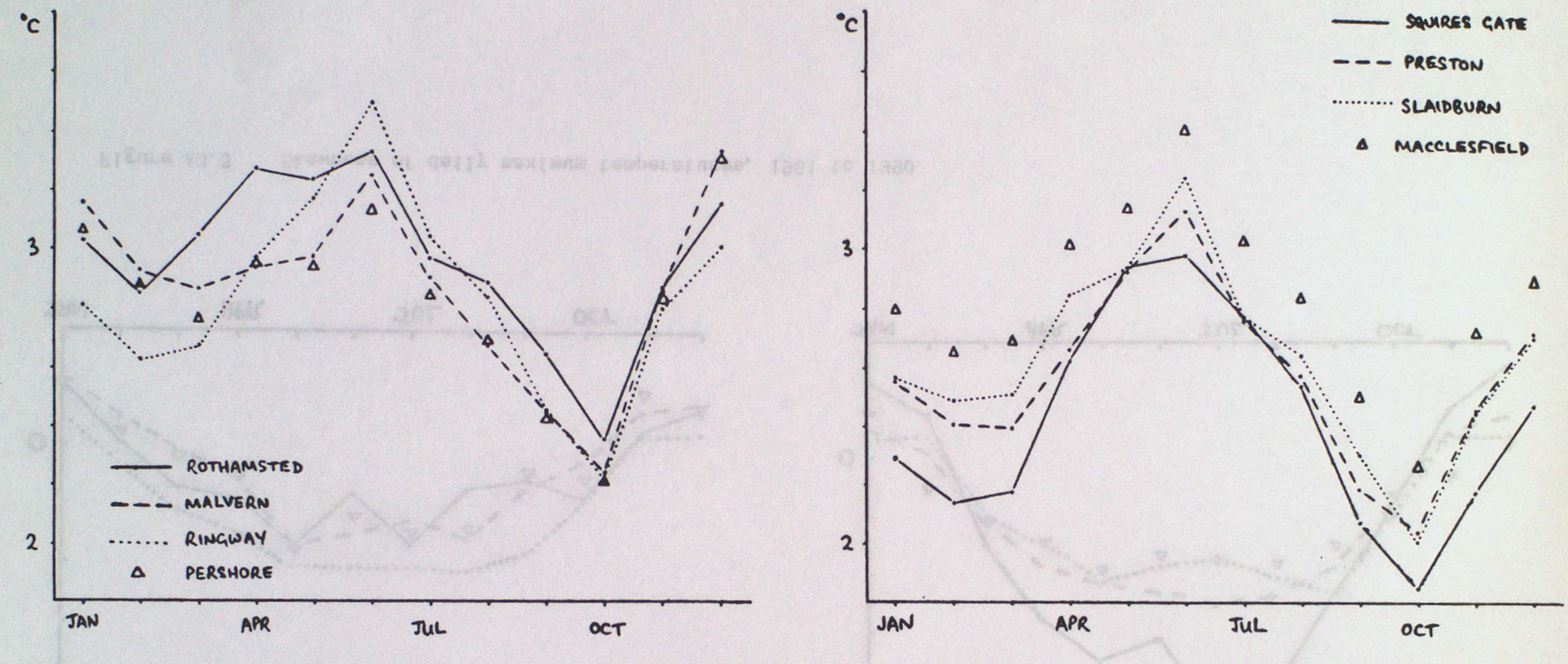



Figure A3.2 Standard deviation of daily maximum temperatures, 1961 to 1990. Values are calculated using anomalies from (daily mean climatology for 1961-90 + individual months' anomalies).

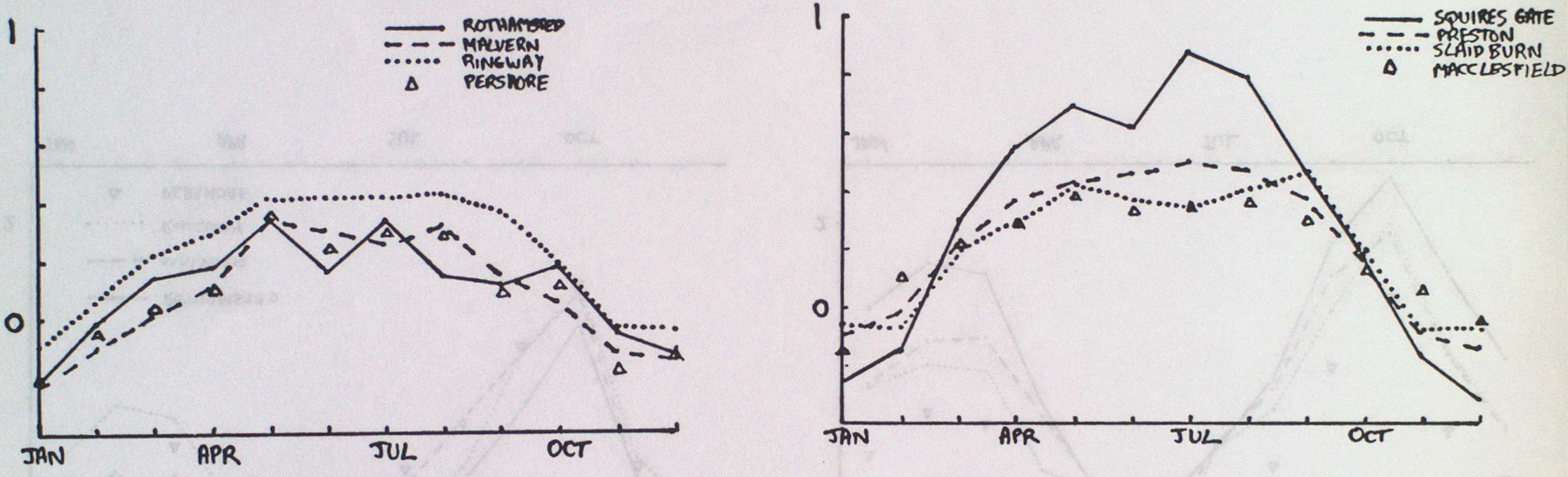



Figure A3.3 Skewness of daily maximum temperatures, 1961 to 1990.

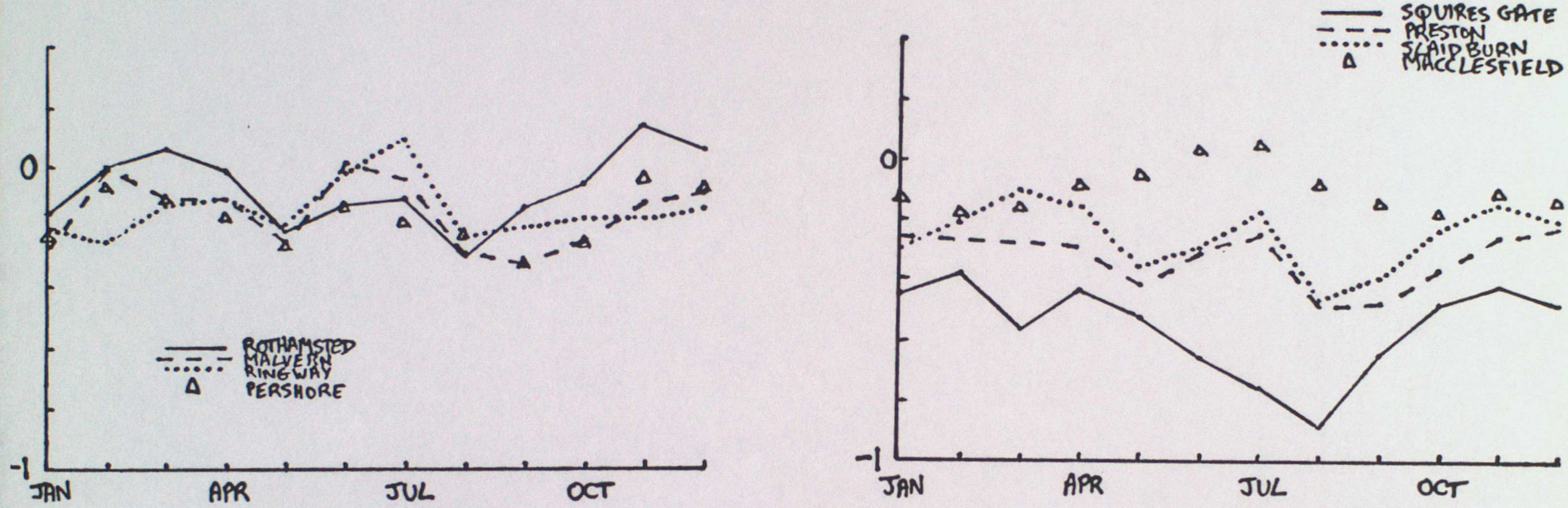



Figure A3.4 Skewness of daily minimum temperatures, 1961 to 1990.

APPENDIX 4 Correlation between stations' temperatures with random errors.

The measured correlation $r_{obs}$ is given by:

$$r_{obs} = \frac{\Sigma(a_i + \alpha_i)(b_i + \beta_i)}{(\Sigma(a_i + \alpha_i)^2 \Sigma(b_i + \beta_i)^2)^{½}} \quad \text{(A4.1)}$$

where a, b are true anomalies from the mean of an individual month in an individual year at the respective stations; and α, β are corresponding random errors.

If the errors are uncorrelated with the true anomalies, then

$$\Sigma a_i\alpha_i = \Sigma b_i\alpha_i = \Sigma a_i\beta_i = \Sigma b_i\beta_i = 0,$$

and if separate stations' errors are uncorrelated then $\Sigma\alpha_i\beta_i = 0$.

In this case:

$$r_{obs} = \frac{\Sigma a_i b_i}{(\Sigma(a_i^2 + \alpha_i^2)\Sigma(b_i^2 + \beta_i^2))^{½}} \quad \text{(A4.2)}$$

or

$$r_{obs} = \frac{cov_{ab}}{(\sigma_a^2\sigma_b^2 + \sigma_\alpha^2\sigma_b^2 + \sigma_a^2\sigma_\beta^2 + \sigma_\alpha^2\sigma_\beta^2)^{½}} \quad \text{(A4.3)}$$

If there had been no errors, we would have obtained:

$$r_{true} = \frac{cov_{ab}}{\sigma_a\sigma_b} \quad \text{(A4.4)}$$

Now let $\sigma_a = \sigma_b = \sigma$ and $\sigma_\alpha = \sigma_\beta = \sigma_\epsilon$, i.e. the stations have equal true variance and equal error-variance.

Then

$$r_{obs} = \frac{cov_{ab}}{(\sigma^4 + 2\sigma^2\sigma_\epsilon^2 + \sigma_\epsilon^4)^{½}} = \frac{cov_{ab}}{\sigma^2 + \sigma_\epsilon^2} \quad \text{(A4.5)}$$

Therefore $r_{obs} = r_{true} \dfrac{\sigma^2}{\sigma^2 + \sigma_\epsilon^2}$ (A4.6)

The correlation for colocated stations, for which $r_{true} = 1$, is therefore

$$r_o = \frac{\sigma^2}{\sigma^2 + \sigma_\epsilon^2} \qquad \text{(A4.7)}$$

so that $r_{obs} = r_{true} r_o$ (A4.8)

CLIMATE RESEARCH TECHNICAL NOTES

| | | |
|---|---|---|
| CRTN 1 | Oct 1990 | Estimates of the sensitivity of climate to vegetation changes using the Penman-Monteith equation.<br>P R Rowntree |
| CRTN 2 | Oct 1990 | An ocean general circulation model of the Indian Ocean for hindcasting studies.<br>D J Carrington |
| CRTN 3 | Oct 1990 | Simulation of the tropical diurnal cycle in a climate model.<br>D P Rowell |
| CRTN 4 | Oct 1990 | Low frequency variability of the oceans.<br>C K Folland, A Colman, D E Parker and A Bevan |
| CRTN 5 | Dec 1990 | A comparison of 11-level General Circulation Model Simulations with observations in the East Sahel.<br>K Maskell |
| CRTN 6 | Dec 1990 | Climate Change Prediction.<br>J F B Mitchell and Qing-cun Zeng |
| CRTN 7 | Jan 1991 | Deforestation of Amazonia - modelling the effects of albedo change.<br>M F Mylne and P R Rowntree |
| CRTN 8 | Jan 1991 | The role of observations in climate prediction and research.<br>D J Carson |
| CRTN 9 | Mar 1991 | The greenhouse effect and its likely consequences for climate change.<br>D J Carson |
| CRTN 10 | Apr 1991 | Use of wind stresses from operational N.W.P. models to force an O.G.C.M. of the Indian Ocean.<br>D J Carrington |
| CRTN 11 | Jun 1991 | A new daily Central England Temperature series, 1772-1991.<br>D E Parker, T P Legg and C K Folland |