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A NEW DAILY CENTRAL ENGLAND TEMPERATURE SERIES, 1772–1991

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ABSTRACT

In 1974 Manley produced a time series of monthly average temperatures representative of central England for 1659–1973. The present paper describes how a series of homogenized daily values representative of the same region 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 1961–1990. We also show sequences of daily central England temperature for sample years. All the daily data are available on request.

KEY WORDS Temperature Climatic variability Urban warming Central England Homogeneous time series

1. INTRODUCTION

Manley (1953) published a time series of monthly mean temperatures representative of central England for 1698–1952, followed (Manley, 1974) by an extended and revised series for 1659–1973. 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 1760s there are no gaps in the composite instrumental record, but the observations generally were 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 summarized by Jones (1987). Our paper is an abridged version of Parker *et al.* (1991), which also is unpublished.

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

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(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 making adjustments to help retain 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 (section 3.6).

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. Manley's adjustments, however, were designed for monthly data, and so are less accurate for daily data, because of day-to-day variations of non-climatic influences, which depend on the balance between radiative and advective heat fluxes.

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). We show sequences of daily CET for sample years, but the entire daily series is too extensive to be printed, and is available on disk or microfiche.

In an Appendix we discuss the uncertainties in the early part of the daily CET series, and some incompatibilities between the climate statistics of the stations used.

2. CHOICE OF STATIONS

2.1. Selected stations

The stations chosen to represent central England are listed in Table I, 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

Table I. (a) 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)*
January 1777–June 1789 (except December 1786)	Lyndon Hall, Rutland* (Barker's record)
December 1786	London (Syon House, Kew) (Hoy's record)
July 1789–December 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 (Lancashire) and Ringway, with weights 1:1:0·5:0·5

Table I. (b) Locations of stations used in our daily CET series, in JCS's series, and in our urban–rural comparisons

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 (Royal Horticultural Society)	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	*ca.* 102
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

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, namely:

(i) avoidance of severely urbanized 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 optimize the homogeneity of the series.

Ideally, the entire late eighteenth 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 of Parker *et al.* (1991)); for the remainder of the late eighteenth 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

Figure 1. Locations of stations used in the daily series (bold capitals and stars), to assess recent urban warming (light capitals and dots), and other places mentioned in the text (lower case and dots). The two stippled areas and intermediate regions represent Manley's 'central England'

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 oversheltered 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 of Parker *et al.* (1991)), in view of Manley's (1964) remark that the Royal Society's record contains misread 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 I), 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 criticized for our choices of single stations up to 1877 (Table I(a)), 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's (1946) '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 available only as monthly means plus a few other fragments of information. There are thus substantial periods before the mid-1840s when there are no known reliable daily data for Lancashire: see figure 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 1840s 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 (section 3 and Figure 2). We could have used Oxford and Stonyhurst for 1868–1877, but use of a single transition from one to three stations in 1877–1878 made homogenization of the variance of the daily series (section 3.5) 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 north-west of central England. Other possible single stations, such as Preston and Macclesfield, were rejected owing to urban influences, and Slaidburn (192 m) was not used because of its upland location. The relationship between Stonyhurst and $\frac{1}{2}$(Squires Gate + Ringway) is discussed in Appendix 3 of Parker *et al.* (1991), where analyses of variance are used to show that the latter combination of stations has daily temperature statistics that are adequately similar to those of Stonyhurst. 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 section 3.6.

Ross on Wye was closed from 1975 to 1985. We replaced it by Malvern in 1959, to minimize the number of discontinuities. 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 I(a)) 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 of Parker *et al.* (1991) gives details of all the sites used since 1878 in our series.

2.2. Comparisons with the choices of JCS after 1877

We did not use JCS's stations after 1877 (see also Jones, 1987) because they inadequately represent Manley's central England. Jenkinson *et al.* (1979) 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).

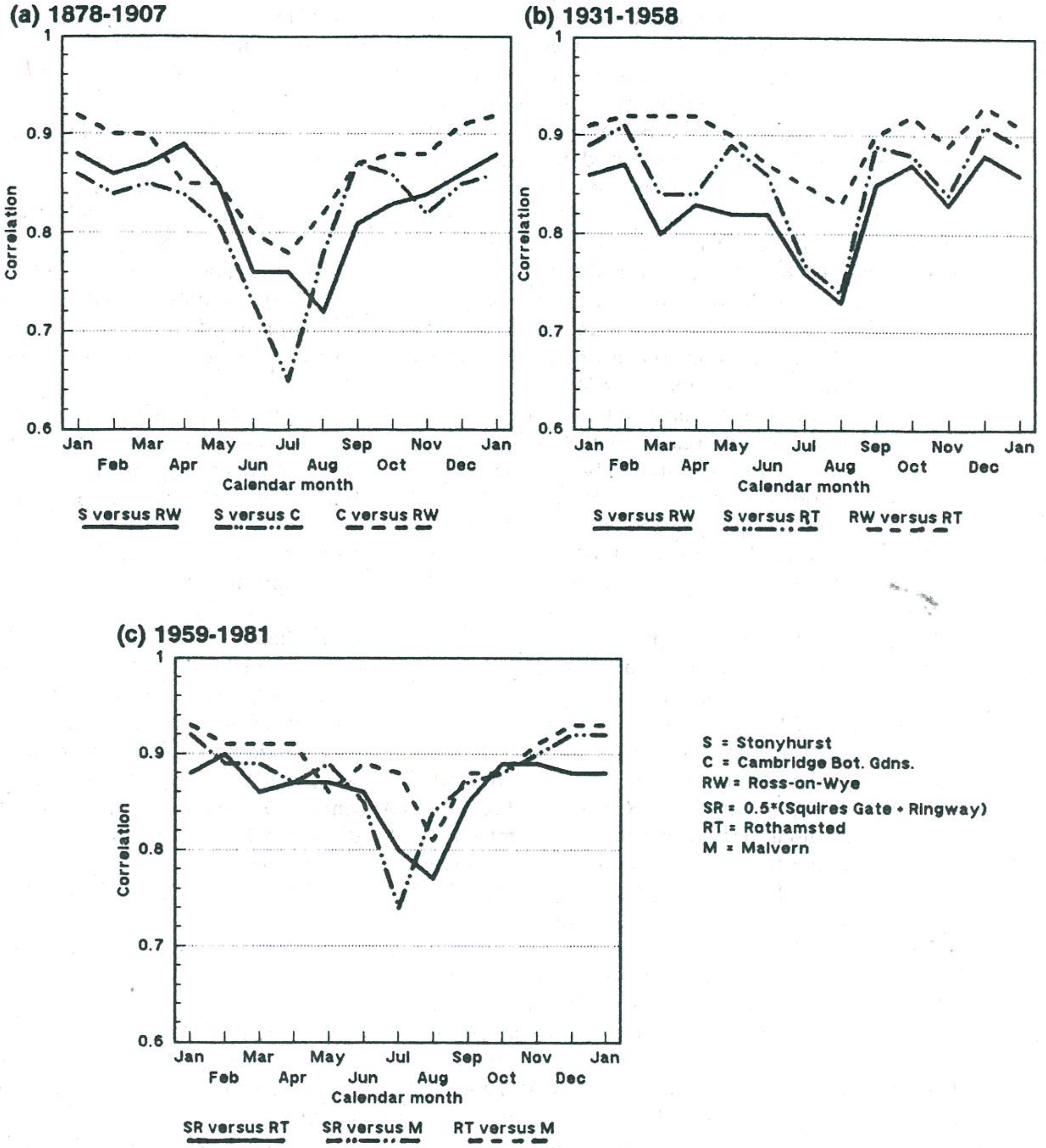

Figure 2. Correlation coefficients between mean daily temperatures at stations used for the daily series for 1878 onwards

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 3.5). To yield a homogeneous variance, the mean simultaneous correlation of daily temperatures between stations needs to be kept as constant as possible (section 3.5), 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 3.5) in order to represent that of the 'central England' area. Our replacement of Stonyhurst by $\frac{1}{2}$(Squires Gate+Ringway) in 1959 did not affect the variance of the new CET series (Appendix 3 of Parker *et al.* (1991)).

3. CONSTRUCTION OF THE DAILY SERIES

3.1. 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. This adjustment reduced their variance expressed relative to the averages for individual months in individual years, but did not change these averages. Finally, corrections for urban warming were made from 1974 onwards. Since our values up to 1973 were anchored to Manley's monthly series, which is already compensated (section 4.3), no corrections were appropriate.

3.2. Calculation of daily values for individual stations

The daily value for station z was calculated as

$$t_z = \sum_{h=1}^{m} W_h t_h \Big/ \sum_{h=1}^{m} W_h \qquad (1)$$

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 of Parker *et al.* (1991), for the late eighteenth century data. The number m of temperatures averaged was generally 2, again with a few exceptions given in Appendix 1 of Parker *et al.* (1991). Up to 1877, the temperatures were generally morning and afternoon values; thereafter, they were 24 h maxima and minima read at 9 a.m.

3.3. Combination of stations

Composite daily values were calculated from:

$$t_c = \sum_{z=1}^{n} W_z t_z \Big/ \sum_{z=1}^{n} W_z \qquad (2)$$

where $n=1$ and $W_z=1$ before 1878, $n=3$ and $W_z=1$ from 1878 to 1958, and $n=4$, $W_1=W_2=1$, $W_3=W_4=0{\cdot}5$ from 1959. Weights W_3 and W_4 were applied to Squires Gate and Ringway (Table I).

3.4. 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 $6{\cdot}2-6{\cdot}32=-0{\cdot}12$°C is used as a fixed daily correction for March 1973 and is added to each value of t_c.

In general

$$\text{Daily CET}=t_d=t_c+C \qquad (3)$$

where $C=$(Manley's monthly mean)$-$(monthly mean of daily means from equation 2). The value of C was calculated separately for all 2424 months between 1772 and 1973.

All the corrections for 1878–1973 are tabulated by Parker *et al.* (1991). They were generally within $\pm 0{\cdot}5$°C. Small systematic variations took place in the size of the corrections as stations changed. For a given set of stations, the corrections were not strongly related to Manley's monthly temperature anomalies: for example, for 1878–1930 only September and November had a 95 per cent significant correlation between corrections and monthly anomalies, and these correlations were of opposite sign. It was therefore not considered useful to apply daily corrections depending on synoptic type or daily temperature anomaly. See, however, the discussion in section 4.2.

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°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 1953–1973 (24 years) were used to calculate the post-1973 corrections to maximize 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 (Mitchell *et al.* 1966). The statistic t_i is defined by

$$t_i=\left[\frac{n(N-2)}{N-n(1+T_i^2)}\right]^{1/2} T_i \qquad (i=1,\ldots,12) \qquad (4)$$

where

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

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 $(=24\times 12=288)$ 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 per cent significance level. Therefore the corrections were allowed to vary through the year, with some smoothing to reduce sampling error (Table II).

3.5. 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 necessary therefore to adjust the variance of the pre-1878 single-station data to make it homogeneous with that of the subsequent three-station data.

The variance of the mean of n' independent variables, assumed to have equal individual variances S_0^2, is

$$S^2=S_0^2/n' \qquad (5)$$

From 1878, n' is considerably less than the number $n(=3)$ of stations used, because day-to-day variations of

Table II. Corrections applied from 1974 onwards to give consistency with Manley's series

Month	Correction (°C)
January	+0·1
February	0·0
March	0·0
April	−0·1
May	−0·1
June	−0·1
July	−0·1
August	−0·2
September	−0·1
October	0·0
November	+0·1
December	+0·1

temperature at the stations are strongly positively correlated. The effective number n' of stations is shown by Yevjevich (1972) to be

$$n' = \frac{n}{1 + \bar{r}(n-1)} \tag{6}$$

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.

Figure 2 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 interannual variations. The effects of autocorrelation of the daily data were minimized by correlating simultaneous daily anomalies measured at 5-day intervals. The average of Squires Gate and Ringway was treated as a single station (see Appendix 3 of Parker *et al.* (1991)).

For January, $n' = 1{\cdot}08$, 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 per cent 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 III and Figure 3). 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 $(d = 1, 2, \ldots, N)$ having mean $\bar{x}$ and variance σ_x^2. The series bx_d has mean $b\bar{x}$ and variance $b^2\sigma_x^2$. 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 also is reduced, to $b\bar{x}$. Because the mean is required to stay constant, we must multiply temperature *anomalies*, calculated from a suitable mean, by b. Choice of the appropriate mean is not straightforward. The daily values of CET derive from statistical populations that

Table III. F tests of variances of unadjusted daily central England temperatures. The variances were calculated using deviations from individual month's avarages

	Variance ratio, F (1772–1877 versus 1878–1990)	Significance[a] (per cent)
January	1·41	5
February	1·42	5
March	1·44	5
April	1·66	1
May	1·35	–
June	1·26	–
July	1·33	–
August	1·39	5
September	1·25	–
October	1·37	5
November	1·32	–
December	1·43	5

[a] The significances were assessed assuming one degree of freedom per year, because the lag-one-year correlations of the variances for given calender months ranged between +0·15 and −0·07 and therefore can be neglected.

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. *Monthly* central England temperatures for 1901–1930, 1931–1960 and 1961–1990 had 95 per cent significant variance ratios (with unity as the null hypothesis) in only two out of 36 cases, each calendar month being compared between each period. Corresponding *daily* data had no such significant variance ratios (see also Figure 3). The data used to calculate b were chosen therefore by assuming that two 30-year sections of the *daily series* should have similar variance in a given calendar month if Manley's corresponding *monthly* 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 1848–1877 and 1878–1907, respectively. In all months, except October, there was no significant difference at the 5 per cent level between the variances of the monthly values; even the October variance ratio only just exceeded the 5 per cent F value. Accordingly, the variance σ_{3i}^2 of daily anomalies as defined above for 1878–1907 were divided separately for each calendar month i by corresponding variances σ_{1i}^2 for 1848–1877 to yield provisional values of b_i^2:

$$b_{1i}^2 = \sigma_{3i}^2 / \sigma_{1i}^2 \tag{7}$$

As b_{1i} is based on sample estimates of variance, its calendar monthly values do not vary smoothly through the year (Table IV). 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 (5) and (6) with $n=3$ to give

$$b_{2i}^2 = \frac{1}{n'} = \frac{1+2\bar{r}_i}{3} \tag{8}$$

The value of $\bar{r}_i$ was calculated for 1878–1907 from the values plotted in Figure 2. The b_{2i} value was found to change more smoothly through the year than b_{1i} (Table IV), mainly because the statistic $\bar{r}$ is less affected by geographically coherent sampling errors than are the variances in equation (7).

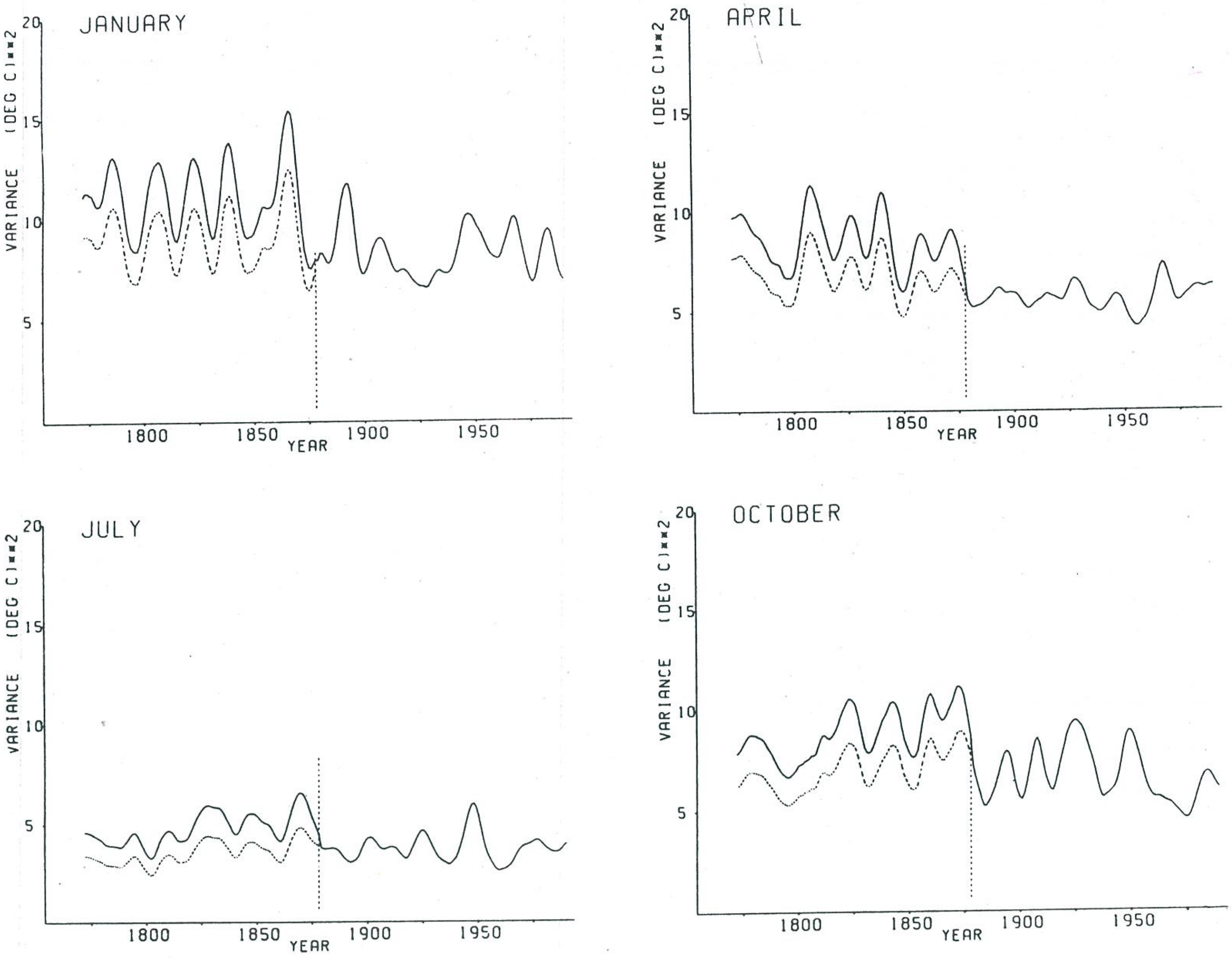

Figure 3. Low-pass filtered unadjusted (solid) and adjusted (dashed) variances of the daily series for January, April, July, and October, 1772–1990. A 25-term Craddock filter (Craddock, 1968) was used. Values are plotted at the centre of the filter interval. Variances were calculated using anomalies from the mean of each individual month and

Table IV. Scaling of variances: Calculation of scaling factors b

Month	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
January	0·90	0·89	1·08	0·96	0·90
February	0·89	0·87	1·09	0·96	0·90
March	0·91	0·87	1·09	0·96	0·90
April	0·84	0·86	1·10	0·95	0·89
May	0·81	0·84	1·12	0·94	0·88
June	0·90	0·76	1·19	0·92	0·86
July	0·85	0·73	1·22	0·91	0·86
August	0·82	0·78	1·17	0·92	0·86
September	0·98	0·85	1·11	0·95	0·89
October	0·82	0·86	1·10	0·95	0·89
November	0·90	0·85	1·11	0·95	0·89
December	0·93	0·88	1·09	0·96	0·90
Annual mean	0·88			0·94	

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:

$$b_i = \frac{\bar{b}_1}{\bar{b}_2} b_{2i} \tag{9}$$

Table IV 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 $\bar{b}_1/\bar{b}_2$, 0·94, could be interpreted to mean that earlier instrumental and observing practices 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 include automatically the effects of such changes, along with any climatic changes of $\bar{r}$, 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 for changes in the number of stations, systematic changes, if any, in the spatial scale of temperature anomalies, and systematic changes in instrumental practices between the two 30-year periods.

The value of b varies seasonally, being slightly smaller in summer, because the daily temperatures have a slightly lower spatial correlation then than in winter (Table IV). Thus the variance of the daily series up to 1877 has been reduced in summer by a greater proportion than in winter.

In Figure 3 we include, for contrast with the unadjusted variances, 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 per cent level for any calendar month.

As expected, the distributions of daily temperatures within individual months retain a similar shape after transformation but the more extreme values are closer to the monthly mean (figure 3 of Parker *et al.* (1991)).

3.6. *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 (see maps in Parker *et al.* (1991)). We therefore compared the temperatures at each stations, except Rothampsted, used since 1974 with those at nearby, relatively rural, sites over approximately the last 30 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 1). See Table I(b) for exact locations and altitudes.

(i) Rural stations for comparison with Malvern: Luddington, Lyonshall, Pershore, and Preston Wynne.
(ii) Stations for comparison with Squires Gate: Preston (not truly rural) and Slaidburn.
(iii) Station for comparison with Ringway: Macclesfield (not truly rural).

Digitized daily data for most of these stations begin in 1959, giving approximately 30 years' data from which to derive relative temperature trends. For (iii), data for the nearer station at Knutsford (Figure 1) 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).

Malvern warmed relative to Luddington considerably more strongly than relative to Preston Wynne, Lyonshall, and Pershore (Parker *et al.*, 1991), suggesting that these latter three stations also may 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.

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 (192 m 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.

Ringway warmed significantly relative to Macclesfield over the year as a whole (Parker *et al.*, 1991). The screen at Ringway is exposed to airport activities; nearby building work in the mid-1980s 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 10 km^2, 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, we constructed a parallel series of daily values, starting in January 1959, replacing Malvern with $\frac{1}{2}$(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 V.

The trends were strongest in April to July, equivalent to about 0·08°C per 10 years. In order to obtain a smooth seasonal cycle of urbanization 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°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 VI(a) shows the urbanization corrections. No corrections are applied until 1980 or later. At present all urbanization 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.

3.7. Total corrections

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

Table V. Linear trend regressions diagnosing urban warming in central England temperature

Month	Trend equation of A relative to B[a] (Y is year)	Trend correlation (r)	Smoothed trend coefficient (m)
January	$\Delta T=0{\cdot}33+0{\cdot}0075\,(Y-1973)$	0·67	0·0059
February	$\Delta T=0{\cdot}31+0{\cdot}0042\,(Y-1973)$	0·44	0·0051
March	$\Delta T=0{\cdot}32+0{\cdot}0043\,(Y-1973)$	0·41	0·0054
April	$\Delta T=0{\cdot}37+0{\cdot}0087\,(Y-1973)$	0·66	0·0071
May	$\Delta T=0{\cdot}36+0{\cdot}0068\,(Y-1973)$	0·54	0·0076
June	$\Delta T=0{\cdot}40+0{\cdot}0083\,(Y-1973)$	0·63	0·0081
July	$\Delta T=0{\cdot}43+0{\cdot}0093\,(Y-1973)$	0·72	0·0083
August	$\Delta T=0{\cdot}40+0{\cdot}0062\,(Y-1973)$	0·53	0·0066
September	$\Delta T=0{\cdot}37+0{\cdot}0048\,(Y-1973)$	0·44	0·0056
October	$\Delta T=0{\cdot}33+0{\cdot}0066\,(Y-1973)$	0·53	0·0059
November	$\Delta T=0{\cdot}36+0{\cdot}0054\,(Y-1973)$	0·54	0·0055
December	$\Delta T=0{\cdot}36+0{\cdot}0045\,(Y-1973)$	0·40	0·0055
Year	$\Delta T=0{\cdot}37+0{\cdot}0077\,(Y-1973)$	0·78	

[a] Series A is [Rothamsted + Malvern + $\frac{1}{2}$(Squires Gate + Ringway)]/3 and Series B is [Rothamsted + $\frac{1}{2}$(Luddington + Preston Wynne) + $\frac{1}{2}$(Squires Gate + Macclesfield)]/3

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, for example, from changes in instruments, in observing sites or surroundings of sites, and in times of measurement, 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 3.4), and why from 1974 we made

Table VI. (a) Corrections to central England temperature based on $\frac{1}{3}$[Rothamsted + Malvern + $\frac{1}{2}$(Ringway + Squires Gate)] to compensate for urban warming

Month	Correction −0·1°C	Correction −0·2°C
January	1982–1998	1999–2015
February	1983–2002	2003–2022
March	1983–2000	2001–2019
April	1981–1994	1995–2008
May	1980–1992	1993–2005
June	1980–1991	1992–2003
July	1980–1991	1992–2003
August	1981–1995	1996–2010
September	1982–1999	2000–2017
October	1982–1998	1999–2015
November	1983–2000	2001–2018
December	1983–2000	2001–2018
Year	1980–1992	1993–2005

Table VI. (b) Total corrections applied to central England temperatures for 1991. These corrections are the sum of the adjustments in Table II and the urbanization correction of −0·1°C from Table VI(a).

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

adjustments for urban warming trends (Section 3.6). However, we made only minor within-month compensations for non-meteorological effects (Appendix 1 of Parker *et al.* (1991)). 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.

4.1. 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-nineteenth century, followed by Stevenson screens in the 1870s. 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 VII gives 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 3.5) will have slightly reduced this excess day-to-day variability.

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

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum	−0·01	0·01	0·19	0·53	0·67	0·87	0·91	0·77	0·49	0·25	0·00	−0·08
Minimum	−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

4.2. *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 3.4). 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 for by its coastal location and its $\frac{1}{6}$ 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, south-south-west wind and pressure 988 mbar, implying that the centre of a depression passed north-west 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-north-west 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 a.m. 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 (1793–1835) reported a day's mean of 5·9°C at Holywell, a climatologically slightly milder location near the Dee estuary in North Wales, about 300 km north-west 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 south-east.

4.3. *Urbanization*

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 urbanization, on a monthly average, by being anchored to Manley's up to 1973 and by our own adjustments (section 3.6) 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 longwave radiation loss, as opposed to advection, dominates the heat balance. The parts of our series that use observations made in London, and in recent decades, Malvern and Ringway airport (near Manchester) (Table I and section 3.6), thus may 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.

4.4. *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. However, because our daily values up to 1877 are based on observations for a variety of hours rather than the standard $t_d = \frac{1}{2}$(24-h maximum + 24-h 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_d.

Table VIII 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 a.m and 3 p.m.; the Royal Society's 7 a.m. (8 a.m. in winter) and 2 p.m.) contributed to a >1·5°C root-mean-square difference in the 1770s and 1780s, 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.

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

Table VIII. Comparison of Hoy's and the Royal Society's record

Month		Correlation r between daily means	Root mean square difference of daily anomalies (relative to individual stations' monthly averages) (°C)
January	1774[a,b]	0·96	1·4
April	1774	0·86	1·4
July	1774	0·75	1·3
October	1774	0·52	2·5
January	1775	0·91	1·8
April	1775	0·93	1·6
July	1775	0·59	1·6
October	1775	0·83	2·1
January	1781	0·94	1·1
April	1781	0·86	1·6
July	1781[c]	0·70	1·7
January	1787[c]	0·94	1·2
April	1787	0·64	1·7
July	1787	0·83	1·5
October	1787	0·96	1·1
January	1795	0·95	1·1
April	1795	0·95	1·0
July	1795	0·84	1·3
October	1795	0·95	0·8
January	1800	0·97	0·8
April	1800	0·79	1·1
July	1800	0·82	1·1
October	1800	0·96	0·7
January	1805	0·95	0·9
April	1805	0·89	1·2
July	1805	0·82	1·1
October	1805	0·98	0·8

[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.

5. TABULATION OF MONTHLY SERIES WITH REVISED NORMALS

Table IX updates Manley's (1974) monthly CET series to 1991 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 Organization standard climatological period. The averages also are 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 1931–1960. These changes are placed in a long-term context by Figure 4, which shows low-pass filtered time-series from 1659, when Manley's series commenced, to the present. There are some substantial seasonally specific climatic variations on a variety of time-scales. These will be discussed elsewhere.

Because of day-to-day persistence, the standard deviation σ_m of the monthly values in 1961–1990 greatly exceeds $\sigma_d/n^{1/2}$, where σ_d, given in Table IX, is a standard deviation of daily values and n is the number of days in the month. The σ_d value 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. The σ_m value 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 IX 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 (Figure 1).

We show in Figure 5 sequences of daily CET for 1784, a cold year (mean 7·8°C) from Barker's record; 1816, the 'year without a summer' which may have resulted from the eruption of Tambora in 1815 but which was not universally cold (Stothers, 1984; Neumann, 1990); 1947, in which a severe winter was followed by a hot summer; and 1990, the warmest year in the period (mean 10·6°C). The plots are superimposed on the 1961–1990 daily mean CET to give a clear impression of anomalies. All the daily data are available on disk or microfiche on request.

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 a major building within a few hundred metres. If the stations are in areas where progressive urbanization 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 1 year, preferably longer.

ACKNOWLEDGEMENTS

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	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1998	5·2	7·2	7·9	7·7	13·1	14·2	15·5	15·9	14·9	10·6	6·2	5·5	10·3
1999	5·5	5·3	7·4	9·4	12·9	13·9	17·7	16·1	15·6	10·7	7·9	5·0	10·6
2000	4·9	6·3	7·6	7·8	12·1	15·1	15·5	16·6	14·7	10·3	7·0	5·8	10·3
2001	3·2	4·4	5·2	7·1	12·6	14·3	17·2	16·8	13·4	13·3	7·5	3·6	9·9
2002	5·5	7·0	7·6	9·3	11·8	14·4	16·0	17·0	14·4	10·1	8·5	5·7	10·6
2003	4·5	3·9	7·5	9·6	12·1								

Table IX. Monthly and annual central England temperatures (°C), 1974–1991, compensated for urban warming. These extend Manley (1974)'s series

	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	7·9	7·9	10·8	12·1	17·3	17·1	14.7	10.2	6.8	4.7	9.5
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 σ_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 σ_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	

1992	3·7	5·4	7·5	8·7	13·6	15·7	16·2	15·3	13·4	7·8	7·4	3·6	9·9
1993	5·9	4·6	6·7	9·5	11·4	15·0	15·2	14·6	12·4	8·5	4·6	5·5	9·5
1994	5·3	3·2	7·7	8·1	10·7	14·5	18·0	16·0	12·7	10·2	10·1	6·4	10·2

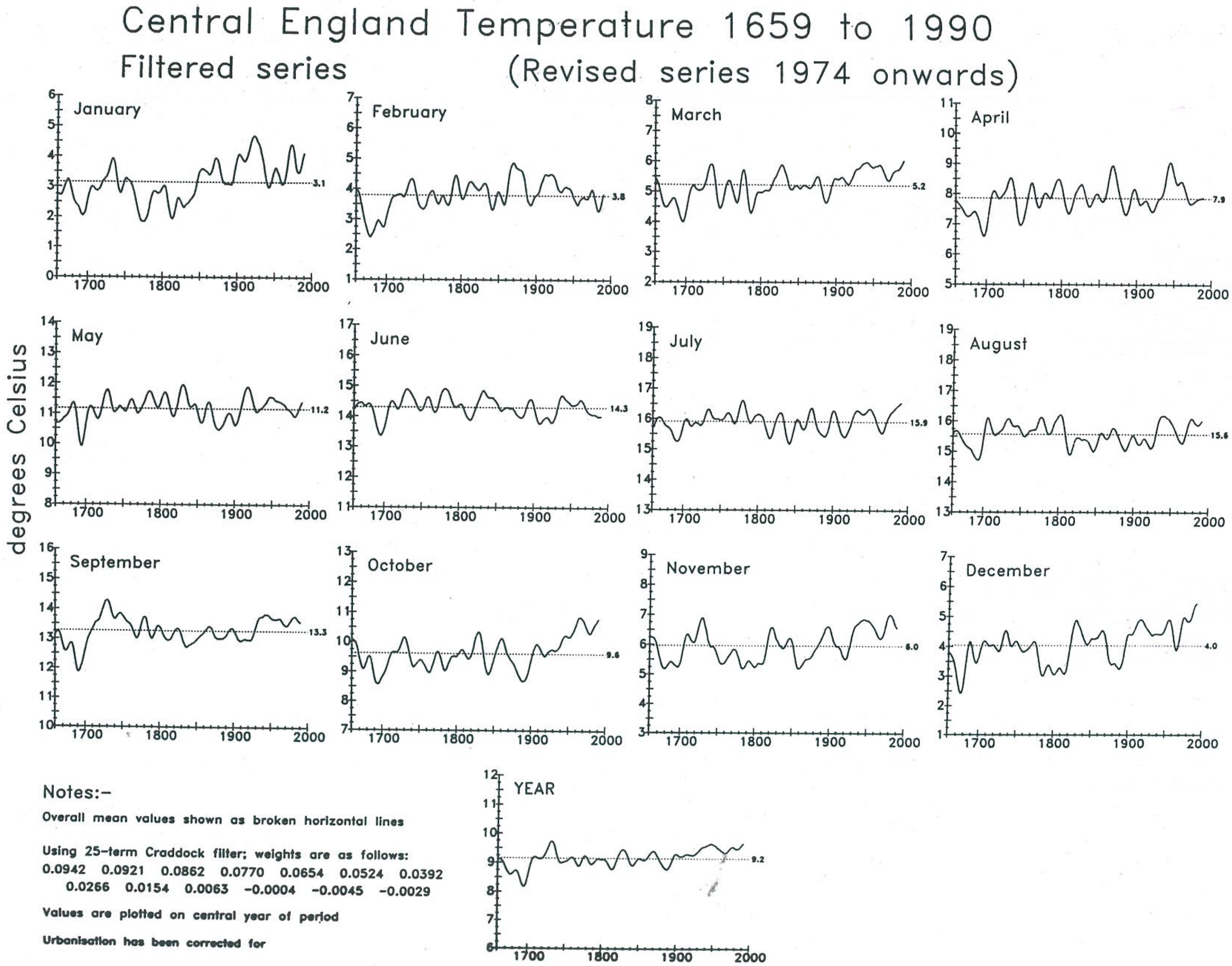

Figure 4. Low-pass filtered monthly central England temperature, 1659–1990. A 25-term Craddock filter (Craddock, 1968) was used. Values are plotted at the centre of the filter interval. Dotted horizontal lines represent the

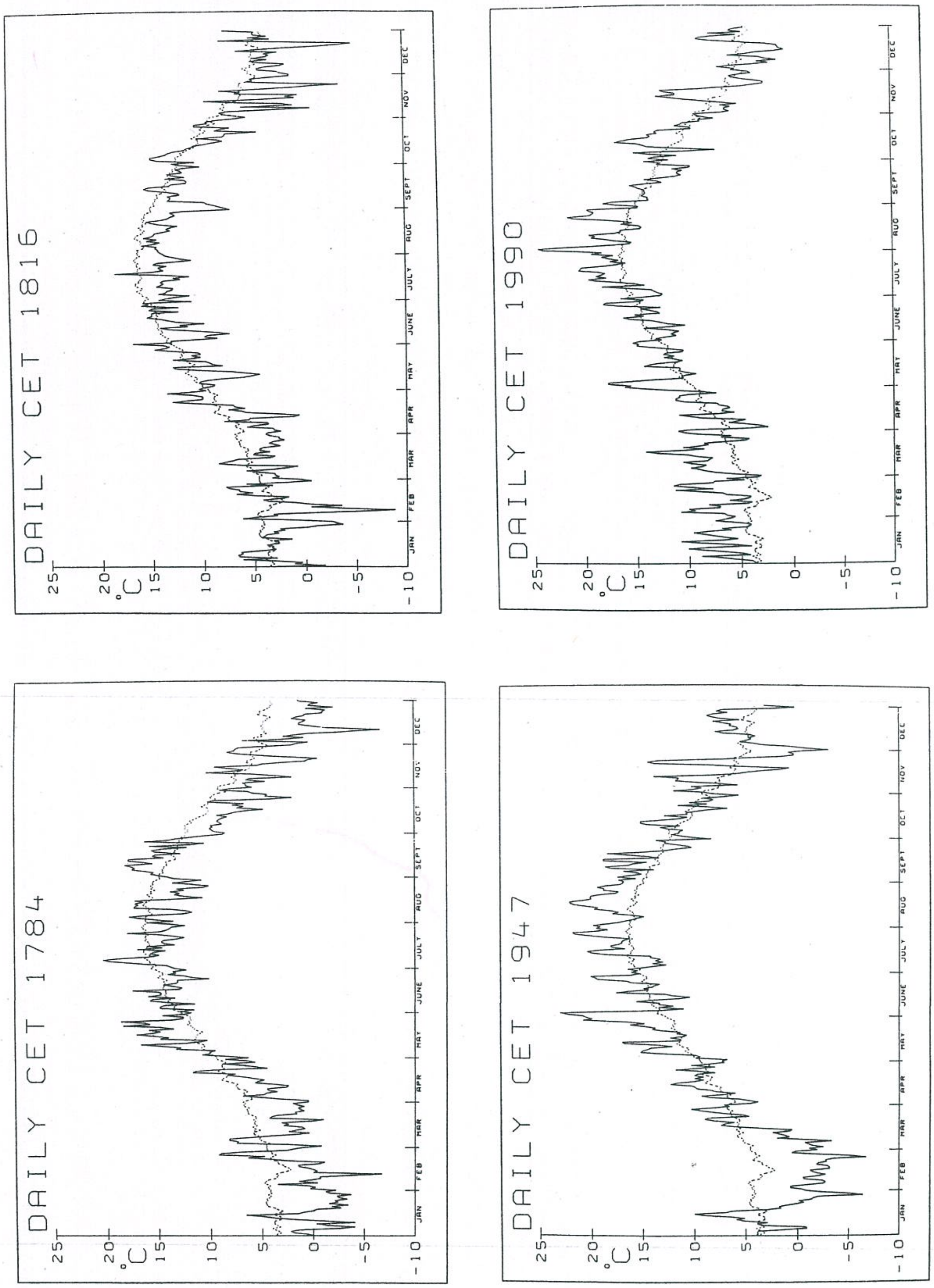

Figure 5. Daily central England temperatures for 1784, 1816, 1947 and 1990. The smoother (dashed) curve is, in each case, the 1961–1990 climatology

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

APPENDIX: SOME UNCERTAINTIES IN THE CORRECTED DAILY CET SERIES

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 AI. 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 of Parker *et al.* (1991), for 1787 onwards, but not for 1777–1781, which pre-dates 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 1777–1781 in Table AI are likely to be representative of levels of uncertainties in our CET series for 1774–1776, when unamended Royal Society data were used, whereas the values for 1787–1789 may be more representative of uncertainties in our CET series for 1789–1799. The uncertainties are a combination of genuine errors in the data, and meteorologically induced scatter $\sigma_g=(\Sigma(\mathrm{LTA}-\mathrm{CETA})^2/N)^{1/2}$ resulting from the location of London on the periphery of 'central England'. Here, LTA and CETA are daily temperature anomalies (relative to individual months' means) for London and CET, and N is number of data. If the variances of daily LTA and CETA are equal, then

$$\sigma_g=2^{1/2}\sigma_d(1-r_g)^{1/2} \tag{A1}$$

Table AI. (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

	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	—	—	—	—	—	—

Table AI. (b) Correlations corresponding to (a). The Royal Society data for 1787–1789 had been amended as described in Appendix 1 of Parker *et al.* (1991)

	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	—	—	—	—	—	—

where σ_d is the corrected standard deviation of daily CETA. The value of σ_d ranges from 2·9°C in winter to 1·8°C in summer (Figure 3 and Table IX). Variable r_g is the true correlation between daily temperatures in London and in central England calculated using anomalies from individual months' averages. The value of r_g is estimated to range from 0·93 in winter to 0·86 in summer, using correlations r_{150} between daily temperatures at stations 150 km apart. These values of r_g have been 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 of Parker *et al.* (1991)), with r_0 estimated graphically from plots of correlation versus distance. 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 AI. The use of Hoy's data for 1772–1773 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 section 4·4 and Table VIII, 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 I(a)), 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 I and Figure 1).

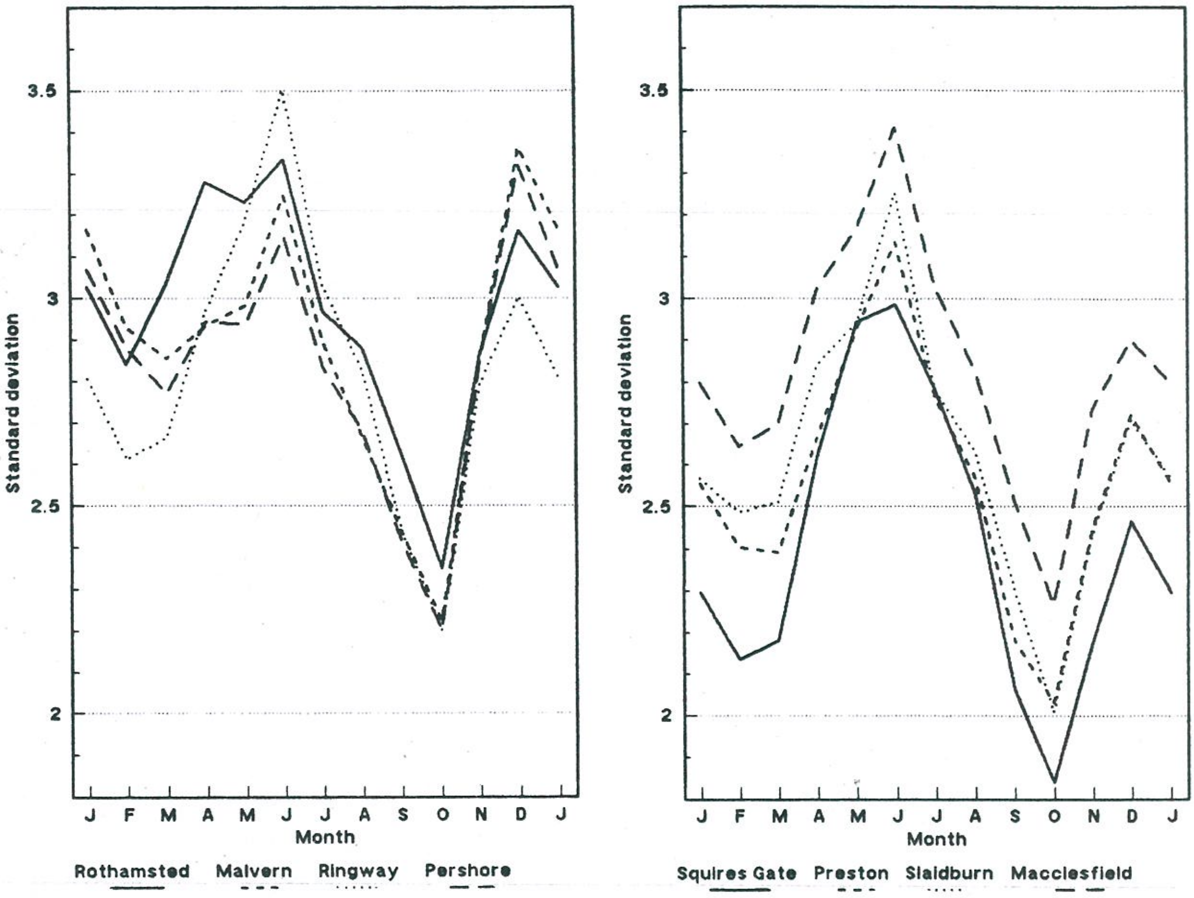

Figure A1. Standard deviation of daily maximum temperatures, 1961–1990. Values are calculated using anomalies from (daily mean climatology for 1961–1990 + individual months' anomalies)

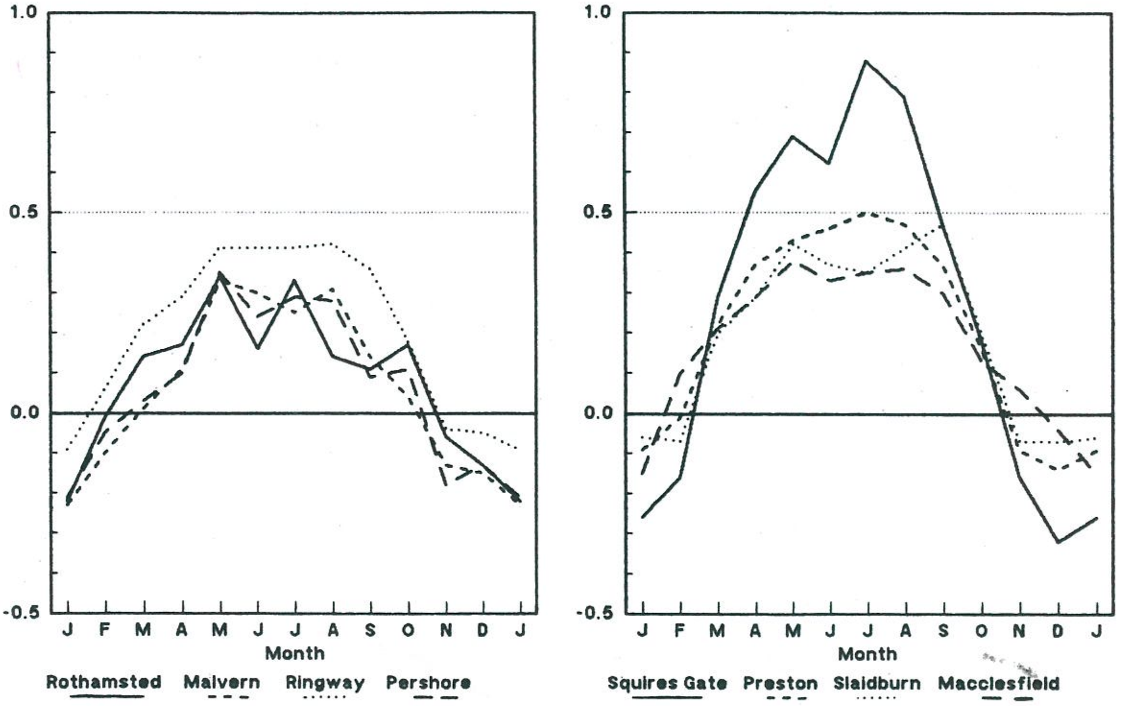

Figure A2. Skewness of daily maximum temperatures, 1961–1990

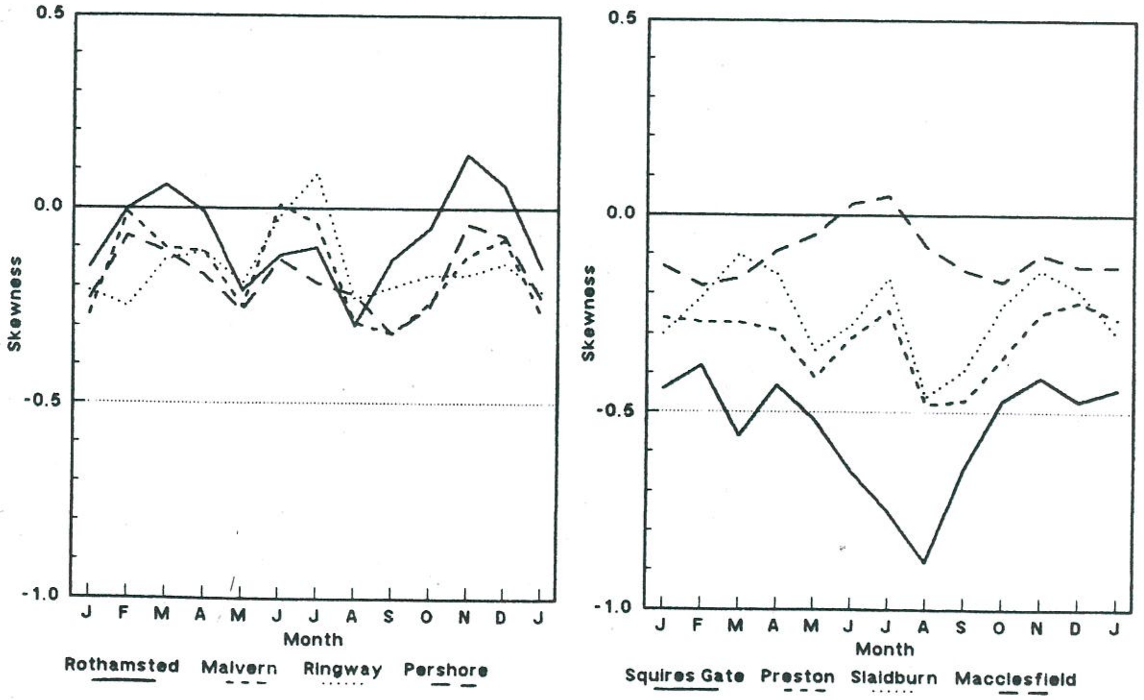

Figure A3. Skewness of daily minimum temperatures, 1961–1990

Extent of climatic heterogeneity of the 'central England' area

Parker *et al.* (1991) confirmed 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 by Parker *et al.* (1991) to be smaller at Squires Gate than at Ringway or Stonyhurst. Figure A1 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 1961–1990, and are calculated by averaging individual months' variances. Other Lancashire stations' standard deviations of maximum temperature also are smaller than those of Ringway, though not as small as those of Squires Gate (Figure A1). This is mainly because Lancashire is more maritime than the Midlands.

Corresponding standard deviations of daily minimum temperatures (not shown) show greater variability at Squires Gate than at Ringway, Squires Gate being a frost-prone location. There are no systematic differences between Lancashire and the Midlands.

Figure A2 shows greater positive skewness in daily maxima in summer at the north-western 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 south-easterly (offshore) winds (e.g. 33°C at Squires Gate, 2 August 1990).

Figure A3 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.

REFERENCES

Barker, T. 1777–1789. Meteorological Register made at Lyndon Hall, Rutland, 371 pp. Unpublished manuscript: available in National Meteorological Library and Archive, Bracknell, UK.

Barker, T. 1796. 'Abstract of a Register of the Barometer, Thermometer and Rain at Lyndon in Rutland, 1795. Communicated by Thomas White, Esq. FRS', *Philos. Trans. R. 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*.

Craddock, J. M. 1968. *Statistics in the Computer Age*, English University Press, London, 214 pp.

Cramer, H. 1946. *Mathematical Methods of Statistics*, Princeton University Press, Princeton, N.J. USA., 575 pp.

Draper, N. R. and Smith, H. 1966. *Applied Regression Analysis*, Wiley, New York, 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', *Q.J.R. Meteorol. Soc.*, **17**, 240–249.

Giles, B. D. 1991. 'Late eighteenth century temperatures in Birmingham, England', *J. Meteorol.*, **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 Syon House. Unpublished manuscript: available in National Meteorological Library and Archive, Bracknell, UK.

Hughes, T. 1771–1813. Meteorological records made at Stroud, Gloucestershire. Unpublished manuscript: available in National Meteorological Library and Archive, Bracknell, UK.

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: available in National Meteorological Library and Archive, Bracknell, UK).

Johnson, M. J. 1842–1855. *Astronomical Observations made at the Radcliffe Observatory, Oxford, in the Years 1840–1853*. Published by J. H. Parker, Oxford, by order of the Radcliffe Trustees.

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, Rutland Record Society, Oakham, xiv + 217 pp.

Knox-Shaw, H. and Balk, J. G. 1932. *Radcliffe Observations*, 55, Appendix. Oxford. Oxford University Press. Published by Order of the Radcliffe Trustees.

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

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

Lamb, H. H. and Johnson, A. I. 1966. 'Secular variations of the atmospheric circulation since 1750', *Meteorol. Office Geophys. Mem.*, **11** 125 pp.

Manley, G. 1946. 'Temperature trend in Lancashire, 1753–1945', *Q.J.R. Meteorol. Soc.*, **72,** 1–31.

Manley, G. 1952. 'Thomas Barker's meteorological journals, 1748–1763 and 1777–1789', *Q.J.R. Meteorol. Soc.*, **78,** 255–259.

Manley, G. 1953. 'The mean temperature of Central England, 1698 to 1952', *Q.J.R. Meteorol. Soc.*, **79,** 242–261.

Manley, G. 1960. *Bibliography of the principal sources of daily meteorological observations for the London area.* (Unpublished: available i National Meteorological Library and Archive, Bracknell, UK.)

Manley, G. 1964. *London Weather Diary.* (Unpublished manuscript: available in National Meteorological Library and Archiv Bracknell, UK.)

Manley, G. 1974. 'Central England Temperatures: monthly means 1659 to 1973', *Q.J.R. 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 a Camden Square, London', *Q.J.R. Meteorol. Soc.*, **50,** 209–226 and 363.

Mawley, E. 1897. 'Shade temperature', *Q.J.R. Meteorol. Soc.*, **23,** 69–87.

Meteorological Office 1874. *Hourly readings from the self-recording instruments at the seven observatories in connection with th Meteorological Office*, 1874. Lithograph copy of unpublished manuscript held in National Meteorological Library and Archiv Bracknell, UK

Mitchell, J. M., Dzerdeevskii, B., Flohn, H., Hofmeyr, W. L., Lamb, H. H., Rao, K. N. and Wallén, C. C. 1966. 'Climate change', *WM Technical Note No. 79*, WMO No. 195, TP 100, World Meteorological Organization, Geneva, 79 pp.

Neumann, J. 1990. 'The 1810s in the Baltic region, 1816 in particular: air temperatures, grain supply and mortality', *Climatic Change*, **17** 97–120.

Oke, T. R. 1982. 'The energetic basis of the urban heat island', *Q.J.R. Meteorol. Soc.*, **108,** 1–24.

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

Parker, D. E., Legg, T. P. and Folland, C. K. 1991. *A New Daily Central England Temperature Series, 1772–1991,* Meteorological Offic Climate Research Technical Note CRTN11. (Unpublished: available in National Meteorological Library and Archive, Bracknell, UK.

Pennant, D. 1793–1835. Meteorological record made at Holywell, Flintshire. Unpublished manuscript: available in Nationa Meteorological Library and Archive, Bracknell, UK.

Perry, S. J. 1872. *Results of Meteorological and Magnetical Observations at Stonyhurst College Observatory, 1871*, J. Robinson, Preston pp. 34–37.

Royal Society 1774–1780, 1787–1843. 'Daily weather observations, Royal Society, London', Published in *Philos. Trans. Roy. Soc London.*

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 ne monthly average values 1974 to 1985*. Synoptic Climatology Branch Memo. No. 107. (Unpublished: available in Nationa Meteorological Library and Archive, Bracknell, UK.)

Stothers, R. B. 1984. 'The great Tambora eruption in 1815 and its aftermath', *Science*, **224,** 1191–1198.

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, CO, 302 pp.