

Uncertainties in the Central England Temperature series 1878-2003 and some changes to the maximum and minimum series

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Abstract

We assess the random and systematic errors affecting the Central England Temperature (CET) record since 1878 on daily, monthly and annual time-scales. The largest contribution to the uncertainty in CET on these time-scales arises from the areal sampling error. For annual CET the thermometer calibration error is comparable, whereas the random thermometer precision and screen errors are much smaller. For the monthly series the thermometer calibration error also comes second to the areal sampling error; the random precision and screen errors, while still much smaller, are now similar in magnitude to the uncertainties arising from climatic and microclimatic offsets in temperature between observing stations. For the daily series the random precision and screen errors are next most important after the areal sampling error but are an order of magnitude smaller. As expected, annual CETs are least uncertain, with daily CETs being most uncertain. We find some heterogeneities in the published series of Central England maximum and minimum temperatures, and propose systematic adjustments of up to $\pm 0.2^{\circ}\text{C}$ to the summer values up to 1921 and up to $\pm 0.1^{\circ}\text{C}$ to the values since 1980. These adjustments are of opposite sign in maximum and minimum temperature so they do not affect mean CET, but they yield a more homogeneous series of diurnal temperature range.

1. Introduction

Quantification of uncertainties in climatic data records is a prerequisite for the interpretation of trends and extreme values. Here we estimate the uncertainties in the most recent and reliable 125 years of the longest instrumental record in the world: Central England Temperature (CET). This record represents a roughly triangular area of England extending from the Lancashire plains in the north, to London in the south east and Herefordshire in the south west. CET is a composite series using data from a succession of observing sites that have been carefully adjusted to remove bias and inhomogeneities (Manley, 1953, 1974, Parker et al., 1992). We include mean, maximum and minimum CET (CET_{mean} , CET_{max} and CET_{min}) on daily, monthly and annual time-scales in our analysis of uncertainties. Although CET_{max} and CET_{min} are constrained to have an average equal to CET_{mean} , as published by Manley (1974), their uncertainties do not bear an exact

relationship to the uncertainties in CET_{mean} , because different observing stations were used (Table 1).

Despite the careful adjustments made whenever contributing stations have changed, several types of uncertainty continue to affect the CET series. These include random and systematic measurement errors, uncertainties due to climatic and microclimatic offsets in temperature between observing stations, including urban warming, and areal sampling errors. We assume that all these uncertainties are independent, so that the error variances can be summed. Although the monthly and daily mean series extend back to 1659 and 1772 respectively, we only assess the daily to annual series since 1878. Before 1878, the uncertainties are more difficult to estimate, and certainly increase, owing to the use of different equipment (e.g. housing thermometers in Glaisher stands, north facing walls or in unheated north facing rooms), the splicing together of temperature records from many different observers, the use of only a single site at any one time, and, for the earliest part of the series, the use of diaries and anecdotal evidence to corroborate temperature records.

We estimate the various types of uncertainty in Sections 2, 3 and 4. In Section 5 we combine the individual uncertainties into total uncertainties on daily, monthly, seasonal and annual scales. In Section 6 we propose minor but systematic adjustments to the series of maximum and minimum temperatures, owing to biases not previously taken into account. Although these adjustments do not affect mean temperature, they have a marked effect on the homogeneity of diurnal temperature range. Section 7 concludes.

Table 1. Stations used to calculate the CET series since 1878

Dates	Description of temperature series	Stations: monthly CET _{mean} series	Stations: daily CET _{mean} series	Stations: daily CET _{max} and CET _{min} series
1878-1930	Monthly (Manley, 1974) and daily mean (Parker et al., 1992) series calculated using at least three stations within the CET region. The daily values are not always calculated using the same stations as the monthly values.	0.5*(Lancashire + Oxford). Lancashire is derived from 4-7 stations in the North West of England reduced to a common standard (Manley, 1946) Oxford is the corrected Radcliffe Observatory monthly mean (Knox-Shaw and Balk, 1932)	Stonyhurst, Cambridge Botanical Gardens, Ross-on-Wye	Stonyhurst, Rothamsted, Ross-on-Wye
1931-1958			Stonyhurst, Rothamsted, Ross-on-Wye	
1959-1973			Rothamsted, Malvern, 0.5*(Squires Gate + Ringway)	
1974-2003	Monthly and daily series calculated using at least three stations within the CET region. All series are calculated using data from the same stations (Parker et al., 1992).	Rothamsted, Malvern, 0.5*(Squires Gate + Ringway)		

2. Measurement errors

Measurement errors include thermometer calibration errors, errors from reading and recording temperatures (precision errors), and errors arising from the method of housing the thermometers.

2.1. Calibration errors

Current Met Office practice is to calibrate instruments on receipt from the manufacturer and at intervals after deployment with the aim of ensuring that the accuracy of the measurement is better than 0.2°C (Section 1.4.2 of MIDAS Data Users' Guide available at <http://www01/opr/mdataguide.html#1.6>). Calibration errors in the late 19th century cited by the Met Office (1879, 1880) have a standard deviation of about 0.2°C in magnitude. So we assume a single thermometer standard error of 0.15°C throughout and assume the errors are random between thermometers, yielding a single thermometer error variance v_{cal} of 0.0225°C². For CET_{max} and CET_{min} , this variance is divided by three (0.0075°C²) when 3 stations are used to calculate CET. When 4 daily stations are used from 1959 onwards, two stations (Squires Gate and Ringway) are averaged first (Table 1) so the calibration error variance of this combination is 0.0112°C² for maximum or minimum temperature. For CET_{max} and CET_{min} the calibration error variance becomes $\{(0.0112+0.0225+0.0225)/3\}/3$ (Table 2). For CET_{mean} , the resulting calibration error variances are further halved because $CET_{mean} = 0.5 (CET_{max} + CET_{min})$. These estimates are expressed as standard errors in Table 2.

Table 2. Calibration standard errors e_{cal} (°C)

	Number of stations	Calibration standard error for CET_{max} and CET_{min}	Calibration standard error for CET_{mean}
1878-1958	3	0.087	0.061
1959 on	4	0.079	0.056

2.2. Reading precision error

For much of the CET record, temperatures were observed to the nearest degree Fahrenheit, but temperatures at Squires Gate and Ringway have been observed to the nearest 0.1 degree Celsius since 1961 and at Rothamsted and Malvern since 1971. When observations are made to the nearest °F, the mean square precision error of a given observation ("precision error variance") is the average of x^2 over the range $x=-0.5$ to $x=+0.5$ °F, i.e. 0.083°F² which is 0.026°C². With a precision of 0.1°C, the precision error variance is 0.00083°C². For either CET_{max} or CET_{min} , the precision error variance is divided by three when 3 stations are used to calculate CET. When 4 stations are used from 1959 onwards, the precision error variance of

CET_{\max} or CET_{\min} is calculated as in Section 2.1. For CET_{mean} , the resulting precision error variances are halved as in Section 2.1. Daily precision standard errors in CET are summarized in Table 3.

Table 3. Precision standard errors e_p (°C)

	Number of Fahrenheit thermometers	Number of Celsius thermometers	Precision standard error for daily CET_{\max} and CET_{\min}	Precision standard error for daily CET_{mean}
1878-1958	3	0	0.093	0.066
1959-1960	4	0	0.085	0.060
1961-1970	2	2	0.076	0.054
1971 on	0	4	0.015	0.011

2.3. Random screen error

For thermometers housed in Stevenson screens, the type and condition of the screen affects the accuracy of the measured value. A comparison of temperatures taken from digital thermometers housed in various screens in Sweden (Andersson and Mattisson, 1991) revealed much bigger extreme differences between the screen thermometers and an aspirated thermometer (the 'true' value) than those given in the World Meteorological Organization (WMO) Guide to Meteorological Instruments and Methods of Observation (WMO, 1983). However, the extreme differences generally occurred when the screen lagged the rapidly changing record of the aspirated thermometer just after sunrise and at sunset, and not at the times of maximum and minimum temperature. The mean differences for T_{\max} and T_{\min} were about -0.13 and 0.2°C indicating that on average the assessed diurnal range within the screen tends to be smaller than in reality. The overall accuracy of the temperature measurements (digital thermometers, circuitry and logging) was estimated to be $\pm 0.04^{\circ}\text{C}$. Andersson and Mattisson calculated RMS errors of 0.26°C , 0.31°C and 0.05°C for daily T_{\max} , T_{\min} and the arithmetic mean daily temperature calculated from temperatures recorded every minute (not $0.5 \cdot (T_{\max} + T_{\min})$) for a large Stevenson screen in good condition. The differences were dependent upon the prevailing weather conditions, with the largest differences occurring on days with no cloud cover and/or very light winds. We use Andersson and Mattisson's RMS errors for T_{\max} and T_{\min} , yielding screen error variances e_{scr}^2 of $0.26^2 = 0.068^{\circ}\text{C}^2$ and $0.31^2 = 0.096^{\circ}\text{C}^2$ respectively. However because our T_{mean} data are $0.5 \cdot (T_{\max} + T_{\min})$ we average the error variances accorded to T_{\max} and T_{\min} and divide the result by 2. For CET_{\max} , CET_{mean} and CET_{\min} we divide the variances further by 3 for 1878-1958 when 3 stations were used, and by $3/\{(0.5+1+1)/3\}$ thereafter to allow for the way the 4 stations were averaged to form CET.

2.4. Combining the measurement errors

Table 4 combines the random precision and screen errors, $e_{mr}^2 = e_p^2 + e_{scr}^2$, for daily CET, but expresses the results in terms of standard error.

Table 4. Combined precision and screen standard errors e_{mr} ($^{\circ}\text{C}$)

	1878-1958	1959-1960	1961-1970	1971 on
Daily CET_{mean}	0.13	0.12	0.12	0.11
Daily CET_{\max}	0.18	0.16	0.16	0.14
Daily CET_{\min}	0.20	0.18	0.18	0.16

Monthly and annual values of uncertainty due to precision and screen errors can be determined by dividing e_{mr}^2 by the number of days in the month or year. However calibration errors are systematic because thermometer inspections are made only every few years. So the monthly and annual calibration errors must not be scaled down.

3. Uncertainties arising from climatic and microclimatic offsets in temperature between observing stations

Owing to the availability of additional digitized daily data, Parker et al (1992) used different stations for daily CET_{mean} than Manley (1974) had used for monthly CET (Table 1). Because of these differences in stations, the areal average temperature at Parker et al's stations differed slightly from Manley's values. So Parker et al. (1992) adjusted their daily CET_{mean} values to make their monthly averages consistent with Manley (1974). For similar reasons, when we created daily CET_{max} and CET_{min} series, again using a different sequence of stations (Table 1), we adjusted the values so that each day's average of CET_{max} and CET_{min} equaled that day's adjusted CET_{mean} and was therefore also compatible with Manley (1974). In this section, we estimate the uncertainties arising from these adjustments. We also estimate the uncertainties stemming from the adjustments applied by Parker et al. (1992) to the CET_{mean} data from 1980 onward to compensate for urban warming. These adjustments differed between calendar months and have been increased in magnitude to reach -0.2°C in all months by 2003. In Section 6 we consider the biases arising from the application of double these adjustments to CET_{min} and no urban adjustment to CET_{max} .

3.1. Adjustment of daily CET_{mean} , CET_{max} and CET_{min} values to make them compatible with Manley's monthly values

The adjustments applied to daily CET_{mean} account for differences in station position, instruments and time of day of observation between the Manley (1974) data and the Parker et al. (1992) data. The adjustments were calculated by Parker et al. (1992) for individual months from 1772 to 1973, the period covered by both Manley's monthly series and Parker et al.'s daily series. The adjustments for 1878 to 1973 are tabulated in Parker et al. (1991). Since 1974, the CET for each month has been adjusted by the mean adjustment for that month calculated using available Rothamsted, Malvern, Squires Gate and Ringway data over the years 1944, 1948, 1949 and 1959-73 (Parker et al., 1992). This was done before the urban warming adjustments were applied.

Figure 1 shows the annual mean adjustments to daily CET_{mean} for 1878 to 1973. These annual adjustments are the mean of the constituent monthly adjustments. From 1878 to 1930 the annual adjustments are almost random about a mean adjustment slightly below zero, with a slight rising trend between 1900 and 1930. In 1931, when Cambridge was replaced by the colder Rothamsted site in the daily series the adjustments increase significantly, but then decline with a trend of about $-0.018^{\circ}\text{C}/\text{year}$, implying warming in the sites then used for daily CET_{mean} (Stonyhurst, Rothamsted and Ross-on-Wye) relative to those used by Manley. Manley used the average temperature in Lancashire and the temperature record of Radcliffe Observatory in Oxford to calculate the monthly CET from 1815 to 1973. The Lancashire series was composed of between 4 and 7 stations in the north west of England, reduced to a common standard (Manley, 1946); the Oxford series was an adjusted monthly mean though the adjustment was smaller

than 0.1°C (Knox-Shaw and Balk, 1932). The scatter and slight trend in Parker et al's adjustments before 1931 could be due to changes in the stations used in the Lancashire series. Manley (1974) noted that after 1935 the Oxford series exhibits a warming trend relative to nearby rural stations, indicating that it may have been suffering the effects of urbanisation (Manley, 1953); Manley began to correct for urbanisation after 1960. There were also slight changes in the Oxford Radcliffe Observatory site in this period. The negative trend after 1930 in Figure 1 implies, however, relative cooling, not warming, at Manley's sites overall.

We estimated the uncertainty variance e_o^2 in CET_{mean} arising from the Parker et al. (1992) adjustments separately for each of the three periods in the Manley (1974) series having different sets of stations in the daily CET series: 1878-1930, 1931-1958 and 1959-73. This was done separately for annual values and for each calendar month. We assume that e_o^2 is reflected by the interannual variability of the adjustments and not by their mean value or their slowly varying trends which are taken to reflect real, consistent or slowly varying biases between stations. So we detrended the adjustments when they showed significant trends (i.e. in 1931-1958 and 1959-1973 but not 1878-1930: Figure 1), before using their standard errors as estimates of e_o^2 . The error variances for the fixed adjustments that have been in use since 1974 were calculated from the monthly adjustments for 1959-1973. This was done without detrending the adjustments for 1959-1973 because our fixed adjustments are based on a similar multi-year average (see above). Table 5 includes our estimates of monthly and annual standard error e_o .

We estimated the uncertainties due to the adjustments to daily CET_{max} and CET_{min} data in a similar way. These adjustments were calculated on a daily basis as $adj = CET_{mean} - (CET_{max} + CET_{min})/2$, and were added equally to CET_{max} and CET_{min} . Figure 2 shows the annual averages of the adjustments that were applied. The adjustments after 1930 are the same as those in Figure 1, because the same stations were used for daily CET_{max} and CET_{min} as for CET_{mean} . Table 5 includes the standard errors for the adjustments up to 1930 when the stations used for daily CET_{max} and CET_{min} differed from those used for daily CET_{mean} . The monthly error variances corresponding to all the values of e_o in Table 5 are also added to the error variances of the daily data within respective calendar months.

Table 5. Standard errors e_o (*thousandths* °C) of monthly adjustments applied to daily CET_{mean} , CET_{max} and CET_{min} to reproduce Manley's monthly values.

	J	F	M	A	M	J	J	A	S	O	N	D	Ann
1878-1930: CET_{mean}	27	29	24	21	22	24	23	23	20	19	22	21	10
1878-1930: $CET_{max, min}$	29	27	24	20	18	20	23	23	19	18	22	23	9
1931-1958: all daily CET	18	27	17	21	21	21	16	24	29	21	20	29	9
1959-1973: all daily CET	45	25	31	25	19	43	26	29	26	29	33	46	14
1974 +: all daily CET	45	38	43	34	29	46	27	29	27	37	49	48	22

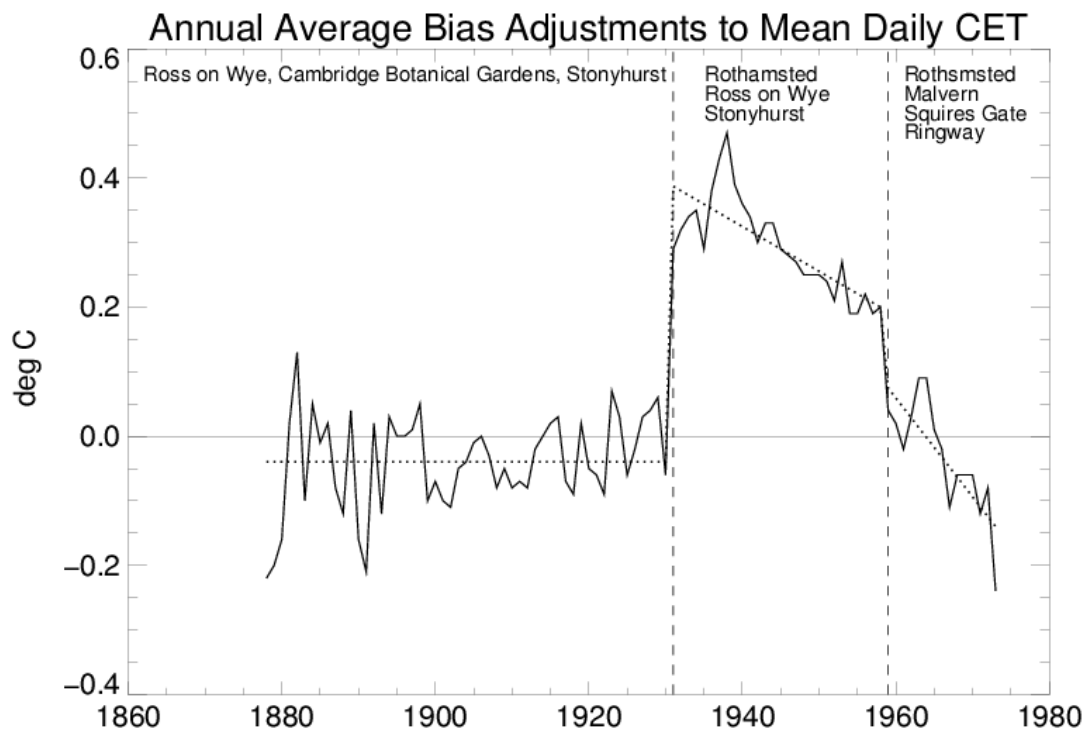


Figure 1. Annual average adjustments applied to the daily CET_{mean} series to make it compatible with Manley's monthly series over 1878 to 1973 as in Parker et al (1992). The dotted line indicates the mean adjustment (1878-1930) or the trends in adjustments (1931 onwards) and the vertical dashed lines delimit the periods when different groups of stations were used to calculate the daily series.

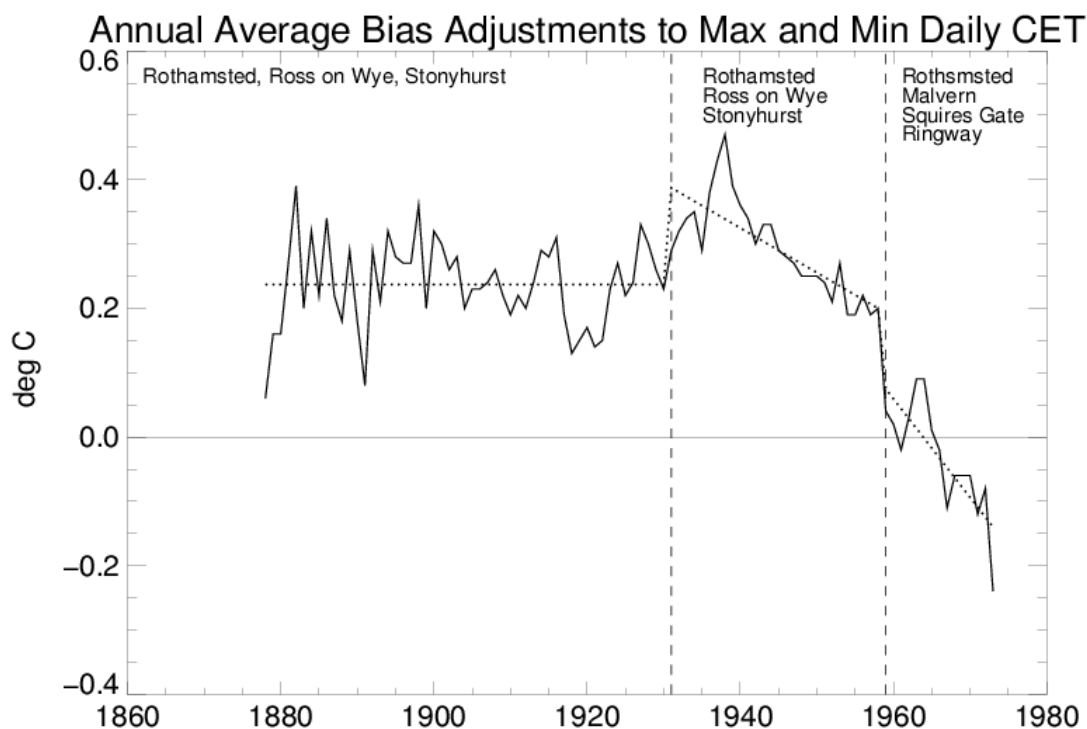


Figure 2. As Figure 1 but for the daily CET_{max} and CET_{min} series.

3.2. Correction of urbanisation bias since 1974

From 1960 to 1973 Manley subtracted 0.1-0.2°F from the Oxford Radcliffe Observatory mean temperatures in most months before calculating CET to account for urbanisation effects at the Radcliffe Observatory site during that period (Manley, 1974). From 1974 onwards Legg (1989) calculated urbanisation adjustments for mean CET by comparing the monthly CET series with a 'rural' version over the period 1959-86. The separate urbanisation adjustments for each calendar month were expressed as trends and linearly extrapolated to reach -0.2°C in all calendar months by 2003 (Parker et al., 1992). When the CET_{max} and CET_{min} series were calculated, Legg's urbanisation adjustments were doubled for CET_{min} but no urbanisation adjustments were made to the CET_{max} series because urbanisation is known to affect minima much more than maxima (Johnson et al., 1991). To investigate the uncertainty associated with adjustments for urbanisation, we recreated the rural T_{mean} series over the period 1959-1986 (unfortunately one of the constituent stations, Luddington, closed in 1986, so it was not possible to extend the rural series further). Rural T_{max} and T_{min} series were also calculated over the same period. To assess the reliability of the urbanisation corrections, the rural series (T_{mean} , T_{max} and T_{min}) were compared with the corresponding CET series before and after 1974, and a t-test performed for each month. No months in any series showed a significant difference at the 5% significance level, indicating that the urbanisation adjustments for each of CET_{mean} , CET_{max} and CET_{min} are reasonable.

The monthly values were then grouped separately for the CET_{mean} , CET_{max} and CET_{min} series as follows: a) all months during 1959-73 (180 months); b) months that had zero urbanisation adjustment applied to the CET_{mean} series during 1974-1986 (92 months); and c) months that had -0.1°C urbanisation adjustments applied to the CET_{mean} series during 1974-86 (64 months). The error variance (standard error squared) of the differences (CET-rural) was then calculated for each group. The excess error variances in b) and c) over that in a) were assumed to represent the uncertainty e_{ou}^2 arising from the urbanisation correction, including the choice of making no correction.

For CET_{mean} , the standard errors for each group were 0.015, 0.020 and 0.030°C respectively. Subtracting variances shows that after 1974 there is additional uncertainty ($=e_{ou}$) of 0.013°C for all unadjusted months and 0.025°C for all months adjusted by -0.1°C. The increase in uncertainty with the size of the urban warming correction is expected. This is because the variability of the magnitude of the urban heat island is expected to increase as its mean value increases, because it remains near-zero in cloudy and windy conditions irrespective of the mean correction. So for 1992 onwards, when some months had an urbanisation adjustment to CET_{mean} of -0.2°C, the increase in the value of e_{ou}^2 is assumed to be proportional to the squared size of the urbanisation adjustment, giving an estimated additional uncertainty of 0.046°C for those months. The values in Table 6 are also used in calculating the error bars on the daily data.

Table 6. Standard errors e_{ou} (°C) due to urbanisation adjustment. Additional working values are shown in italics.

	1959-73 Standard error	All months with zero adjustment (estimated from sample for 1974- 86)		All months with -0.1°C adjustment (estimated from sample for 1974- 86)		All months with -0.2°C adjustment; (derived from sample for 1974- 86)
		Standard error	e_{ou}	Standard error	e_{ou}	
	A	B	$C=(B^2-A^2)^{0.5}$	D	$E=(D^2-A^2)^{0.5}$	$F=(C^2+4(E^2-C^2))^{0.5}$
CET _{mean}	<i>0.015</i>	<i>0.020</i>	<i>0.013</i>	<i>0.030</i>	<i>0.025</i>	<i>0.046</i>
CET _{max}	<i>0.017</i>	<i>0.020</i>	<i>0.011</i>	<i>0.022</i>	<i>0.015</i>	<i>0.024</i>
CET _{min}	<i>0.023</i>	<i>0.028</i>	<i>0.018</i>	<i>0.045</i>	<i>0.039</i>	<i>0.071</i>

4. Areal sampling error (e_s)

For the period since 1878, CET is based on three or four stations (Table 1). We calculated the areal sampling standard errors on daily, monthly, seasonal and annual timescales, and separately for each different combination of stations in use since 1878, treating the combination of Squires Gate and Ringway as a single station. We used the method of Jones et al. (1997) to calculate the areal sampling standard error SE due to incomplete sampling of the CET region:

$$SE^2 = \frac{\overline{s_i^2} \bar{r} (1 - \bar{r})}{1 + (n - 1) \bar{r}}$$

where \bar{r} = average correlation of each station with every other station

n = number of stations

and

$$\overline{s_i^2} = \frac{\hat{S}^2 n}{1 + (n - 1) \bar{r}}$$

where \hat{S} = standard deviation of the combined series.

This formula assumes that the constituent stations have the same variance (Folland et al, 2003, Appendix). This is not quite true, particularly as one “station” after 1959 is the mean of two stations, but it only has slightly lower variance because the two stations are highly correlated.

Both the variance and \bar{r} exhibit seasonality, with increased variance during the winter half year, and decreased \bar{r} in the summer half of the year. So in the winter the areal sampling error is influenced more by the variability of the combined series, but in summer \bar{r} is the controlling factor.

The monthly and annual areal sampling standard errors are given in Table 7. Statistics applicable to the stations used before 1958 are based on 1931-60; statistics for the more recent set of stations are based on 1961-1990.

The daily areal sampling standard errors for each month are given in Table 8. Statistics are based on the same training periods as for monthly and annual sampling errors. The inter-site correlations for daily data are a little lower than for monthly data and the standard deviations of the combined daily series are much higher, leading to higher areal sampling errors.

Daily uncertainties are all lower for the modern period, but this is not true for the monthly or annual uncertainties. Uncertainties in daily and monthly CET_{\max} tend to be higher in summer than in winter, whereas the opposite holds true for CET_{\min} , so that the uncertainties in daily and monthly CET_{mean} vary little through the year.

Table 7. Monthly and annual areal sampling standard errors (e_s) (°C)

	J	F	M	A	M	J	J	A	S	O	N	D	Ann
CET_{mean} 1878- 1930	0.19	0.24	0.16	0.18	0.20	0.19	0.17	0.17	0.16	0.17	0.19	0.18	0.06
CET_{mean} 1931- 1958	0.19	0.23	0.15	0.14	0.19	0.17	0.17	0.15	0.17	0.15	0.17	0.18	0.06
CET_{mean} 1959 +	0.15	0.16	0.16	0.16	0.19	0.19	0.15	0.14	0.15	0.15	0.15	0.21	0.06
CET_{max} 1878- 1958	0.18	0.25	0.22	0.22	0.31	0.28	0.25	0.26	0.27	0.18	0.16	0.18	0.10
CET_{max} 1959 +	0.14	0.17	0.20	0.25	0.30	0.32	0.26	0.30	0.21	0.17	0.15	0.20	0.10
CET_{min} 1878- 1958	0.26	0.31	0.23	0.24	0.19	0.19	0.18	0.22	0.28	0.26	0.24	0.23	0.12
CET_{min} 1959 +	0.20	0.21	0.23	0.16	0.16	0.14	0.13	0.16	0.20	0.19	0.21	0.26	0.06

Table 8. Daily areal sampling standard errors (e_s) (°C)

	J	F	M	A	M	J	J	A	S	O	N	D
CET_{mean} 1878- 1930	0.65	0.63	0.61	0.60	0.64	0.66	0.60	0.57	0.58	0.61	0.66	0.66
CET_{mean} 1931- 1958	0.59	0.58	0.57	0.54	0.59	0.59	0.55	0.53	0.54	0.56	0.60	0.59
CET_{mean} 1959 +	0.49	0.49	0.48	0.51	0.53	0.53	0.52	0.49	0.49	0.51	0.55	0.55
CET_{max} 1878- 1958	0.65	0.70	0.79	0.79	0.90	0.89	0.85	0.79	0.70	0.61	0.61	0.63
CET_{max} 1959 +	0.51	0.60	0.66	0.75	0.81	0.82	0.83	0.77	0.64	0.58	0.57	0.58
CET_{min} 1878- 1958	0.83	0.82	0.81	0.78	0.77	0.72	0.67	0.75	0.86	0.94	0.91	0.84
CET_{min} 1959 +	0.72	0.68	0.66	0.67	0.64	0.67	0.64	0.67	0.78	0.80	0.80	0.78

5. Total Uncertainty

The total uncertainty for a given time-scale is the square root of the sum of all of the individual error variances on that time-scale. Table 9 gives the total uncertainties for annual CET_{mean} , CET_{max} and CET_{min} for 1878 to 2003. The uncertainties are shown as $\pm 2\sigma$ error bars on the annual time-series in Figure 3. This shows that temperature differences between at least the 10 warmest years are not statistically significant given (especially) the areal sampling and calibration errors. Therefore statements such as “2003 was the 7th warmest year in the CET record” must be qualified with reservations regarding the uncertainty. By contrast, 1879 was clearly the coldest year in the entire period 1878-2003.

Table 9. Total Uncertainty (°C): Annual CET

	Mean	Max	Min
1878-1930	0.09	0.13	0.15
1931-1958	0.09	0.13	0.15
1959-1960	0.09	0.13	0.10
1961-1970	0.09	0.13	0.10
1971-1973	0.08	0.13	0.10
1974-1979	0.09	0.13	0.10
1980-1992	0.09	0.13	0.11
1993-2003	0.10	0.13	0.13

The temperature trend for 1900-2003 has been calculated from the annual values in Figure 3 using the restricted maximum likelihood technique (Diggle et al., 1999) which takes account of the uncertainties and of the autocorrelation in the residuals from the fit. The best estimate, 0.073 °C per decade has a $\pm 2\sigma$ error range of ± 0.040 °C per decade and is statistically different from zero at the 1% level. It slightly exceeds the global trend of 0.060 ± 0.021 °C per decade for the same period estimated from the combined land air and sea surface temperature “HadCRUTv” dataset (Parker et al., 2004).

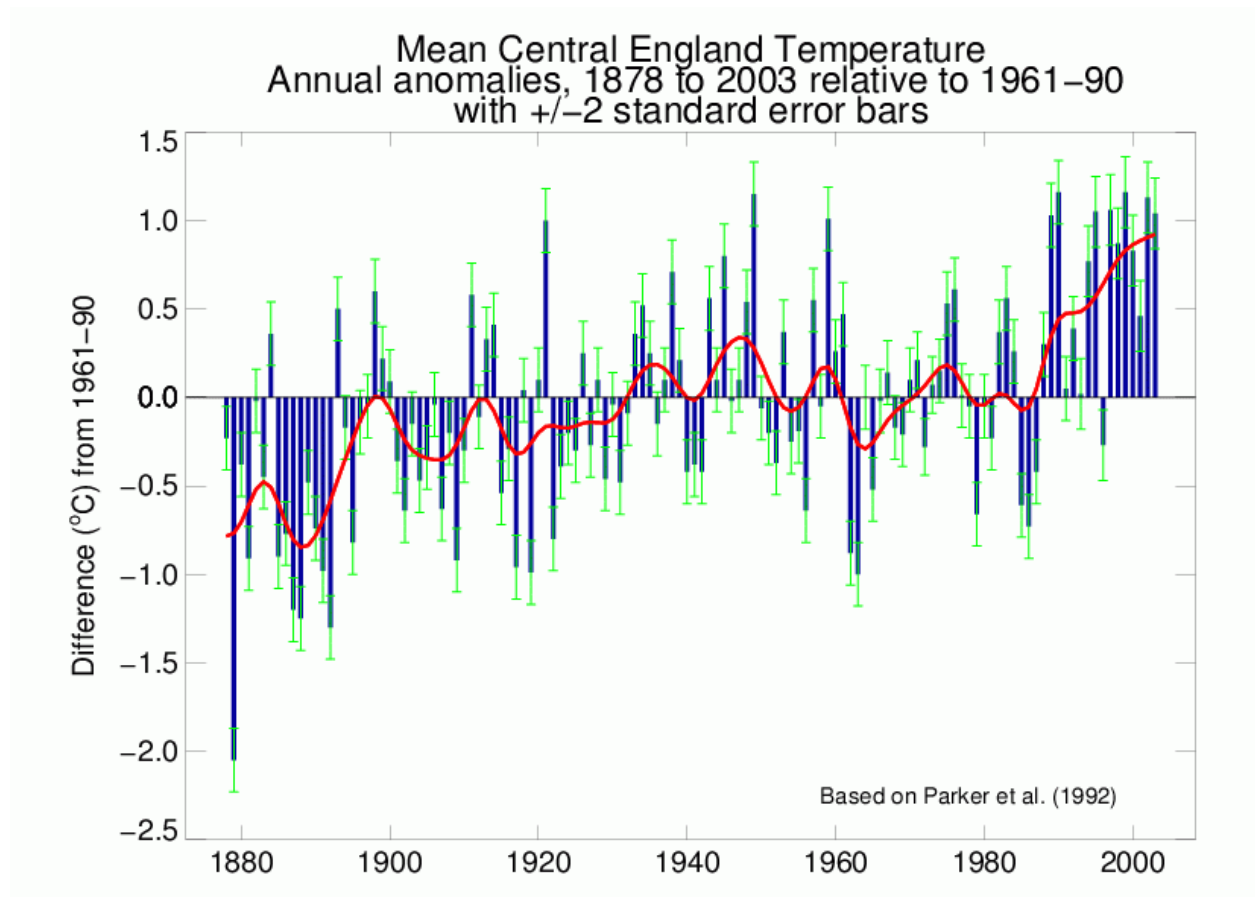
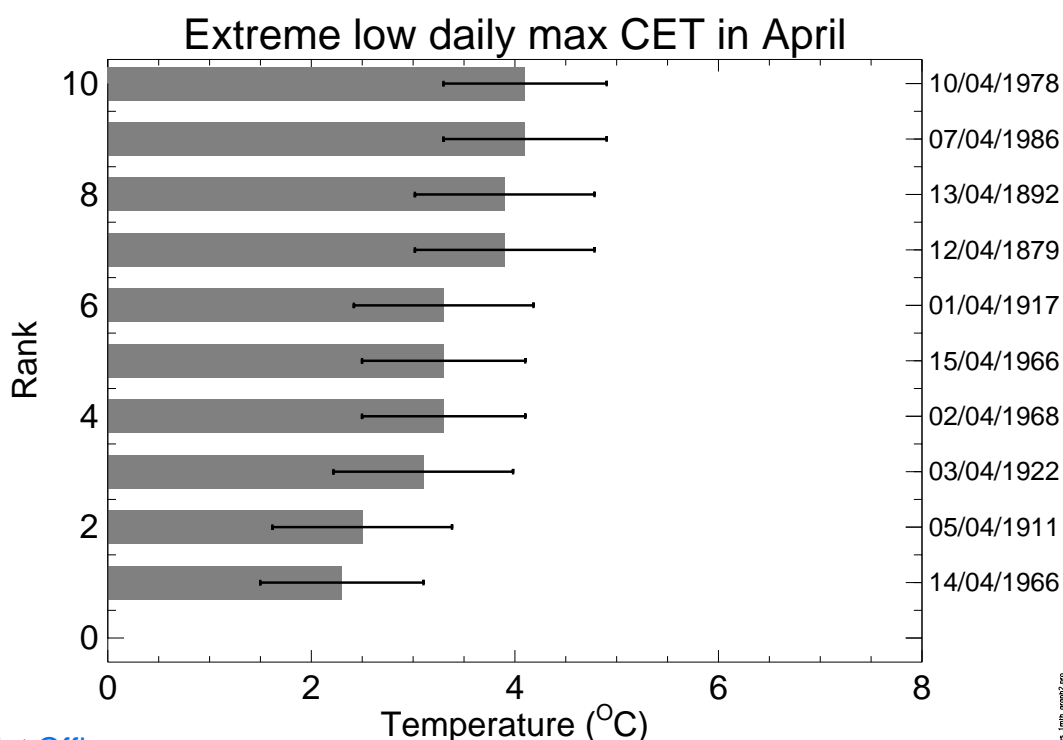
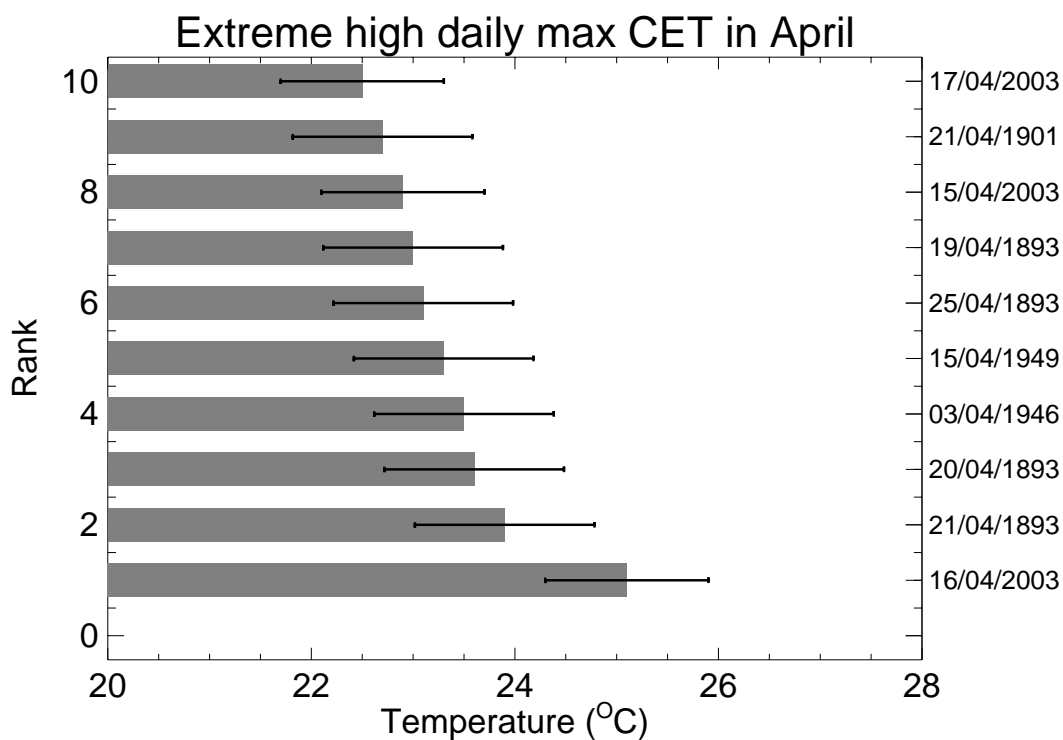


Figure 3. Annual anomalies (relative to 1961-1990) of CET including error bars.

The daily uncertainties can be used to illustrate how likely it is that a record has been broken. For example, the warmest CET_{max} on record in April occurred on the 16th in 2003. Although it exceeded the previous warmest April CET_{max} by 1.2°C, the top panel of Figure 4 reveals that it may not have been the warmest April day on record, because the error bars for that day and the now second warmest day overlap.

One way of deciding whether April 16th 2003 was clearly the warmest April day on record is to scale the difference D between the highest and second highest April values by the 95th percentile of the expected uncertainty in this difference. This scaled difference n_d is equal to $D/(2\sqrt{(\sigma_1^2 + \sigma_2^2)})$, where σ_1 and σ_2 are the uncertainties applicable to the warmest and second warmest dates, in this case 0.77°C for April 16th 2003 and 0.81°C for April 21st 1893. The difference is significant if $n_d > 1$. In this case, $D = 1.2^\circ\text{C}$, so $n_d = 0.54$ and the difference is not significant. The adjustments to CET_{max} recommended below in Section 6 reduce it by 0.1°C in 2003 and by 0.2°C in 1893; then $n_d = 0.58$, slightly larger, but these conclusions are unchanged.



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Figure 4. Extreme daily maximum temperatures in April, with error bars plotted. These data do not include the adjustments described in Section 6 below

6. Proposed further systematic adjustments to CET_{max} and CET_{min}

6.1 Compensation for biases at Ross on Wye up to 1921

We noted in Section 3 that the adjustments to make daily CET_{max} and CET_{min} agree with Manley's monthly means were added equally to CET_{max} and CET_{min} . This procedure is not rigorous because there may be disparate biases in T_{max} and T_{min} at the constituent stations. Figure 5a confirms the existence of biases in T_{max} at Ross on Wye until the early 1920s. There are smaller biases in T_{min} (not shown). Here we propose adjusting CET_{max} and CET_{min} to compensate for the heterogeneities at Ross on Wye. Removal of the biases in CET_{max} arising from those at Ross on Wye will lower CET_{max} and reduce the apparent cold biases in the other 2 stations in Figure 5a before the early 1920s. What follows has no influence on the mean temperature.

Suppose that 3 stations ($i = 1, 2, 3$) have biases, relative to their climatological averages, b_{xi} in T_{max} and b_{ni} in T_{min} . Then the biases in their T_{mean} are $0.5(b_{xi} + b_{ni})$. Now suppose that, because the sites used differed from those used by Manley (1974), the true average T_{mean} of the 3 sites differs by b_m from the true CET_{mean} assumed to be Manley's value. Then the adjustment a_0 made in Section 3 to both CET_{max} and CET_{min} to align daily CET_{mean} with Manley's was:

$$a_0 = - (b_m + \sum 0.5(b_{xi} + b_{ni})/3) \dots \dots \dots (1)$$

However the adjustments should have been:

$$a_1 = - (b_m + \sum b_{xi}/3) \dots \dots \dots (2a) \text{ to } CET_{max}$$

and

$$a_2 = - (b_m + \sum b_{ni}/3) \dots \dots \dots (2b) \text{ to } CET_{min}.$$

So the CET_{max} series needs to be further adjusted by:

$$a_x = a_1 - a_0 = -\sum b_{xi}/6 + \sum b_{ni}/6 \dots \dots \dots (3a)$$

and the CET_{min} series by

$$a_n = a_2 - a_0 = -\sum b_{ni}/6 + \sum b_{xi}/6 \dots \dots \dots (3b)$$

The Ross on Wye biases b_{x1} and b_{n1} have been calculated using the 1878-1921 average discontinuities d_x and d_n in (Ross minus CET) anomaly for each month, taking into account the biases in the CET series (equations (3a) and (3b)). Table 10 lists d_x , d_n , b_{x1} , b_{n1} and the required adjustments a_x and a_n to CET_{max} and CET_{min} . Because d_n is small in March to October, we have counted it as zero in these months. Additional small biases in T_{min} at Ross on Wye are evident in some months between 1920 and 1945 but are not coherent through the seasonal cycle

so we do not treat these here. Unfortunately we do not have access to a station history for Ross on Wye.

Table 10. Biases b_{x1} and b_{n1} ($^{\circ}\text{C}$) in Ross on Wye T_{\max} and T_{\min} , 1878-1921, and proposed adjustments a_x and a_n to CET_{\max} and CET_{\min} in this period.

	J	F	M	A	M	J	J	A	S	O	N	D
d_x	-0.05	0.24	0.60	0.80	1.16	1.07	1.13	1.08	0.80	0.37	0.19	0.02
d_n	-0.46	-0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.26	-0.30
b_{x1}	0.05	0.40	0.75	1.00	1.45	1.34	1.41	1.35	1.00	0.46	0.30	0.10
b_{n1}	-0.56	-0.56	-0.15	-0.20	-0.29	-0.27	-0.28	-0.27	-0.20	-0.09	-0.37	-0.38
a_x	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1
a_n	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1

The magnitudes of most of the adjustments to CET_{\max} and CET_{\min} have been rounded down to the next 0.1°C to prevent an excessive reduction of diurnal temperature range (see Section 6.3 below) while maintaining an unchanged CET_{mean} . Application of the adjustments to the CET_{\max} and Ross on Wye T_{\max} series yields a CET_{\max} series which is also consistent with the T_{\max} series from the other two stations (Figure 5b), implying that the Rothamsted and Stonyhurst and T_{\max} series are homogeneous. The adjusted series of annual T_{\min} relative to CET_{\min} show the biases at Ross on Wye between 1925 and 1945 (Figure 5c) but are otherwise homogeneous.

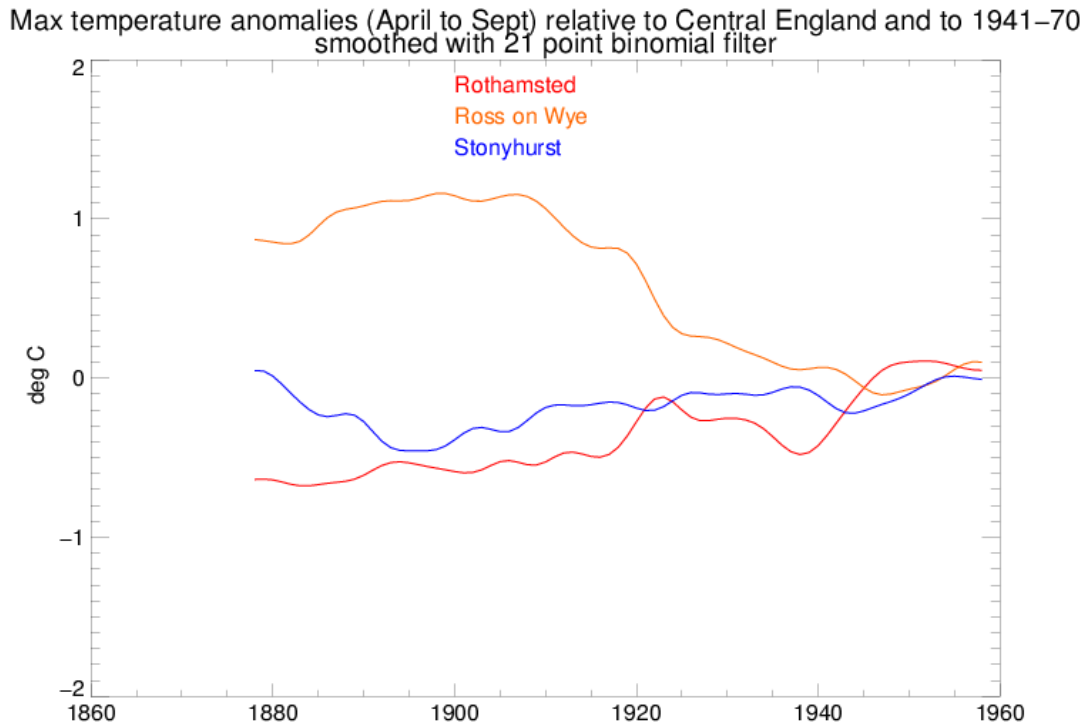


Figure 5a. April to September average unadjusted T_{\max} anomalies relative to unadjusted CET_{\max} . A 1941-70 reference period is used because Ross on Wye closed temporarily in the 1970s.

Max temperature anomalies (April to Sept) relative to Central England (adjusted) and to 1941–70
smoothed with 21 point binomial filter

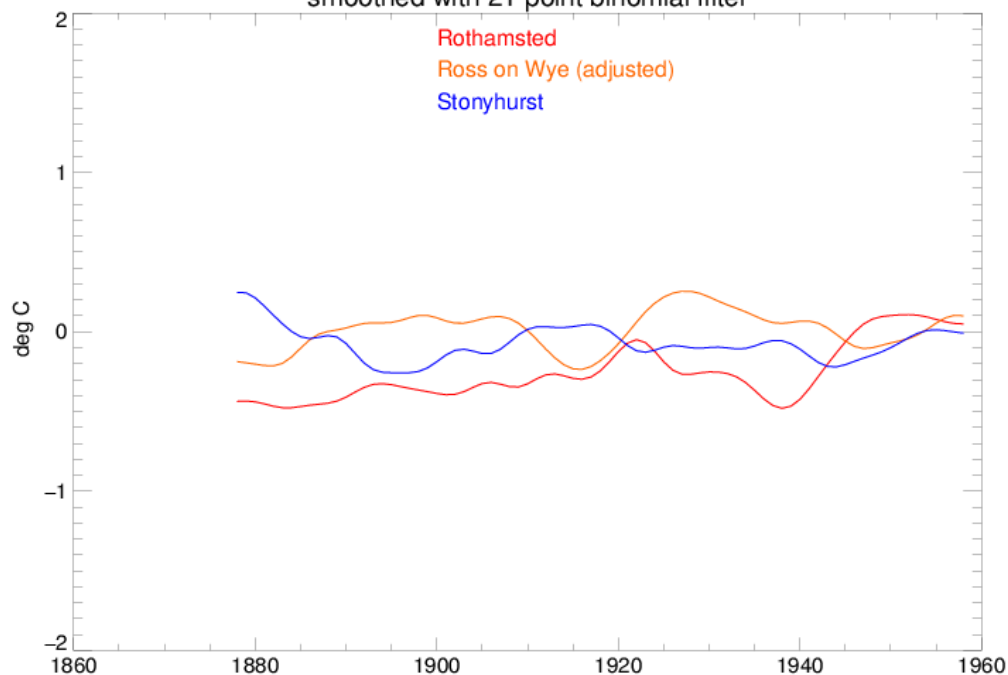


Figure 5b. As Figure 5a but after adjustment of the Ross-on-Wye T_{\max} and CET_{\max} series.

Min temperature anomalies (Annual) relative to Central England (adjusted) and to 1941–70
smoothed with 21 point binomial filter

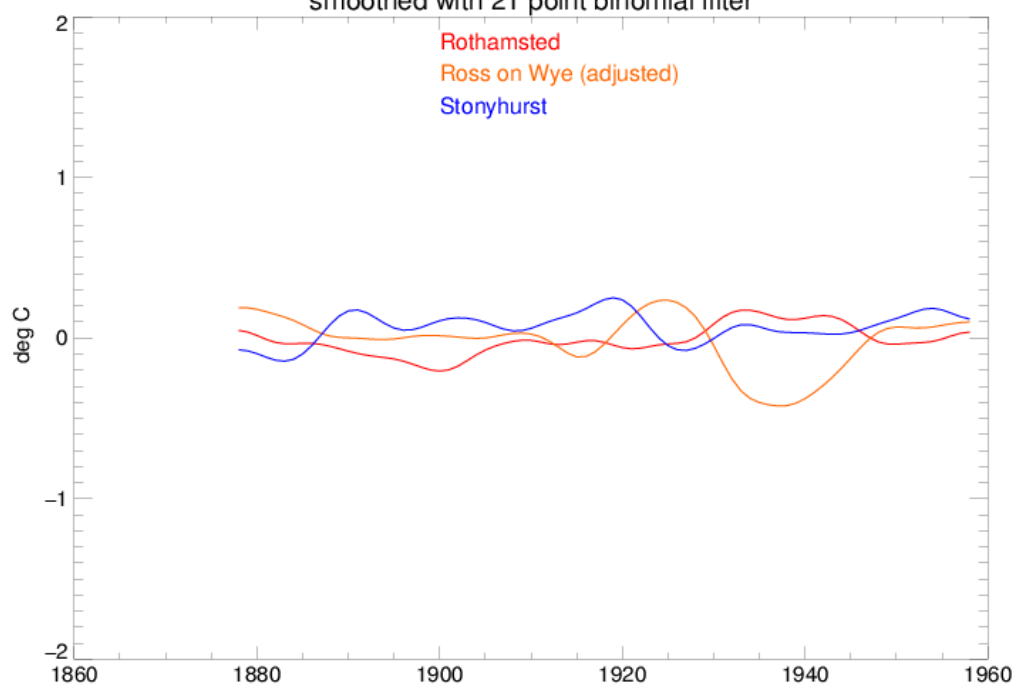


Figure 5c. As Figure 5a but for annual T_{\min} after adjustment of the Ross-on-Wye T_{\min} and CET_{\min} series.

6.2 Urban warming at Oxford Radcliffe Observatory

Figure 6 shows that Oxford Radcliffe Observatory T_{\min} has risen relative to CET_{\min} but that most of the rise has been since the late 1950s. This suggests that Manley (1974) compensated for this bias just adequately by applying adjustments (based on differences from local rural stations) from 1960, though 1955 would have been better. The daily temperatures for Oxford Radcliffe Observatory used in Figure 6 do not include the adjustments applied by Knox-Shaw and Balk (1932) to the monthly data ($-0.3^{\circ}\text{F} \approx -0.17^{\circ}\text{C}$ to pre-1923 T_{\min}), whereas Manley (1974) used the adjusted monthly mean data. The higher values of Oxford Radcliffe Observatory T_{\min} relative to CET_{\min} before the early 1920s would be removed by the application of the Knox-Shaw and Balk adjustments to T_{\min} . Oxford Radcliffe Observatory data are only used directly in Manley (1974)'s monthly CET_{mean} series; they are not used directly in the daily CET_{mean} , CET_{max} and CET_{\min} series (Table 1). We do not propose any changes to the CET record arising from urban warming at Oxford Radcliffe Observatory.

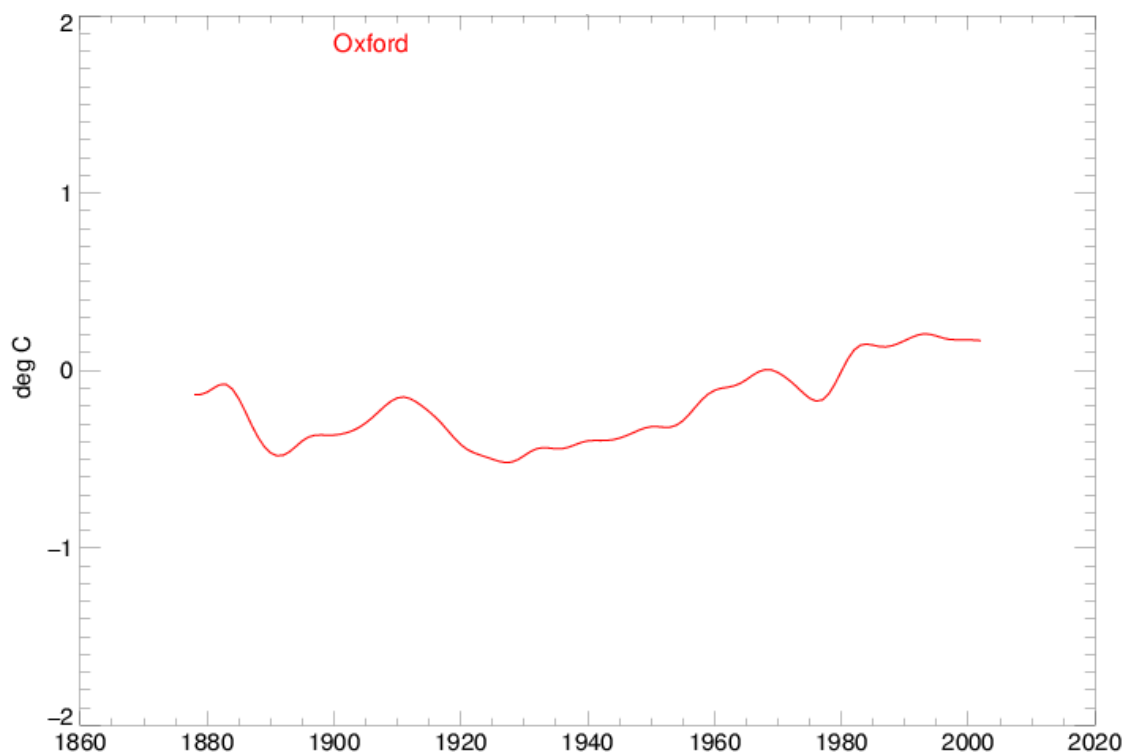


Figure 6. Annual T_{\min} anomalies (relative to 1961-1990) at Oxford Radcliffe Observatory, relative to adjusted CET_{\min} . Values are smoothed with a 21-point binomial filter.

6.3 Urban warming since 1974

When the CET_{max} and CET_{min} series were calculated, Legg (1989)'s adjustments were doubled for CET_{min} but no adjustments were made to the CET_{max} series (Section 3). The adjustments to CET_{min} are now therefore -0.4°C and diurnal temperature range is increased by this amount relative to the original station data. The solid lines in Figure 7 shows annual, April to September and October to March anomalies of diurnal range of CET based on the existing CET_{max} and CET_{min} series. If the adjustments to CET_{max} and CET_{min} suggested in Section 6.1 to compensate for biases at Ross on Wye are made, the diurnal range up to 1921 is reduced, especially in the summer half-year, as shown by the dashed lines in Figure 7, yielding effectively constant diurnal range on multidecadal timescales before the 1980s. The subsequent increase in diurnal range then appears to be exceptional in a historical context. The known increase in sunshine in the United Kingdom in recent decades (Parker et al., 2004) is consistent with an increase in diurnal temperature range. However if the recent urban warming adjustment is apportioned 75% to CET_{min} and 25% to CET_{max} rather than 100% to CET_{min} , this reduces the recent diurnal range by up to 0.2°C and renders the recent change less extreme as shown by the dashed lines in Figure 7. It also reduces by 0.1°C the apparent relative warming of T_{min} at Oxford Radcliffe Observatory shown in Figure 6. However the change is too small to alter the conclusions of Parker et al. (2004) regarding the exceptional warmth in CET_{max} in 1989-2003 in February-March and July-August. Daytime urban warming (albeit much less than at night) is shown for cities in the USA by Gallo and Owen (1999) (their Figure 2). In a detailed review, Arnfield (2003) cites cooling, or at least no warming, in cities by day in his Table III but notes a case of daytime warming also in his text. Our proposed reassignment of the urban warming adjustment (75% to CET_{min} and 25% to CET_{max}) is thus plausible: the true daytime effect is likely to depend on the surface characteristics at each site (Arnfield, 2003; Peterson, 2003). According to Table 9, the one-sigma uncertainty in annual diurnal range, being the square root of the summed error-variances of CET_{max} and CET_{min} , approaches 0.2°C ; thus the data may be inadequate for the task of confirming the recent increase of diurnal range.

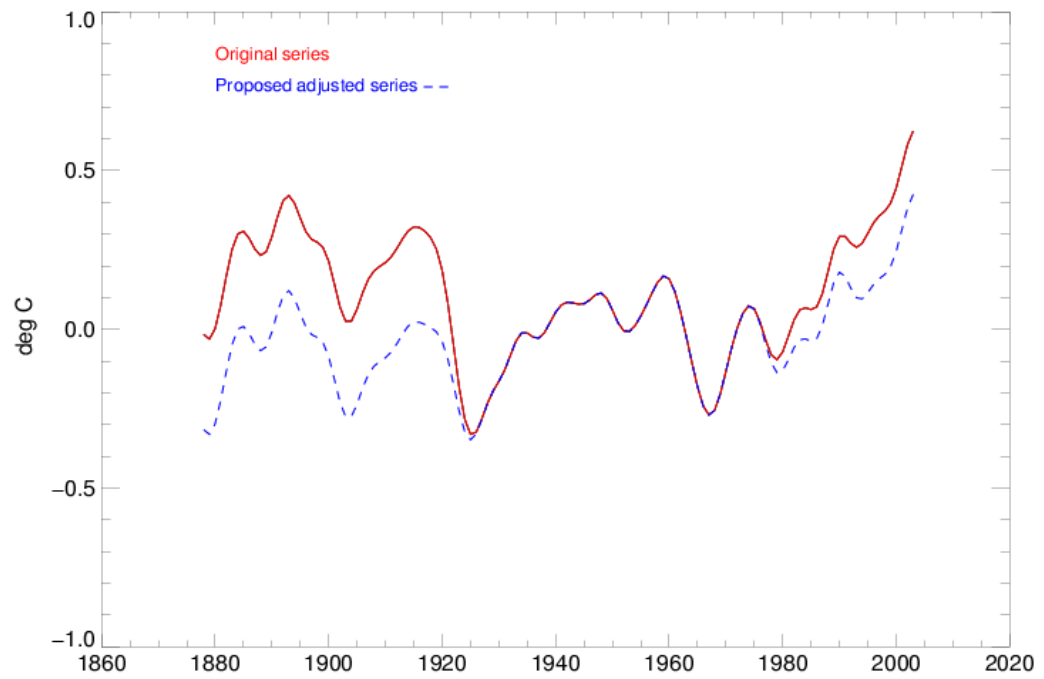


Figure 7a. Annual Central England diurnal temperature range anomalies (relative to 1961-1990), smoothed approximately decadally with a 21-point binomial filter.

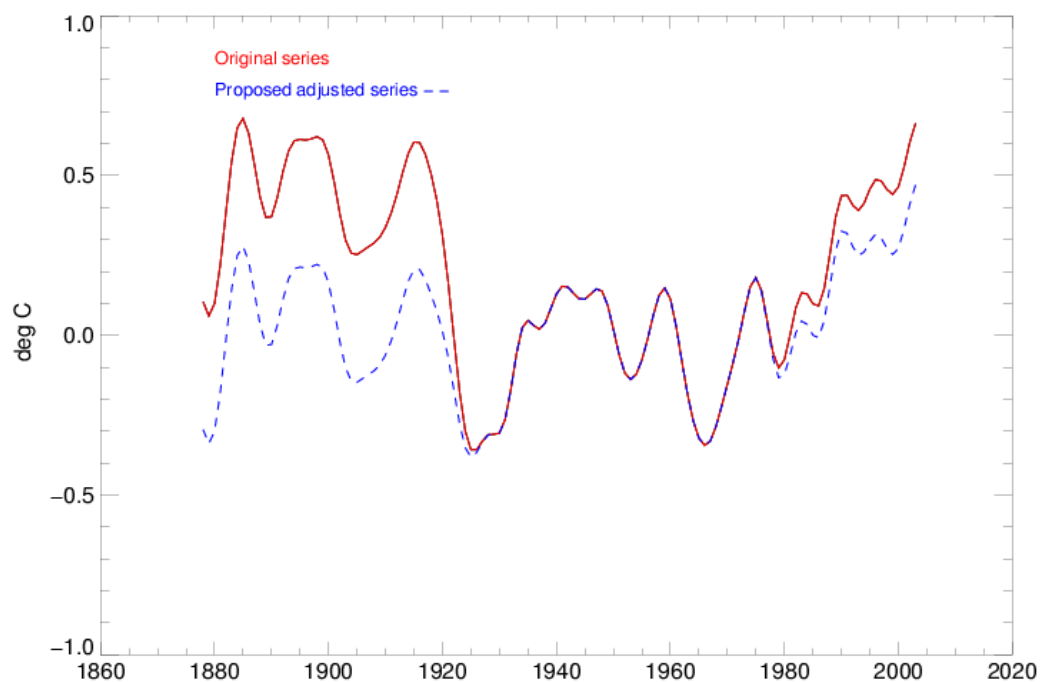


Figure 7b. As Figure 7a, but for April to September.

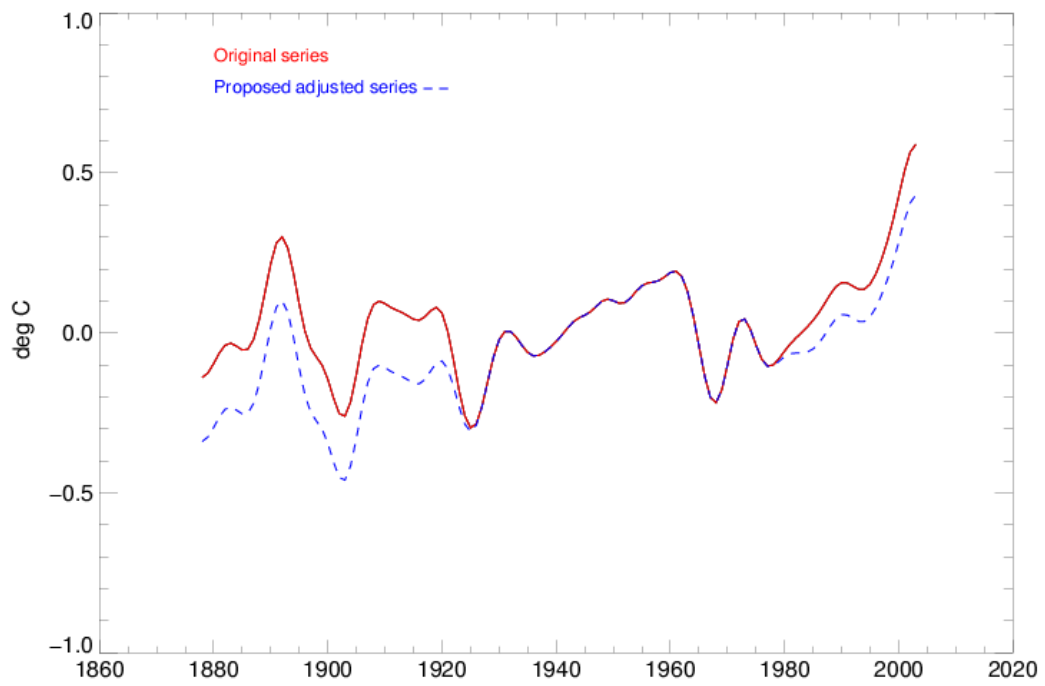


Figure 7c. As Figure 7a, but for October to March.

6.4 Ringway and Rothamsted since 1990

Figure 8a shows differences of T_{\max} anomalies at the constituent CET stations, plus Cambridge as a cross-check on Rothamsted, from the CET_{\max} series, for 1959 to 2002. The series are filtered to pass time scales beyond about 2 years and therefore to detect any multi-annual calibration or microclimate drifts, especially near the end of this period of accelerating operational and environmental change. There are no apparent relative drifts at individual stations, or excursions beyond about $\pm 0.5^{\circ}\text{C}$. The variability is in accord with expectation because the annual station uncertainties will exceed the annual CET_{\max} uncertainties ($\sigma \approx 0.13^{\circ}\text{C}$) given in Table 9. Table 11 presents estimated uncertainties for annual station T_{\max} and T_{\min} , based on the earlier sections of this paper: the estimate for station T_{\max} is $\sigma \approx 0.23^{\circ}\text{C}$.

The same stability is not evident for CET_{\min} (Figure 8b). However the relative rising trends of station T_{\min} relative to CET_{\min} in recent years are expected because no urban warming adjustments have been applied to the station data shown here. Furthermore the scatter between stations, allowing for this expected trend, is only slightly greater than that in Figure 8a, and is not unexpected in view of the estimated annual station T_{\min} uncertainties (again $\sigma \approx 0.23^{\circ}\text{C}$) derived in Table 11. So the coldness of Ringway around 1993 and the warmth of Rothamsted around 1993 and 2001, while disconcerting, may not be outliers in view of the expected uncertainties. That Rothamsted T_{\min} is not fully supported by Cambridge T_{\min} suggests calibration or siting biases rather than real spatial variations of temperature anomalies. If any biases can be ascertained following further investigation of Ringway and Rothamsted, then the CET series should be adjusted accordingly.

Table 11. Expected standard errors ($^{\circ}\text{C}$) of annually-averaged single-station T_{\max} and T_{\min} for 1959 to 2002.

	T_{\max}	T_{\min}
Calibration (Section 2.1)	0.15	0.15
Precision (Section 2.2) [$\sqrt{(0.00083/365)}$]	0.00	0.00
Random screen (Section 2.3) [$\sqrt{(0.068/365)}$ and $\sqrt{(0.096/365)}$]	0.01	0.02
Urbanization (Table 6) [column F x 2 because we used 4 stations]	0.05	0.14
Sampling (Section 4) [$\sqrt{(\overline{s_i^2} \bar{r} (1-\bar{r}))}$]	0.16	0.11
Total [$\sqrt{(\text{sum of squares of the constituents})}$]	0.23	0.23

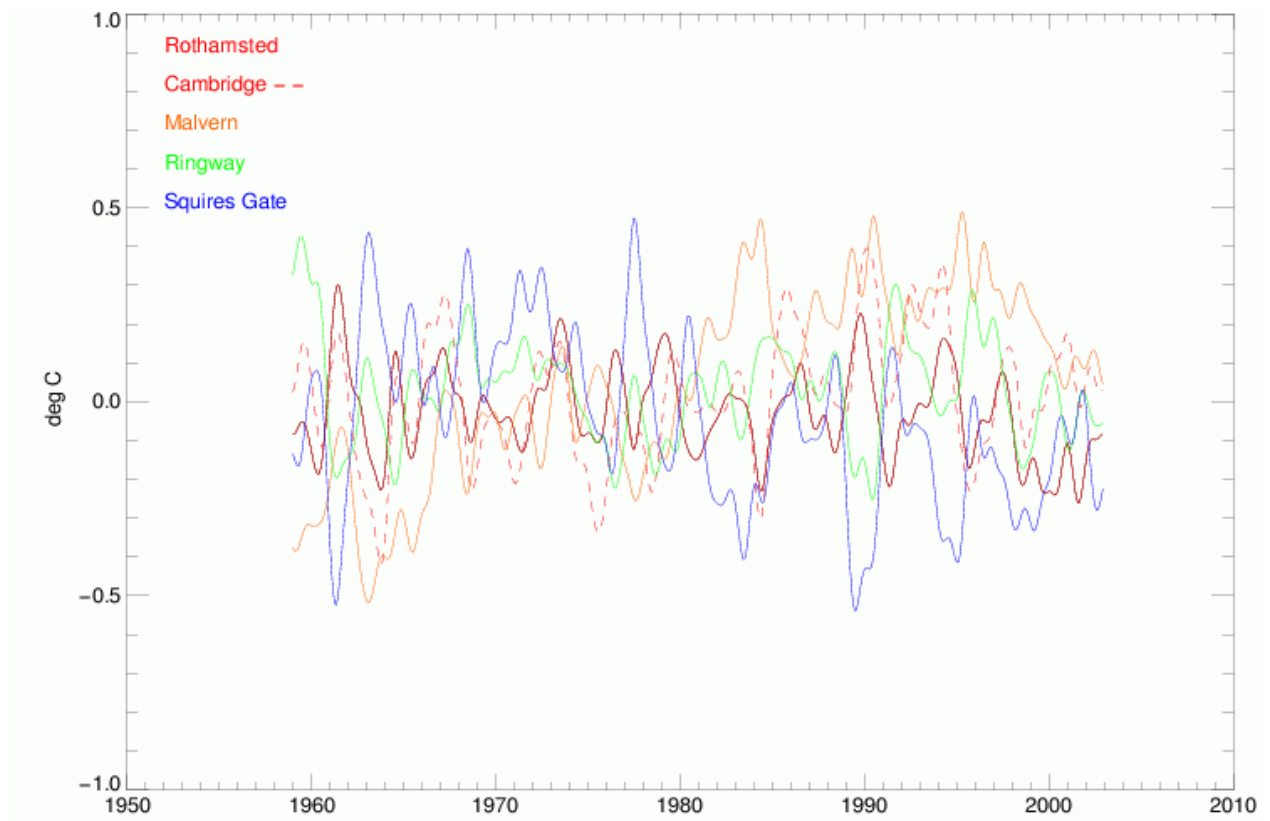


Figure 8a. Anomalies (relative to 1961-1990) of T_{\max} at five stations relative to CET_{\max} , 1959 to 2002. Plots are monthly anomalies smoothed with a 61-point binomial filter.

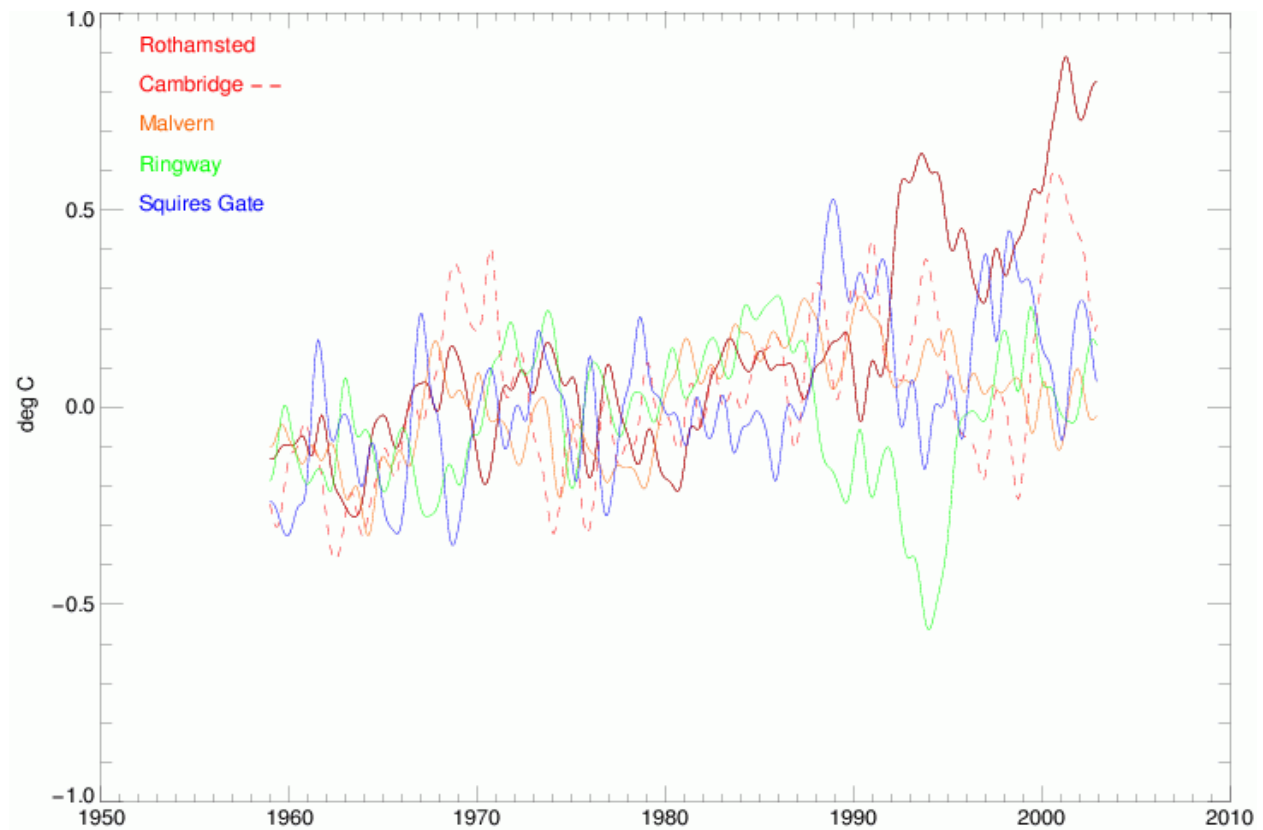


Figure 8b. As Figure 8a, but for T_{\min} .

7. Conclusions.

Contributions from different sources to uncertainties in CET are summarized in Table 12. The largest contribution to the uncertainty in CET on all timescales up to annual arises from the areal sampling error. For annual CET the calibration error is comparable to the areal sampling error, whereas the random precision and screen errors are much smaller. For the monthly series the calibration error comes second to the areal sampling error; the random precision and screen errors are still much smaller and are similar in magnitude to the uncertainties arising from climatic and microclimatic temperature offsets between stations, including urban warming. For the daily series the random precision and screen errors are next most important after the areal sampling error but are half an order of magnitude smaller than it. As expected, annual CETs are the least uncertain, with daily CETs being the most. So the most efficient way to improve the daily series is to introduce more high quality observing stations.

Since we did not remove the random or systematic measurement errors from the observations before calculating the areal sampling error, our estimates of the areal sampling error may have been augmented by the measurement errors, so

that we have implicitly duplicated the measurement errors in the total uncertainties. However, biases arising from local changes at the sites, such as growth or lopping of trees, and movements or renovations of the instrument shelters, have not been explicitly included, so the total uncertainties may not be too high.

We investigated the series of maximum and minimum Central England Temperature and recommend changes of $\pm 0.2^{\circ}\text{C}$ before the early 1920s. These are being implemented in revised daily CET_{max} and CET_{min} series. The mid-20th century CET record appears to be homogeneous but the urban warming adjustments applied from 1980 onwards are being reapportioned 25%: 75% to CET_{max} and CET_{min} instead of entirely to CET_{min} . These changes yield a more homogeneous series of diurnal temperature range. Scatter between the constituent stations used since 1959 is not greater than expected given the estimated uncertainties, but the record since 1990 may be improved if possible biases at two of the stations can be ascertained.

Finally, we note that from late 2004 Squires Gate and Ringway are to be replaced by a new station at Stonyhurst, and Malvern by a station at Pershore, taking due account of any offsets between observations which have been running in parallel during 2003-4.

Table 12. Approximate typical contributions ($^{\circ}\text{C}$) to standard errors of uncertainty in CET.

	CET_{mean}	CET_{max}	CET_{min}
Calibration (Section 2.1: all timescales)	0.06	0.09	0.09
Precision and random screen errors (Sections 2.2 & 2.3) (daily)	0.1	0.2	0.2
(monthly)	0.02	0.03	0.03
(annual)	0.007	0.008	0.009
Offset adjustments (Section 3.1) (daily and monthly)	0.03	0.03	0.03
(annual)	0.02	0.02	0.02
Urbanization (Section 3.2: all timescales)	0.03	0.02	0.06
Sampling (Section 4) (daily)	0.6	0.7	0.8
(monthly)	0.2	0.25	0.25
(annual)	0.06	0.1	0.1
Total (daily)	0.6	0.7	0.8
(monthly)	0.2	0.25	0.25
(annual)	0.09	0.13	0.13

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References

Andersson T, Mattisson I. 1991. A field test of thermometer screens. Swedish Meteorological and Hydrological Institute SMHI RMK No 62.

Arnfield AJ. 2003 Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. . *International Journal of Climatology* **23**: 1-26.

Diggle PJ, Liang KY, Zeger SL. 1999. *Analysis of longitudinal data*. Clarendon Press, Oxford, UK.

Folland CK, Salinger MJ, Jiang N, Rayner NA. 2003. Trends and Variations in South Pacific Island and Ocean Surface Temperatures. *Journal of Climate*, **17**, pp. 2859-2874.

Gallo KP, Owen TW. 1999. Satellite-based adjustments for the urban heat island temperature bias. *Journal of Applied Meteorology*, **38**, 806-813.

Johnson GT, Oke TR, Lyons TJ, Steyn DG, Watson ID, Voogt JA. 1991. Simulation of surface urban heat islands under "ideal" conditions at night: Part 1: Theory and tests against field data. *Boundary-Layer Meteorology* **56**: 275-294.

Jones PD, Osborn TJ, Briffa KR. 1997. Estimating sampling errors in large-scale temperature averages. *Journal of Climate* **10**: 2548-2568.

Knox-Shaw H, Balk JG. 1932. Results of Meteorological Observations made at the Radcliffe Observatory, Oxford in the five years 1926-1930. In: Radcliffe Observations, Volume 55, Appendix, pp. 91-113. Oxford University Press.

Legg TP. 1989. Removal of urbanisation effects from the Central England Temperature data-sets. *LRFC 33*, Hadley Centre, Met Office, Exeter, U.K.

Manley G. 1946. Temperature trend in Lancashire. *Quarterly Journal of the Royal Meteorological Society* **72**: 1-31.

Manley G. 1953. The mean temperature of central England, 1698-1952. *Quarterly Journal of the Royal Meteorological Society* **79**: 242-261.

Manley G. 1974. Central England temperatures: monthly means 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society* **100**: 389-405.

Met Office. 1879. Minutes of the Meteorological Council 1878-9.

Met Office. 1880. Minutes of the Meteorological Council 1879-80.

Parker DE, Alexander LV, Kennedy J. 2004. Global and regional climate in 2003. *Weather*, **59**: 145-152.

Parker DE, Legg TP, Folland CK. 1991. A new daily Central England Temperature series, 1772-1991. **CRTN 11**, Hadley Centre, Met Office, Exeter, U.K.

Parker DE, Legg TP, Folland CK. 1992. A new daily Central England Temperature series. *International Journal of Climatology* **12**: 317-342.

Peterson TC. 2003. Assessment of urban versus rural in situ surface temperatures in the contiguous United States: no difference found. *Journal of Climate* **18**: 2941-2959.

World Meteorological Organization (WMO). 1983. Guide to meteorological instruments and methods of observation. 5th edition, **WMO - No 8**, 1983, pp. 1.23, 4.3.