INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **25**: 1173–1188 (2005)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.1190

UNCERTAINTIES IN CENTRAL ENGLAND TEMPERATURE 1878–2003 AND SOME IMPROVEMENTS TO THE MAXIMUM AND MINIMUM SERIES

DAVID PARKER* and BRIONY HORTON
Hadley Centre, Met Office, Exeter, UK

Received 9 September 2004
Revised 7 February 2005
Accepted 7 February 2005

ABSTRACT

We assess the random and systematic uncertainties affecting the central England temperature (CET) record since 1878 on daily, monthly and annual time scales. The largest contribution to uncertainty in CET on all these time scales arises from areal sampling, followed for annual and monthly CET by thermometer calibration. For the daily series, random thermometer precision and screen errors are the second largest source of uncertainty. Annual CETs are least uncertain, whereas daily CETs are most uncertain. Despite the uncertainties in annual mean CET, the trend of 0.077 °C per decade since 1900 is significant at the 1% level.

In an additional investigation, we detect biases in the published series of central England maximum and minimum temperatures, and implement systematic adjustments of up to ±0.2 °C to the values up to 1921 and up to ±0.1 °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 improve the homogeneity of the diurnal temperature range, which then shows little trend before 1980 and a reduced rising trend thereafter. The uncertainties in maximum and minimum temperature make the data inadequate for the task of establishing the magnitude of the recent increase of diurnal range. © Crown Copyright 2005. Reproduced with the permission of Her Majesty's Stationery Office. Published by John Wiley & Sons, Ltd.

KEY WORDS: central England; temperature; uncertainty; biases; climatic variations; extremes

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 since 1878 in the longest instrumental record in the world, the 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 southeast and Herefordshire in the southwest. CET is a composite series using data from a succession of observing sites that have been carefully adjusted to remove heterogeneities (Manley, 1953, 1974; Parker *et al*., 1992).

We anchor daily CET to Manley's monthly series owing to his major pioneering work in homogenizing the data. Long-term changes in mean CET since the late 19th century are corroborated by several other series, e.g. for Sweden (Yan *et al*., 2001), Northern Ireland (Jones and Lister, 2004), and a nearly independent Scottish series (Jones and Lister, 2004). Any remaining time-varying biases affecting CET or other local series, if not arising from a systematic cause such as urban development, may be regarded as random when assessing global temperature trends. The implications of a recent study (Parker, 2004) are that even such systematic biases have not had a major impact on estimates of global surface air temperature trends since 1950.

Although Manley (1974) and Parker *et al*. (1992) made careful adjustments whenever contributing stations changed, several types of uncertainty continue to affect the CET series. These include random and systematic measurement errors, uncertainties in the systematic climatic and microclimatic differences in temperature

* Correspondence to: David Parker, Hadley Centre, Met Office, FitzRoy Road, Exeter, Devon EX1 3PB, UK;
e-mail: david.parker@metoffice.gov.uk

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

Dates	Monthly CET_{mean} series	Daily CET_{mean} series (Parker *et al.*, 1992)	Daily CET_{max} and CET_{min} series
1878–1930	0.5(Lancashire + Oxford) Lancashire is derived from four to seven stations in the northwest 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 equally weighted	Stonyhurst, Rothamsted, Ross-on-Wye equally weighted
1931–58		Stonyhurst, Rothamsted, Ross-on-Wye equally weighted	
1959–73		Rothamsted, Malvern, 0.5(Squires Gate + Ringway)	
1974–Oct 2004	Rothamsted, Malvern, 0.5(Squires Gate + Ringway)		
Nov 2004–	Rothamsted, Malvern, Stonyhurst equally weighted		

between observing stations, including urban warming, and weather-related areal sampling errors. We assume that all these uncertainties are independent, so that the error variances can be summed. This follows because if errors e_1 and e_2, having zero mean, are independent, then $\sum(e_1e_2) = 0$ so that $\sum(e_1 + e_2)^2 = \sum e_1{}^2 + \sum e_2{}^2$. See Wilks (1995: 123) for further discussion. Although the monthly and daily mean series extend back to 1659 and 1772 respectively, we only assess the series since 1878, when sufficient reliable data became readily available for daily CET to be based on at least three stations (Parker *et al.*, 1992). Before 1878, the uncertainties are larger and more difficult to estimate, owing to the use of different equipment (e.g. thermometers on 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 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}. This is because different observing stations were used for monthly CET_{mean} (Manley 1974), daily CET_{mean} (Parker *et al.*, 1992) and daily CET_{max} and CET_{min} (Table I). These choices were guided by data availability at the time (Manley, 1974; Parker *et al.*, 1992) and, for daily CET_{max} and CET_{min}, the desirability of minimizing the number of changes of stations.

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 and annual scales, and assess some impacts on estimates of trends and extremes. As the result of an additional investigation, in Section 6 we implement 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 the diurnal temperature range (DTR). Section 7 concludes.

2. ERRORS AFFECTING THE DATA

In this section we discuss several types of error affecting the data. All of these affect the deviation of the recorded temperature from the true air temperature. The smaller this deviation, the more 'accurate' the data. A generally small, random contribution to error comes from imprecision of the reading or recording, which may be, for example, to the nearest 0.1 °C, and we refer to this as 'precision error'; it is affected by both instrument design and observing and recording practice. Systematic differences between recorded and true temperature are described as 'biases'. The errors with the most serious implications for monitoring climate are biases that change with time. These may, for example, be jumps caused by changes of the instrumentation or rehousing of the instruments, drifts arising from unstable instrumental calibration, or jumps or drifts resulting from changes in the environment of the instrumentation, such as the growth or lopping of a tree or the construction or demolition of a building close to the instrumental enclosure.

2.1. *Calibration errors*

Calibration biases from 46 pairs of thermometer checks in the late 19th century cited by the Met Office (1879, 1880) changed from one year to the next by an average of very close to zero, but with a standard deviation (see Wilks (1995: 25) for definition) of 0.15 °C. Current Met Office practice is to replace a thermometer if its bias relative to a certified check thermometer exceeds 0.2 °C. These checks are made once every 3 years. The standard deviation of a rectangular distribution limited by ±0.2 °C is about 0.12 °C. So here we assume that the bias of a single thermometer has a standard deviation of 0.15 °C, yielding a single thermometer calibration error variance v_{cal} of 0.0225 °C^2. We also assume that the biases are random between thermometers, so that the variance of the summed T_{max} or T_{min} of three stations is $3v_{cal}$; the variance of the average is then $3v_{cal}/9 = 0.0075$ °C^2 (see also Wilks (1995: 122)); the standard error of this average is then $\sqrt{0.0075}$ or 0.087 °C (Table II). When four daily stations are used from 1959 onwards, two stations (Squires Gate and Ringway) are averaged first (Table I). The calibration error variance of this combination is 0.0112 °C^2 for maximum or minimum temperature. For CET_{max} and CET_{min} the calibration error variance then becomes $(0.0112 + 0.0225 + 0.0225)/9$, yielding a standard error of 0.079 °C (Table II). For CET_{mean}, the resulting calibration error variances are further halved because $CET_{mean} = 0.5(CET_{max} + CET_{min})$.

2.2. *Reading precision error*

For much of the CET record, temperatures were observed to the nearest degree Fahrenheit, but temperatures have been observed to the nearest 0.1 °C at Squires Gate and Ringway since 1961 and at Rothamsted and Malvern since 1971. When observations are made to the nearest degree Fahrenheit, 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 °F^2, which is 0.026 °C^2. With a precision of 0.1 °C, the precision error variance is 0.00083 °C^2. For either CET_{max} or CET_{min}, the precision error variance is divided by 3 when three stations are used to calculate CET. When four 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 III.

2.3. *Random screen error*

The type and condition of the thermometer housing affects the accuracy of the measured temperature. Important factors include solar radiation entering the housing directly or after reflection, infrared radiation between the sensor and the interior surfaces of the housing, and conduction and convective transfer of heat between the thermometer and the housing and the air inside the housing. These factors are mitigated in windy weather (Lin *et al.*, 2001).

A comparison between a large Stevenson screen in good condition and a ventilated reference screen in Sweden (Andersson and Mattisson, 1991) yielded root-mean-square (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 respectively. The latter was calculated

Table II. Calibration standard errors

	No. of stations	Calibration standard error (°C)	
		CET_{max} and CET_{min}	CET_{mean}
1878–1958	3	0.087	0.061
1959 on	4	0.079	0.056

Table III. Precision standard errors

	No. of Fahrenheit thermometers	No. of Celsius thermometers	Precision standard error (°C)	
			Daily CET_{max} and CET_{min}	Daily CET_{mean}
1878–1958	3	0	0.093	0.066
1959–60	4	0	0.085	0.060
1961–70	2	2	0.076	0.054
1971 on	0	4	0.015	0.011

Table IV. Combined precision and screen uncertainties

	1878–1958	1959–60	1961–70	1971 on
Daily CET_{mean} (°C)	0.13	0.12	0.12	0.11
Daily CET_{max} (°C)	0.18	0.16	0.16	0.14
Daily CET_{min} (°C)	0.20	0.18	0.18	0.16

from temperatures recorded every minute, not $0.5(T_{max} + T_{min})$. The largest differences occurred 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 $0.26^2 = 0.068\,^{\circ}C^2$ and $0.31^2 = 0.096\,^{\circ}C^2$ respectively. However, because our T_{mean} data are $0.5(T_{max} + T_{min})$ 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 three stations were used. Thereafter, we have two single stations with error variance $e_{scr}{}^2$ and a combined station with error variance 0.5 $e_{scr}{}^2$, so the error variance of the mean is $(0.5 + 1 + 1)e_{scr}{}^2/9$.

2.4. Combining the measurement errors

We sum the random precision and screen error variances to obtain composite daily measurement error variances. Table IV expresses them in terms of standard error. Monthly and annual values of composite error variance are determined by dividing by the number of days in the month or year. However, calibration errors are systematic on sub-annual time scales because thermometer inspections may be made only every few years, so the monthly and annual calibration errors must not be scaled down.

3. UNCERTAINTIES ARISING FROM CLIMATIC AND MICROCLIMATIC DIFFERENCES 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 I). Because of these differences in stations, the areal average temperature at the Parker *et al.* stations differed slightly from the Manley values. So, to maintain homogeneity (Section 1), Parker *et al.* (1992) adjusted their daily CET_{mean} values to make their monthly averages consistent with Manley (1974). For the same reason, when we created daily CET_{max} and CET_{min} series, again using a different sequence of stations (Table I), 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). Here, we estimate the uncertainties arising from these adjustments. We also estimate the uncertainties stemming from the adjustments applied by Parker *et al.* (1992) to recent CET_{mean} to compensate for urban warming.

3.1. Adjustment of daily values to match 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. They were calculated by Parker *et al.* (1992) for individual months in their common period, 1772 to 1973. 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 is done before the urban warming adjustments are applied.

Figure 1 shows the annual means of the monthly adjustments to daily CET_{mean} for 1878 to 1973. From 1878 to 1930 the annual mean adjustments varied almost randomly about an average of 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 annual mean adjustments increased to over 0.3 °C, but by 1958 they declined to about 0.2 °C, implying warming in the sites then used for daily CET_{mean} (Stonyhurst, Rothamsted and Ross-on-Wye) relative to those used by Manley. The annual mean adjustments fell to less than 0.1 °C when the stations changed in 1958–59; after that there was a further decline to below −0.1 °C by 1973.

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 (Table I). The Lancashire series was composed of between four and seven stations in the northwest 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 urbanization (Manley, 1953); Manley began to correct for urbanization after 1960. There were also slight changes in the Oxford Radcliffe Observatory site in this period. However, the negative trend after 1930 in Figure 1 implies relative cooling, not warming, at Manley's sites overall.

We estimated the uncertainties in CET_{mean} arising from the Parker *et al.* (1992) adjustments separately for 1878–1930, 1931–58 and 1959–73 because these periods had different sets of stations in the daily CET_{mean} series (Table I). This was also done separately for annual values and for each calendar month. We assume that the uncertainties are reflected by the interannual variability of the adjustments and not by

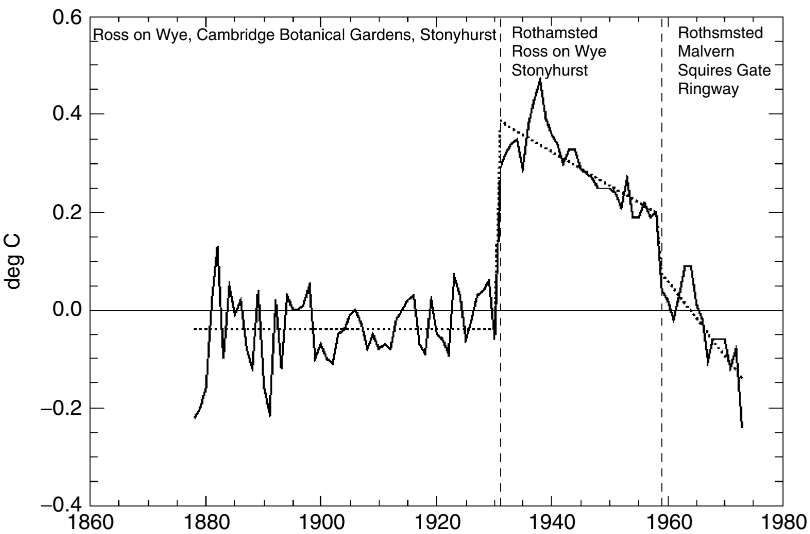

Figure 1. Annual average adjustments applied to the daily CET_{mean} series to make it compatible with Manley's monthly series over 1878 to 1973 (Parker *et al.*, 1992). The dotted line indicates the mean adjustment (1878–1930) or the trends in adjustments (1931 onwards) and the vertical dashed lines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

their mean value or their slowly varying trends, which are taken to reflect real, consistent or slowly varying differences between stations. So, we detrended the adjustments when they showed significant trends (i.e. in 1931–58 and 1959–73, but not for 1878–1930; Figure 1) before using their standard errors as estimates of the uncertainties. The uncertainties arising from the fixed adjustments used since 1974 were calculated from the standard errors of the original monthly adjustments for 1959–73. These are appropriate estimates because the post-1974 adjustments are based on a multi-year average largely coinciding with 1959–73. Up to 1958, estimated calendar monthly (annual) standard errors were typically 0.015 to 0.03 °C (0.01 °C). Thereafter, calendar monthly standard errors were typically 0.025 to 0.045 °C; annual standard errors were estimated as 0.014 °C for 1959–73 and 0.022 °C subsequently. Values are tabulated in full by Parker and Horton (2005).

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 = adjusted CET_{mean} − (unadjusted CET_{max} + unadjusted CET_{min})/2. The adjustments were added equally to CET_{max} and CET_{min}. Only up to 1930 did the adjustments differ from those for CET_{mean}, because only then did the stations used differ (Table I). However, even then the uncertainties differ little from those for CET_{mean} (Parker and Horton, 2005). All these calendar monthly uncertainties, expressed as variances, need to be added to the error variances of the daily data estimated in Section 2.

3.2. Correction of urbanization bias since 1974

From 1960 to 1973, Manley (1974) subtracted 0.1–0.2 °F from the Oxford Radcliffe Observatory mean temperatures in most months before calculating CET_{mean}, to account for urbanization. For 1974 onwards, Legg (1989) calculated urbanization adjustments to CET_{mean} by comparing the monthly CET_{mean} series with a rural version over the period 1959–86. The urbanization adjustments were expressed as linear trends and extrapolated forwards in time. They were zero for each calendar month until 1980, when they became −0.1 °C in May, June and July; they reached −0.2 °C in all calendar months by 2003 (Parker *et al.*, 1992: Table VI). When the CET_{max} and CET_{min} series were calculated, Legg's urbanization adjustments were doubled for CET_{min}, but no urbanization adjustments were made to the CET_{max} series. This choice was made because urbanization is known to affect minima much more than maxima (Johnson *et al.*, 1991; Arnfield, 2003), but has subsequently been changed, as discussed in Section 6.3.

To investigate the uncertainty associated with adjustments for urbanization, we used the rural T_{mean} series over the period 1959–86: one of the constituent stations, Luddington, closed in 1986, so it was not possible to extend the rural series further. We also calculated rural T_{max} and T_{min} series for the same period. First, to test for bias, 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, suggesting that, up to 1986, the urbanization adjustments for each of CET_{mean}, CET_{max} and CET_{min} were valid.

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 urbanization adjustment applied to the CET_{mean} series during 1974–86 (92 months); and (c) months that had −0.1 °C urbanization adjustments applied to the CET_{mean} series during 1974–86 (64 months). The error variance (standard error squared) of the differences (CET minus 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 arising from the urbanization 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 (Table V). Subtracting variances shows that, after 1974, there is urbanization uncertainty of 0.013 °C for all unadjusted months and 0.025 °C for all months adjusted by −0.1 °C. This 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, we assume that the urbanization uncertainty variance is proportional to the squared size of the urbanization adjustment, giving an uncertainty of 0.046 °C whenever the urbanization adjustment to CET_{mean} is −0.2 °C (Table V). Table V also summarizes the urbanization

Table V. Uncertainties arising from the urbanization adjustments u. The classification of months is defined by Parker *et al.* (1992: Table VI), e.g. in January $u = 0$ through 1981, $u = -0.1\,^{\circ}$C in 1982–98 and $u = -0.2\,^{\circ}$C thereafter. The statistics were estimated using comparisons with rural stations as described in the text

	Standard error A 1959–73	All months with $u = 0$		All months with $u = -0.1\,^{\circ}$C		All months with $u = -0.2\,^{\circ}$C
		Standard error B	Uncertainty $C = (B^2 - A^2)^{0.5}$	Standard error D	Uncertainty $E = (D^2 - A^2)^{0.5}$	Uncertainty $F = [C^2 + 4(E^2 - C^2)]^{0.5}$
CET_{mean} (°C)	*0.015*	*0.020*	0.013	*0.030*	0.025	0.046
CET_{max} (°C)	*0.017*	*0.020*	0.011	*0.022*	0.015	0.024
CET_{min} (°C)	*0.023*	*0.028*	0.018	*0.045*	0.039	0.071

uncertainties for CET_{max} and CET_{min}. The urbanization uncertainties also contribute to the error bars on the daily data.

4. AREAL SAMPLING ERROR e_S

For the period since 1878, CET is based on three or four stations (Table I). We calculated the areal sampling standard errors on daily, monthly and annual time scales, 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 equation of Jones *et al.* (1997) to calculate the areal sampling standard error SE^2 arising from incomplete sampling of the CET region:

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

where $\overline{r}$ is the average of the correlations of each station with every other station, n is the number of stations, and $\overline{s_i^2}$ is the constituent station variance given by

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

where $\hat{S}$ is the 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 this mean has only slightly lower variance because the two stations are highly correlated.

Both the variance and $\overline{r}$ exhibit seasonality, with increased variance during the winter half year and decreased $\overline{r}$ 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 $\overline{r}$ is the controlling factor.

The estimated monthly areal sampling standard errors are typically 0.2 °C for CET_{mean} and 0.25 °C for CET_{max} and CET_{min}. On annual time scales, they are 0.06 °C for CET_{mean} and 0.1 °C for CET_{max} and CET_{min}. Calendar monthly and annual estimates are tabulated in full by Parker and Horton (2005). Statistics applicable to the stations used before 1959 are based on 1931–60; statistics for the more recent set of stations are based on 1961–90, but differences between the two periods are not large.

The daily areal sampling standard errors for each month are also tabulated in full by Parker and Horton (2005). 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. The estimated daily areal sampling standard errors are typically 0.6 °C for CET_{mean}, 0.7 °C for CET_{max} and 0.8 °C for CET_{min}. Daily areal sampling uncertainties for the period since 1959, when four stations were used, are all lower than before 1959.

Areal sampling 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 (Parker and Horton, 2005: tables 8 and 9).

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. For annual CET_{mean} and CET_{max} the total uncertainties are close to 0.09 °C and 0.13 °C respectively (Parker and Horton, 2005: Table 10). For annual CET_{min}, total uncertainties are 0.15 °C until 1958, then 0.10 °C until a recent rise to 0.13 °C owing to the urbanization uncertainty. The uncertainties in annual CET_{mean} are shown as $\pm 2\sigma$ error bars on the annual time series in Figure 2, in which 2004 is included with the same error range as 2003 (see Section 7). To estimate whether differences D between years are statistically significant, we scale D 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 of the individual years. The difference is significant if $n_d > 1$. For $\sigma_1 = \sigma_2 = 0.09$ °C, D must exceed 0.25 °C to be significant. Clearly, the differences between the recent warm years are not statistically significant, and statements such as '2003 was equal sixth 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 1878–2004.

The temperature trend for 1900–2004 has been calculated from the annual values in Figure 2 using the restricted maximum likelihood technique (REML; Diggle *et al.*, 1999) to take account of the uncertainties of the annual values and to allow for autocorrelation in the residuals from the fit. The best estimate, 0.077 °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, despite the uncertainties in annual mean CET. This is because the uncertainties in CET are not coherent on long time scales. For example, calibration biases vary on time scales of a few years because thermometers are changed; urban warming biases have been compensated for and their uncertainties (Table V) are much smaller than the integrated trend since 1900 (0.80 °C). If the REML is applied to the series in Figure 2, but with the annual uncertainties constrained to be zero, then the $\pm 2\sigma$ error range of the trend remains ± 0.040 °C

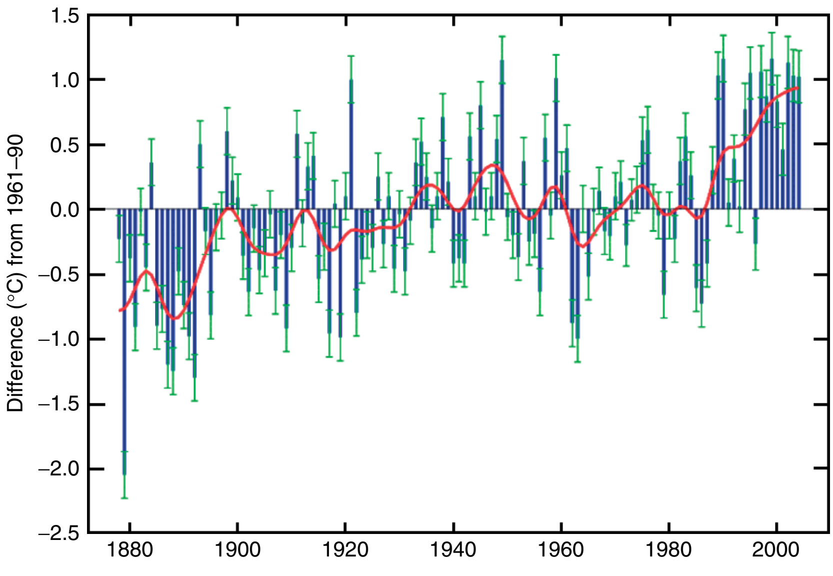

Figure 2. Annual anomalies in CET_{mean} for 1878 to 2004 (relative to 1961–90) including error ($\pm 2\sigma$) bars

per decade (with a decline only in the next decimal place). The uncertainty in the trend arises almost entirely from the interdecadal variability of CET, which increases the autocorrelation of the residuals and so reduces the effective number of degrees of freedom underlying the estimated trend. The trend in annual mean CET slightly exceeds the global trend of $0.061 \pm 0.019\,^{\circ}$C per decade for the same period estimated from the combined land-air and sea-surface temperature 'HadCRUTv' dataset (Parker *et al.*, 2004).

The daily uncertainties can be used to illustrate how confident we can be that a record has been broken. For example, the warmest CET_{max} on record in occurred on 16 April 2003 and exceeded the previous warmest April CET_{max} in 1893 by 1.3 °C after the adjustments applied in Section 6. However, because $\sigma_1 = 0.77\,^{\circ}$C (for 2003) and $\sigma_2 = 0.81\,^{\circ}$C (for 1893), $n_d = 0.58$ and the difference is not significant.

6. FURTHER SYSTEMATIC ADJUSTMENTS TO CET_{max} AND CET_{min}

In this section we test for biases in CET_{max} and CET_{min}. As a result of these tests, we make systematic adjustments to CET_{max} and CET_{min} up to 1921 and since 1980. These analyses and changes are independent of the foregoing analyses of uncertainty in CET.

6.1. Compensation for biases at Ross-on-Wye up to 1921

The adjustments to make daily CET_{max} and CET_{min} agree with Manley's monthly means (Section 3) were added equally to CET_{max} and CET_{min}. This procedure assumed equal overall biases in T_{max} and T_{min}. However, Figure 3(a) shows large warm biases in T_{max} in summer at Ross-on-Wye until the early 1920s, whereas there were no similar biases in T_{min} (not shown). Here, we estimate and apply adjustments to 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 lowered CET_{max}, raised CET_{min} by the same amount (see below), and reduced the apparent cold biases in T_{max} at the other two stations in Figure 3(a) before the early 1920s.

Suppose that three stations ($i = 1, 2, 3$) had biases b_{xi} in T_{max} and b_{ni} in T_{min}. Then the biases in their T_{mean} were $0.5(b_{xi} + b_{ni})$. Now suppose that, because the sites used differed from those used by Manley (1974), the true average T_{mean} of the three sites differed 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

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

However, the adjustments should have been

$$a_1 = -(b_m + \sum b_{xi}/3) \quad (2a)$$

to CET_{max} and

$$a_2 = -(b_m + \sum b_{ni}/3) \quad (2b)$$

to CET_{min}. So the CET_{max} series needed to be further adjusted by

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

and the CET_{min} series by

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

The sum of a_x and a_n is zero, i.e. CET_{mean} is unchanged.

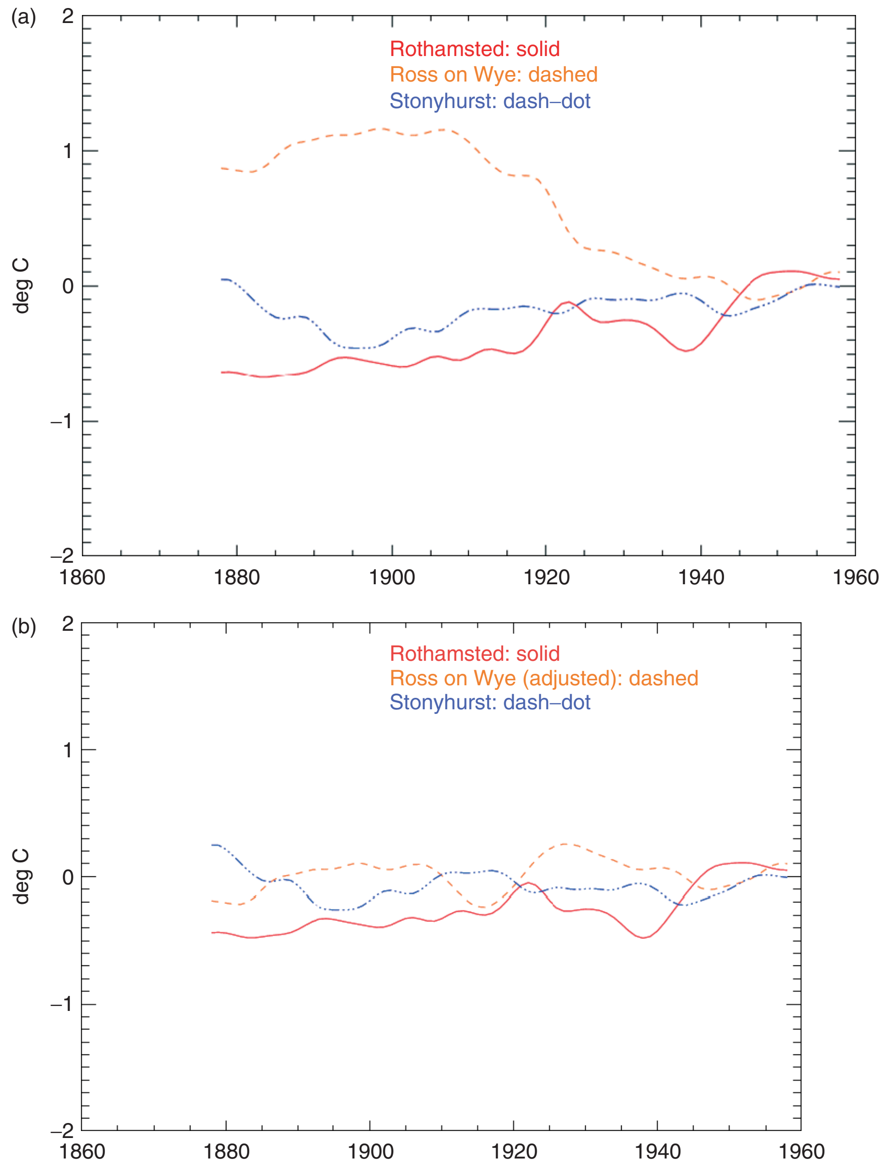

Figure 3. (a) April to September average unadjusted T_{max} anomalies relative to unadjusted CET_{max}. Yearly values are smoothed with a 21-point binomial filter. A 1941–70 reference period is used because Ross-on-Wye closed temporarily in the 1970s. (b) As (a), but after adjustment of the Ross-on-Wye T_{max} and CET_{max} series

We calculated the Ross-on-Wye biases b_{x1} and b_{n1} using average calendar monthly offsets from unadjusted CET, i.e. $b_{x1} - a_x$ and $b_{n1} - a_n$, for 1878–1921. We did this using anomalies relative to 1941–70, because Ross-on-Wye subsequently closed for several years. We assumed that the other two stations were unbiased. Because the offsets in Ross-on-Wye T_{min} minus CET_{min} were small in March to October, we counted them 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 they are not coherent through the seasonal cycle so we did not treat these here. Unfortunately, we do not have access to a station history for Ross-on-Wye.

The adjustments to CET_{max} (CET_{min}) for 1878–1921 were −0.2 °C (0.2 °C) in April to September and −0.1 °C (0.1 °C) in the remaining months, after rounding down to the next 0.1 °C to prevent an excessive reduction of DTR (see Section 6.3). Application of the adjustments to the CET_{max} and Ross-on-Wye T_{max} series yielded a CET_{max} series that is also consistent with the T_{max} series from the other two stations (Figure 3(b)), supporting our assumption that the Rothamsted and Stonyhurst T_{max} series are homogeneous. The adjusted series of annual T_{min} relative to CET_{min} show the biases at Ross-on-Wye between 1920 and 1945 (Parker and Horton, 2005) but are otherwise homogeneous. The series of CET_{max} and CET_{min} now issued include these adjustments.

6.2. Urban warming at Oxford Radcliffe Observatory

Figure 4 shows that Oxford Radcliffe Observatory T_{min} has risen relative to CET_{min}, but that most of the rise has been since the mid 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 (note the debate between Smith (1975) and Manley (1975)). Oxford Radcliffe Observatory data are not used directly in the daily CET_{mean}, CET_{max} and CET_{min} series (Table I), and we do not propose any changes to the CET record arising from urban warming at Oxford Radcliffe Observatory.

6.3. Urban warming since 1974

When the CET_{max} and CET_{min} series were originally calculated, Legg's (1989) adjustments were doubled for CET_{min}, but no adjustments were made to the CET_{max} series (Section 3.2). The adjustments to CET_{min}, therefore, were $-0.4\,°C$ in all months by 2003 and DTR was increased by this amount relative to the original station data. The solid line in Figure 5 shows annual anomalies of DTR based on the original CET_{max} and CET_{min} series. April to September and October to March series show similar features (Parker and Horton, 2005). When we adjusted CET_{max} and CET_{min} to compensate for biases at Ross-on-Wye (Section 6.1), the DTR up to 1921 was reduced, as shown by the dashed line in Figure 5, yielding effectively constant DTR on multidecadal time scales before the 1980s. The subsequent increase in DTR then appeared to be exceptional in a historical context. The increase in sunshine in the UK in recent decades (Parker *et al.*, 2004) is consistent

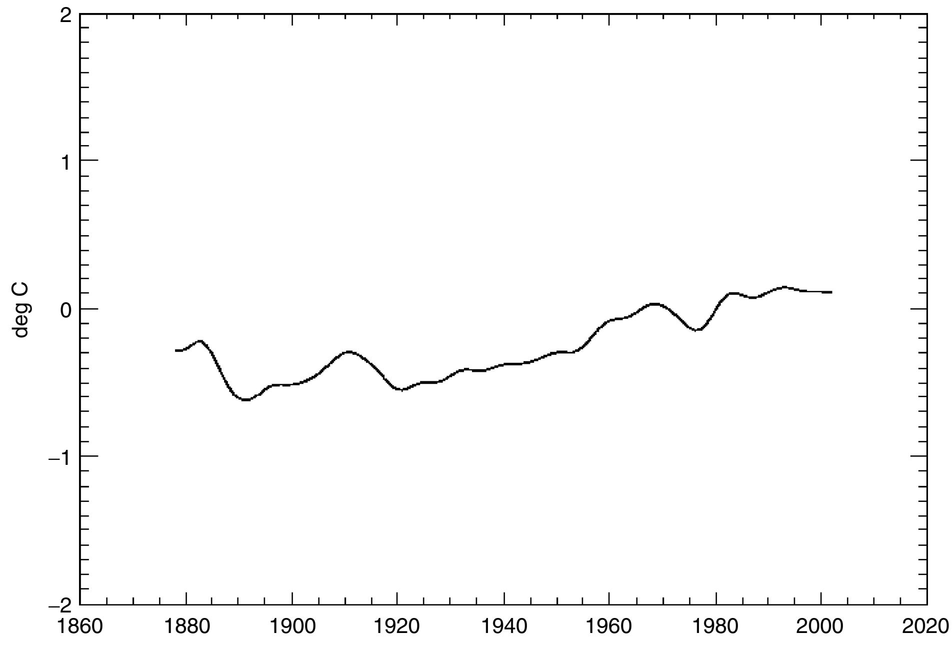

Figure 4. Annual T_{min} anomalies, relative to 1961–90, at Oxford Radcliffe Observatory, relative to CET_{min}. The Oxford temperatures include the adjustments applied by Knox-Shaw and Balk (1932) to the monthly data ($-0.3\,°F \approx -0.17\,°C$ to pre-1923 T_{min}); Manley (1974) used the adjusted data. The CET_{min} series used has been adjusted to compensate for biases at Ross-on-Wye, and incorporates the revised urban warming adjustments from Section 6.3. Values are smoothed with a 21-point binomial filter

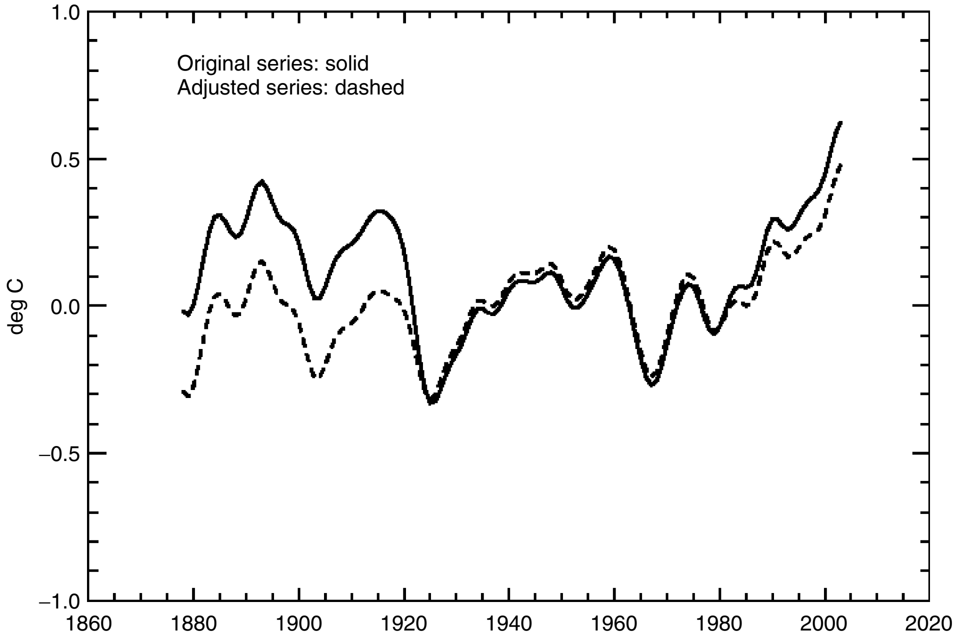

Figure 5. Annual central England DTR anomalies (relative to 1961–90), smoothed approximately decadally with a 21-point binomial filter, before and after the adjustments to CET_{max} and CET_{min} described in Sections 6.1 and 6.3. The small offset in the adjusted curve in the period 1922–79 when no changes were made to CET_{max} or CET_{min} arose from changes to the 1961–90 climatology of CET_{max} and CET_{min} when the post-1980 data were adjusted (Section 6.3)

with an increase in DTR, but Jones and Lister (2004) did not find an increase in DTR at stations in Scotland and Northern Ireland. So the recent increase in DTR shown by the solid line may be too great. The strong balance of evidence remains for a greater urban effect at night than by day (Arnfield, 2003), but there is also some evidence for daytime urban warming (Gallo and Owen, 1999; Arnfield, 2003), the details of which depend on the characteristics of the surface (Arnfield, 2003; Peterson, 2003). Therefore, we amended our previous adjustments, now apportioning 75% of the urban adjustment to CET_{min} and 25% to CET_{max} rather than 100% to CET_{min}. This reduced the recent rise in DTR by 0.2 °C, as shown by the dashed line in Figure 5. 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. We consider that the new adjustments, although still somewhat arbitrary, are optimal in view of the overall evidence on urban heat islands and the unavailability of reliable, updated data for rural sites near Malvern and Ringway.

The one-sigma uncertainty in annual DTR, being the square root of the summed error-variances of CET_{max} and CET_{min}, approaches 0.2 °C (Section 5); thus, the data are inadequate for the task of estimating the magnitude of the recent increase of DTR. However, even if we had applied equal adjustments to CET_{min} and CET_{max} (which would be indefensible in view of the literature on urban heat islands) then there would still have been a recent rise in DTR to levels above those in the rest of the record.

6.4. Ringway and Rothamsted since 1990

Figure 6(a) 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 2003. 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 ±0.5 °C. The variability is in accord with expectation, because the estimated annual *station* uncertainty for T_{max} exceeds that for CET_{max} and is about 0.23 °C (Table VI). An apparent anticorrelation between Squires Gate and Malvern may be real; for example,

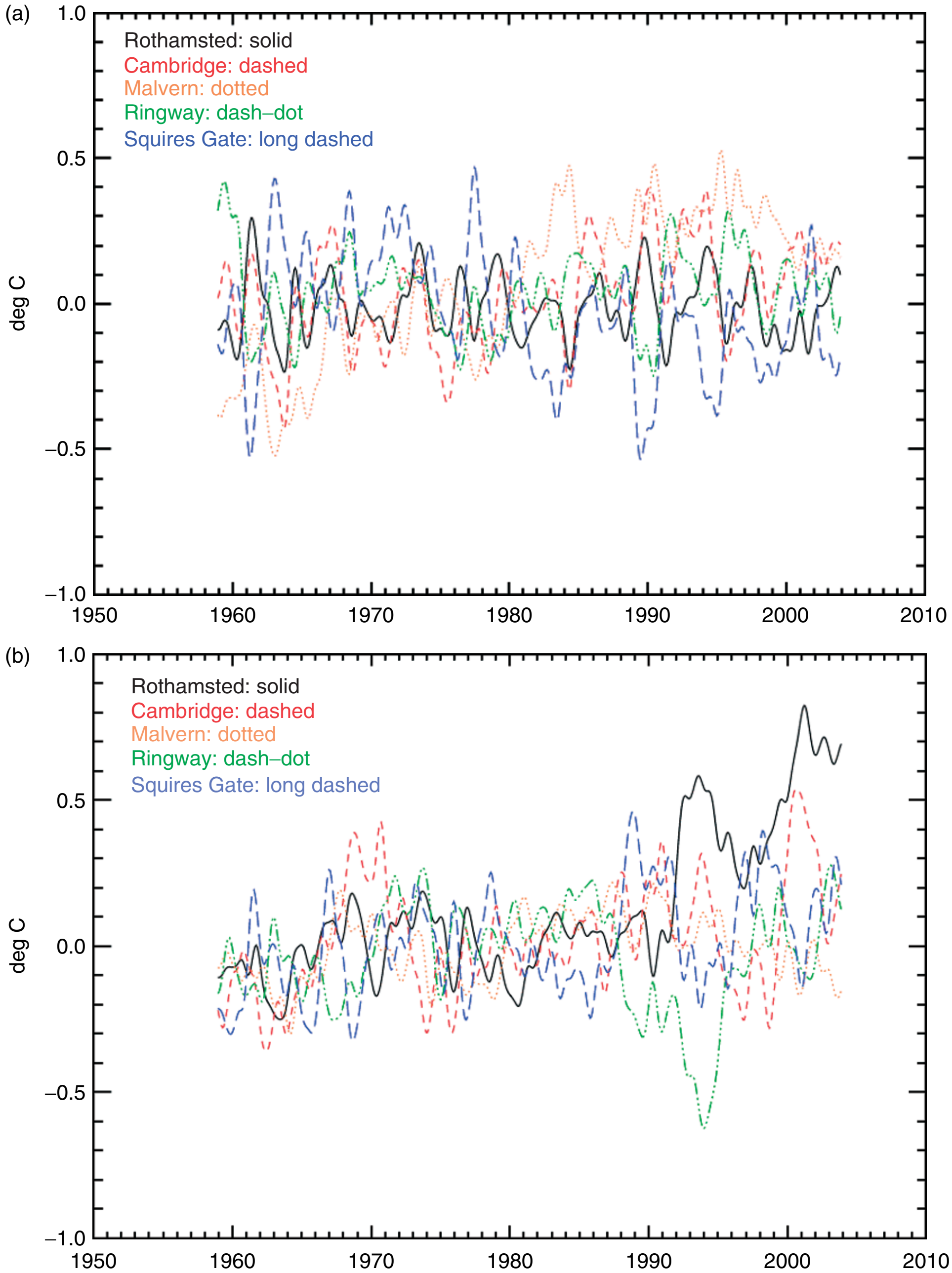

Figure 6. Anomalies (relative to 1961–90) of T_{max} at five stations relative to CET_{max}, 1959 to 2003. The CET_{max} series used incorporates the revised urban warming adjustments from Section 6.3. Plots are monthly anomalies smoothed with a 61-point binomial filter. (b) As (a), but for T_{min}

with westerly winds in spring and summer Squires Gate will be cool owing to the sea upwind, whereas Malvern will be warm owing to mountains upwind. In addition, the curves for CET stations in Figure 6 are expected to be weakly anticorrelated because they are differences from the composite average.

The relative rising trends of station T_{min} relative to CET_{min} in recent years (Figure 6(b)) are because no urban warming adjustments have been applied to the station data shown here. Furthermore, the scatter between stations, is not unexpected in view of the estimated annual station T_{min} uncertainties (again $\sigma \approx 0.23\,^{\circ}C$)

Table VI. Expected standard errors of annually averaged single-station T_{max} and T_{min} for 1959 to 2003

	T_{max} (°C)	T_{min} (°C)
Calibration (Section 2.1)	0.15	0.15
Precision (Section 2.2), $\sqrt{(0.026/365)}$ then $\sqrt{(0.00083/365)}$	<0.01	<0.01
Random screen (Section 2.3), $\sqrt{(0.068/365)}$ and $\sqrt{(0.096/365)}$	0.01	0.02
Urbanization (Table V; column $F \times 2$ because we used four 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

derived in Table VI. So, the coldness of Ringway around 1993 and the warmth of Rothamsted around 1993 and 2001–03 may not be spurious. Also, Rothamsted T_{min} is partly supported by Cambridge, and Ringway T_{min} is partly supported by Squires Gate.

6.5. Automation

All the CET data up to the end of October 2004 have come from liquid-in-glass thermometers, except Ringway from March 1998 and Rothamsted from September 1999, when automated electronic thermometry was installed. Data recorded from these instruments are 1 min means with a precision of 0.1 °C. Owing both to this finite data interval and to the sensor-response time constant, the data could be expected to underestimate the true T_{max} and overestimate the true T_{min}. Furthermore, the liquid-in-glass thermometers may have a different response time constant than the electronic sensors. For monitoring climate, changes in the effective time constant (which for automated instrumentation depends on both the sensor response characteristics and the data-logging interval) may be important. So, before electronic thermometry was installed, a 2 year trial comparison of electronic with liquid-in-glass T_{max} and T_{min} was made at 49 locations in the UK (Allott, 1999). T_{max} was, on average, only 0.02 °C lower in the electronic system than in the liquid-in-glass thermometers; for T_{min}, the averages were identical. Therefore, we make no adjustments to T_{max} or T_{min} on this score.

7. CONCLUSIONS

Contributions from different sources to uncertainties in CET are summarized in Table VII. The largest contribution to the uncertainty in CET on all time scales up to annual arises from the areal sampling error. For annual CET, the calibration error is comparable to the areal sampling error, whereas other random and systematic errors are much smaller. For the monthly series, the calibration error also comes second to the areal sampling error. For the daily series, the random thermometer precision and screen errors are next most important after the areal sampling error. As expected, annual CETs are the least uncertain, with daily CETs being the most uncertain. 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 CET and applied adjustments of up to ±0.2 °C up to 1921 to compensate for biases at Ross-on-Wye. The mid-20th century CET record appears to be homogeneous, but we have reapportioned the urban warming adjustments applied from 1980 onwards 25% : 75% to CET_{max} and CET_{min} instead of entirely to CET_{min}. These changes yield a more homogeneous series of DTR. Scatter

Table VII. Approximate typical contributions to standard errors of uncertainty in CET

	CET_{mean} (°C)	CET_{max} (°C)	CET_{min} (°C)
Calibration (Section 2.1, all time scales)	0.06	0.09	0.09
Precision and random screen errors (Sections 2.2 and 2.3)			
Daily	0.1	0.2	0.2
Monthly	0.02	0.03	0.03
Annual	0.007	0.008	0.009
Adjustments for systematic differences between stations (Section 3.1)			
Daily and monthly	0.03	0.03	0.03
Annual	0.02	0.02	0.02
Urbanization (Section 3.2, all time scales)	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

in anomalies of T_{max} and T_{min} between the constituent stations used since 1959 is not greater than expected, given the estimated uncertainties.

On 1 November 2004, Squires Gate and Ringway were replaced by a new automated station at Stonyhurst, owing to closure of Ringway. We took account of systematic differences in CET_{max}, CET_{mean} and CET_{min} in each calendar month by using parallel observations made during 2001–04. We also plan to replace Malvern by an automated, more rural station at Pershore when adequate parallel observations have been made and analysed.

ACKNOWLEDGEMENTS

Chris Folland, Simon Tett and two anonymous referees provided helpful comments. Jen Hardwick and John Kennedy provided graphics software. The UK Government Meteorological Research programme supported the authors' work. This paper is British Crown Copyright.

REFERENCES

Allott T. 1999. Comparison of conventional and electronic air temperature thermometry. Observations, Plans and Requirement (OPR) Climate Studies Memorandum No. 10, Met Office, Exeter, UK.

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.

Folland CK, Salinger MJ, Jiang N, Rayner NA. 2003. Trends and variations in South Pacific island and ocean surface temperatures. *Journal of Climate* **17**: 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, Lister D. 2004. The development of monthly temperature series for Scotland and Northern Ireland. *International Journal of Climatology* **24**: 569–590.

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*, Oxford University Press: 91–113.

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

Lin X, Hubbard KG, Walter-Shea EA, Brandle JR. 2001. Some perspectives on recent *in situ* air temperature observations: modeling the microclimate inside the radiation shields. *Journal of Atmospheric and Oceanic Technology* **18**: 1470–1484.

Manley G. 1946. Temperature trend in Lancashire, 1753–1945. *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.

Manley G. 1975. Reply to correspondence by Smith, CG on central England temperatures; monthly means of the Radcliffe Meteorological Station, Oxford. *Quarterly Journal of the Royal Meteorological Society* **101**: 387–389.

Met Office. 1879. Minutes of the Meteorological Council 1878–9. Met Office, Exeter, UK.

Met Office. 1880. Minutes of the Meteorological Council 1879–80. Met Office, Exeter, UK.

Parker DE. 2004. Large-scale warming is not urban. *Nature* **432**: 290.

Parker DE, Horton EB. 2005. Uncertainties in central England temperature 1878–2003 and some improvements to the maximum and minimum series. Hadley Centre Technical Notes **HCTN63.** http://www.met-office.gov.uk/research/hadleycentre/pubs/HCTN/index.html.

Parker DE, Legg TP, Folland CK. 1991. A new daily central England temperature series, 1772–1991. CRTN 11, Hadley Centre, Met Office, Exeter, UK.

Parker DE, Legg TP, Folland CK. 1992. A new daily central England temperature series. *International Journal of Climatology* **12**: 317–342.

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

Peterson TC. 2003. Assessment of urban versus rural *in situ* surface temperatures in the contiguous United States: no difference found. *Journal of Climate* **16**: 2941–2959.

Smith CG. 1975. Central England temperatures; monthly means of the Radcliffe Meteorological Station, Oxford. *Quarterly Journal of the Royal Meteorological Society* **101**: 385–387.

Wilks DS. 1995. *Statistical Methods in the Atmospheric Sciences*. Volume 59 in International Geophysics Series. Academic Press.

Yan Z, Jones PD, Moberg A, Bergström H, Davies TD, Yang C. 2001. Recent trends in weather and seasonal cycles: an analysis of daily data from Europe and China. *Journal of Geophysical Research* **106**: 5123–5138.