Anomalies of Central England Temperature Classified by Air Source

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ABSTRACT

Daily anomalies of mean central England temperature (CET), relative to daily 1961–90 climatology, are analyzed in terms of the source of the air estimated from fields of mean sea level pressure. The average CET anomaly for a given source and calendar month during 1961–90 is taken as an estimate of the influence of atmospheric circulation for that source and calendar month, and the uncertainty in this influence is provided by the associated standard error. The atmospheric circulation influences are subtracted from the daily CET anomalies since the late nineteenth century to yield “residual anomalies,” which represent the influence of forcings other than atmospheric circulation. The use of air sources captures more circulation-related daily CET variance than the airflow indices used in previous studies. The warming in central England since the 1970s is not predominantly a result of atmospheric circulation changes, and the long-term changes of CET for air from major source regions are on the whole very similar to each other and to the overall long-term changes.

1. Introduction

Regional and local temperature series such as central England temperature (CET) (Manley 1974; Parker et al. 1992; Parker and Horton 2005) and De Bilt, Netherlands, temperature (Brandsma et al. 2003) depend on atmospheric circulation, sea surface temperature, and natural and anthropogenic forcings external to the climate system as well as on local influences (Osborn et al. 1999; Osborn and Jones 2000, 2003; Sexton et al. 2003; van Oldenborgh and van Ulden 2003; Karoly and Stott 2006; van Ulden and van Oldenborgh 2006; van Oldenborgh 2007). The oceanic influences and the effects of external forcings would be more readily attributable if it were possible to compensate the temperatures for the influence of atmospheric circulation. Owing to the near-coastal continental location of De Bilt, van Oldenborgh and van Ulden (2003) were able to do this effectively for De Bilt using only wind direction as an index of atmospheric circulation. However, when Sexton et al. (2003) did this for CET, building on the work of Osborn and Jones (2000) and using near-surface wind direction, speed, and vorticity, they were unable to account for more than a third of the variance in daily CET at any time of the year during 1900–98. The present study uses an air-tracking technique that extracts atmospheric circulation influences from CET more effectively by determining air sources on a daily basis. This technique also enables ready calculation of the uncertainties in the atmospheric circulation influences, which was not done by Sexton et al. (2003). The improved estimates of atmospheric circulation influences, along with the uncertainties, will allow more rigorous attribution of anthropogenic influences on CET. The interpretation of extreme events in particular will be improved.

In this paper, CET anomalies are defined as differences from an annual cycle of 11-term binomially smoothed daily normals for the period 1961–90 (Jones et al. 1999). Residual anomalies of CET are estimates of what the CET anomaly would have been without the influence of atmospheric circulation. Residual CET is then defined as the smoothed 1961–90 normal CET plus the residual anomaly of CET. Residual CET may be calculated for daily maximum, minimum, or mean temperatures and averaged for months, seasons, and years. In this paper the focus is on daily mean temperatures and their longer-period averages.

Section 2 describes the air-tracking technique and section 3 demonstrates the ability of this technique to yield daily residual anomalies of CET. In section 4,
climatic variations of the residual anomalies are presented. Finally, section 5 discusses the potential for further development of these analyses.

2. Air tracking

Six-hourly (0000, 0600, 1200, 1800 UTC) mean sea level pressure (MSLP) fields for the area 25°–70°N, 70°W–50°E were extracted from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) for 1961 onward. In addition, daily-average mean sea level pressure fields for the same area from 1871 to 2003 were taken from the European community funded European and North Atlantic Daily to Multi-decadal Climate Variability Project (EMULATE) (Ansell et al. 2006) MSLP (EMSLP) dataset. These datasets, on a 5° latitude × 5° longitude grid (an example point being 50°N, 5°W), were used to track air back from central England.

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<th>Technique</th>
<th>Period</th>
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<td>(g) EMSLP track 2d</td>
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<td>(i) Sexton et al. (2003)</td>
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FIG. 1. January mean CET anomalies relative to 1961–90 (°C) by air source for (a) 1900–98 based on EMSLP, (c) 1961–90 based on EMSLP, and (e) 1961–90 based on NMSLP. (b), (d), (f) The corresponding air-source counts in days. Two-day tracking was used throughout.
The fields for the target date and the preceding dates were used to calculate geostrophic surface winds for tracking the air. Although near-surface winds are to varying extents subgeostrophic and cross-isobaric, winds above the surface layer are more nearly geostrophic, and heat advected above the surface layer will be transferred to the surface by turbulent and radiative processes. The air was tracked back in 6-h steps from central England (52.5°N, 1.8°W) to its location 1–6 days previously or, if more recent, when it entered the area 35°–65°N, 50°W–30°E. The air locations or “sources” were classified into 48 5° latitude × 10° longitude boxes: 60°–65°N, 40°–50°W; 60°–65°N, 30°–40°W; ... 60°–65°N, 20°–30°E; 55°–60°N, 40°–50°W; ... 35°–40°N, 20°–30°E. For each class in each calendar month, the mean daily CET anomaly in a reference period such as 1961–90 or 1900–98 [because that was used by Sexton et al. (2003)] was calculated and subtracted from the anomaly for each individual day in that class and calendar month to form residual anomalies.

The NCEP–NCAR reanalysis MSLP (NMSLP) fields were first used to determine the optimum tracking period, defined as that which maximized the proportion of variance in daily CET during 1961–90 explained by the class-average daily CET anomalies. Rows a–f of Table 1 show the percentages of variance explained for each calendar month for 1–6 day tracking: 2-day tracking was found to capture most variance, so that was adopted. When using NMSLP, the first field used was for 0600 UTC on the target day because its validity can be assumed to extend to 0900 UTC, which is between the typical times of minimum and maximum temperature, so that it is representative of daily mean CET. When using the daily-average EMSLP fields, the first two steps used the MSLP field for the target date; the next four steps used the MSLP field for the previous day, and so on, because the fields are nominally for 1200 UTC.

3. Daily residual anomalies of CET

Figures 1–4 show for January, April, July, and October, respectively, mean CET anomalies (°C) by air source class: for 1900–98 based on EMSLP (Figs. 1a,b; 2a,b; 3a,b; and 4a,b), for 1961–90 based on EMSLP (Figs. 1c,d; 2c,d; 3c,d; and 4c,d), and for 1961–90 based on NMSLP (Figs. 1e,f; 2e,f; 3e,f; and 4e,f). The temperature patterns are generally consistent between the three samples, despite the differences in air-source distribution even between the alternate 1961–90 samples. Comparison of rows b and g of Table 1 shows that EMSLP-based 2-day tracking captures on average only about 1% less daily CET variance than NMSLP-based 2-day tracking, but the
variance capture is reduced by typically a further 5% when the period 1900–98 is analyzed. This is likely to reflect sparser data inputs to EMSLP in the earlier years and some overfitting in the 1961–90 analysis because the sample is smaller.

Nevertheless, rows h and i of Table 1 demonstrate that, for 1900–98, the air-tracking technique using EMSLP was much more effective in explaining daily CET anomaly variance than the Sexton et al. (2003) local air circulation technique. Air sources account for between 33% (June) and 54% (January) of the variance of daily CET anomalies. The better fit is not a result of the use of more fitting parameters because 48 classes were used here whereas Sexton et al. (2003) used 50–55 effective fitting parameters (see their Fig. 2b). For 1881–1993, Osborn et al. (1999), like Sexton et al. (2003) for 1900–98, captured only about 30% of daily CET variance in winter, and about 20% in other seasons, using daily airflow indices (direction, strength, and vorticity) calculated using a 5° latitude × 10° longitude grid centered over the United Kingdom.

For 1900–98, the standard errors of the calendar monthly mean anomalies for individual EMSLP-based classes were 0.5°C or less in every calendar month for 17 well-sampled boxes; they exceeded 1°C in some calendar months for 20 more rarely sampled boxes, mainly over central and eastern Europe or the Mediterranean. In contrast, for the smaller 1961–90 sample using EMSLP (NMSLP), standard errors were always 0.5°C or less in only 6 (3) boxes and sometimes exceeded 1°C in 21 (22) of the 48 boxes. The slightly greater uncertainties in the NMSLP-based analysis arose because more boxes were sampled (Figs. 1–4f), leading to a greater number of small samples. These standard errors represent uncertainty estimates for the influence of atmospheric circulation on daily mean CET, including misclassifications owing to imperfect tracking. They take account of the serial correlation of the daily CET anomalies for the individual air-source classes, using Eq. (3.1b) of Trenberth (1984). If the sample size was 2–4, the sample standard deviation was used as the standard error.

Table 2 indicates that, for 1961–90, EMSLP and NMSLP yielded identical sources on about 25% of days, sources differing substantially (i.e., by 10° or more of latitude or 20° or more of longitude) on about 15% of days and sources differing slightly (i.e., by 5° of latitude and/or 10° of longitude) on the remainder. Thus, tracking using 6-hourly geostrophic flow estimated from 24-hourly EMSLP data is a useful but approximate tool. For further discussion, see appendix A.

The air temperature in central England will be influenced by its three-dimensional route from its source as well as by the actual source. An interesting example is for the last three days of May 1997, when the CET anomalies were +1.0°C, +3.3°C, and +3.0°C. With
2-day tracking using NMSLP, which yielded a source over the eastern North Sea, the CET residual anomalies were +1.2°C, +2.2°C, and +1.9°C, but with 5-day tracking, yielding a source north of 60°N, the CET residual anomalies were +2.7°C, +5.0°C, and +4.7°C. Thus the air was much warmer than expected for a northern source. Stohl and Trickl (1999) show, in their Plate 1, that the air had descended from the upper troposphere in an anticyclonic circulation. A two-dimensional tracking scheme cannot capture such features, but there may be a risk of statistical overfitting in a corresponding 3D tracking scheme (see discussion in section 5). Variations of the route of the air from its source will become more important for longer tracking times and are a likely reason for the decline in explained variance as tracking time increases beyond two days.

The direct influence of the air source is also expected to be limited by noncirculation factors influencing CET anomalies. These factors are expected to include anomalies of surface conditions at the source, en route, and in central England, for example, sea surface temperature (SST) anomalies, snow cover, and soil moisture; increases in greenhouse gas forcing; and variations of cloud cover affecting the radiation balance in central England. The latter is most important in summer when monthly sunshine duration projects onto 35%–60% of the variance of monthly mean CET and 40%–60% of the variance of monthly mean CET residual anomalies (see

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**TABLE 2. Comparison of daily air sources during 1961–90 obtained using EMSLP and NMSLP. Numbers are counts of days.**

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<td>163</td>
<td>206</td>
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FIG. 4. As in Fig. 1 but for October.
appendix B): daily sunshine totals are not at present available for assessing their influence on daily CET.

Anomalies of SST and land surface conditions often develop as a result of atmospheric circulation patterns. For example, persistent mild southwesterly winds in winter result in above-normal SST around the United Kingdom. The SST anomaly will then augment the direct influence of persistent atmospheric circulation on CET so that the overall effect of atmospheric circulation on seasonal CET will exceed that directly resulting from each day’s circulation. Thus, the squared correlations $R^2_{op}$ between observed seasonal CET anomalies and those predicted from the daily atmospheric circulation will exceed the fractions $V_r$ of seasonal variance of CET captured by the daily atmospheric circulation types. This is discussed by Osborn and Jones (2000) and by van Oldenborgh and van Ulden (2003).

Table 3 shows that the values of $R_{op}$ based on daily air tracking exceed those of Osborn and Jones, in accord with the greater capture of daily variance, and

<table>
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<tr>
<th>Dec–Feb</th>
<th>Mar–May</th>
<th>Jun–Aug</th>
<th>Sep–Nov</th>
<th>Year</th>
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</thead>
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<tr>
<td>(a) $V_r$ (%) this study 1961–90</td>
<td>75</td>
<td>36</td>
<td>36</td>
<td>60</td>
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<td>(b) $V_r$ (%) this study 1950–99</td>
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<td>(c) $R_{op}$ this study 1961–90</td>
<td>0.94</td>
<td>0.60</td>
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<td>(d) $R_{op}$ this study 1950–99</td>
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<td>(e) $R_{op}$ Osborn and Jones (2000) 1950–99</td>
<td>0.78</td>
<td>0.47</td>
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<td>(f) $R_{op}$ this study 1904–2002</td>
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<td>(g) $R_{op}$ OU2003 1904–2002</td>
<td>0.86</td>
<td>0.52</td>
<td>0.76</td>
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**Table 3.** Effects on seasonal and annual variability of using daily residual anomalies instead of daily anomalies of CET. (a) Seasonal and annual variance $V_r$ captured by daily atmospheric circulation, this study 1961–90 using NMSLP for air tracking; (b) $V_r$, this study 1950–99 using EMSLP for air tracking up to 1960 then NMSLP; (c) correlations $R_{op}$ between observed seasonal or annual temperatures and those predicted from atmospheric circulation, this study 1961–90 with air tracking as in (a); (d) $R_{op}$ this study 1950–99 with air tracking as in (b); (e) $R_{op}$ Osborn and Jones (2000), 1950–99; (f) $R_{op}$ this study 1904–2002 with air tracking as in (b); (g) van Oldenborgh and van Ulden (2003) (OU2003) but for De Bilt, 1904–2002.

Fig. 5. Anomalies (solid) and residual anomalies (dashed) of CET relative to 1961–90: (a) winter (January–December); (b) spring (March–May); (c) summer (June–August); (d) autumn (September–November). Residual anomalies were estimated using air sources derived from EMSLP for 1871–1960 and from NMSLP for 1961–2007 and are relative to air-source class average CET anomalies in 1961–90 based on corresponding pressure datasets. Smoothing uses a 21-term binomial filter. Full-record-length smooth curves were created by first extending the original series at each end by 10 terms, each containing the average of the initial (at the beginning) or final (at the end) original 10 terms. This technique approximates the “minimum slope” method of Mann (2004).
that the air-tracking \( R_{\text{op}}^2 \) exceed the corresponding \( V_r \), as in Osborn and Jones (2000), especially in winter, summer, and annually. Note that van Oldenborgh and van Ulden obtained greater \( R_{\text{op}} \) in summer and annually than in this study (Table 3), even though they only used wind direction. This is probably because wind direction is a better discriminant of continental versus maritime air at the near-coastal continental De Bilt site than in England, which is surrounded by sea.

This feedback with SST led van Ulden and van Oldenborgh (2006) to include a memory term with typically 0.5–1 month time scale in their model of De Bilt temperatures. The present approach, without a memory term, has the advantage of specifying the direct effects of air sources, which will be influential in, for example, short-term extremes of CET. The influence of SST, worldwide as well as local, can be treated separately at a subsequent stage of the attribution (Sexton et al. 2003).
4. Residual anomalies and climatic changes

Daily residual CET anomalies for 1871–2007 were averaged into monthly and annual residual anomalies to assess the contribution of atmospheric circulation to longer-term climatic variations. Air sources were derived from EMSLP for 1871–1960 and from NMSLP for 1961–2007. Because of systematic differences in air tracking (section 3, Table 2, and appendix A), EMSLP (NMSLP)-based CET residuals were always estimated using EMSLP (NMSLP) air-source mean CET anomalies. Some air-source boxes were not sampled in some calendar months during 1961–90 (Figs. 1–4); to enable calculation of residual CET anomalies for the occasions outside 1961–90 when these source boxes were sampled, the 1961–90 air-source class average CET anomalies for single or two consecutive missing calendar months were linearly interpolated in time within the same box; then remaining missing values (over 35°–40°N, 20°–30°E and 40°–45°N, 20°–30°E between May and September) were substituted from adjacent boxes at the same latitude.

The standard errors associated with the influence of atmospheric circulation on daily mean CET (section 3) were also combined into monthly, seasonal, and annual uncertainties, assuming that successive day uncertainties were independent. The daily uncertainties depend on air source and are greater for the more rarely sampled sources (section 3). Days with no calculable uncertainty (because the air source occurred less than twice in 1961–90) were accorded an uncertainty equal to the standard deviation of daily CET anomalies in the relevant calendar month during 1961–90, ranging from 2.1°C in
September to 3.4°C in January. So the monthly uncertainties were greater for months with more unusual air sources and were generally 0.1°–0.3°C (one standard error) in winter months and 0.1°–0.2°C in summer months. Seasonal uncertainties were 0.05°–0.13°C in winter, 0.04°–0.09°C, in spring and autumn, and 0.04°–0.13°C in summer. Annual uncertainties were 0.03°–0.05°C. These uncertainties should be combined in quadrature with the uncertainties in CET (Parker and Horton 2005) when calculating the uncertainties in CET residual anomalies or in CET residuals. For example, the typical uncertainty of 0.09°C in annual CET (one standard error; Parker and Horton 2005) combined with a circulation influence uncertainty of 0.03°C (as in 2006) yields an uncertainty of nearly 0.10°C in the annual residual anomaly of CET.

Comparison of long-term variations of anomalies and residual anomalies shows that atmospheric circulation can explain much of the decadal and multidecadal variation of CET in winter (Fig. 5a) and some of this variation in spring (Fig. 5b) in accord with van Oldenborgh and van Ulden (2003). The differences between anomalies and residual anomalies on these time scales are often much greater than the uncertainties in atmospheric circulation influence, which (dividing the typical individual seasonal uncertainties by $\sqrt{10}$) are of the order of 0.01°–0.04°C. However, the climatic changes in summer and autumn CET appear to have arisen from other causes than atmospheric circulation (Figs. 5c,d), and on an annual average (Fig. 6) the long-term influence of atmospheric circulation appears to be small compared with the climatic variations in CET anomalies (though much larger than the 0.01°–0.02°C uncertainties in decadal annual circulation influence). The spring and summer sequences match that of midlatitude North Atlantic SST (Fig. 7c). The summers in 1871–1910 would have been even cooler relative to the present but for atmospheric circulation favoring warmth.

If the influence of air sources had been augmented to match the seasonal CET anomaly versus air-source influence correlation (section 3 and Table 3), the residuals in winter (Fig. 5a) would have been nearly 10% further away from the anomalies, generally but not always bringing them toward zero. In summer they would be about 30% further away from the anomalies, making them generally further from zero before 1910. For the year as a whole, they would be about 20% further away from the anomalies, making them generally further from zero before 1910. For the year as a whole, they would be about 20% further away from the anomalies, making them generally further from zero before 1910. For the year as a whole, they would be about 20% further away from the anomalies, making them generally further from zero before 1910. For the year as a whole, they would be about 20% further away from the anomalies, making them generally further from zero before 1910. For the year as a whole, they would be about 20% further away from the anomalies, making them generally further from zero before 1910. For the year as a whole, they would be about 20% further away from the anomalies, making them generally further from zero before 1910. For the year as a whole, they would be about 20% further away from the anomalies, making them generally further from zero before 1910.
anomaly of $-0.25^\circ$C, had a residual anomaly of $+0.18^\circ$C. In other words, 1996 was only colder than average because the anomalous atmospheric circulation cooled it by an estimated $0.43^\circ$C ($\pm 0.03^\circ$C standard error).

The availability of daily air sources also allows analysis of climatic variations of CET for different air-source regions (Figs. 8 and 9). The uncertainties (one standard error, not shown) of any point in the smoothed seasonal plots in Fig. 8 were estimated assuming that individual standard errors of seasonal CET are typically $0.14^\circ$C (an estimate based on the method of Parker and Horton 2005) and then scaling this by $(N/N_{\text{eff}})^{0.5}$ in which $N$ is the number of days in a season (90.25 on average in winter, 92 in spring and summer, and 91 in autumn); $N_{\text{eff}} = \sum_{i=1,2,...}N_{i}(f/f_{\text{max}})$, where $N_{i}$ is the number of days in the air-source class (e.g., westerly) in the season under the $i$th term of the moving 21-term binomial moving filter that has terms $f_{i}$ with a central (maximum) value of $f_{\text{max}}$. The resulting error estimates have not been augmented to allow for persistence; that was already done implicitly by Parker and Horton (2005) through the spatial coherence of monthly and seasonal CET. Furthermore, the daily CET anomalies underlying the air source plots in Fig. 8 are not necessarily for successive days. Typical standard errors of the seasonal plots are $O(0.15^\circ$C) for the air-source class plots and $0.06^\circ$C for the all-days plots. A similar method was used to estimate the standard errors of the annual plots in Fig. 9, using the Parker and Horton’s (2005) estimate of $0.09^\circ$C for individual standard errors of annual CET. This yielded estimated standard errors typically $0.09^\circ$C for the annual air-source class plots and $0.04^\circ$C for the annual all-days plots. Recent warming $O(1^\circ$C) (which is highly statistically significant in view of the estimated standard errors) has affected air from all major air sources in all seasons (Fig. 8) as expected given the local and midlatitude North Atlantic increase of SST (Fig. 7). Climatic variations of temperature of the air from particular directions have generally been similar to the overall variations. One exception is that the coldness of autumn pre-1925 was associated with northerlies that were extra cold by about $0.25^\circ$C, whereas the westerlies at that time were extra mild relative to the all-days sample. Another exception is the marked fluctuations of the temperature anomalies of easterlies in spring. However, variations of temperature anomalies for easterlies in spring and autumn may, in principle, have been affected by redistributions of easterly events toward or away from those months when easterlies are associated with most positive anomalies, that is, May and September. A final exception is easterlies in summer, which were extra warm by about $1^\circ$C around 1930–50, matching very warm local sea surface temperatures in July–September (Fig. 7b). This feature is highly statistically significant in view of the estimated standard errors.

There is, however, structural uncertainty, in the results in Figs. 8 and 9, arising from the imperfection of the air-tracking technique (appendix A). This should be borne in mind when interpreting the plots, but the impacts are usually minor (cf. Fig. 8 with Fig. A1).

In the very warm year 2006, the average anomaly of central England temperature was $+1.34^\circ$C, whereas the average residual anomaly was $+1.25^\circ$C. Figure 10 and Table 4 show that residual anomalies were generally less negative or more positive than anomalies early in 2006 when the air often came from climatologically cold (continental) sources. In January 2006, residual anomalies exceeded anomalies by a greater margin than in February or March (Table 4), possibly because SST anomalies around the United Kingdom changed from positive in January to negative in February and March (Folland et al. 2006). In July and September 2006, when the air was from climatologically warm (lower latitude) sources, the residual anomalies were less positive than the anomalies but still strongly positive. The warmth of the North Atlantic Ocean (Fig. 7), arising from both natural variations in the meridional overturning circulation [i.e., the Atlantic multidecadal oscillation, Knight et al. (2006)] and increased greenhouse forcing, is likely to have been an underlying cause of the positive residual anomalies. But the persistent advection of warm air over the seas around the United Kingdom will have also raised SSTs locally, augmenting the residual anomalies (section 3). These high SSTs contributed to the exceptionally warm summer of 2006 in northwestern Europe (van Oldenborgh 2007).

<p>| Table 4. Monthly anomalies and residual anomalies of central England temperature ($^\circ$C), 2006. |
|---|---|---|---|---|---|---|---|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>Anomaly</th>
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<th>Feb</th>
<th>Mar</th>
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<th>Nov</th>
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<tr>
<td>Residual anomaly</td>
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<td>0.7</td>
<td>1.1</td>
<td>1.7</td>
<td>3.7</td>
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<td>3.2</td>
<td>2.4</td>
<td>1.5</td>
<td>1.8</td>
<td>1.34</td>
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<tr>
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</table>
5. Discussion

Residual anomalies could easily be calculated in the same way from daily maximum and minimum CET (CET$_{\text{max}}$ and CET$_{\text{min}}$) but starting the tracking 6 h later (earlier) for CET$_{\text{max}}$ (CET$_{\text{min}}$) than for daily mean CET when using the NMSLP 6-hourly fields. This refinement would not be optimal using EMSLP, which contains 24-h means, but the target day MSL pressure field could be used for three (one) 6-h steps instead of two.

Residual anomalies can also be calculated from U.K. vapor pressure series with the aim of, for example, attributing heat stress episodes. In a preliminary experiment, this was done for Rothamsted daily (0900 UTC) vapor pressures and NMSLP 6-hourly fields. The reduction of variance was greater than that obtained for CET for the same period and tracking in ten months and the same in two months (Table 5, compare with row b of Table 1).

The residual anomalies can readily be updated and made operational as the NCEP–NCAR reanalysis is updated in near–real time. An alternative procedure could be to use ECMWF analyses and the Met Office’s Numerical Atmospheric Dispersion Modeling Environment (NAME) model (Ryall and Maryon 1998), which is used operationally to track pollution episodes in three dimensions. Three-dimensional tracking is likely to be more accurate than single-level tracking in mountainous areas (Shadbolt et al. 2006) and in regions of dynamically induced vertical motion (Stohl and Trickl 1999). NAME uses the 40-yr ECMWF Re-Analysis (ERA-40) and subsequent operational analyses, and this would allow optimized determination of sources of air daily from 1958 to the present, and residual anomalies of central England temperature could be estimated in near–real time. NAME also estimates the uncertainty or spread in the track through turbulence and mixing. However, the substantial extra computational effort will yield only limited gains for climate analysis because no tracking can be done before 1958, whereas EMSLP extends into the nineteenth century and the NCEP–NCAR reanalysis goes back to 1948.1 Also, if elevation of air source is taken into account in addition to latitude and longitude, the solution is likely to be overfit if the short period of ERA-40 is used. Overfitting could possibly be avoided by using a simplified geographical scheme such as

$$T_{\text{anom}} = a_i \text{lat}_{\text{source}} + b_i \text{long}_{\text{source}} + c_i \text{lat}_{\text{source}} \text{long}_{\text{source}} + e_i \text{elev}_{\text{source}}, \quad (1)$$

where $i$ denotes the calendar month, but this would lose some geographical discrimination by comparison with

1 Accordingly, the EMSLP air-source estimates could be replaced by NCEP–NCAR reanalysis estimates for 1948–60, though the gain may be small because the early parts of the reanalysis have fewer input observations than the later parts and may therefore be less reliable.
the 48-box scheme. So a longer reanalysis would potentially yield more reliable statistics, and air tracking is a potential application of planned longer-term reanalyses based mainly on surface data (Compo et al. 2006).

Finally, given local daily data, this air-tracking technique can be applied anywhere in the world during the periods covered by the NCEP–NCAR reanalysis. However, the technique may be unreliable in mountainous regions where local and mesoscale winds are not resolved by existing reanalyses and where inversions disconnect the surface from the free atmosphere. Near the equator, where geostrophy is invalid, the tracking should be done with low-level free atmosphere winds instead of mean sea level pressure.

Acknowledgments. Tara Ansell provided access to EMSLP, Paul James provided access to the NCEP–NCAR reanalysis, and John Kennedy provided guidance on plotting software. Alistair Manning provided information on the NAME model. Daily dry- and wet-bulb temperatures for Rothamsted were provided by Gill Tuck of Rothamsted Research. Tim Osborn and Geert Jan van Oldenborgh provided very valuable comments as referees. This paper was supported by the Joint Defra and MoD Integrated Climate Programme GA01101, CBC/2B/0417_Annex C5, and is British Crown copyright.

APPENDIX A

Uncertainty in Air Sources

Figures 1–4 show that EMSLP yields fewer air sources than NMSLP in the boundary boxes; that is, the EMSLP-based winds are systematically slacker than those calculated from NMSLP. Because of this systematic difference, EMSLP (NMSLP)-based CET residuals were always estimated using EMSLP (NMSLP) air-source mean CET anomalies. If EMSLP air sources in 1961–90 were accorded NMSLP air-source CET anomalies averaged over 1961–90, the systematic difference in the tracking would lead to air-source frequency-weighted anomalies (i.e., the normalized dot products of Figs. 1d,e; 2d,e; etc.) of about 0.3°C in winter and 0.1°C in summer, instead of zero.

However, if the same MSLP dataset is used in the historical record as in the reference period, the choice of MSLP dataset leads to smaller structural uncertainties than are implied by the above 1961–90 offsets. Figure A1 shows an analysis of climatic variations of CET for different air source regions using EMSLP air sources throughout the EMSLP 1871–2003 time span. It should be compared with Fig. 8, which is the same up to 1960 but uses NMSLP air sources and 1961–90 air-source mean CET anomalies from 1961 to 2007. The 1961–2003 sections of Fig. A1 are similar to those of Fig. 8, but show, for example, stronger warming of winter easterlies around the 1970s and colder northerlies and westerlies and warmer easterlies in summer.

APPENDIX B

Central England Temperature and Sunshine Duration

Daily sunshine duration data are not available, but monthly durations for the English Midlands (Met Office climatological district 4) for 1929–2007, provided by the Met Office’s National Climate Information Centre, were used to assess the relationship between sunshine duration and monthly mean CET. Table B1 demonstrates that monthly sunshine duration projects onto nearly 60% of the variance of July monthly mean CET, and over a third of the variance in June and August. Relationships are not significant from October through to January and

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<th>Jan</th>
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<td>0.32</td>
<td>-0.06</td>
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</table>

Table B2. As in Table B1 but using monthly mean central England temperature residual anomalies based on EMSLP up to 1960 and on NMSLP thereafter.
are weak in February to May and in September. When monthly residual anomalies of mean CET were used to eliminate the direct influence of air sources, the significant results were strengthened (Table B2): monthly sunshine duration projects onto nearly 60% of the residual anomaly variance in July and over 40% in June and August.

REFERENCES


