NOTES AND CORRESPONDENCE

Evaluation of a Long-Term (1882–2005) Equivalent Temperature Time Series

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ABSTRACT

A 124 (1882–2005) summer record of total surface energy content consisting of time series of surface equivalent temperature (T_E) and its components T (mean air temperature) and Lq/c_p (moist enthalpy, denoted Lq) is developed, quality controlled, and analyzed for Columbus, Ohio, where long records of monthly dewpoint temperature are available. The analysis shows that the highest T_E occurs during the summer of 1995 when both T and Lq were very high, associated with a severe midwestern heat wave. That year contrasts with the hot summers of 1930–36, when Lq and T_E had relatively low or negative anomalies (low humidity) compared to those of T. Following the 1930–36 summers, T and Lq departures are much more typically the same sign in individual summers, and the two parameters develop a statistically significant high positive correlation into the twenty-first century. Mean T and Lq departures from the long-term normal have opposite signs, however, when summers are stratified either by seasonal total rainfall amounts or by the Palmer drought severity soil moisture index. Normalized trends of T, Lq, and T_E are downward from 1940 to 1964 with those of T_E exceeding T. Since 1965, however, significant positive T trends slightly exceed T_E in magnitude and those of dewpoint temperature and Lq are comparatively lower. A highly significant upward trend in minimum temperatures especially dominates the T variability, creating a significant downward trend in the temperature range that dominates recent summer climate variability more than moisture trends. Regional moisture flux variations are largest away from Columbus, over the upper Midwest and western Atlantic Ocean, during its seasonal extremes in total surface energy.

1. Introduction

The use of surface air temperature data is one of the cornerstones in the analysis of global change (e.g., Mann and Jones 2003; Jones and Moberg 2003). Air temperature, however, only measures the atmospheric dry static energy and is not a complete measure of the total surface energy content. Moist static energy is potentially a more comprehensive variable for analysis of global warming as it represents the total surface warming and energy content (Pielke et al. 2004). Moist static energy accounts for variations due to both air temperature and moisture content changes, and near the earth's surface (where $z \gg 0$) the total energy content per unit mass (h) can be written as

$$h = c_p T + Lq, \tag{1}$$

where T is the observed air temperature, L is the latent heat of vaporization (2.5×10^6 J kg^{-1}), and q is the specific humidity (g kg^{-1}). Following Haltiner and Martin (1957, p. 26) and Davey et al. (2006, hereafter DPG), we define the isobaric equivalent air temperature (T_E) at the earth's surface as

$$T_E = h/c_p, \tag{2}$$

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where c_p is the specific heat of air at constant pressure (1005 J kg^{-1} K^{-1}).

Few studies have analyzed total surface energy content using observational data. Pielke et al. (2004) show the annual cycles of T_E and T using 2 yr of Fort Collins, Colorado, data, illustrating that T_E exceeds T by a large amount during the summer growing season when the annual cycle in specific humidity peaks over the United States. DPG compared monthly T and T_E trends from 1982–97 at over 150 stations in the eastern United States and evaluated them in light of differing land surface conditions around each site. They found that T_E trends were generally the same sign as those of T with net warming in all seasons but autumn. The trends of T and T_E varied widely from station to station depending on land cover; sites dominated by grass and shrub had T_E trends exceeding those of T, while the converse occurred in dominantly forested and agricultural settings. Trends in T_E are likely related to recent observed increases in both summertime tropospheric water vapor content (Ross and Elliott 1996, 2001) and surface dewpoint temperatures (Sandstrom et al. 2004), potentially having economic and human impacts (Gaffen and Ross 1998; Sparks et al. 2002).

The purpose of this paper is to evaluate the long-term historical variability in summer total surface energy content and to compare it with variability occurring in surface air temperatures, rainfall, and measures of earth surface moistness. The analysis is performed on the long-term first-order weather service record (1882–2005) at Columbus, Ohio, which is used since we have access to its long-term moisture records, particularly dewpoint temperature and station sea level pressure data, needed for calculating mean values of moist enthalpy Lq/c_p (hereafter denoted Lq). The total surface energy content will also be evaluated in terms of its extreme values and its decadal-scale trends and will be placed in the context of regional moisture flux variability.

2. Data and methodology

a. Data

June–August maximum (T_{max}), minimum (T_{min}), and mean air temperature (T), as well as dewpoint temperature (T_d), sea level pressure, total rainfall, cloud cover percentages, and percentage of maximum possible sunshine are available for Columbus, Ohio, from several sources. Data for 1882–90 are available as original handwritten Weather Bureau data observation logs located in the State Climate Office of Ohio. From 1891 to 1934, monthly data are from the U.S. Department of Agriculture–Weather Bureau (1893–1936) annual publication *Report of the Chief of the Weather Bureau.* From 1935 to 1942 these volumes become the *United States Meteorological Yearbook* (U.S. Department of Commerce 1937–49). Data from 1943 to 1948 are on Weather Bureau form 1030 (*Monthly Meteorological Summary*), while the monthly publication *Local Climatological Data,* from the National Climatic Data Center (NCDC), is used for 1949–2005. Daily mean values of T, T_{max}, and T_{min} available from 1882 to1890 and 1943 to 2005 are used to generate monthly averages and then seasonal averages. Only monthly averages are published from 1891 to 1942. The same applies to T_d data except that they are replaced by relative humidities in 1943 and 1944. Monthly T_d from 1891 to 1942 is based on averages of morning and evening observations. Air temperature data for other cooperative weather stations, used for data homogeneity analyses, are obtained from the Midwestern Climate Center. Cloud cover and sunshine data only extend to 1995 and 1987, respectively. Monthly values (1895–2005) of the Palmer drought severity index (PDSI) for Ohio climate division 5 (central Ohio) are obtained from the NCDC, as are climate division air temperatures.

b. Methodology

Monthly specific humidity (q) is determined by obtaining the vapor pressure of the air (e) from observed monthly mean surface T_d using Bolton's (1980) empirical relationship, accurate to within 0.3% between $T = -35°$ to $+35°$C:

$$e = 6.112 \exp\left(\frac{17.67T_d}{T_d + 243.5}\right). \tag{3}$$

From this we obtain

$$q = \frac{0.622e}{p - 0.378e}, \tag{4}$$

where p is the monthly mean sea level pressure in hPa.

Monthly T_d values are not published in 1943 and 1944, and q is determined using published mean values of relative humidity percentage. Equation (3) is then solved for saturation vapor pressure (e_s) in an identical form of the equation in which e_s replaces e and T replaces T_d (Bolton 1980). The value of e is then obtained by multiplying the monthly relative humidity percentage and e_s.

Elements of the atmospheric moisture budget are compared during humid and drier Columbus summers using National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data. The atmospheric moisture budget is represented as follows:

$$P - E = -\frac{\partial w}{\partial t} - \nabla \cdot \frac{1}{g}\int_{p_{top}}^{p_s} \overline{q\mathbf{V}}\, dp, \tag{5}$$

TABLE 1. Station movement and instrumentation changes (thermometers and psychrometers only) occurring at the Columbus, OH, weather service office since 1882. Data are presented from the viewpoint of summer season and dates of station moves occur outside of summer unless otherwise noted. Data include the site ground elevation (m), as well as relative instrumentation elevations (m) above ground level. Data are from the NCDC metadata files, as well as annual summaries from *Local Climatological Data.*

Summers	Site (m)	Instruments (m)	Comments
1882–84	230.1	15.8	Location at downtown main crossroads
1885–88	230.1	23.8	Same location, instruments elevated on roof
1889–92	NA	31.1	Moved 0.5 blocks east
1893–94	231.3	38.4	Moved 0.5 blocks west but east of 1882–84
1895–1901	234.7	26.5	Moved 0.4 km south
1902–30	231.3	52.7	Moved 0.4 km north, just east of 1893–94
1930–34	231.3	65.8	Moved to next building west in midsummer on 1 Jul 1930
1935–72	220.7	27.4	Moved 0.4 km northwest to post office roof; site is not the official weather service office after 1948
1949–54	248.4	1.5	Airport Administration building 11.8 km east-northeast
1954–58	248.4	9.8	Same location, instruments moved to rooftop on 21 Jun 1954
1959	248.1	9.8	Moved to Terminal building 1.6 km northwest, psychrometer placed at 7 m
1960–81	247.5	1.5	Thermometer discontinued; hygrothermometer installed 0.8 km east
1963–81	247.5	4.6	Psychrometer lowered to 4.6 m on 15 Jul 1963
1981–95	247.8	1.5	Movement 1.6 km north on 1 Jul 1981; thermometers reinstalled by 1981 at unknown date
1996–present			No movement, Automated Surface Observing System (ASOS)

where E is the column evaporation rate, P is the precipitation rate, w is the precipitable water, g is the earth's gravitational constant, p is the pressure integrated from the surface (p_s) to the upper boundary of the humidity data ("top"; 300 hPa), $\mathbf{V}$ is the horizontal wind vector with x and y components u and v, respectively, and q is the specific humidity. The precipitable water w is given as

$$w = \frac{1}{g}\int_{P_{\text{top}}}^{P_s} q\, dp. \tag{6}$$

Data are available on a 2.5° × 2.5° latitude–longitude grid. Results are obtained for the 850-hPa moisture flux components $\overline{qu}$ and $\overline{qv}$ and for the total moisture flux vector.

c. *Evaluation of data homogeneity*

Long climate time series are often characterized by inhomogeneities caused by changes in site location, surrounding environment, instrumentation, and observing practices (Peterson et al. 1998; Changnon and Kunkel 2006). A list of station moves and instrument changes for the Columbus weather office are presented in Table 1. Lateral station movements were small (Table 1) from 1882–1948, a period when the weather station sites are located on downtown building rooftops. One potential inhomogeneity in this era is associated with the rise in temperatures and dewpoints (see Figs. 1a–d) in the late 1890s through 1901, occurring in conjunction with a downtown station relocation in 1895 that lasted until 1901 (Table 1). Table 2 shows that Columbus air and dewpoint temperatures are all significantly higher in 1895–1901 compared to 1902–29. The same is true, however, of the mean temperatures at nearby cooperative stations at Delaware, Ohio, and The Ohio State University (Table 2), as well as for climate division 5 and statewide averages. Significant increases in T_{max} and T_{min} from 1895 to 1901 relative to 1902–29 also occur at the cooperative stations but are not shown in Table 2. Dewpoint temperatures were also not available at sites near Columbus. When the city weather station changes location again in 1902 (Table 2), the decline in Columbus temperature values in that, and subsequent, years (Figs. 1a–c) also occurs in the other data time series evaluated as part of Table 2.

A similar significant data discontinuity also occurs from 1930 to 1944 when 15 consecutive warmer than normal summers occur (Figs. 1a–c). The 15 consecutive abnormally warm summers occur, however, in all climate divisions in Ohio, Indiana, Illinois, and in some adjacent divisions in Michigan, Wisconsin, Pennsylvania, West Virginia, and Kentucky (not shown). This suggests that the fluctuation is a regional event affecting both large and small city reporting stations composing the climate division data. These 15 summers incorporate the extraordinary heat and droughts of 1930, 1934, and 1936. No dataset adjustments were performed for 1895–1901 or the 1930–44 period of elevated temperatures.

The largest station move (Table 1) occurs in 1949 when the downtown site is relocated to the rural airport, an event that is coincident with the onset of publication of airport weather office data in *Local Clima-*

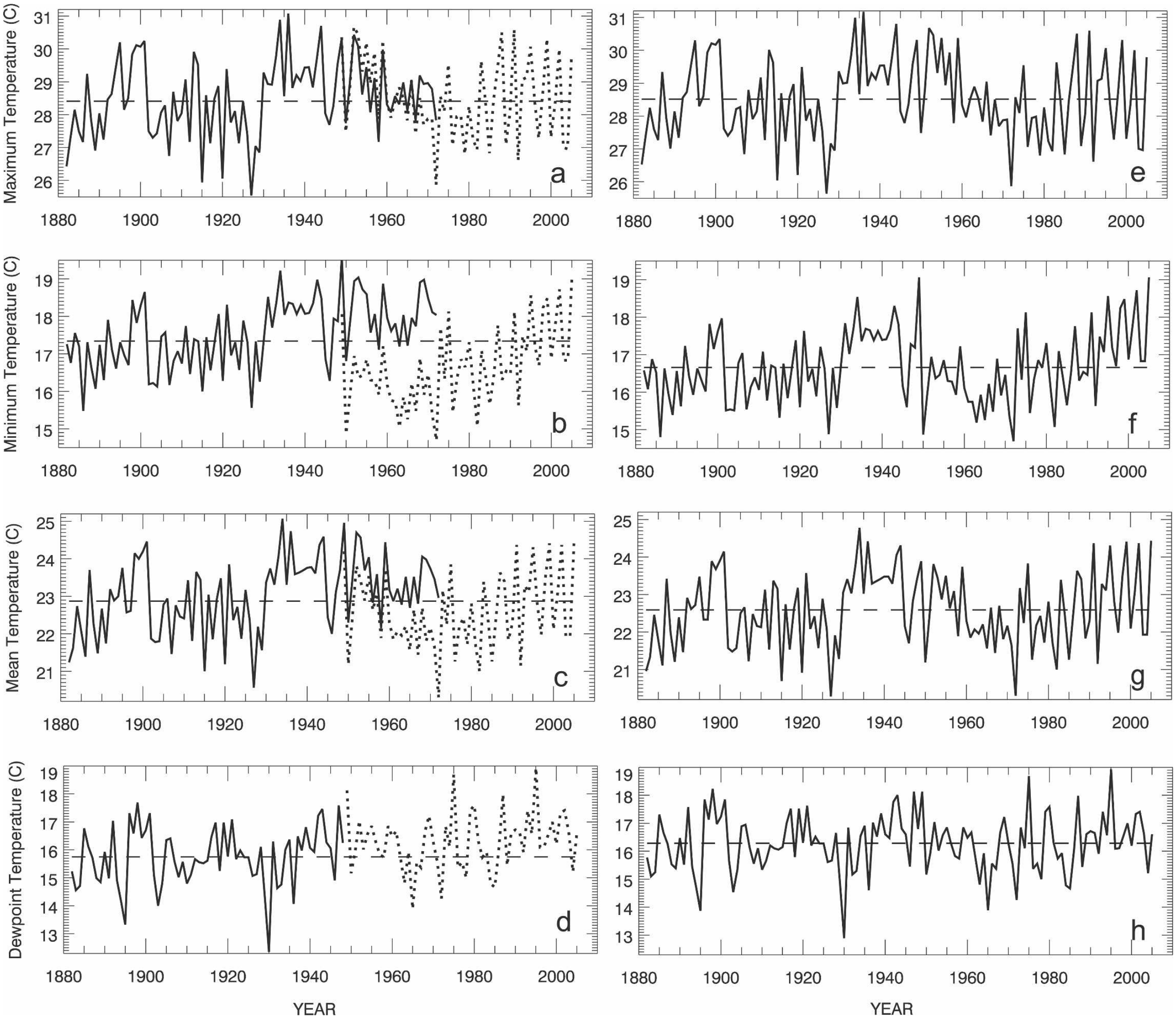

FIG. 1. Time series for Columbus, OH, summer downtown/city (solid lines spanning 1882–1972) and airport (dotted lines spanning 1949–2005) of air temperature (a) maximum, (b) minimum, and (c) mean; and (d) dewpoint temperature (1882–1948 for solid). Dashed horizontal lines in (a)–(d) are 1882–1948 city averages. Merged and adjusted Columbus city–airport mean summer values of air temperature (e) maximum, (f) minimum, and (g) mean; and (h) dewpoint temperature. Mean values are created by raising or lowering all city 1882–1948 values so that they have the mean for the 1949–2005 period, shown as dashed lines in (e)–(h).

tological Data. It is noted (Table 1) that the downtown site continued in operation after 1948 and until summer 1972, and its overlapping summer $T_{\max}$, $T_{\min}$, and T (mean) time series are shown in Figs. 1a–c. Correlations between the two overlapped data series are highest between 1949 and 1968, ranging from $r = 0.89$ to $r = 0.92$ among the three parameters, declining slightly to between $r = 0.77$ and $r = 0.80$ when the final 4 yr are included (1969–72). Airport $T_{\max}$ values (Fig. 1a) slightly exceed those of the city near 1949 but are overall lower than city values closer to 1972. The $T_{\min}$ values (Fig. 1b) at the airport are considerably lower than those of the city throughout the period, while the mean values (T; Fig. 1c) are also lower due to the impact of $T_{\min}$. Overlapping city–airport T_d data do not exist, but close examination (Fig. 1d) indicates that the city T_d average is lower than that occurring at the airport in subsequent years.

The mean data values for the full subperiods 1882–1948 and 1949–2005, shown in Table 3, exhibit the same tendencies as illustrated from 1949 to 1972 in Figs. 1a–c. For example, lower (higher) average $T_{\max}$ ($T_{\min}$) occurs in 1882–1948 relative to recent decades. Differences in T_E between these periods (Table 3) are large but not statistically significant due to large standard deviations with respect to the mean. Following from Table 3, in-

TABLE 2. Comparison of mean air and dewpoint temperatures (°C) between the periods 1895–1901 and 1902–29 for Columbus, OH, climate division 5 (central OH), statewide (Ohio) averages, and data for two nearby cooperative stations at Delaware, OH, and The Ohio State University. Std devs about the mean temperatures are in parentheses. Values of the t statistic, based on a two-tailed test between the period mean values, are statistically significant and 95%, 99%, and 99.9% above values of 2.1, 2.7, and 3.4, respectively.

Location	Temperature parameter	Mean (std dev)		t value
		1895–1901	1902–29	
Columbus	T_{max}	29.6 (0.86)	27.8 (1.07)	4.1
Columbus	T_{min}	17.8 (0.77)	17.0 (0.70)	2.7
Columbus	Mean	23.7 (0.76)	22.4 (0.84)	3.7
Columbus	T_d	16.5 (1.46)	15.6 (0.75)	2.3
Delaware	Mean	23.2 (0.80)	21.7 (0.94)	3.6
The Ohio State University	Mean	22.9 (0.86)	21.9 (0.87)	2.6
Division 5	Mean	22.5 (0.64)	21.5 (0.89)	2.8
Ohio	Mean	22.3 (0.64)	21.3 (0.82)	3.0

TABLE 4. The summers that compose the highest and lowest 13-yr deciles of mean summer temperature (T), moist enthalpy Lq ($=Lq/c_p$), and effective temperature (T_E) at Columbus, OH, over the period 1882–2005.

Highest T	Lowest T	Highest Lq	Lowest Lq	Highest T_E	Lowest T_E
1934	1972	1995	1930	1995	1972
1936	1927	1975	1965	1975	1930
2005	1915	1898	1895	1898	1965
1999	1920	1949	1972	1949	1985
2002	1882	1947	1903	1943	1903
1991	1982	1943	1936	1901	1929
1995	1886	1987	1985	1987	1927
1944	1992	1901	1894	2002	1950
1901	1950	1896	1984	1947	1883
1943	1889	1942	1963	1942	1963
1900	1907	1921	1929	1921	1895
1949	1976	1980	1978	1999	1889
1898	1985	1892	1883	1900	1976

dividual summer averages were adjusted upward or downward to bring the 1882–1948 mean to that of 1949–2005, and these are evident in comparisons of time series means between the left and right sides of Fig. 1. The adjusted T, T_{max}, T_{min}, and T_d data are shown in Figs. 1e–h. Adjustments to T_d removed the mean Lq differences (Table 3) between the two subperiods and the same occurs with T_E differences when considering both T and Lq adjustments.

3. Results

a. Moist static energy extremes and trends

Time series of Columbus summer moist static energy parameters are shown in Fig. 2 and seasons with the greatest surface energy content extremes are listed in Table 4. The highest T_E and Lq values occur in the summer of 1995 when a mid-July heat wave dominated the midwestern United States (Kunkel et al. 1996; Changnon et al. 1996), producing high human mortality regionally and especially in Chicago. Kunkel et al. (1996) point out that the 1995 heat wave was the worst since 1934 and 1936. Indeed the second highest summer-mean T occurs in 1936, but its Lq is the sixth *lowest* (Table 4). The summer of 1930, when extreme midwestern drought occurred, had the lowest T_d (Fig. 1h) and Lq (Table 4; Fig. 2) on record and the second lowest T_E (Fig. 2), while T was only slightly above normal. Overall, T_E and Lq are below normal in four summers between 1930 and 1936 (Fig. 2) when persistently high T values occurred as part of the 15 hot summers. In comparison to 1930–36, the Ohio drought of 1952–56 (Rogers 1993) is characterized by high T_{max} values (Fig. 1e), while T_{min} and T_d (Figs. 1f,h) had relatively small fluctuations near or below their long-term means. As a result, T and T_E are both moderately above normal in 1952–56, while Lq is closer to normal (Fig. 2). Data for Kansas City (Chang and Wallace 1987, their Table 1) also show relatively lower T_d's in the hot summer months in the 1930s compared to those of the 1950s. The eastern U.S. drought of 1962–66 was notable for its anomalously cool summers (Namias 1966; Barlow et al. 2001) and moist static energy is consistently below normal (Fig. 2) in these years.

TABLE 3. Summer averages and std devs of Columbus maximum (T_{max}), minimum (T_{min}), and mean air temperature (T), dewpoint (T_d), Lq ($= Lq/c_p$), and equivalent temperature (T_E), all in °C, for the periods 1882–1948 (N = 67) and 1949–2005 (N = 57). The t statistic is based on a two-tailed t test of the differences between the means, and values above 2.1 (2.7) are significant with 95% (99%) confidence.

	T_{max}	T_{min}	T	T_d	Lq	T_E
1882–1948	28.41	17.34	22.87	15.75	27.46	50.33
Std dev	1.22	0.86	1.00	1.07	1.83	2.12
1949–2005	28.51	16.66	22.59	16.29	28.41	51.00
Std dev	1.21	1.05	1.01	1.00	1.85	2.59
t statistic	−0.46	4.00	1.56	−2.94	2.96	1.87

Five summers from 1991 to 2005 are in the highest T decile, exceeding by one the number during 1930–44 (Table 4). Highest decile T_E values in 1999 and 2002 (Table 4) accompanied the high air temperatures, as in 1995, but the same does not occur in 1991 and 2005. High Lq summers are more frequent since 1975, compared to the 1950s and 1960s, (Fig. 2) but only exceed

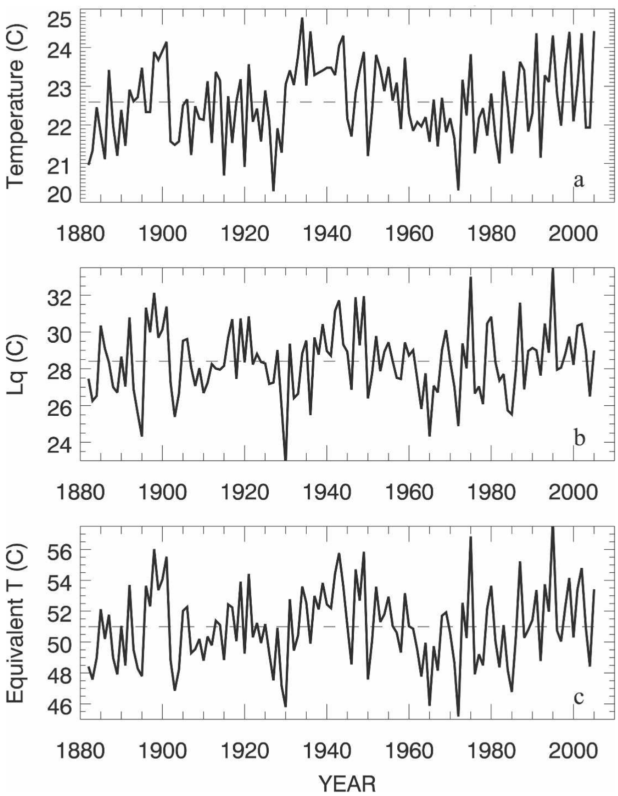

FIG. 2. Time series, 1882–2005, of Columbus mean summer (a) air temperature T, (b) moist enthalpy Lq ($=Lq/c_p$), and (c) equivalent temperature T_E, all in °C.

an arbitrary high value, such as 30°C, about twice a decade.

The relative magnitudes of Columbus mean T, T_E, Lq, cloud cover, and percentage of possible sunshine are compared (Table 5) during the wettest and driest summer quintiles of Ohio climate division 5 PDSI data and station total rainfall. The PDSI categorizes soil moisture conditions from dry (negative index values) to normal to wet (positive index). PDSI quintiles are comprised of 22 yr (1895–2005), while there are 25 summers per quintile (1882–2004) for rainfall. During the dry/negative PDSI quintile (Table 5), it is unusually warm (T) with relatively high sunshine percentage and low cloud cover compared to the wet/highest PDSI quintile summers. Here, Lq is relatively low (high) in the dry (wet) quintile soil conditions, as might be expected, but its standard deviation is high (see also Table 3) and the mean difference (-0.83 K) between extremes is not significantly different from zero. The resulting T_E values are small and positive regardless of mean soil moisture conditions.

Stratification by total rainfall quintiles (Table 5) also indicates that dry (wet) summers are warmer (cooler) and sunnier (cloudier) than normal and have anomalously low (high) Lq values. Numerical mean Lq departures now significantly differ between wet and dry summers, having absolute magnitudes large enough to create T_E anomalies that exceed those of T but which are still not statistically significant. The significant temperature differences (e.g., dry associated with hot) are in keeping with generally negative correlations between mean summer temperatures and total rainfall occurring over the United States (Madden and Williams 1978; Trenberth and Shea 2005), and indeed the summer T–rainfall correlation at Columbus is $r = -0.31$ since 1882. The Columbus summer Lq–rainfall correlation is $r = +0.28$, although this association, in particular, varies with time such that $r = 0.48$ from 1882 to 1936 and $r = 0.13$ from 1937 to 2005 (discussed further below). Both long-term ($N = 124$) coefficients are low but statistically significant at the 99% confidence interval due to the large number of cases.

Overall, Table 5 indicates that T and Lq are out of phase when stratified by moisture indicators, such as the PDSI and summer rainfall totals. Consecutively running T–Lq correlation coefficients (Fig. 3) are, however, largely positive and maintain statistical significance above the 95% confidence interval starting in 1956 (the coefficient for which is based on 1937–56 data). The highest T–Lq coefficient is $+0.75$ in 1977 (1958–77, a period spanning the 1962–65 drought but during which anomalously cold dry summers contributed positively to T–Lq covariances). Much lower nonsignificant T–Lq coefficients (Fig. 3) persist in all 20-yr segments containing 1930–36 data (spanning 1930–55 on the x axis) and the only small negative coefficient in the series occurs in 1936 (1917–36 data). Symptomatic of the differences in T–Lq correlation coefficient magnitudes before and after 1936/37 is the fact that 26 of 55 summers (47%) in 1882–1936 had Lq anomalies (from the 1882–2005 average) opposite in sign to those for T. The same only occurs in 16 of 69 (23%) summers after 1936. Overall, the period 1882–1936 is one in which Lq and T both have significant correlations, but of opposite sign, to rainfall ($r = +0.48$ for Lq, as mentioned above, and $r = -0.38$ for T). Since 1937, Lq is more dissociated from summer rainfall ($r = +0.13$) at the same time that the T–Lq correlation becomes larger and consistently significant. Finally, Fig. 3 also shows that correlations between Lq and T_E always exceed $r = +0.80$, while those for T/T_E are generally lower but usually above the 95% significance level.

Decadal trends in moist static energy parameters (Table 6) were determined for the periods 1940–64 and 1965–2005, spanning the era when T and Lq are most positively correlated. The trend periods are arbitrarily chosen based on visual examination of Figs. 1 and 2,

TABLE 5. Mean summer departures (from the 1882–2005 mean) and std devs (in parentheses) of Columbus T, Lq, T_E (°C), and percentages of cloud cover and maximum possible sunshine. Departures for all are obtained for the highest and lowest quintiles of both the summer average PDSI (since 1895) and Columbus summer rainfall (since 1882). Two-tailed t test values above absolute 2.1 (2.7) are statistically significant with 95% (99%) confidence.

	T (°C)	Lq (°C)	T_E (°C)	Cloud (%)	Sunshine (%)
PDSI dry (−)	+0.71 (0.96)	−0.39 (2.31)	0.32 (2.87)	52.1 (6.47)	68.6 (5.09)
N	22	22	22	21	21
PDSI wet (+)	−0.34 (0.99)	+0.44 (1.80)	+0.10 (2.59)	56.8 (6.75)	60.3 (7.07)
N	22	22	22	19	19
t statistic	3.57	−1.33	0.27	−2.25	4.28
Summer rainfall low	+0.39 (0.91)	−0.83 (1.84)	−0.44 (2.35)	50.2 (9.62)	68.3 (5.63)
N	25	25	25	20	20
Summer rainfall high	−0.41 (0.96)	+0.81 (2.13)	0.40 (2.97)	58.9 (5.47)	58.3 (7.66)
N	25	25	25	21	21
t statistic	3.02	−2.91	−1.11	−3.61	4.73

which convey a sense of downtrend going into the cold/dry 1960s and a subsequent upward trend. Given the arbitrary choice of start and end points in these periods, the statistical significance of the trends is perhaps less meaningful and is used here only for comparison among the different parameters. Moist static energy parameters all have downward decadal trends from 1940 to 1964 (Table 6), with normalized T_E trends slightly exceeding those of T and Lq. From 1965 to 2005, normalized trends are positive and are largest for T, while the Lq trend does not achieve statistical significance. The air temperature range ($T_{\max}$–$T_{\min}$) trend is positive in 1940–64 as the $T_{\min}$ trend decreased at a larger rate than that of $T_{\max}$. However, from 1965 to 2005, $T_{\min}$ increases rapidly relative to $T_{\max}$ and the range steadily decreases. Decadal trends over 1949–2005 (the airport and LCD era) in Table 6 are shown for comparative purposes, and normalized trends are virtually identical among the moist static energy components. During the 1950s drought, summer $T_{\max}$ values (Fig. 1e) remained at higher 1930s levels while those for $T_{\min}$ (Fig. 1f) were

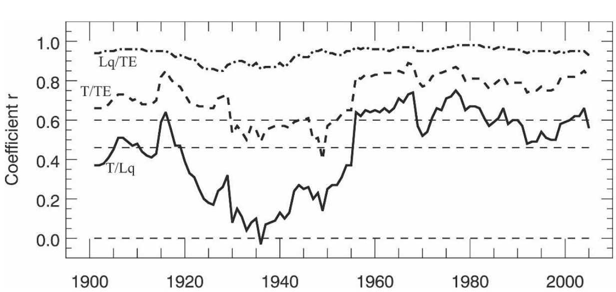

FIG. 3. Overlapping consecutive 20-yr correlation coefficients between moist static energy components. Coefficients begin in 1901 (including data for 1882–1901) for Lq and T_E (thick dash–dot line), T and T_E (thick dashed line), and T and Lq (solid line). Horizontal dashed lines represent coefficients (r = 0.60 and 0.46) significant at the 99% and 95% confidence level and the zero line.

closer to the long-term average of $T_{\min}$. This leads to a net 1949–2005 downward $T_{\max}$ trend (Table 6) while $T_{\min}$ is upward, as it also is in 1965–2005. The net result produces a larger downward temperature range trend in 1949–2005 compared to 1965–2005.

b. Regional correlations and moisture flux analysis

Total energy content parameters over 1949–2005 were obtained for the 850-hPa level from NCEP–NCAR reanalyses at grid points covering the eastern two-thirds of the United States and southern Canada. Correlations between the Columbus surface mean T and T_E and those similarly obtained gridded 850-hPa values (Figs. 4a and 4c) regionally exceed $r = +0.70$ over several states and parts of Canada, centered near Lake Erie. Columbus Lq correlations to those of the 850-hPa data (Fig. 4b) only slightly exceed $r = +0.60$. While these 57 summer correlations are significant with 99.9% confidence for coefficients higher than $r = +0.48$, those lower than approximately $r = +0.71$ have a coefficient of variation (r^2) under 50%, indicating a relatively small amount of shared covariance between Columbus total surface energy content parameters and those of the 850-hPa time series.

Composite means of 850-hPa moisture flux were obtained for a set of years characterized by unusually high summer Lq and T values (Lq+/T+) at Columbus and another with negative departures (Lq−/T−). Differences between the composites, (Lq+/T+) − (Lq−/T−), for meridional ($\overline{qv}$) moisture flux are largest and statistically significant over the Plains and Midwest (Fig. 4e), representing strong southerly (northerly) flux during Lq+/T+ (Lq−/T−) summers. A negative $\overline{qv}$ flux difference occurs over New England and Nova Scotia and represents northerly flux in Lq+/T+ summers. A significant negative zonal flux ($\overline{qu}$) difference occurs over Tennessee and the Carolinas

TABLE 6. Trend (°C decade^{-1}) of Columbus seasonally averaged climate parameters over three spans of time: 1940–64, 1965–2005, and 1949–2005. Trends in parentheses are normalized by the std dev of the individual parameter time series. Trends that are statistically significant with 99% confidence are indicated in bold while those significant with 95% have an asterisk. Temperature range is T_{max} minus T_{min}.

	T_{max}	T_{min}	T	Range	T_d	Lq	T_E
1940–64	−0.26 (−0.26)	**−0.77 (−0.77)**	−0.51* (−0.60)*	+0.51* (+0.62)*	−0.61* (−0.65)*	−1.15* (−0.65)*	**−1.66 (−0.68)**
1965–2005	+0.23 (+0.20)	**+0.52 (+0.49)**	**+0.38 (+0.36)**	**−0.28 (−0.35)**	+0.27 (+0.25)	+0.48 (+0.24)	+0.86* (+0.31)*
1949–2005	−0.12 (−0.10)	**+0.28 (+0.27)**	**+0.10 (+0.10)**	**−0.40 (−0.39)**	+0.10 (+0.10)	+0.17 (+0.09)	+0.27 (+0.10)

(Fig. 4d), representing net easterly (westerly) flux in Lq+/T+ (Lq−/T−) summers. The net 850-hPa total moisture flux differences, (Lq+/T+) − (Lq−/T−), have an anticyclonic flux centered on the Great Lakes (Fig. 4f). The vectors represent the direction of the fluxes in Lq+/T+ summers, while the reverse direction of the vectors would occur in Lq−/T− summers. The net moisture flux differences are small over the Great Lakes and Ohio, where T and Lq correlations are highest (Figs. 4a,b). The results of Fig. 4 place Columbus, not surprisingly given the analysis procedures, near the core of summer air masses (whether characterized by Lq+/T+ or Lq−/T−) that exhibit their largest moisture fluxes along the air-mass fringes (Figs. 4d–f), with some regional correlation between the station's surface energy content parameters and those of data from relatively nearby grid points (Figs. 4a–c).

4. Concluding discussion

This paper examines mean summer surface moist static energy at Columbus, Ohio, by evaluating a long time series (1882–2005) of equivalent temperature (T_E) and its components T and Lq ($=Lq/c_p$). The moist static energy is evaluated in terms of its (i) extreme seasonal events, (ii) response to surface moisture and summer rainfall anomalies, (iii) trends, and (iv) associations with total energy content and moisture fluxes from regional reanalysis data. In terms of distinctive seasonal extremes, mean values of all three moist static energy components for the summer of 1995 are highest decile events. That year is in contrast to four hot summers between 1930 and 1936 when T was abnormally high, but Lq and T_E anomalies were in (e.g., 1936), or near, their lowest deciles (Table 4). The 1930–36 droughts appear to mark the end of an era when T and Lq anomalies are often out of phase, marking a transition to their positive covariation in recent decades despite subsequent drought periods in the 1950s and 1960s. Nonetheless, mean T and Lq anomalies have opposite signs when summers are stratified into highest and lowest quintiles of soil moisture conditions and summer rainfall. The Lq anomaly varies in phase with both the soil moisture and rainfall anomalies, while air temperature (T) varies out of phase with them. This is in agreement with the negative summer correlations between temperature and rainfall observed around the United States (Madden and Williams 1978; Trenberth and Shea 2005). While the net T_E values are small and vary nonsignificantly in response to soil moisture conditions (measured by the PDSI), their differences in response to summer rainfall extremes are larger and covary with Lq, which also has large magnitude differences between the wettest and driest summers.

Moisture flux is generally low around Columbus when composite differences are obtained (Figs. 4d–f) between sets of summers with high and low Lq and T values; the most sizeable flux departure differences occur instead in the Plains and off the eastern seaboard. Correlations between Columbus surface latent energy (Lq) are only moderately correlated ($r \approx +0.60$) to gridded 850-hPa Lq in a localized region around Ohio. Sandstrom et al. (2004) find that decadal increases in extreme summer dewpoints across the Midwest do not necessarily exhibit similar trends since 1950 and are not necessarily linked to advection increases from the Gulf of Mexico but rather to changes in regional moisture sources, potentially due to vegetation changes. DPG find that T and T_E trends generally have the same sign while the relative magnitudes of the trends vary with type of land cover. We find also that Columbus moist static energy parameters generally have the same sign (Table 6), while the relative magnitudes of T and T_E trends seem to vary depending on the magnitude of the Lq trend. From 1940 to 1964, downward trends of T_E and Lq exceed those of T. From 1965 to 2005, Lq trends are positive but nonsignificant, and the T trend is larger than T_E. Associated decadal upward trends in summer dewpoint temperatures have been noted in earlier studies (e.g., Ross and Elliott 1996, 2001). From 1965 to 2005, however, the large upward increases in Columbus T and T_{min} (Table 6) are especially notable while trends in T_d and Lq are relatively smaller. The mean daily T_{max} trends are smaller than those of T_{min} and may even have the opposite sign, generally reducing the magnitude of the mean air temperature (T) trend. The net effect is a pronounced downward trend in the mean

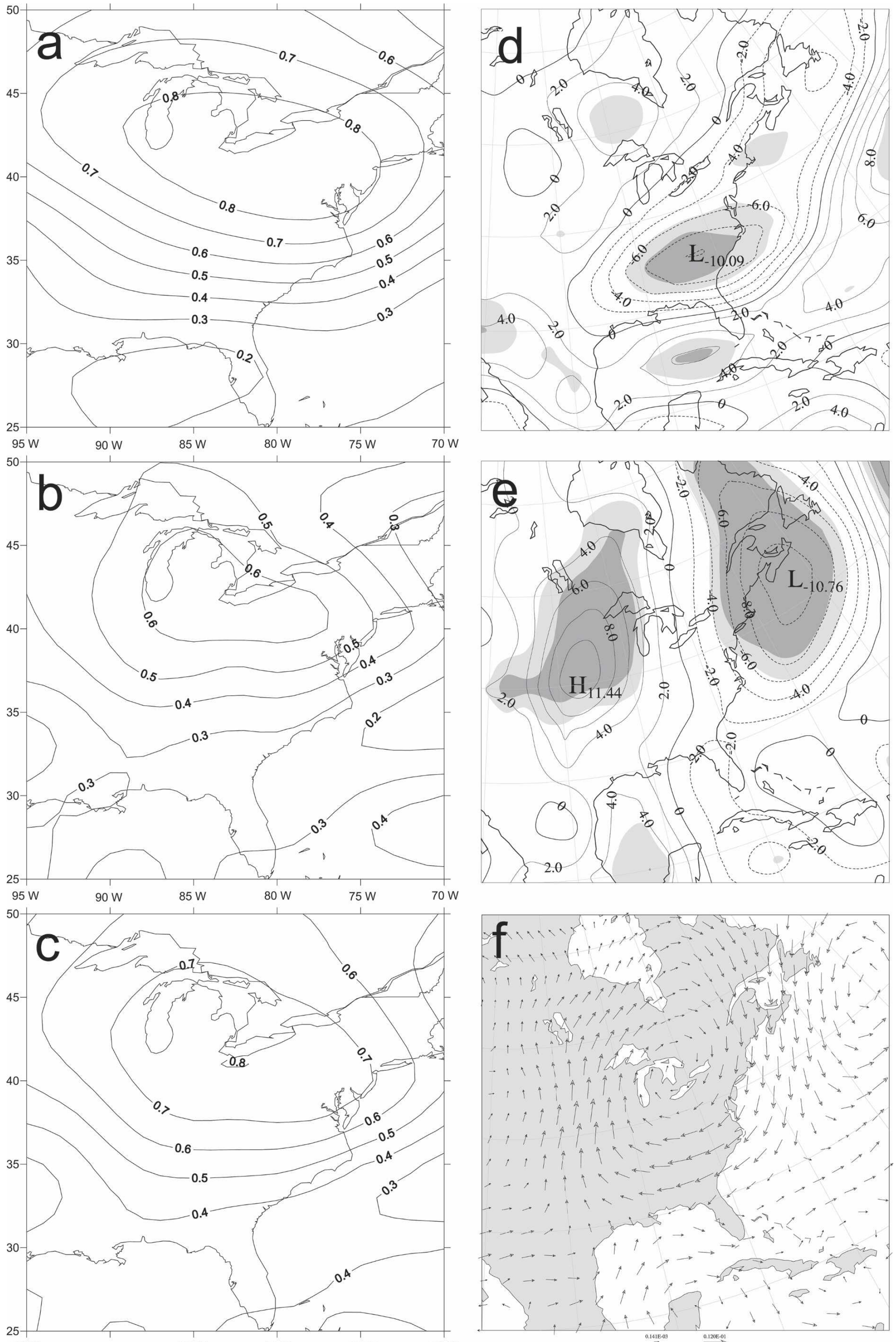

FIG. 4. Correlations between Columbus surface energy content and that of 850-hPa gridpoint reanalyses for summer averages from 1949 to 2005 of parameters (a) T, (b) Lq, and (c) T_E. Composite differences in gridded summer mean 850-hPa (d) zonal ($\overline{qu}$), (e) meridional ($\overline{qv}$), and (f) total moisture fluxes (g kg^{-1} m s^{-1}) between years with positive and negative Lq and T anomalies, (Lq+/T+) − (Lq−/T−), at Columbus, OH. The longest vector in (f) is 12 g kg^{-1} m s^{-1}. Mean differences that are statistically significant with 95% and 99% confidence are lightly and heavily shaded, respectively.

summer air temperature range of the last half century, a notable feature of the climatic variability of the United States and the world (Braganza et al. 2004; Collatz et al. 2000; Dai et al. 1999).

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