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Assessing trends in lower tropospheric heat content in the Central USA using equivalent temperature

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Abstract

Isobaric equivalent temperature (T_E) is the temperature that an air parcel would have if all associated water vapor were condensed and the resulting latent heat used to increase the temperature of the parcel. It is therefore an ideal metric for assessing changes in (1) total near surface heat content associated with both temperature and moisture content and (2) the joint behavior of temperature and humidity, which is relevant to both lower atmospheric stability and human heat stress during extreme temperature events. We present results from an analysis of 50-years (1961-2010) of daily T_E and its temperature and moisture components at seven stations in the central USA. The annual means of daily T_{Emax} and T_{Emin} increased at all stations during the period of analysis with the largest changes occurring in T_{Emin}, largely as a result of increasing minimum air temperature. At western locations significant increases in the annual mean T_{Emax} were also observed, resulting from a combination of increases in T_{max} and humidity. Despite small summer (JJA) trends in maximum air temperature, summer T_E trends were generally larger than their annual counterparts. The timing of the observed variations and the resulting spatial pattern are consistent with observed changes in meridional moisture flux associated with the Great Plains low-level jet. Heat waves in the region were found to be characterized by increasing T_{Emin}, primarily resulting from increases in minimum air temperature. At western stations, heat waves were also characterized by increasing T_{Emax} as a result of positive trends in humidity. In most cases, equivalent temperature provides a perspective on local environmental change that differs from what is provided by consideration of temperature alone.

1. Introduction

Variations and trends in lower tropospheric heat content are usually assessed using near-surface air temperature data. However, this approach ignores variations in heat related to changes in moisture content and therefore provides an incomplete description of available energy near the surface (Pielke et al. 2004; Rogers et al. 2007). Pielke et al. (2004) recommend using moist static energy (H) for this purpose. Moist static energy (H) is given by:

$$H = C_p T + L_v q \tag{1}$$

where C_p is the specific heat of air at constant pressure (1005 J/kg°C), T is the air temperature (°C), L_v is the latent heat of vaporization (J/kg) and q is the specific humidity (kg/kg). Division of H by C_p yields equivalent temperature (T_E; °C), which quantifies near surface heat content with separate terms for the dry and moist contributions:

$$T_E = \frac{H}{C_p} = T + \frac{L_v q}{C_p} \tag{2}$$

Globally, increases in humidity are well documented (e.g., Dai 2006) and further increases in lower-tropospheric water vapor are likely under future climate scenarios defined by increases in radiative forcing from greenhouse gases (Held and Soden 2006). This large scale response is likely to be regionally modified as a result of synoptic-scale moisture transport. For example, the Great Plains low-level jet (GPLLJ) – a feature characterized by strong lower tropospheric winds in the region between the Gulf of Mexico and the lee of the Rocky Mountains - is a key player in warm season hydroclimate variability in the central US (Weaver and Nigam 2011) and is an important factor in the moisture budget of the eastern US (Higgins et al. 1997). Locally, land cover is also likely to play an important role. Fall et al. (2010) found that trends in T_E, over the US, were larger than trends in T as a result of the moisture term (i.e., the 2nd term in Equation 2) but with substantial influence from presence/absence of vegetation.

Since human heat stress is a function of both air temperature and atmospheric moisture content, there is also a need to assess changes in heat wave characteristics using metrics that account for changes in both temperature and humidity. The thermodynamic basis of equivalent temperature, as well as the clear separation of the dry and moist contributions to its magnitude, makes it an excellent choice for understanding such changes. In this study, we focus on a set of stations in the central United States (Figure 1) and use equivalent temperature to quantify several aspects of near surface equivalent temperature variability. The western part of the study region constitutes an area that has been referred to as “the warming hole” due to weak positive or nearzero trends in summer air temperature in recent decades, particularly in daily maximum air temperatures (Pan et al. 2004; Kunkel et al. 2006; Liang et al. 2006). Pan et al. (2004) attributed these trends to increases in precipitation associated with changes in the GPLLJ. In addition, some areas in the southeast US exhibit negative trends in annual mean near-surface air temperature that originate from internal decadal variability associated with Pacific sea-surface temperatures (Meehl et al. 2012). Including these areas in the study region therefore provides an opportunity to investigate changes in total heat content in a region where warming has been modest or even absent. Our primary objectives are to (1) assess trends in T_E and its components and (2) determine the effect of these trends on the characteristics of regional heat waves.

The data used to address our objectives are described in Section 2, along with an assessment of data homogeneity. Section 3 includes a description of the methods employed in our analysis. The results are presented in Section 4, followed by a brief discussion in Section 5.

2. Data

Hourly values of temperature (T), dew point temperature (T_d), and station pressure (P) were extracted for eight stations (Figure 1) from the National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD) available from the National Climatic Data Center (NCDC) along with available station metadata for the period of 1961-2010. The consistency of reports in the ISD varies considerably over the period of record. Observations are often reported hourly, but not at the same time within the hour. In these cases, observations were assigned to the nearest hour using traditional rounding principles. Furthermore, during the period from 1966-1981, values were only reported every three hours. To ensure consistency over the period of analysis, we partitioned each day into eight 3-hour blocks. For the daily T_{Emax} and T_{Emin} to be considered for further analysis, each 3-hour block had to have at least one hour with valid data.

Homogeneity of climate data is affected by factors ranging from station relocations and changes in instrumentation to changes in the surrounding environment, such as urbanization (Peterson et al. 1998; Changnon and Kunkel 2006), resulting in either discontinuities or gradual trends in the resulting time series (Easterling et al. 1996). Unfortunately, station location data for the early part of the record were kept with low precision making definitive distance calculations for station moves impossible. Nevertheless, the dates of station moves are available in the station history files available from NCDC, so time series can be objectively evaluated for associated discontinuities. Impacts from changes in sensors, specifically those related to implementation (1980s) and modification (early 1990s) of the HO-83 hygrothermometer have been addressed in several previous studies (Gall et al. 1992; Jones and Young 1995; Karl et al. 1995; Gaffen and Ross 1999; Robinson 2000). An additional change in dew point temperature measurement occurred with the installation of the Vaisala DTS1 dew point temperature sensor, which was installed at the stations considered here between 2003 and 2006.

Following Gaffen and Ross (1999) we conducted t-tests (with α=0.01) using four years of monthly anomalies of maximum and minimum air temperature (T_{max}, T_{min}) and dew point temperature (Td_{max}, Td_{min}) before and after each documented station move and for the instrumentation changes that occurred in 1964, 1985, the mid-1990s (ASOS installation) and in the early 2000s (DTS1 installation). The implementation of ASOS and the installation of DTS are associated with specific dates in the station histories. The changes in the mid-1960s and mid-1980s happened over a period of several years, so 1964 and 1985 are used as best estimates as in Gaffen and Ross (1999). In our examination of these differences, we considered whether any significant changes accompanied documented station changes, but also whether significant changes occurred simultaneously at neighboring stations where no changes in observation practices were noted.

During the 50-year period considered here, the seven stations in Figure 1 were moved a combined total of 20 times. Using the available location data as estimates, the station moves ranged from a few meters to 4.05 km, but only one move was larger than 2 km. The majority of the moves (13) were not associated with significant changes in any of the variables considered. Only one move (Moline, IL in 1992) was associated with a significant difference in temperature (T_{max}). However, a significant change in T_{max} in 1992 was also found at several other stations, suggesting that the difference was due to a true climatic influence rather than a station move. Similarly, changes in dew point temperature associated with six of the documented station moves were also coincident with significant changes (same direction, with α between 0.1 and 0.01) at nearby stations where moves were not documented. On the basis of this analysis, we concluded that documented station moves did not contribute to inhomogeneity in the station time series. The original time series were therefore subjected to further analyses corresponding to the dates of instrumentation changes.

The instrumentation changes that occurred around 1964 resulted in only one significant change between preceding and following 4-year periods (T_{min} at Indianapolis). However, five of the six remaining stations also have a lower T_{min} during the period from 1960-1963 relative to 1965-1968 (also significant at St. Louis with $\alpha=0.1$). The change to the HO-83 hygrothermometer in the mid-1980s has been associated with a warm bias in some environments (see Gall et al. 1992) and possibly a moist bias as well (Robinson 2000). Using 1985 as an approximate date for this change resulted in no significant changes in T_{max} or T_{min} at the stations considered here. A single station (St. Louis, MO) exhibits a significant difference in both maximum and minimum dew point temperature in 4-year periods surrounding 1985. However, St. Louis exhibits a decrease in dew point temperatures associated with this change. This outcome is opposite in sign to what would be expected from documented effects of the change to the HO-83 sensor.

Installation of the Automated Surface Observation System (ASOS) occurred in 1995 (3 stations), 1996 (3 stations) and 1999 (1 station) and included an upgrade to the HO-83 hygrothermometer designed to reduce warm bias. None of the stations exhibit a significant change in T_{max} or T_{min} associated with ASOS installation. A single station (St. Louis, MO), exhibited a significant change in both maximum and minimum dew point temperature. However, this change was also observed at several other stations and therefore was unlikely to have resulted from the implementation of ASOS instrumentation. The installation of the DTS1 dew point temperature sensor was similarly associated with a significant change in maximum and minimum dew point temperature at St. Louis, MO, but again with similar changes at two other stations (Indianapolis, IN and Nashville, TN) that had no documented changes in instrumentation.

The analyses conducted using known and estimated changes in location and instrumentation did not identify any clear inhomogeneities in the station data, so no changes were made to the time series. However, non-climatic influences may also result from changes occurring in the environment around the stations, such as urbanization, changes in land use, or changes in agricultural practices. Existing station histories and ancillary data are inadequate to assess such changes. Without long-term records from reference stations, the first-order stations considered here provide the best long-term coincident temperature and dew-point temperature data available.

3. Methodology

As shown in Eq. 2, computation of equivalent temperature requires specific humidity data. For each available station observation, the empirical relation of Bolton (1980) was first used to derive vapor pressure (e) from the measured dew point temperature (T_d; °C):

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

The vapor pressure and observed station pressure were then used to compute specific humidity (q; kg/kg):

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

Latent heat of vaporization (L_v, J/kg), which also appears in Eq. 2, was computed as a function of temperature (T, °C) following the Priestley-Taylor method as in Fall et al. (2010):

$$L_v = 2.5 - 0.0022T \tag{5}$$

Using these quantities, estimates of daily maximum and minimum equivalent temperature (T_{Emax} and T_{Emin}) were computed.

Our analysis of changes in equivalent temperature and its components focused on two primary analyses. First a trend analysis was conducted to assess changes in equivalent temperature and its components at the stations in Figure 1. Trend analyses were conducted using *median of pairwise slopes regression* (MPWS; Lanzante 1996). MPWS is considered a robust regression technique and was used to minimize the impact of any unidentified inhomogeneities. In addition to annual and summer (JJA) trends, we conducted time-varying percentile trend analyses, similar to those of T_{max} and T_{min} conducted by Robeson (2004). In this approach, trends are computed for each calendar month and for the 5th to 95th percentiles leading to improved assessment of changes across the probability distributions.

A second analysis focuses on heat waves, defined here as multi-day periods in which T_{max} exceeds its station-specific summer (JJA) 90th percentile value. For each year, days associated with this criterion are identified and averaged to compute annual values of daily T_{Emax}, T_{Emin}, T_{max}, T_{min}, L_vq/C_{Pmax}, and L_vq/C_{Pmin} associated with heat waves. The resulting averages are then subjected to a trend analysis to assess changes in the nature of heat waves in the context of equivalent temperature and its components.

4. Results

4.1. Annual and summer (JJA) trends

Linear trends in the annual means of daily maximum and minimum air temperature (T_{max}, T_{min}) are positive at each of the seven stations considered in this study (Table 1), consistent with the large-scale warming that occurred over the period considered (1961-2010). Trends in T_{min} are highly significant (99% level) at all stations and are generally larger than the trends in T_{max} at the same station. A similar decrease in diurnal temperature range has also been observed at larger-scales (Karl et al. 1993; Easterling et al. 1997; Vose et al. 2005). Trends in T_{max} are also significant at six of the seven stations. Annual values of the moisture component (L_vq/C_{Pmax}, L_vq/C_{Pmin}) exhibit positive trends at all stations except Nashville, although the trends are statistically significant at only a few stations (Table 1). These trends in temperature and atmospheric moisture are manifest as highly significant trends in the annual mean daily minimum equivalent temperature (T_{Emin}) at all stations. While all stations exhibit positive trends in both T_{Emin} and T_{Emax}, the significance of T_{Emax} trends is limited to stations with positive trends in both T_{max} and L_vq/C_{Pmax}.

Human health impacts of elevated temperature and humidity are most likely to occur during the summer months, so trends were also computed for summer (JJA) averages of daily T_{Emax}, T_{Emin}, T_{max}, T_{min}, L_vq/C_{Pmax}, and L_vq/C_{Pmin} (Table 2). While the annual trends were characterized by warming in both T_{max} and T_{min}, the JJA trends exhibit a notable lack of warming in T_{max} at most stations, consistent with the "warming hole" described in section 1. Summer trends in T_{min} are similar in magnitude and significance to their annual counterparts. With the exception of Nashville, all of the stations have positive trends in JJA averages of daily L_vq/C_{Pmax}, and L_vq/C_{Pmin}. These trends are significant at stations in the west/northwest part of the study region (Table 2). Trends in JJA average daily T_{Emin} are significant at the 95% level or higher and larger in magnitude than their annual counterparts at all stations. The three stations exhibiting significant trends in annual daily T_{Emax} also exhibit significant trends in JJA daily T_{Emax}.

4.2. Percentile trends

Trends in annual and JJA mean values of equivalent temperature and its components provide a broad perspective on changes in temperature and humidity in the study region. However, focusing on change in the mean has the potential to mask important changes in other parts of the probability distribution. To investigate the nature of the changes presented in Tables 1 and 2, we computed trends for the monthly 5th to 95th percentiles of daily T_{Emax}, T_{Emin}, T_{max}, T_{min}, L_vq/C_{Pmax}, and L_vq/C_{Pmin}. Examples of the resulting trends are presented for Des Moines, IA (Figure 2) and Indianapolis, IN (Figure 3), which are broadly reflective of the nature of the changes observed at the other stations in the western (Springfield, St. Louis, and Moline) and eastern (Memphis and Nashville) parts of the study region, respectively.

The trends in annual and JJA averages of daily T_{max} and T_{min} are positive at all of the stations considered here (Table 1, Table 2). While the overall magnitude of warming varies among the stations, several common features emerge from the analysis of percentile trends. At all of the stations, the largest positive temperature trends have occurred in the lowest percentiles of T_{max} and especially T_{min} in the late winter and early spring (January-March). Each of the stations also exhibits trends of at least 2°C per 50 years in the lowest percentiles of T_{min} during the summer months. At the northernmost stations (Des Moines and Moline, and to a lesser extent Indianapolis), increases in T_{max} have occurred across the distribution during the spring months. Stations in the west and northwest exhibit small decreases in T_{max}, and in the upper percentiles of T_{min}, during the autumn months (SON), as well as decreases in the upper percentile values of T_{max} during the summer.

The four westernmost stations (Des Moines, Springfield, Moline, and St. Louis) exhibit large trends (>2°C per 50 years) in both the maximum and minimum values of the equivalent temperature moisture term (L_vq/C_P) during August, followed by a decrease during the autumn months (Figure 2). At the eastern stations (Indianapolis, Memphis, and Nashville), summer increases in L_vq/C_P are smaller or absent, and fall decreases in L_vq/C_P are larger. The relative spatial coherence of the patterns in L_vq/C_P suggests that changes in large-scale circulation are involved. To investigate this possibility, we computed the average and trend in monthly 925 mb meridional moisture transport (qv; $gkg^{-1}\ ms^{-1}$) in the NCEP-NCAR reanalysis over the same period used to compute the trends presented above. The 925 mb level is used to capture moisture transport associated with the GPLLJ. The results, presented in Figure 4, indicate that July and August trends in moisture transport have been positive over the western stations, but that September trends are negative over the same region. These changes in large-scale moisture transport are consistent with the trends in L_vq/C_P observed at the stations.

The percentile trends in temperature (T_{max}, T_{min}) and moisture (L_vq/C_{Pmax}, L_vq/C_{Pmin}) ultimately govern the percentile trends in equivalent temperature (T_{Emax}, T_{Emin}). The largest trends in T_E therefore occur when the sign of the trends in the temperature and moisture terms agree. The contribution from the moisture term sometimes leads to trends in T_E that are opposite in sign to the temperature trend at the same station. As an example, the large positive trend in L_vq/C_{Pmax} during summer in Des Moines, IA leads to a positive trend in T_{Emax}, despite small negative or small positive trends in T_{max} (Figure 2). At stations where T_{Emax} increases during the summer, the change is largely due to changes in moisture. Changes in summer T_{Emin} tend to be larger because they result from changes in both the temperature and moisture terms. While the trends in both the temperature and moisture terms are positive during the winter, changes in T_E are driven primarily by changes in air temperature.

4.3. Analysis of heat waves

Previous work has linked the human health impacts of extreme heat to multi-day events (e.g., Anderson and Bell 2011). While the annual, summer, and monthly percentile-specific trends provide insight into the distribution of equivalent temperature and its components individually, we are also interested in the interactions between temperature and humidity within the context of multi-day events. Here we focus on events of at least 2-days duration for which T_{max} exceeds its station-specific summer (JJA) 90th percentile value on each day. We then consider how the components of equivalent temperature have changed during such events over the period of analysis (1961-2010).

Our focus on multi-day events exceeding the 90th percentile summer T_{max} value results in varying numbers of events identified for each station, ranging from an average of 1.9 events per year (Springfield) to 3.1 events per year (Indianapolis). Similarly, the number of total days meeting the heat-wave threshold varies from 354 days (1.9%) at Springfield to 518 days (2.8%) at Indianapolis (Table 3). Changes in T_{max} during heat waves are small and are not statistically significant. All of the stations have experienced increases in T_{min} during heat waves during the period of analysis, with the largest changes in Springfield, MO and St. Louis, MO (Table 3). These changes in T_{max} and T_{min} are broadly consistent with the summer trends observed at most stations (Fig. 2, Fig. 3, Table 2). Changes in moisture content associated with heat waves appears to be closely related to the trends in meridional moisture flux presented in Section 4.2, with increasing moisture content at western stations and decreasing moisture content at eastern stations. The four westernmost stations are characterized by significant increases in L_vq/C_{Pmax} during heat waves. Des Moines, IA and Moline, IL are also characterized by significant increases in L_vq/C_{Pmin}, while Nashville, TN is characterized by a significant decrease in L_vq/C_{Pmin}. Changes in equivalent temperature during heat waves are dependent on changes in both temperature and moisture. Two stations, Des Moines, IA and Moline, IL, exhibit significant increases in maximum equivalent temperature during heat waves as a result of increasing moisture content. The four westernmost stations have experienced significant changes in minimum equivalent temperature during heat waves, largely resulting from the combined effects of increases in T_{min} and L_vq/C_{Pmin}. None of the stations exhibit significant decreases in equivalent temperature during heat waves.

5. Summary and discussion

We have presented an analysis of changes in equivalent temperature and its components at seven stations in the Midwest USA for the period 1961-2010. Our results indicate that the annual mean of daily equivalent temperature has increased at all stations during this period, with the largest changes occurring (1) in minimum equivalent temperature at all stations and (2) in both maximum and minimum equivalent temperature at the westernmost stations. The former changes result from differential trends in T_{min} and T_{max}, while the latter correspond with concurrent increases in temperature and atmospheric moisture content. During the summer (JJA), trends in T_{max} are small (relative to their annual counterparts), but higher moisture content results in summer equivalent temperature trends that are generally larger than the annual trends, and statistically significant at the same stations.

Analysis of monthly percentile trends led to identification of several commonalities among the stations, including increases in the lowest percentiles of T_{min} during the late winter and summer months, as well as a trend toward late-summer moistening followed by early fall drying. The latter situation appears to be related to changes in the meridional moisture flux associated with the GPLLJ. Recent studies have linked changes in GPLLJ intensity to several large-scale features, including the North Atlantic Oscillation (NAO) and North Atlantic subtropical high (Ruiz-Barradas and Nigam 2005; Patricola and Cook 2013), but also to variability related to the Pacific sector (Weaver and Nigam 2008; Patricola et al. 2013). Increases in mean maximum equivalent temperature during with winter months tend to be associated primarily with increases in the temperature term, while those in the summer months tend to be associated primarily with increases in the moisture term. Increases in mean minimum equivalent temperature result primarily from increases in minimum air temperature that are strongest in the lowest percentiles in the winter and summer. Increases in moisture during the summer at the westernmost stations lead to large trends in minimum equivalent temperature.

Minimum temperatures during heat waves have increased at all of the stations. At all but the two easternmost stations (Indianapolis and Nashville), heat waves are also characterized by higher moisture content and therefore higher equivalent temperatures, especially at western locations where the positive trend in the moisture term has been the largest. Changes in T_{max} have had little effect on heat wave conditions in the study area.

Our findings are subject to several caveats. First, existing station metadata are sufficient to conduct initial assessments of data homogeneity as we have done here, but insufficient to guarantee that the station time series are free of any non-climatic influences. Nevertheless, the data used here represent the best available data for addressing concurrent long-term trends in equivalent temperature and its components, and have also been used in other studies focused on assessing humidity trends (e.g., Gaffen and Ross 1999; Dai 2006). Furthermore, the general spatial coherence of the results suggests that the trends identified represent true climatic signals rather than non-climatic artifacts of urbanization or other changes within the station environment. Second, at large-scales humidity is largely a function of temperature. The breakdown of that relationship in the context of changing climate (i.e., the trends considered in this study), suggests that local humidity variations are also sensitive to processes occurring at smaller scales, such as regional moisture transport or even antecedent soil moisture conditions. Previous studies (e.g., Sandstrom et al. 2013) have described an association between increasing crop acreage and dew point temperatures. Future work will focus on assessing the relative roles of local processes and large-scale circulation changes in equivalent temperature variations in a larger station network.

Our findings suggest that reliance on temperature alone provides a misleading portrait of changes in near-surface energy content of air. A particularly noteworthy example is the increase in equivalent temperature during the summer months, and during heat waves, despite small changes or even decreases, in daily maximum air temperature. In this case, the lack of warming in T_{max} masks changes in heat wave characteristics, such as increasing minimum temperature and increasing humidity, which are important in the context of human health (e.g., Gaffen and Ross 1998). Recent work by Fischer and Knutti (2012) found that the uncertainty in CMIP5 projections of metrics combining temperature and humidity are smaller than they would be for independent variables. We recommend that climate projection work focus on such combined metrics for assessment of changes in near surface energy content and human health impacts of rising temperatures.

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Table 1. Trends in annual averages of daily T_{Emax}, T_{Emin}, T_{max}, T_{min}, L_vq/C_{Pmax}, and L_vq/C_{Pmin}. All values are expressed in units of °C per 50 years. Significance of trends is shown for 90%*, 95%** and 99%***.

Station	**T_{Emax}**	**T_{Emin}**	**T_{max}**	**T_{min}**	**L_vq/C_{pmax}**	**L_vq/C_{Pmin}**
Des Moines	2.5***	2.8***	1.3***	1.4***	1.4**	0.6*
Moline	1.6**	1.9**	1.3***	1.1***	1.0*	0.4
Indianapolis	0.8	2.6***	1.0**	1.5***	0.4	0.2
Springfield	1.3	2.5***	0.3	1.0***	0.9	0.7*
St. Louis	2.0***	3.7***	1.3***	2.3***	1.0*	0.7
Memphis	1.3	2.7***	1.2***	1.6***	0.5	0.0
Nashville	0.0	1.5***	0.6**	1.2***	-0.6	-0.6

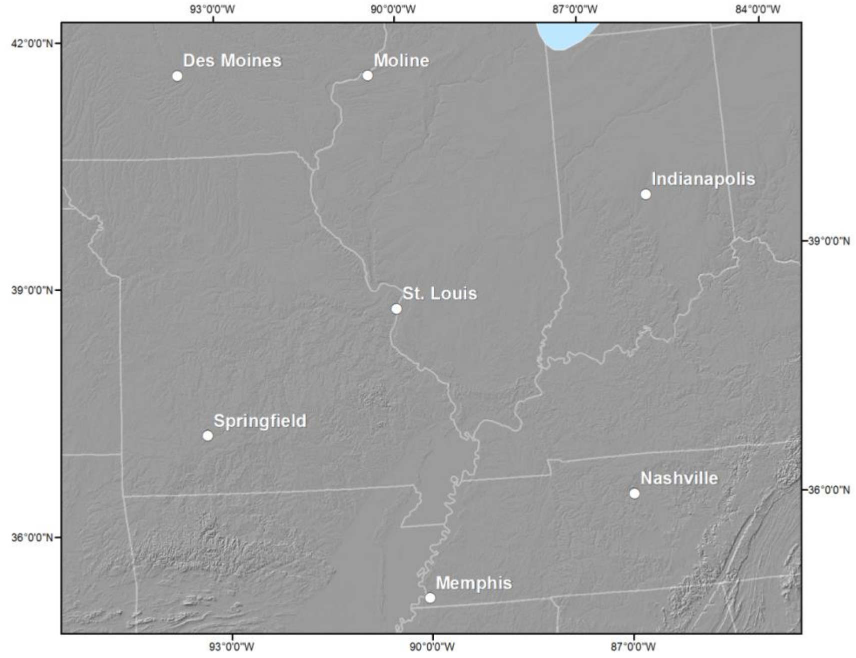
Table 2. Trends in summer (JJA) averages of daily T_{Emax}, T_{Emin}, T_{max}, T_{min}, L_vq/C_{Pmax}, and L_vq/C_{Pmin}. All values are expressed in units of °C per 50 years. Significance of trends is shown for 90%*, 95%** and 99%***.

Station	**T_{Emax}**	**T_{Emin}**	**T_{max}**	**T_{min}**	**L_vq/C_{pmax}**	**L_vq/C_{Pmin}**
Des Moines	2.8^{*}	3.8^{***}	0.1	1.2^{**}	2.8^{***}	1.9^{**}
Moline	1.7^{*}	2.9^{***}	0.0	0.9^{*}	1.8^{**}	1.2
Indianapolis	0.2	3.3^{***}	0.2	1.3^{***}	0.4	0.7
Springfield	1.3	4.7^{***}	0.4	1.6^{***}	1.9^{*}	2.0^{**}
St. Louis	2.8^{**}	5.1^{***}	1.0^{*}	2.5^{***}	1.9^{*}	1.6
Memphis	0.9	3.0^{***}	1.6^{***}	1.6^{***}	0.7	0.0
Nashville	-0.5	2.2^{**}	0.9	1.5^{***}	-0.3	-0.5

Table 3. Trends in annual average values of daily T_{Emax}, T_{Emin}, T_{max}, T_{min}, L_vq/C_{Pmax}, and L_vq/C_{Pmin} associated with warm events, defined as multi-day periods with T_{max} greater than the station-specific 90th percentile value. All values are expressed in units of °C per 50 years. Significance of trends is shown for 90%*, 95%** and 99%***. Also shown are the numerical values of the 90th percentile of T_{max}, number of number of warm events meeting this threshold (N_H) and the total number of days associated with those events (N_{Hday}).

Station	T_{max} P_{90}	N_H	N_{Hday}	T_{Emax}	T_{Emin}	T_{max}	T_{min}	L_vq/C_{pmax}	L_vq/C_{Pmin}
Des Moines	33.3	143	476	6.5^{**}	6.3^{***}	-0.2	1.4^{**}	6.7^{***}	3.7^{**}
Moline	33.3	140	459	6.5^{**}	6.1^{***}	0.2	0.8	6.4^{**}	4.4^{*}
Indianapolis	32.2	157	518	-1.0	2.6	0.3	0.8	-0.9	-0.2
Springfield	35.0	95	354	3.7	7.7^{***}	-0.1	1.8^{***}	5.1^{**}	2.3
St. Louis	35.0	138	432	3.7	4.3^{**}	-0.1	1.5^{***}	3.7^{*}	2.8
Memphis	35.6	111	415	-0.1	3.0	0.3	0.7	1.3	-1.4
Nashville	34.4	122	433	-2.6	0.9	-0.4	1.0^{*}	-1.4	-4.1^{***}

Figure 1. Map of study area, showing the locations of the seven stations used in the analysis**.**



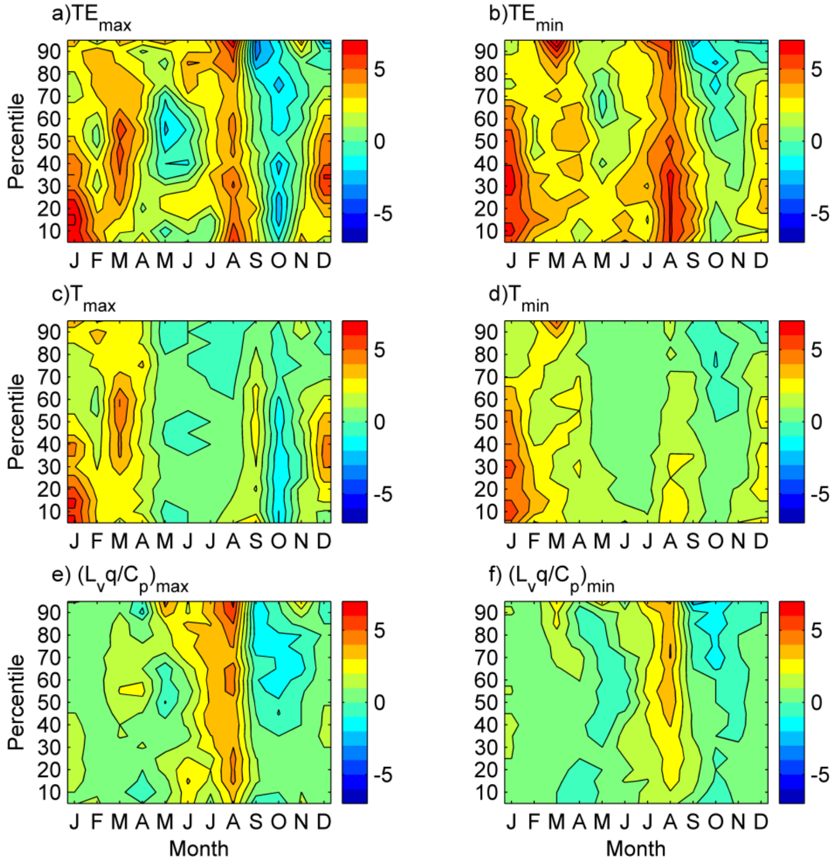


Figure 2. Monthly percentile trends for daily a) T_{Emax}, b) T_{Emin}, c) T_{max}, d) T_{min}, e) L_vq/C_{Pmax}, and f) L_vq/C_{Pmin} for Des Moines, IA. All values are expressed in units of °C per 50 years. The trends presented for Des Moines are also broadly representative of changes at Sprinfield, MO, St. Louis, MO and Moline, IL.

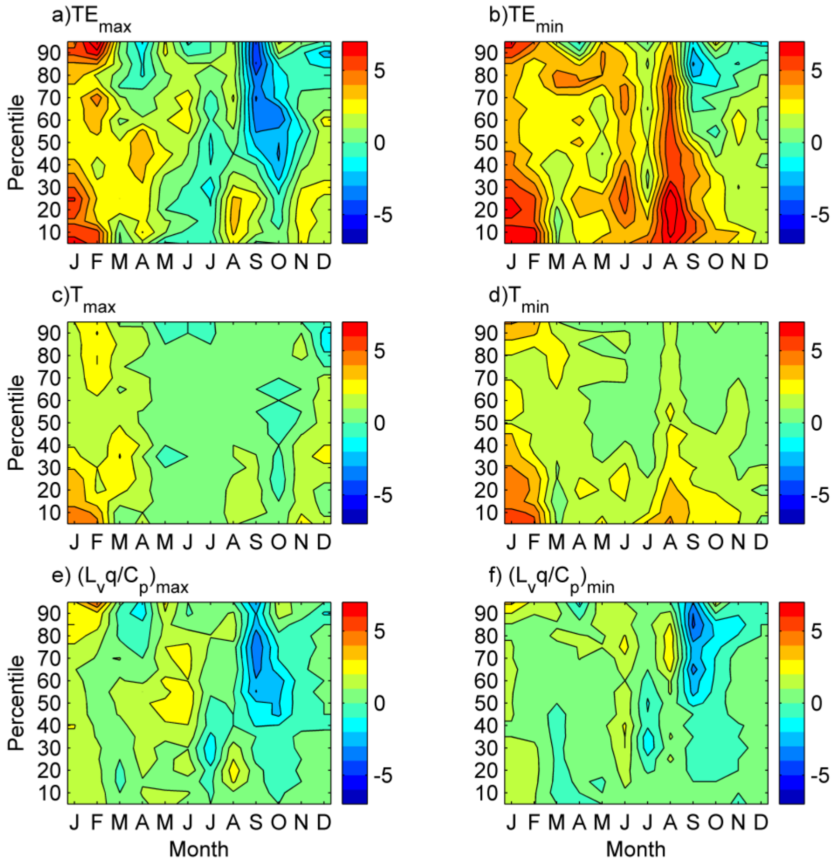


Figure 3. As in Figure 2, but for Indianapolis, IN. The trends presented for Indianapolis are also broadly representative of changes at Memphis, TN and Nashville, TN.

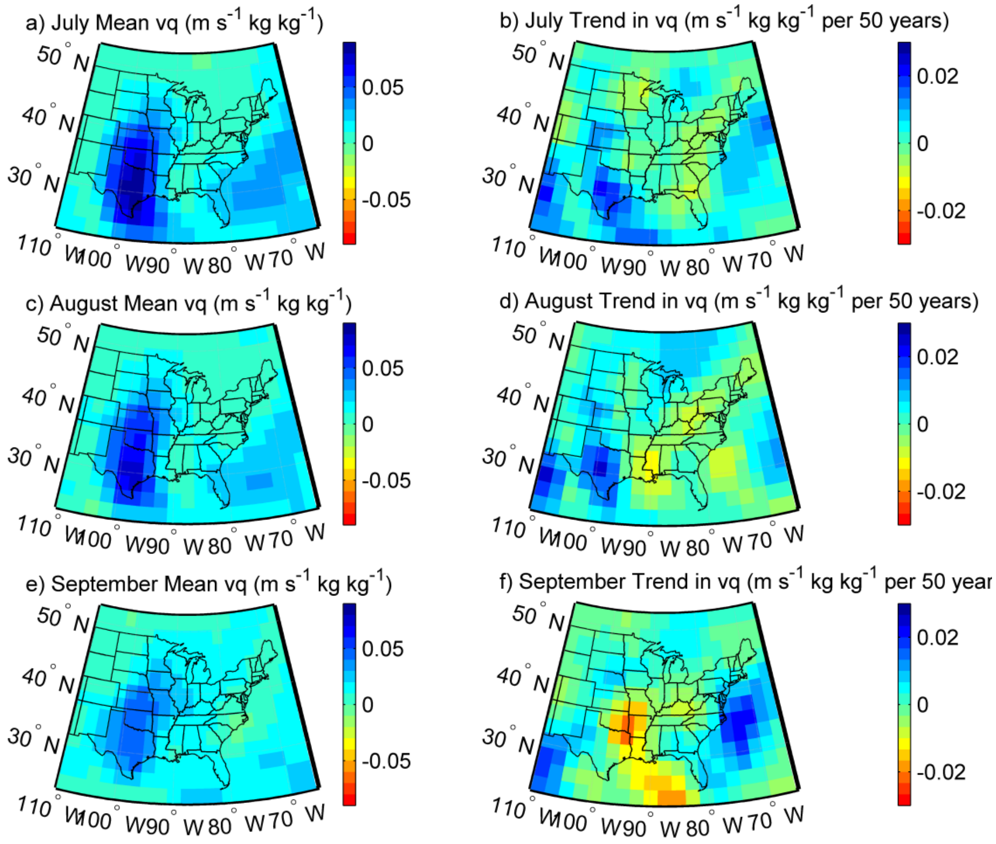


Figure 4. Average (left) and linear trend (right) in meridional moisture flux (vq) at 925 mb (m s^{-1} kg kg^{-1}) for July (a,b), August (c,d), and September (e,f).