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# Assessing trends in lower tropospheric heat content in the central United States using equivalent temperature

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#### **Abstract**

64 Isobaric equivalent temperature  $(T_F)$  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- 70 years (1961-2010) of daily  $T_E$  and its temperature and moisture components at seven stations in 71 the central USA. The annual means of daily  $T_{Emax}$  and  $T_{Emin}$  increased at all stations during the 72 period of analysis with the largest changes occurring in  $T_{Emin}$ , largely as a result of increasing 73 minimum air temperature. At western locations significant increases in the annual mean  $T_{Emax}$ 74 were also observed, resulting from a combination of increases in  $T_{\text{max}}$  and humidity. Despite 75 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 79 increasing  $T_{Emin}$ , primarily resulting from increases in minimum air temperature. At western 80 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:

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

101 where  $C_p$  is the specific heat of air at constant pressure (1005 J/kg<sup>o</sup>C), T is the air temperature 102 ( $\degree$ C), L<sub>v</sub> is the latent heat of vaporization (J/kg) and q is the specific humidity (kg/kg). Division 103 of H by  $C_p$  yields equivalent temperature (T<sub>E</sub>;  $^{\circ}$ C), which quantifies near surface heat content with separate terms for the dry and moist contributions:

105 
$$
T_E = \frac{H}{c_p} = T + \frac{L_v q}{c_p} \tag{2}
$$

 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, 114 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  $2<sup>nd</sup>$  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 near zero 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 132 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**

139 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 147 over the period of analysis, we partitioned each day into eight 3-hour blocks. For the daily  $T_{Emax}$ 148 and T<sub>Emin</sub> 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.

163 Following Gaffen and Ross (1999) we conducted t-tests (with  $\alpha$ =0.01) using four years of 164 monthly anomalies of maximum and minimum air temperature  $(T_{max}, T_{min})$  and dew point 165 temperature ( $Td_{\text{max}}$ ,  $Td_{\text{min}}$ ) 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 177 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 179 (T<sub>max</sub>). However, a significant change in T<sub>max</sub> 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 182 were also coincident with significant changes (same direction, with  $\alpha$  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 188 change between preceding and following 4-year periods ( $T_{min}$  at Indianapolis). However, five of 189 the six remaining stations also have a lower  $T_{min}$  during the period from 1960-1963 relative to 190 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 193 approximate date for this change resulted in no significant changes in  $T_{\text{max}}$  or  $T_{\text{min}}$  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 202 change in  $T_{\text{max}}$  or  $T_{\text{min}}$  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.

#### 219 **3. Methodology**

220 As shown in Eq. 2, computation of equivalent temperature requires specific humidity data. 221 For each available station observation, the empirical relation of Bolton (1980) was first used to 222 derive vapor pressure (e) from the measured dew point temperature  $(T_d; {}^{\circ}C)$ :

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

224 The vapor pressure and observed station pressure were then used to compute specific humidity 225 (q; kg/kg):

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

227 Latent heat of vaporization  $(L_v, J/kg)$ , which also appears in Eq. 2, was computed as a function 228 of temperature  $(T, {}^{\circ}C)$  following the Priestley-Taylor method as in Fall et al. (2010):

$$
L_{\nu} = 2.5 - 0.0022T \tag{5}
$$

230 Using these quantities, estimates of daily maximum and minimum equivalent temperature ( $T_{Emax}$ ) 231 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 238 analyses, similar to those of  $T_{\text{max}}$  and  $T_{\text{min}}$  conducted by Robeson (2004). In this approach, 239 trends are computed for each calendar month and for the  $5<sup>th</sup>$  to  $95<sup>th</sup>$  percentiles leading to improved assessment of changes across the probability distributions. 241 A second analysis focuses on heat waves, defined here as multi-day periods in which  $T_{\text{max}}$ 

242 exceeds its station-specific summer (JJA) 90<sup>th</sup> percentile value. For each year, days associated 243 with this criterion are identified and averaged to compute annual values of daily  $T_{Emax}$ ,  $T_{Emin}$ ,

244  $T_{\text{max}}$ ,  $T_{\text{min}}$ ,  $L_v q / C_{\text{Pmax}}$ , and  $L_v q / C_{\text{Pmin}}$  associated with heat waves. The resulting averages are then

245 subjected to a trend analysis to assess changes in the nature of heat waves in the context of

246 equivalent temperature and its components.

#### 248 **4. Results**

#### 249 *4.1. Annual and summer (JJA) trends*

250 Linear trends in the annual means of daily maximum and minimum air temperature  $(T_{\text{max}})$  $251$  T<sub>min</sub>) are positive at each of the seven stations considered in this study (Table 1), consistent with 252 the large-scale warming that occurred over the period considered (1961-2010). Trends in  $T_{min}$ 253 are highly significant (99% level) at all stations and are generally larger than the trends in  $T_{\text{max}}$  at 254 the same station. A similar decrease in diurnal temperature range has also been observed at 255 larger-scales (Karl et al. 1993; Easterling et al. 1997; Vose et al. 2005). Trends in  $T_{\text{max}}$  are also 256 significant at six of the seven stations. Annual values of the moisture component  $(L_vq/C_{Pmax}$ ,  $257$  L<sub>v</sub>q/C<sub>Pmin</sub>) exhibit positive trends at all stations except Nashville, although the trends are 258 statistically significant at only a few stations (Table 1). These trends in temperature and 259 atmospheric moisture are manifest as highly significant trends in the annual mean daily 260 minimum equivalent temperature  $(T_{Emin})$  at all stations. While all stations exhibit positive trends 261 in both  $T_{Emin}$  and  $T_{Emax}$ , the significance of  $T_{Emax}$  trends is limited to stations with positive trends 262 in both  $T_{\text{max}}$  and  $L_v q / C_{\text{Pmax}}$ .

263 Human health impacts of elevated temperature and humidity are most likely to occur during 264 the summer months, so trends were also computed for summer (JJA) averages of daily  $T_{Emax}$ , 265 T<sub>Emin</sub>, T<sub>max</sub>, T<sub>min</sub>, L<sub>v</sub>q/C<sub>Pmax</sub>, and L<sub>v</sub>q/C<sub>Pmin</sub> (Table 2). While the annual trends were characterized 266 by warming in both  $T_{\text{max}}$  and  $T_{\text{min}}$ , the JJA trends exhibit a notable lack of warming in  $T_{\text{max}}$  at 267 most stations, consistent with the "warming hole" described in section 1. Summer trends in  $T_{min}$ 268 are similar in magnitude and significance to their annual counterparts. With the exception of 269 Nashville, all of the stations have positive trends in JJA averages of daily  $L_v q / C_{Pmax}$ , and  $270$  L<sub>v</sub>q/C<sub>Pmin</sub>. These trends are significant at stations in the west/northwest part of the study region 271 (Table 2). Trends in JJA average daily T<sub>Emin</sub> are significant at the 95% level or higher and larger 272 in magnitude than their annual counterparts at all stations. The three stations exhibiting 273 significant trends in annual daily  $T_{Emax}$  also exhibit significant trends in JJA daily  $T_{Emax}$ .

274

#### 275 *4.2. Percentile trends*

276 Trends in annual and JJA mean values of equivalent temperature and its components provide 277 a broad perspective on changes in temperature and humidity in the study region. However, 278 focusing on change in the mean has the potential to mask important changes in other parts of the

- 279 probability distribution. To investigate the nature of the changes presented in Tables 1 and 2, we 280 computed trends for the monthly  $5^{th}$  to  $95^{th}$  percentiles of daily T<sub>Emax</sub>, T<sub>Emin</sub>, T<sub>max</sub>, T<sub>min</sub>,
- $281$  L<sub>v</sub>q/C<sub>Pmax</sub>, and L<sub>v</sub>q/C<sub>Pmin</sub>. Examples of the resulting trends are presented for Des Moines, IA

282 (Figure 2) and Indianapolis, IN (Figure 3), which are broadly reflective of the nature of the 283 changes observed at the other stations in the western (Springfield, St. Louis, and Moline) and

284 eastern (Memphis and Nashville) parts of the study region, respectively.

285 The trends in annual and JJA averages of daily  $T_{\text{max}}$  and  $T_{\text{min}}$  are positive at all of the stations 286 considered here (Table 1, Table 2). While the overall magnitude of warming varies among the 287 stations, several common features emerge from the analysis of percentile trends. At all of the 288 stations, the largest positive temperature trends have occurred in the lowest percentiles of  $T_{\text{max}}$ 289 and especially  $T_{min}$  in the late winter and early spring (January-March). Each of the stations also 290 exhibits trends of at least  $2^{\circ}$ C per 50 years in the lowest percentiles of  $T_{min}$  during the summer 291 months. At the northernmost stations (Des Moines and Moline, and to a lesser extent 292 Indianapolis), increases in  $T_{\text{max}}$  have occurred across the distribution during the spring months. 293 Stations in the west and northwest exhibit small decreases in  $T_{\text{max}}$ , and in the upper percentiles of  $294$  T<sub>min</sub>, during the autumn months (SON), as well as decreases in the upper percentile values of 295  $T_{\text{max}}$  during the summer.

296 The four westernmost stations (Des Moines, Springfield, Moline, and St. Louis) exhibit large 297 trends ( $>2^{\circ}$ C per 50 years) in both the maximum and minimum values of the equivalent 298 temperature moisture term  $(L_vq/C_P)$  during August, followed by a decrease during the autumn 299 months (Figure 2). At the eastern stations (Indianapolis, Memphis, and Nashville), summer 300 increases in  $L_v q / C_P$  are smaller or absent, and fall decreases in  $L_v q / C_P$  are larger. The relative 301 spatial coherence of the patterns in  $L_v q / C_P$  suggests that changes in large-scale circulation are 302 involved. To investigate this possibility, we computed the average and trend in monthly 925 mb 303 meridional moisture transport  $(qv; gkg^{-1}ms^{-1})$  in the NCEP-NCAR reanalysis over the same 304 period used to compute the trends presented above. The 925 mb level is used to capture moisture 305 transport associated with the GPLLJ. The results, presented in Figure 4, indicate that July and 306 August trends in moisture transport have been positive over the western stations, but that 307 September trends are negative over the same region. These changes in large-scale moisture 308 transport are consistent with the trends in  $L_v q / C_P$  observed at the stations.

309 The percentile trends in temperature  $(T_{\text{max}}, T_{\text{min}})$  and moisture  $(L_v q/C_{\text{Pmax}}, L_v q/C_{\text{Pmin}})$ 310 ultimately govern the percentile trends in equivalent temperature ( $T_{Emax}$ ,  $T_{Emin}$ ). The largest 311 trends in  $T<sub>E</sub>$  therefore occur when the sign of the trends in the temperature and moisture terms 312 agree. The contribution from the moisture term sometimes leads to trends in  $T<sub>E</sub>$  that are opposite 313 in sign to the temperature trend at the same station. As an example, the large positive trend in 314 L<sub>v</sub>q/C<sub>Pmax</sub> during summer in Des Moines, IA leads to a positive trend in  $T_{Emax}$ , despite small 315 negative or small positive trends in  $T_{\text{max}}$  (Figure 2). At stations where  $T_{\text{Emax}}$  increases during the 316 summer, the change is largely due to changes in moisture. Changes in summer  $T_{Emin}$  tend to be 317 larger because they result from changes in both the temperature and moisture terms. While the 318 trends in both the temperature and moisture terms are positive during the winter, changes in  $T_E$ 319 are driven primarily by changes in air temperature.

320

321 *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 326 multi-day events. Here we focus on events of at least 2-days duration for which  $T_{\text{max}}$  exceeds its 327 station-specific summer (JJA)  $90<sup>th</sup>$  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).

330 Our focus on multi-day events exceeding the  $90<sup>th</sup>$  percentile summer  $T_{max}$  value results in 331 varying numbers of events identified for each station, ranging from an average of 1.9 events per 332 year (Springfield) to 3.1 events per year (Indianapolis). Similarly, the number of total days 333 meeting the heat-wave threshold varies from 354 days (1.9%) at Springfield to 518 days (2.8%) 334 at Indianapolis (Table 3). Changes in  $T_{\text{max}}$  during heat waves are small and are not statistically 335 significant. All of the stations have experienced increases in  $T_{min}$  during heat waves during the 336 period of analysis, with the largest changes in Springfield, MO and St. Louis, MO (Table 3). 337 These changes in  $T_{max}$  and  $T_{min}$  are broadly consistent with the summer trends observed at most 338 stations (Fig. 2, Fig. 3, Table 2). Changes in moisture content associated with heat waves 339 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 341 stations. The four westernmost stations are characterized by significant increases in  $L_v q / C_{Pmax}$  during heat waves. Des Moines, IA and Moline, IL are also characterized by significant 343 increases in  $L_v q / C_{Pmin}$ , while Nashville, TN is characterized by a significant decrease in L<sub>v</sub>q/C<sub>Pmin</sub>. 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 349 combined effects of increases in  $T_{min}$  and  $L_v q / C_{P_{min}}$ . 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 358 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 360 (JJA), trends in  $T_{\text{max}}$  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 364 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 380 locations where the positive trend in the moisture term has been the largest. Changes in  $T_{\text{max}}$ 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

402 in  $T_{\text{max}}$  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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| 522 Table 1. Trends in annual averages of daily $T_{Emax}$ , $T_{Emin}$ , $T_{max}$ , $T_{min}$ , $L_v q / C_{Pmax}$ , and $L_v q / C_{Pmin}$ . |  |
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523 All values are expressed in units of  $\mathrm{C}$  per 50 years. Significance of trends is shown for 90%<sup>\*</sup>,

524 95%<sup>\*\*</sup> and 99%<sup>\*\*\*</sup>.



 

|  | 544 Table 2. Trends in summer (JJA) averages of daily $T_{Emax}$ , $T_{Emin}$ , $T_{max}$ , $T_{min}$ , $L_vq/C_{Pmax}$ , and |  |  |  |  |  |
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545 L<sub>v</sub>q/C<sub>Pmin</sub>. All values are expressed in units of  $\rm{^{\circ}C}$  per 50 years. Significance of trends is shown 546 for 90%<sup>\*</sup>, 95%<sup>\*\*</sup> and 99%<sup>\*\*\*</sup>.



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567 **Table 3.** Trends in annual average values of daily  $T_{Emax}$ ,  $T_{Emin}$ ,  $T_{max}$ ,  $T_{min}$ ,  $L_v q / C_{Pmax}$ , and

- 568 L<sub>v</sub>q/C<sub>Pmin</sub> associated with warm events, defined as multi-day periods with  $T_{\text{max}}$  greater than the
- 569 station-specific  $90<sup>th</sup>$  percentile value. All values are expressed in units of  $\degree$ C per 50 years.
- 570 Significance of trends is shown for 90%<sup>\*</sup>, 95%<sup>\*\*</sup> and 99%<sup>\*\*\*</sup>. Also shown are the numerical
- 571 values of the 90<sup>th</sup> percentile of T<sub>max</sub>, number of number of warm events meeting this threshold
- 572 ( $N_H$ ) and the total number of days associated with those events ( $N_{Hday}$ ).



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594 **Figure 2**. Monthly percentile trends for daily a) T<sub>Emax</sub>, b) T<sub>Emin</sub>, c) T<sub>max</sub>, d) T<sub>min</sub>, e) L<sub>v</sub>q/C<sub>Pmax</sub>, 595 and f)  $L_v q / C_{Pmin}$  for Des Moines, IA. All values are expressed in units of  $\degree$ 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  $s^{-1}$ ) 602

603 kg kg<sup>-1</sup>) for July (a,b), August (c,d), and September (e,f).