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

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Schoof, Justin T., Heern, ZA, Therrell, MD and Remo, JWF. "Assessing trends in lower tropospheric heat content in the central United States using equivalent temperature." *International Journal of Climatology* 35 (Sep 2014): 2828-2836. doi:10.1002/joc.4175.

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1	This is the	peer reviewed	version of the	following	article:
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- 3 Schoof JT, Heern ZA, Therrell MD, Remo JWF (2014) Assessing trends in lower tropospheric
- 4 heat content in the central United States using equivalent temperature. *International Journal of*
- *Climatology* 35: 2828-2836.
- 7 which has been published in final form at
- 8 <u>http://onlinelibrary.wiley.com/doi/10.1002/joc.4175/full</u>
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- 11 Conditions for Self-Archiving.
- 13 Final version accepted for publication in *International Journal of Climatology* on Aug. 29, 2014

32	Assessing trends in lower tropospheric heat content in the Central USA using equivalent
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49	Final version accepted by International Journal of Climatology
50	August 29, 2014
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63 Abstract

Isobaric equivalent temperature (T_E) is the temperature that an air parcel would have if all 64 associated water vapor were condensed and the resulting latent heat used to increase the 65 temperature of the parcel. It is therefore an ideal metric for assessing changes in (1) total near 66 surface heat content associated with both temperature and moisture content and (2) the joint 67 behavior of temperature and humidity, which is relevant to both lower atmospheric stability and 68 human heat stress during extreme temperature events. We present results from an analysis of 50-69 years (1961-2010) of daily T_E and its temperature and moisture components at seven stations in 70 the central USA. The annual means of daily T_{Emax} and T_{Emin} increased at all stations during the 71 period of analysis with the largest changes occurring in T_{Emin}, largely as a result of increasing 72 minimum air temperature. At western locations significant increases in the annual mean T_{Emax} 73 74 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 75 76 than their annual counterparts. The timing of the observed variations and the resulting spatial 77 pattern are consistent with observed changes in meridional moisture flux associated with the 78 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 79 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 81 82 change that differs from what is provided by consideration of temperature alone. 83 84 85 86 87 88 89 90 91 92 93

94 **1. Introduction**

Variations and trends in lower tropospheric heat content are usually assessed using nearsurface 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:

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 106 107 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 108 109 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 110 111 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 112 113 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 114 the US, were larger than trends in T as a result of the moisture term (i.e., the 2nd term in Equation 115 2) but with substantial influence from presence/absence of vegetation. 116

Since human heat stress is a function of both air temperature and atmospheric moisture 117 118 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 119 120 temperature, as well as the clear separation of the dry and moist contributions to its magnitude, 121 makes it an excellent choice for understanding such changes. In this study, we focus on a set of 122 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 123 constitutes an area that has been referred to as "the warming hole" due to weak positive or near-124

125 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 126 127 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 128 temperature that originate from internal decadal variability associated with Pacific sea-surface 129 temperatures (Meehl et al. 2012). Including these areas in the study region therefore provides an 130 opportunity to investigate changes in total heat content in a region where warming has been 131 modest or even absent. Our primary objectives are to (1) assess trends in T_E and its components 132 and (2) determine the effect of these trends on the characteristics of regional heat waves. 133 The data used to address our objectives are described in Section 2, along with an assessment 134 of data homogeneity. Section 3 includes a description of the methods employed in our analysis. 135 The results are presented in Section 4, followed by a brief discussion in Section 5. 136

137

138 **2. Data**

Hourly values of temperature (T), dew point temperature (T_d) , and station pressure (P) were 139 140 extracted for eight stations (Figure 1) from the National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD) available from the National Climatic 141 142 Data Center (NCDC) along with available station metadata for the period of 1961-2010. The 143 consistency of reports in the ISD varies considerably over the period of record. Observations are 144 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 145 period from 1966-1981, values were only reported every three hours. To ensure consistency 146 over the period of analysis, we partitioned each day into eight 3-hour blocks. For the daily T_{Emax} 147 148 and T_{Emin} to be considered for further analysis, each 3-hour block had to have at least one hour 149 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 α =0.01) using four years of monthly anomalies of maximum and minimum air temperature (T_{max}, T_{min}) and dew point 164 temperature (Td_{max}, Td_{min}) before and after each documented station move and for the 165 instrumentation changes that occurred in 1964, 1985, the mid-1990s (ASOS installation) and in 166 the early 2000s (DTS1 installation). The implementation of ASOS and the installation of DTS 167 168 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 169 170 Gaffen and Ross (1999). In our examination of these differences, we considered whether any significant changes accompanied documented station changes, but also whether significant 171 172 changes occurred simultaneously at neighboring stations where no changes in observation practices were noted. 173

During the 50-year period considered here, the seven stations in Figure 1 were moved a 174 combined total of 20 times. Using the available location data as estimates, the station moves 175 ranged from a few meters to 4.05 km, but only one move was larger than 2 km. The majority of 176 177 the moves (13) were not associated with significant changes in any of the variables considered. 178 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, 179 suggesting that the difference was due to a true climatic influence rather than a station move. 180 Similarly, changes in dew point temperature associated with six of the documented station moves 181 were also coincident with significant changes (same direction, with α between 0.1 and 0.01) at 182 nearby stations where moves were not documented. On the basis of this analysis, we concluded 183 184 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 185 186 of instrumentation changes.

187 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 188 189 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 α =0.1). The change to the HO-83 191 hygrothermometer in the mid-1980s has been associated with a warm bias in some environments 192 (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 193 194 considered here. A single station (St. Louis, MO) exhibits a significant difference in both 195 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 196 197 outcome is opposite in sign to what would be expected from documented effects of the change to the HO-83 sensor. 198

199 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-83 200 hygrothermometer designed to reduce warm bias. None of the stations exhibit a significant 201 change in T_{max} or T_{min} associated with ASOS installation. A single station (St. Louis, MO), 202 exhibited a significant change in both maximum and minimum dew point temperature. 203 However, this change was also observed at several other stations and therefore was unlikely to 204 have resulted from the implementation of ASOS instrumentation. The installation of the DTS1 205 206 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 207 208 other stations (Indianapolis, IN and Nashville, TN) that had no documented changes in 209 instrumentation.

The analyses conducted using known and estimated changes in location and instrumentation 210 did not identify any clear inhomogeneities in the station data, so no changes were made to the 211 time series. However, non-climatic influences may also result from changes occurring in the 212 213 environment around the stations, such as urbanization, changes in land use, or changes in 214 agricultural practices. Existing station histories and ancillary data are inadequate to assess such 215 changes. Without long-term records from reference stations, the first-order stations considered 216 here provide the best long-term coincident temperature and dew-point temperature data available. 217

219 **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):

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

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):

229

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

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 232 233 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 234 median of pairwise slopes regression (MPWS; Lanzante 1996). MPWS is considered a robust 235 236 regression technique and was used to minimize the impact of any unidentified inhomogeneities. 237 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, 238 trends are computed for each calendar month and for the 5th to 95th percentiles leading to 239 improved assessment of changes across the probability distributions. 240 241 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} ,

244 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.

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_{max} , T_{min}) are positive at each of the seven stations considered in this study (Table 1), consistent with 251 the large-scale warming that occurred over the period considered (1961-2010). Trends in T_{min} 252 are highly significant (99% level) at all stations and are generally larger than the trends in T_{max} at 253 254 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 255 significant at six of the seven stations. Annual values of the moisture component (L_vq/C_{Pmax} , 256 L_vq/C_{Pmin}) exhibit positive trends at all stations except Nashville, although the trends are 257 statistically significant at only a few stations (Table 1). These trends in temperature and 258 259 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 260 in both T_{Emin} and T_{Emax} , the significance of T_{Emax} trends is limited to stations with positive trends 261 in both T_{max} and L_vq/C_{Pmax} . 262

263 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}, 264 265 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 266 267 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 268 Nashville, all of the stations have positive trends in JJA averages of daily Lvq/CPmax, and 269 270 L_{vq}/C_{Pmin} . These trends are significant at stations in the west/northwest part of the study region 271 (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 272 273 significant trends in annual daily T_{Emax} also exhibit significant trends in JJA daily T_{Emax} .

274

275 *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 5^{th} to 95^{th} percentiles of daily T_{Emax} , T_{Emin} , T_{max} , T_{min} ,

281 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 thechanges observed at the other stations in the western (Springfield, St. Louis, and Moline) and

changes observed at the other stations in the western (Springfield, St. Louis, and Molin
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 285 considered here (Table 1, Table 2). While the overall magnitude of warming varies among the 286 stations, several common features emerge from the analysis of percentile trends. At all of the 287 stations, the largest positive temperature trends have occurred in the lowest percentiles of T_{max} 288 and especially T_{min} in the late winter and early spring (January-March). Each of the stations also 289 exhibits trends of at least 2°C per 50 years in the lowest percentiles of T_{min} during the summer 290 months. At the northernmost stations (Des Moines and Moline, and to a lesser extent 291 Indianapolis), increases in T_{max} have occurred across the distribution during the spring months. 292 Stations in the west and northwest exhibit small decreases in T_{max} , and in the upper percentiles of 293 294 T_{min} , during the autumn months (SON), as well as decreases in the upper percentile values of T_{max} during the summer. 295

296 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 297 298 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_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 301 302 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 303 period used to compute the trends presented above. The 925 mb level is used to capture moisture 304 transport associated with the GPLLJ. The results, presented in Figure 4, indicate that July and 305 August trends in moisture transport have been positive over the western stations, but that 306 307 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. 308

309 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 310 311 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 312 in sign to the temperature trend at the same station. As an example, the large positive trend in 313 L_vq/C_{Pmax} during summer in Des Moines, IA leads to a positive trend in T_{Emax} , despite small 314 negative or small positive trends in T_{max} (Figure 2). At stations where T_{Emax} increases during the 315 summer, the change is largely due to changes in moisture. Changes in summer T_{Emin} tend to be 316 larger because they result from changes in both the temperature and moisture terms. While the 317 trends in both the temperature and moisture terms are positive during the winter, changes in T_E 318 are driven primarily by changes in air temperature. 319

320

321 *4.3. Analysis of heat waves*

322 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 323 324 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 325 326 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 327 328 components of equivalent temperature have changed during such events over the period of analysis (1961-2010). 329

Our focus on multi-day events exceeding the 90^{th} percentile summer T_{max} value results in 330 varying numbers of events identified for each station, ranging from an average of 1.9 events per 331 332 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%) at Indianapolis (Table 3). Changes in T_{max} during heat waves are small and are not statistically 334 significant. All of the stations have experienced increases in T_{min} during heat waves during the 335 period of analysis, with the largest changes in Springfield, MO and St. Louis, MO (Table 3). 336 337 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 338 339 appears to be closely related to the trends in meridional moisture flux presented in Section 4.2,

340 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} 341 342 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 343 L_vq/C_{Pmin} . Changes in equivalent temperature during heat waves are dependent on changes in 344 both temperature and moisture. Two stations, Des Moines, IA and Moline, IL, exhibit 345 significant increases in maximum equivalent temperature during heat waves as a result of 346 increasing moisture content. The four westernmost stations have experienced significant 347 changes in minimum equivalent temperature during heat waves, largely resulting from the 348 combined effects of increases in T_{min} and L_vq/C_{Pmin}. None of the stations exhibit significant 349 350 decreases in equivalent temperature during heat waves.

351

352 **5. Summary and discussion**

353 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 354 355 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 356 357 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 358 359 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 360 361 results in summer equivalent temperature trends that are generally larger than the annual trends, 362 and statistically significant at the same stations.

363 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 364 365 summer months, as well as a trend toward late-summer moistening followed by early fall drying. 366 The latter situation appears to be related to changes in the meridional moisture flux associated 367 with the GPLLJ. Recent studies have linked changes in GPLLJ intensity to several large-scale 368 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 369 370 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.

382 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 383 guarantee that the station time series are free of any non-climatic influences. Nevertheless, the 384 data used here represent the best available data for addressing concurrent long-term trends in 385 386 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 387 388 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 389 390 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 391 392 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. 393 394 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 395 of local processes and large-scale circulation changes in equivalent temperature variations in a 396 397 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.

409

410 **6. Acknowledgments**

411 This material is based upon work supported by the National Science Foundation under Grant No.

412 1339655. Any opinions, findings, and conclusions or recommendations expressed in this

- 413 material are those of the authors and do not necessarily reflect the views of the National Science
- 414 Foundation.
- 415

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522	Table 1. Trends	in annual a	verages o	of daily	T _{Emax} ,	T _{Emin} ,	T _{max} ,	T_{min} ,	L_vq/C_{Pmax} ,	and L_vq/C_{Pmin} .
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523 All values are expressed in units of °C per 50 years. Significance of trends is shown for 90%^{*},

524 95%^{**} and 99%^{***}.

Station	TEmax	TEmin	T _{max}	T _{min}	Lvq/Cpmax	Lvq/CPmin
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

544	Table 2. Trends in summer	(JJA) averages of	of daily T _{Emax} ,	T _{Emin} , 7	T _{max} , 7	Γ_{\min} , $L_v q/C_{Pmax}$, and
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 L_vq/C_{Pmin} . All values are expressed in units of °C per 50 years. Significance of trends is shown 546 for 90%^{*}, 95%^{**} and 99%^{***}.

Station	TEmax	T _{Emin}	T _{max}	T _{min}	Lvq/Cpmax	Lvq/CPmin
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

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- **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 90^{th} percentile value. All values are expressed in units of °C per 50 years.
- 570 Significance of trends is shown for 90%^{*}, 95%^{**} and 99%^{***}. Also shown are the numerical
- values of the 90^{th} 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}	N _H	N _{Hday}	T _{Emax}	T _{Emin}	T _{max}	T _{min}	L _v q/C _{pmax}	L_vq/C_{Pmin}
	P 90								
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 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.



599 Figure 3. As in Figure 2, but for Indianapolis, IN. The trends presented for Indianapolis are also

600 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).