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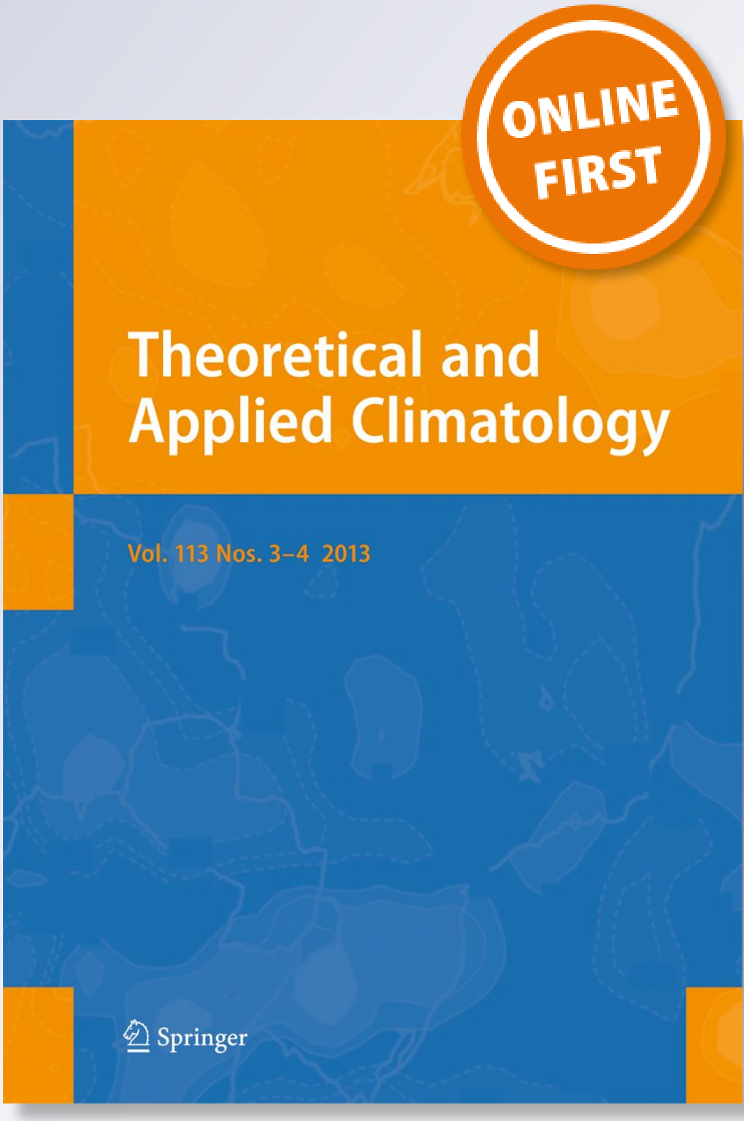

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ORIGINAL PAPER

Mesoscale surface equivalent temperature (T_E) for East Central USA

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Abstract

The purpose of this research is to investigate near surface mesoscale equivalent temperatures (T_E) in Kentucky (located in east central USA) and potential land cover influences. T_E is a measure of the moist enthalpy composed of the dry bulb temperature, T, and absolute humidity. Kentucky presents a unique opportunity to perform a study of this kind because of the observational infrastructure provided by the Kentucky Mesonet (www.kymesonet.org). This network maintains 69 research-grade, in-situ weather and climate observing stations across the Commonwealth. Equivalent temperatures were calculated utilizing high-quality observations from 33 of these stations. In addition, the Kentucky Mesonet offers higher spatial and temporal resolution than previous research on this topic. As expected, the differences ($T_E - T$) were greatest in the summer (smallest in the winter), with an average of 35 °C (5 °C). In general, the differences were found to be the largest in the western climate division. This is attributed to agricultural land use and poorly drained land. These differences are smaller during periods of drought, signifying less influence of moisture.

1 Introduction

Climate change and climate variability have primarily been assessed using surface air temperature variability and trends (e.g., IPCC 2013). However, air temperature alone is not a complete metric of the full near-surface heat content, as it does not account for the heat content changes associated with moisture changes (moist enthalpy; Pielke et al. 2004). In fact, at the surface, an increase of 1 °C in the dew point temperature produces the same change in heat content as an air temperature increase of 2.5 °C (Pielke 2001). This means that if there is a simultaneous 1 °C increase in air temperature and 1 °C decrease in dew point temperature (typical during boundary layer mixing linked to diurnal heating), there will actually be a net reduction in the near surface heat content. This relationship between moisture and heat content has the greatest impact in warmer, moist environments, and has the least impact in a cooler, drier atmosphere (Pielke 2001). The use of a moist enthalpy calculation, written as equivalent temperature (T_E), defined as $T_E = \frac{c_p T + L_v q}{c_p}$, allows for a comparison between air temperature and the full heat content of the near surface atmosphere (cf., Pielke et al. 2004; Davey et al. 2006; Rogers et al. 2007; Fall et al. 2010; Peterson et al. 2011).

In order to explore this relationship between moisture and heat content adequately, knowledge of land-atmosphere interactions is necessary. Surface energy and moisture budgets incorporate the effects of net longwave and solar radiative fluxes, turbulent sensible and latent heat partitioning, soil heat flux, precipitation, physical evaporation and transpiration (referred to as evapotranspiration), runoff, and infiltration. These budgets are fundamentally interconnected, with changes in any component of one budget affecting change in another. Any land use land cover change (LULCC) that considerably alters any of these properties can have a non-trivial influence on the climate system at global, regional, and local scales, which is why LULCC research is an important facet of understanding potential climate change (Mahmood et al. 2014). Since T_E is more sensitive to surface vegetation, via evapotranspiration, than temperature alone, it represents

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near-surface atmospheric heat content more accurately. Thus, land use land cover and their changes (LULCCs) can also affect T_E. In addition, overall patterns of T_E follow those of air temperature, but with higher values than air temperature itself. The differences between T and T_E were found to be more significant during the growing season, as well as in areas with higher surface evaporation and transpiration rates. These results indicated that T_E is a more appropriate metric for identifying regional heat content characteristics, especially in the context of land use and land cover.

The research presented here evaluates atmospheric heat content at the mesoscale, using the more complete metric of T_E. Specifically, the purpose of this research is to provide a mesoscale assessment of T_E at daily, seasonal, and annual timescales over Kentucky for the period of 2009–2014. It is expected that these differences are greatest during the growing season and vary based on the type of vegetation cover at the site. This research shows that T_Es are higher than air temperature alone on warm, wet days, and smaller on cool, dry days. This is a first of this type of study which is focused on mesoscale. There is a unique opportunity to perform this research in Kentucky because of the high-quality weather and climate observation by the Kentucky Mesonet (www.kymesonet.org). The Kentucky Mesonet consists of 69 research-grade surface stations across the state and this research utilizes a subset of data from 33 stations (Fig. 1). The time period of 2009–2014 was selected based on the rationale that it provides the highest spatio-temporal density of the data compared to any previous research (e.g., Davey et al. 2006; Fall et al. 2010; Schoof et al. 2014). We would also like to note that these 5 years nicely capture a range of prevailing hydroclimatic conditions, including historic drought (2012) and flooding (2010) conditions. In other words, potentially, this timeseries could be quite representative of a longer timeseries. Moreover, while this is relatively a short time series, the results of this research should provide valuable information about heat content variations at the mesoscale and various timescales, and serve as a basis for similar future research. These results could also be beneficial for areas located in comparable climates, with similar land cover attributes that do not have a comprehensive mesonet to conduct research of this type.

As indicated above, different land cover types influence moisture availability through varying moisture storage capability and evapotranspiration rates. Thus, T_E can be used as a supplementary metric for evaluating near-surface heat content with respect to land cover use (Fall et al. 2010). Additional research questions addressed include how extreme precipitation periods (drought and wet conditions) impact T_E distributions and how synoptic patterns impact daily fluctuations in heat content.

2 Data and methods

2.1 Data

All mesonet stations directly observe 5-min air temperature, relative humidity, precipitation, solar radiation, wind speed, and wind direction, and calculate the dew point temperature at 5-min interval. This network also measures soil moisture and temperature at 22 sites and at 5 depths at each site. For this study, hourly air temperature and dew point temperature values were used, calculated from arithmetic averages of the reported 5-min data. The hourly pressure data used for this analysis were obtained from the nearest Automated Surface Observation Station (ASOS) archived by the Midwest Regional Climate Center (MRCC 2014). Again, Fig. 1 shows the locations of all Kentucky Mesonet stations, the sites included in this research, and the ASOSs within Kentucky. Data from ASOS stations were used to estimate pressure, needed to calculate T_E. ASOS locations in neighboring states were also used as the source of pressure data if they were located closest to the chosen mesonet site.

There were two possible options available to estimate pressure. The first option was to apply a spatial statistical interpolation method (such as kriging) to produce pressure estimates at each grid point in the study area. The second option was to use pressure data from the nearest ASOS. Both methods would introduce small biases. Through observation of 3 months of data at multiple sites ($n = 2184$ h), it was determined that differences in pressure values across the state are well within a 10 hPa range. To quantify possible errors from using the nearest ASOS for data, a pressure sensitivity test was performed. For one time step at the Warren County mesonet, T_E was recalculated accounting for a 10-hPa pressure bias. With everything else held constant, pressure was changed systematically in 1-hPa increments from 1012.58 to 1022.58 hPa (actual pressure, 1017.58). This resulted in an error range of 0.035 °C in T_E. The Warren County mesonet site was chosen for this test because of the location and availability of data from nearby ASOS station for the estimation of error. Since pressure does not vary much at the mesoscale (except under severe weather conditions), it is acceptable to use pressure data from nearby ASOS stations. In addition, this sensitivity analysis shows that even if large errors get introduced due to using pressure from a non-local source, impacts on the T_E calculation would be minimal.

To help explain anomalous observations in T_E patterns over Kentucky, two drought indices were considered: Palmer Z-Index and Palmer Drought Severity Index (PDSI). The Z-Index quantifies short-term moisture departure from climatological normals based on monthly conditions with no consideration for previous deficits or surpluses of moisture (NCDC 2013). This index responds rapidly to current weather conditions, and may reflect short-term wet periods during extended

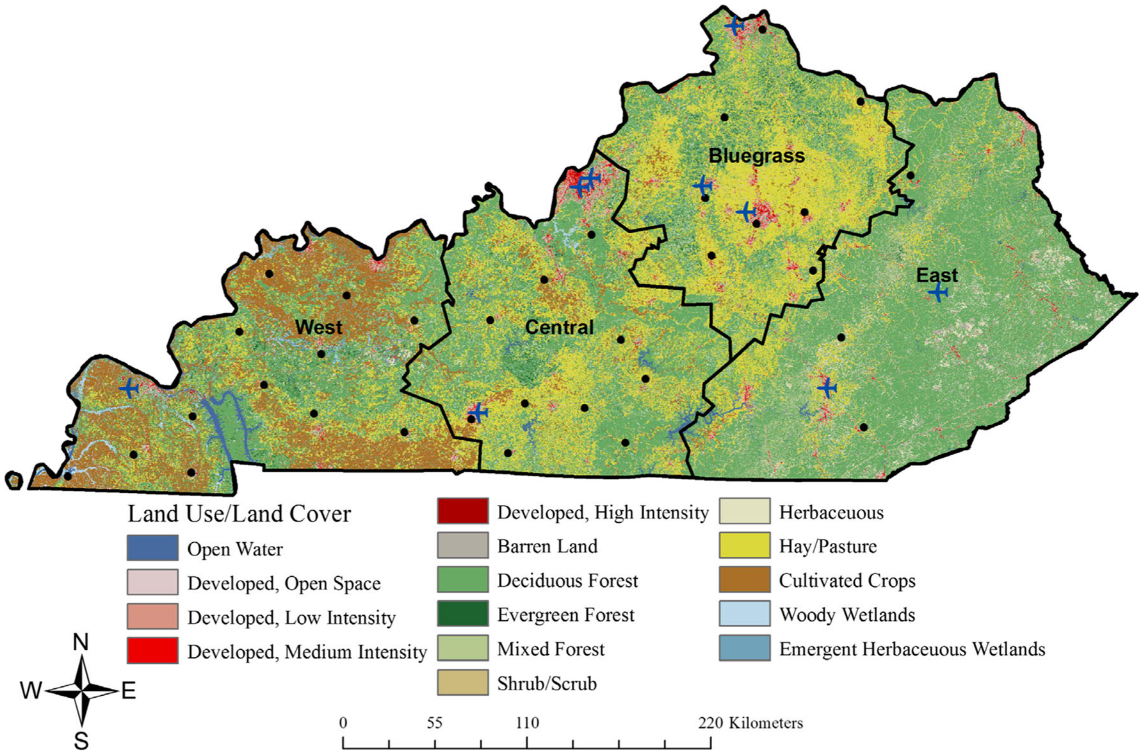

Fig. 1 Locations of the mesonet stations included in the analysis and land cover/land use of Kentucky, as well as the climate division boundaries. Blue airplane symbols are showing ASOS stations maintained by NWS/NOAA

droughts, and vice versa. The PDSI identifies long-term drought based on dominant, recurring circulation patterns and is calculated using both current and prior monthly weather patterns (NCDC 2013). Data for both of these indices were accessed from the Midwestern Regional Climate Center (2014) archive.

2.2 Mesonet site selection

The site selection was based on three criteria: location, predominant land cover, and the length of time series. Kentucky can be categorized into four distinct climate divisions (CD). These CDs are western = CD 1, central = CD 2, bluegrass = CD 3, and eastern = CD 4), as defined by the National Climatic Data Center (NCDC 2015) (Fig. 1). The sites were selected to represent the most diverse range of dominant land covers as possible. To overcome potential added complexities related to elevation, this study avoided including stations from the mountainous eastern Kentucky region. There are only two from the Appalachian region (Eastern Climate Division) and their elevation is less than 475 m, while for the rest of the stations, elevation range between105 and 305 m (with majority (16) within the range of 201–259 m and another eight in the range of 155–181 m). In other words, we have minimized the impacts of regional variations of elevation on T_E.

Aerial photos from 2012 at a 1-m resolution were accessed from the National Agriculture Imagery Program (NAIP). These digital images were taken across the continental USA during the agricultural growing seasons. Aerial photographs for Kentucky are available from the Kentucky Geography Network archive (KGN 2012). Photographs were examined around each chosen station at a 1.5-km radius to depict the dominant surrounding land cover. Each station within the study area can be classified based on its land use and land cover. These data were obtained from the 2011 National Land Cover Database prepared by the Multi-Resolution Land Characteristics (MRLC) Consortium (Jin et al. 2013). Figure 1 shows the locations of each mesonet station chosen for analysis and the underlying land cover. We have successfully included NAIP and MRLC data as a part of an approach to record meteorological/climatological station metadata, known as *Geoprofile* (cf., Mahmood et al. 2006). In addition, these data and the approach can be used to assess the influence of exposure on long-term climate data (Mahmood et al. 2006). Kentucky Mesonet has been using this approach to record its station metadata.

2.3 Methods

Moist enthalpy, or heat content, is expressed as:

$$H = c_p T + L_v q$$

where c_p is the isobaric specific heat of air (1005 Jkg^{-1} K^{-1}), T is the air temperature (K), L_v is the latent heat of vaporization

(2.5×10^6 Jkg^{-1}), and q is the specific humidity (Pielke et al. 2004). Moist enthalpy has units of joules per kilogram; so, to enable comparison with air temperature, equivalent temperature in Kelvin is calculated by:

$$T_E = \frac{H}{c_p}.$$

Since the products available from the mesonet do not include a direct measure for specific humidity (q), it is calculated from the dew point temperature (T_d) and the vapor pressure of the air (e), using Bolton's (1980) empirical relationship:

$$e = 6.112\exp\left[\frac{17.67\mathrm{T_d}}{T_d + 243.5}\right]$$

From this, q is calculated as

$$q = \frac{0.622e}{P{-}0.37e}$$

where P is the station pressure in hectopascals, obtained from the nearest ASOS (Rogers et al. 2007).

Data for each of the 33 locations were analyzed on hourly, daily, monthly, seasonal, and annual timescales. T_E was calculated at hourly time steps for each station from 1 December, 2009, through 30 November, 2014, and then aggregated to different timescales. Seasons were defined as follows: Winter—December, January, February; Spring—March, April, May; Summer—June, July, August; and Fall—September, October, November. Averaging the hourly values for each day allowed daily comparisons between air temperature and T_E, presented yearly and seasonally for each station. To represent and compare the distribution of T_E values graphically, yearly boxplots, grouped by season, were made for all stations. Additionally, boxplots per climate division (CD) were made and grouped seasonally.

A selection of ten stations—Calloway (CD 1), Fulton (CD 1), Ohio (CD 1), Bullitt (CD 2), Hardin (CD 2), Warren (CD 2), Campbell (CD 3), Fayette (CD 3), Owen (CD 3), and Knox (CD 4)—were used to identify individual daily cases of large and small temperature differences ($T_E - T$) to assess synoptic influences on T_E. These stations were chosen to represent geographical diversity of the region, as well as varying land covers.

3 Results and discussions

The seasonal 5-year averages of T, T_E, and specific humidity (q) are shown in Fig. 2. As expected, both T and T_E follow similar seasonal patterns, warmer in the summer and cooler in the winter, with T_E values larger than T throughout the year. During winter, when specific humidity was at its lowest, the differences between T_E and T were

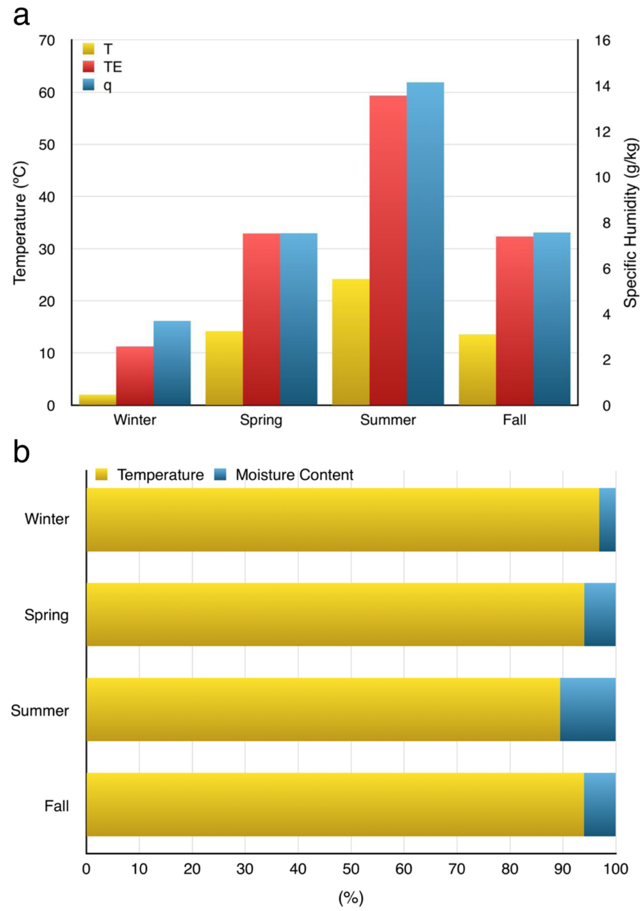

Fig. 2 **a** Five-year average seasonal temperature (T), equivalent temperature (T_E), and specific humidity (q) for Kentucky from December, 2009, to November, 2014. **b** Composite seasonal contribution of temperature and moisture to the magnitude of T_E for all study sites from December, 2009, to November, 2014

also the smallest (0.97 °C on 28 January 2014). During summer, when humidity was at its highest, differences between T_E and T were also the largest (59.70 °C on 12 July 2011). T mostly follows the magnitude of T_E, with moisture contributing a small percentage of heat content (Fig. 2b). Summer had the maximum contribution from moisture with 10.53%, and winter had the minimum contribution from moisture with 3.16%. However, it is also evident that even a small contribution from moisture has a great impact on T_E. For example, in the summer, a moisture content of 10.53% or 14.14 g kg^{-1} leads to a T_E of 59.33 °C in comparison to the air temperature of 24.16 °C.

Seasonal averages were also calculated for each CD and the results were comparable for each division (not shown). Averaging over each climate division produced similar results to the full composite averages over the entire study area. The Western climate division had the highest average specific humidity and the highest moisture contributions to T_E during spring and summer, the Eastern climate division had the highest values for fall, and the Central climate

Table 1 Seasonal average specific humidity (g kg^{-1}) and contribution of moisture for different climate divisions. Highest values are italicized and underlined

	Winter	Spring	Summer	Fall
Western climate division				
Average specific humidity (q)	3.74	*7.78*	*14.38*	7.62
Moisture contribution (%)	3.20	*6.16*	*10.66*	6.05
Central climate division				
Average specific humidity (q)	*3.76*	7.57	14.31	7.67
Moisture contribution (%)	*3.22*	6.02	10.64	6.10
Bluegrass climate division				
Average specific humidity (q)	3.49	7.17	13.59	7.26
Moisture contribution (%)	3.01	5.73	10.18	5.81
Eastern climate division				
Average specific humidity (q)	3.73	7.32	14.07	*7.72*
Moisture contribution (%)	3.20	5.85	10.53	*6.17*
Composite				
Average specific humidity (q)	3.69	7.53	14.14	7.55
Moisture contribution (%)	3.16	5.99	10.53	6.02

division had the highest values for winter (Table 1). The Western division is predominantly cultivated crops, and the results suggest that increased evapotranspiration during the growing season influenced the higher values in spring and summer.

Below we present additional analyses of mesoscale seasonal and inter-annual variations of T_E. These analyses will provide further evidence of the role of underlying land surface and atmospheric conditions on T_E and difference between T_E and T (i.e., $T_E - T$).

3.1 Spring

The seasonal distribution of T_E values is shown in Fig. 3 for spring of each year for the entire study area. Median T_E and the distributions about the median were nearly the same for 2010 and 2011. In 2012, the median was highest at 39 °C, compared to 31 °C for the preceding years and 29 °C for the following years, and also had the smallest interquartile range. A similar analysis was completed for the four climate divisions of Kentucky where all climate divisions exhibited similar T_E distributions (not shown). The Central division represents the most diverse range of land cover and land use where forests, cultivated cropland, pasture and hay land dominate. This division had the warmest maximum and minimum T_E. The Bluegrass division is broadly characterized by pasture and hay land and forests and had the coolest maximum and minimum T_E.

Daily averages of T_E and T were calculated for each station and results from Warren County station for 2014 are shown in Fig. 4. During the spring, both T and T_E begin as cool and steadily increase with approaching summer. Fluctuations in T_E closely followed those of T. This observation was expected as T_E magnitude is directly related to air temperature. Small differences are noted at the beginning of spring, and begin to increase as the season progressed. This was due to increasing temperatures, as well as increasing moisture availability, as spring is a wet season. To understand these observations further, the monthly average difference between T_E and T, ($T_E - T$), for each station and month was calculated. Average of the 10 individual stations listed above is presented for 2010 (Fig. 5). During the spring, differences between T_E and T start at approximately 10 °C in March and steadily increased to 30 °C in May.

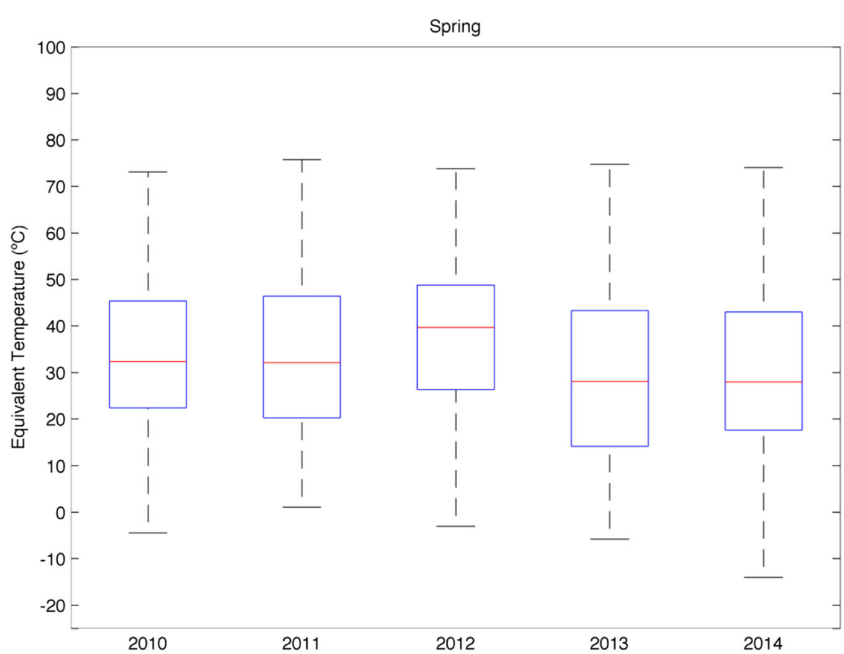

Fig. 3 Distribution of T_E values during spring for each year for all stations

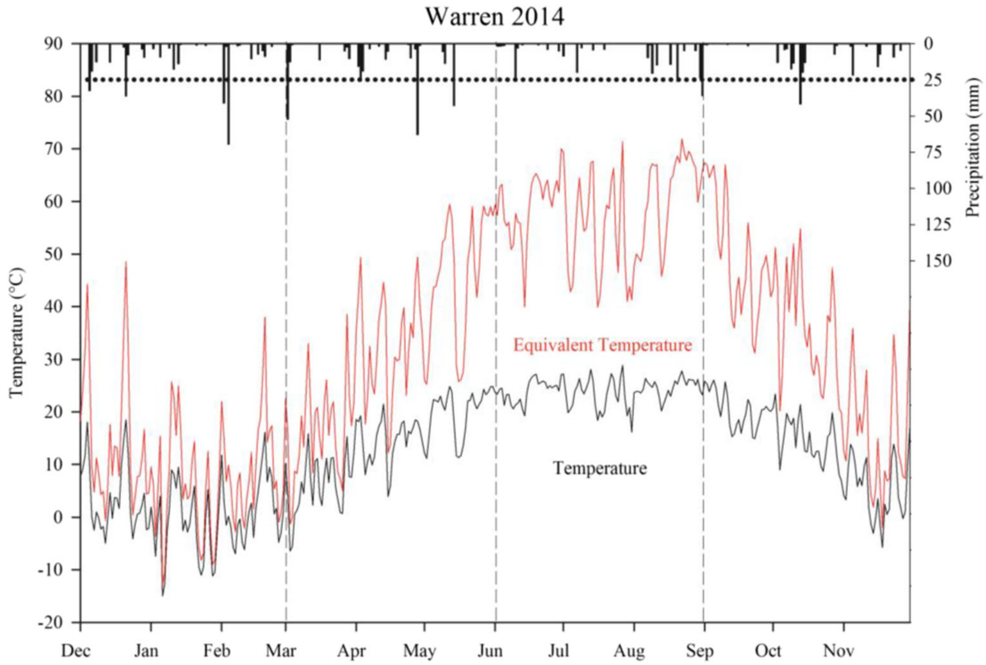

Fig. 4 Daily mean temperature, equivalent temperature (T_E) and total daily precipitation of 2014 for Warren County mesonet station

Variations of these differences are small from station to station. Fulton County station (western-most station) had the largest differences during spring 2010 and 2011. The stations in Calloway and Warren counties had the largest differences during spring 2013 and 2014.

Spatial patterns of differences between T_E and T for spring in Kentucky are presented in Fig. 6a–e. Western Kentucky exhibited larger differences when compared to the rest of the state throughout the study period. The land in this region is poorly drained with wetlands, possibly allowing for increased moisture available to the lower atmosphere. Additionally, this region is also dominated by agricultural land use with crops that begin growing in late spring.

Inter-annually, Spring 2010 and 2011 generally had similar $T_E - T$ differences across the state, with 2011 having slightly larger differences for stations located in Caldwell (1), Hopkins (1), Warren (2), Barren (2), Cumberland (2), Mason (3), and Jackson (4) counties. A drought began developing in western Kentucky in the spring of 2012 and intensified throughout the summer (USDM 2012). The Palmer Drought Severity Index

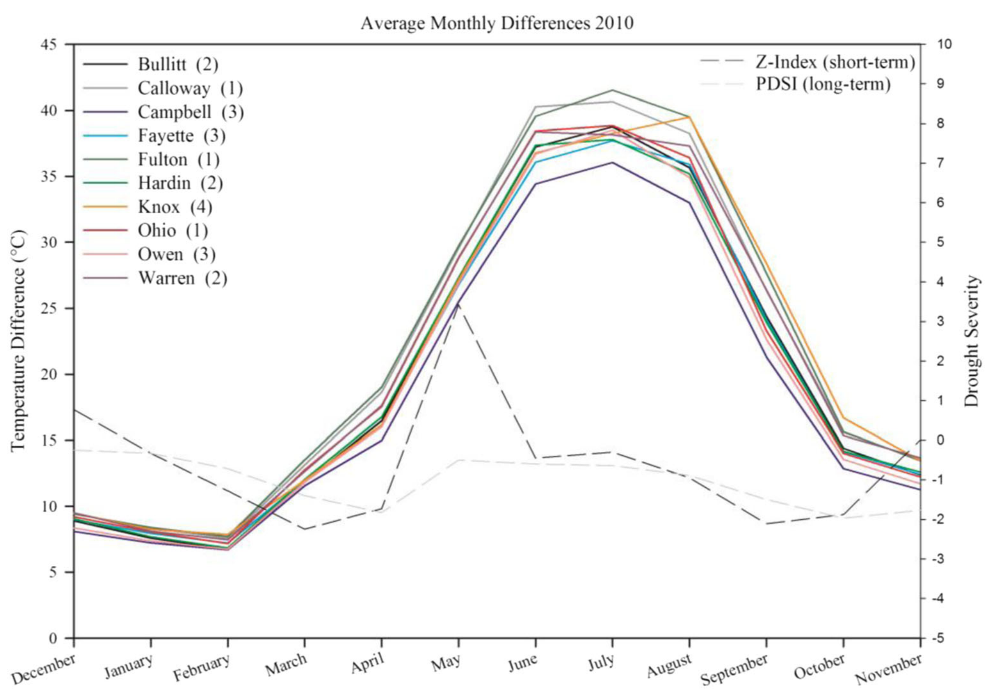

Fig. 5 Monthly average difference ($T_E - T$) for a selection of 10 stations for 2009–2010. Monthly PDSI and Z-Index values for long- and short-term drought in Kentucky also are shown

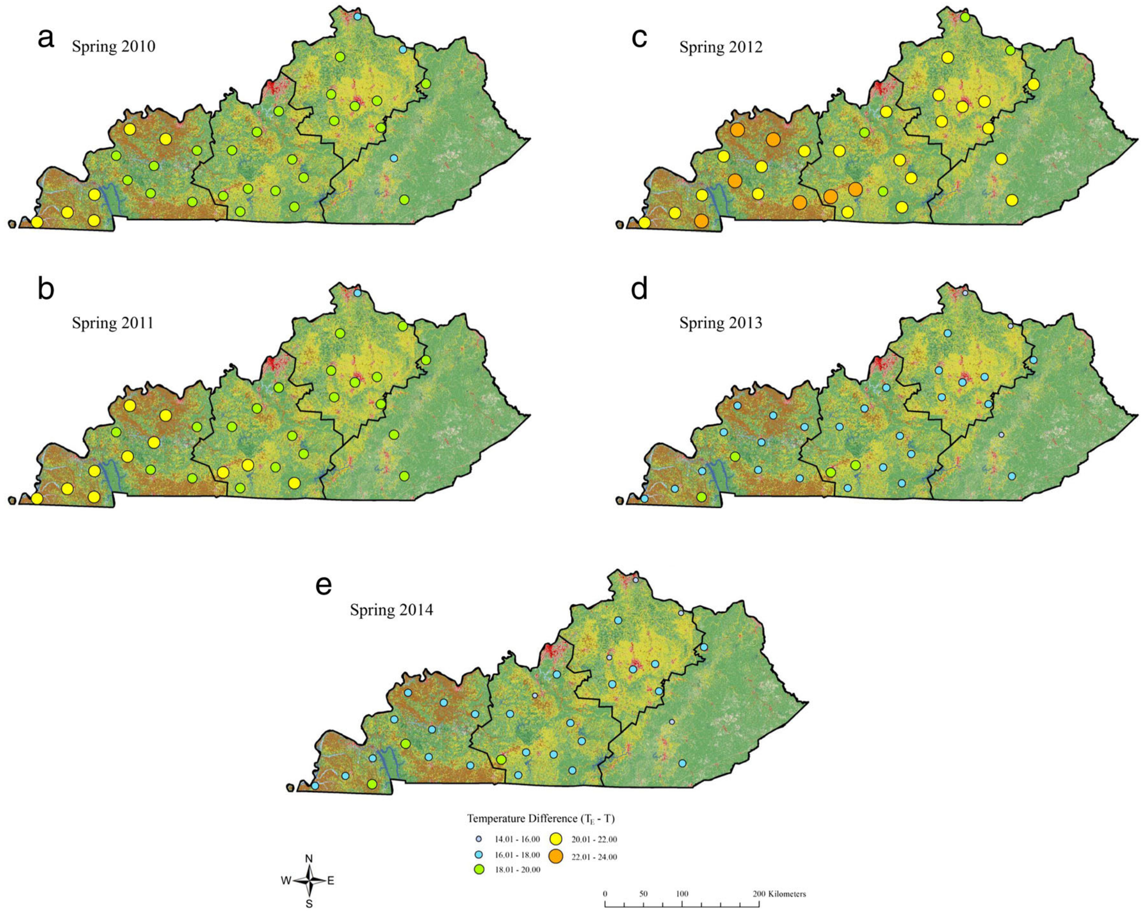

Fig. 6 Average equivalent and air temperature differences ($T_E - T$) for Spring: **a** 2010, **b** 2011, **c** 2012, **d** 2013, and **e** 2014

(PDSI) for Kentucky in May, 2012, was −1.9, indicating drought conditions throughout the state (MRCC 2014). This drought was most intense in the Western climate division, with a PDSI of −3.36 in May, 2012 (MRCC 2014). Despite drought conditions, spring 2012 had the largest $T_E - T$ differences. This suggests that water vapor was available in the atmosphere and was not realized in precipitation. The spring seasons of 2013 and 2014 had the smallest $T_E - T$ differences.

3.2 Summer

The seasonal distribution of T_E values is shown in Fig. 7e for summer of each year. The range of T_E values in the summertime was approximately 60 °C, as compared to 80 °C in the spring. This is consistent with a smaller range of temperatures in summer compared to the transition seasons, spring and fall. Median values and the distributions about the median for each year were generally similar during summer. Summer of 2012 had the "lowest" median, maximum and minimum T_Es. These low T_Es can be attributed to the drought Kentucky experienced during 2012 (discussed later in this section). Some of the higher T_Es each year were linked to frontal passages at the beginning and end of the season. The maximum T_E, 93.24 °C, occurred on 12 July, 2011, while the minimum T_E, 21.76 °C, occurred on 2 June, 2012. In eastern USA and Kentucky, moisture advection from the Gulf of Mexico can occur due to a warm frontal passage while moist air can be replaced with dry and cool air after a cold frontal passage.

An analysis was completed for the four climate divisions. Based on the overall temporal distribution of data, all climate divisions had generally similar T_E distributions for summer. However, the Western division had the largest range of T_E values at 71.23 °C, while the Eastern division had the smallest at 64.04 °C. As expected, average daily T_E was higher than air temperature throughout the year, with the greatest differences noted during the summer season. In all seasons except summer, the fluctuations in T_E followed closely with those of T. Compared to daily T_E, T did not vary as much throughout the summer and large variations in T_E are attributed to moisture content changes and the heightened exchange of moisture between the land and atmosphere due to actively growing plants and increased evaporation. During the peak of summer, the average monthly differences ($T_E - T$) were approximately 40 °C for most years, compared to as low as 5 °C during winter. The Fulton County station reported the largest differences for summers 2010 and 2011, Warren reported the largest

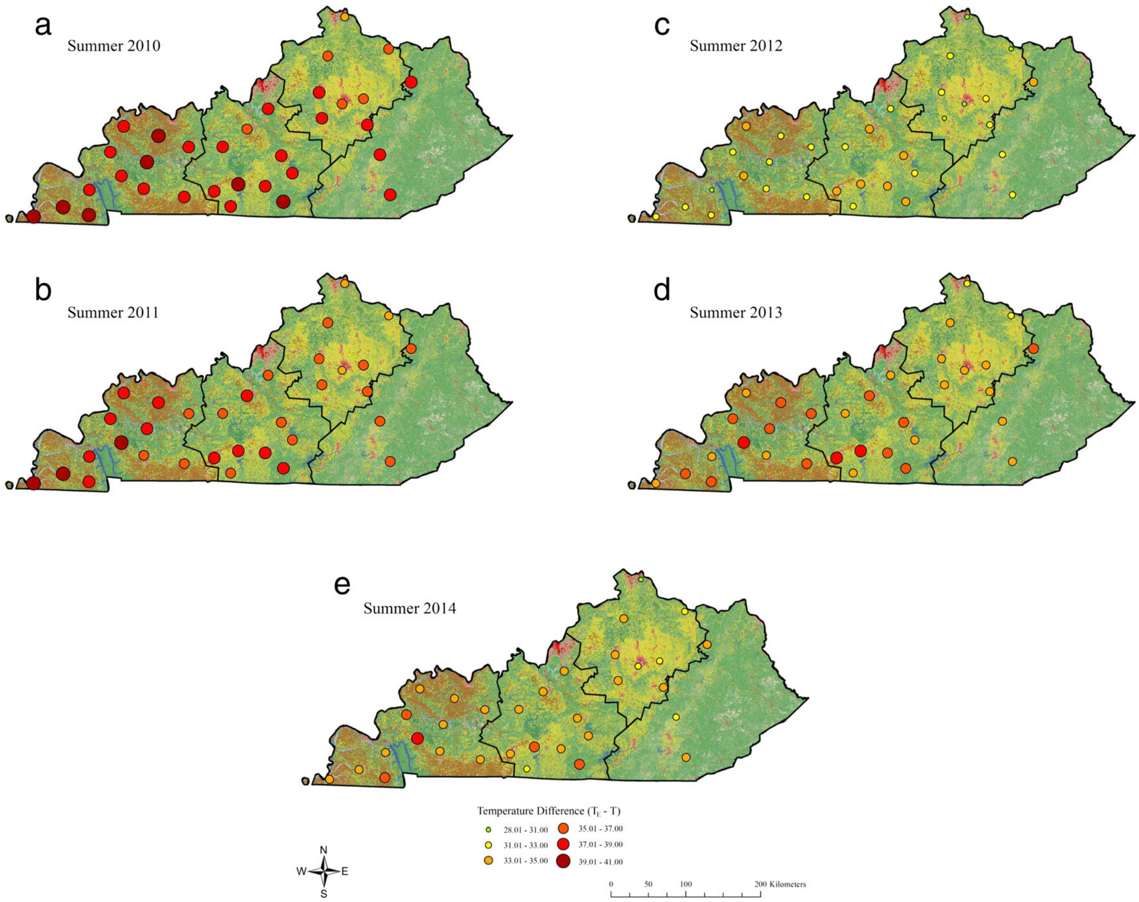

Fig. 7 Average temperature differences ($T_E - T$) for Summer: **a** 2010, **b** 2011, **c** 2012, **d** 2013, and **e** 2014 Fig. 4.1.2. Histograms (bins = 30) showing the distribution of T_E values during spring for each year. This includes all spring data from every study station in the area

differences for summers 2012 and 2013, and Calloway had the largest differences in the summer of 2014. The mesonet station in Campbell County (northern-most station) consistently had the smallest differences throughout summer for each year.

Average monthly differences throughout Kentucky peaked in July for all years except 2013 and 2014. July 2014 exhibited differences of 2–7 °C less than June and August, 2014. These smaller values are most pronounced at the stations in the Western climate division (Calloway, Fulton, and Ohio). A short-term drought is evident using the Palmer Z-Index in western Kentucky for July, 2014, with values of 0.7, − 1.72, and 1.32 for June, July, and August, 2014, respectively (MRCC 2014). This short-term dryness is likely to have contributed to the smaller T_E values observed at these stations, and the resultant smaller differences.

Spatial patterns of differences between T_E and T in Kentucky (Fig. 7e) are analyzed for summer. In general, differences were largest in the cultivated croplands of western and central Kentucky. This suggests that as summer is the growing season for Kentucky, increased near-surface moisture associated with evapotranspiration from crops and other vegetation influenced these larger differences.

Inter-annually, the summers of 2010 and 2011 exhibited the larger differences, while the differences were much smaller during the summer of 2012. The summer of 2011 was relatively wet throughout all of Kentucky, with a PDSI value of 3.85 for June (MRCC 2014). Wet conditions across Kentucky contributed to the larger differences observed during the summer of 2011. Western Kentucky developed a severe drought during late spring and summer 2012, culminating in an exceptional drought, the highest intensity assigned by the US Drought Monitor, by early July (USDM 2012). This drought was an extension of the historical 2012 Central Great Plains drought, which rivaled the conditions observed during the Dust Bowl of the 1930s (Hoerling et al. 2014). The 2012 drought is evident in the western climate division's cumulative PDSI value of − 20.07 during spring and summer 2012 (MRCC 2014). As the summer progressed, the drought expanded east to the rest of Kentucky, reaching severe conditions in central Kentucky (cumulative PDSI of − 11.29) by the end of August (USDM 2012). Exceptionally dry and hot conditions across the Commonwealth during this summer contributed to the smaller differences between T_E and T (small contribution of moisture).

3.3 Fall

Fall 2010 had the smallest range of T_Es with the highest and lowest T_E of 78.12 and 76.69 °C, respectively. The largest T_E was observed during the fall of 2013, with the maximum 80.92 °C, occurring on 10 September. Climate division analysis suggests that maximum and minimum T_E values were slightly warmer in fall than in spring. The Western division had the largest range of T_E, while the Bluegrass and Eastern divisions had similar T_E distributions.

During the fall, daily averages of T and T_E begin warm and steadily decrease approaching winter. Similar to spring, fall daily fluctuations in T_E closely followed those of T. Larger average monthly differences ($T_E - T$) were observed at the beginning of fall (approximately 25 °C in September), and decreased as the season progressed (approximately 12 °C in November). This can be attributed to decreasing temperatures and moisture availability, as cold, dry air masses began to move through Kentucky. Of the ten stations identified previously, the Knox County station had the largest differences for fall 2010 and 2011, while the Calloway, Warren, and Fulton County stations had the largest differences for Fall 2012, 2013, and 2014 (not shown).

Spatial patterns of differences between T_E and T were also analyzed for fall. Generally, differences were largest in western and south-central Kentucky. Fall exhibited similar spatial patterns as spring, but with smaller magnitudes, due to the fact that it is a drier season in Kentucky compared to spring and also due to the lower evapotranspiration following the harvest. During fall 2010, differences were smallest throughout Kentucky as a drought developed. PDSI values for Kentucky were −1.5, −1.97, and −1.77 for September, October, and November 2010, respectively (MRCC 2014). The largest Fall differences were observed in 2013 across the state with Calloway and Caldwell County stations reporting the highest. In 2011, the differences were nearly identical at all stations, except for two counties: Rowan and Adair counties had the largest and smallest average differences, respectively, in fall 2011. Differences were most varied across the state during Fall, 2014. Small differences were observed at the Caldwell, Hopkins and Christian County stations in western Kentucky, as well as at the Campbell and Mason county stations in the Bluegrass division. Larger differences were observed throughout south-central Kentucky. As expected, fall had a geographic spread of differences that were generally similar to spring season.

3.4 Winter

Each year, winter season had a large number of days with high T_E, caused by warm frontal passages at the beginning and end of the season. The bulk of the winter T_E distribution in 2012 and 2013 was, on average, 5–10 °C warmer than other years. Winter of 2013 had the warmest T_E value (56 °C), which occurred on 12 January, 2013. The central climate division had the warmest median (10.02 °C) and the largest range of T_Es (76.39 °C). Winter season T_E values show a relatively smaller range of values, unlike the spring and fall seasons.

As expected, daily averages of T and T_E were the coolest during the winter season. Consistent with what was observed in spring and fall, daily fluctuations in T_E in the winter closely followed those of T. Differences ($T_E - T$) did not fluctuate throughout season. This was unlike the spring and fall seasons, as differences throughout those seasons considerably increase and decrease, respectively. Spatial patterns of differences between T_E and T in Kentucky were analyzed for winter. As expected, the temperature differences were smallest in the winter, with a range of only 6–12 °C. In general, the differences were largest throughout southern Kentucky, however it is important to note that with such a small range of differences, "largest" is a relative term. The winters of 2010 and 2014 had the smallest differences across the state, with slightly higher values in 2010. The differences were also small in 2011; however, the stations in McLean and Fulton Counties in the Western climate division had differences that were 1–3 °C larger than the rest of the state. The winters of 2012 and 2013 exhibited similar differences but were 2–5 °C warmer across the state than other years.

4 Conclusions

The use of air temperature alone to describe heat content is not an adequate measure of heating or cooling, as it does not account for near-surface moisture. Equivalent temperature (T_E) is an appropriate metric for analyzing the near-surface heat content as it accounts for both the sensible air temperature and moisture. This research provided a mesoscale climatological assessment of T_E at daily, seasonal, and annual timescales in Kentucky.

Throughout Kentucky, both T and T_E follow similar seasonal patterns, warmer in the summer and cooler in the winter, with T_E values larger than T throughout the year. The differences between T_E and T were smallest during winter (greatest during summer), when specific humidity was at its lowest (highest). It is found that even a small moisture contribution can have notable impacts on T_E. Although each climate division exhibited similar patterns, the Western climate division had the greatest average specific humidity and the highest moisture contributions to T_E during spring and summer. Temperature differences ($T_E - T$) were also generally largest in western Kentucky. Land cover in this region is dominated by cultivated cropland, and it is suggested the increased evapotranspiration during the growing season influenced the greater difference values in spring and summer.

Heat content was greatest in the summer seasons, with differences between T_E and T approaching 50 °C in some locations. Conversely, it was at a minimum in the winter seasons, with differences as low as 5 °C. Periods of extreme precipitation also influenced the average heat content. An exceptional drought developed in Kentucky throughout the summer of 2012, and expanded eastward, reaching severe conditions in central Kentucky by the end of July (USDM 2012). Compared to other years, summer 2012 had the smallest temperature differences, which were attributed to the extreme dry and hot conditions across the Commonwealth (small contribution of moisture). The 2011 summer exhibited large differences, and was relatively wet in Kentucky, with a PDSI value of 3.85 (MRCC 2014).

Results suggest that the influence of land cover and land surface condition (e.g., moistness) is more apparent on the seasonal-scale modulation of T_E while synoptic patterns are more apparent at the daily timescale, although land cover may affect the magnitude of the daily fluctuations. During winter and early spring, it was observed that days with "cooler" T_E and surface high pressures were associated with predominantly northerly winds, and little-to-no moisture throughout the atmosphere. On the other hand, days with "warmer" T_E and low pressures were characterized by a trough over the Plains and advection of southerly warm air. Generally, low-pressure systems and approaching cold fronts were located to the northwest of the region which placed Kentucky in the warm sector with winds at the surface from the south-southwest accompanied by moisture advection. These observations were consistent with the conceptual understanding of the coupled effect of air temperature and moisture on the near-surface heat content, supporting the conclusion that daily fluctuations in T_E are more closely related to synoptic-scale circulation than vegetation characteristics.

The findings presented in the paper show that climate divisions across Kentucky exhibited somewhat similar T_E distributions. We suspect that in some years this is partly linked to large-scale forcing (for example, during the drought of 2012) and partly linked to exposure of some of the stations to similar land cover. However, we recognize that it needs further investigation and we are currently completing a follow-up research project and plan to report it in the scientific literature.

Future research priorities include analyses of microclimates of a selection of Kentucky mesonet sites in more detail to identify possible causes of the inter-annual variations in T_E. These could include a trend analysis of air temperature, T_E and Lq (moisture contribution), soil analyses of each site, as well as additional factors that may impact the near-surface heat content such as the local wind and solar radiation variability. These analyses would lead to eventually quantifying relative role local land cover and synoptic conditions on atmospheric heat content. Additionally, the influence on the near-surface moisture budget and resultant T_E of poor versus well-drained epikarst and karst regions throughout Kentucky should be investigated. Furthermore, the correlation of T_E to different air mass types needs to be investigated.

It is clear that LULCCs have a non-trivial effect on the climate system at regional scales. The increase in research performed in this area over the past decades has helped shift perceptions of human-caused climate change to a broader spectrum that includes many forcings, not solely limited to greenhouse gas emissions (NRC 2005; Mahmood et al. 2010; Pielke et al. 2011; Mahmood et al. 2014). While extensive research have been completed, further studies can be performed utilizing high-quality, in situ observation networks to detect impact of LULCCs more effectively (Mahmood et al. 2014). With regard to T_E, data from a high-resolution observation network can be analyzed to improve understanding of meso-climates and possible impacts on local heat content characteristics. Increased knowledge of how LULCCs link to the climate system at all spatial and temporal scales is necessary to model our climate system more accurately and to provide more precise predictions of the future.

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