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Growing Season Air mass Equivalent Temperature (T$_E$) in the East Central USA

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Abstract: Equivalent temperature (T$_E$), which incorporates both dry (surface air temperature, T) and moist heat content associated with atmospheric moisture, is a better indicator of overall atmospheric heat content compared to T alone. This paper investigates the impacts of different types of air masses on T$_E$ during the growing season (April–September). The study used data from the Kentucky Mesonet for this purpose. The growing season was divided into early (April–May), mid (June–July), and late (August–September). Analysis suggests that T$_E$ for moist tropical (MT) air mass was as high as 61 and 81 °C for the early and mid-growing season, respectively. Further analysis suggests that T$_E$ for different parts of the growing seasons were statistically significantly different from each other. In addition, T$_E$ for different air masses was also statistically significantly different from each other. The difference between T$_E$ and T (i.e. T$_E$-T) is smaller under dry atmospheric conditions but larger under moist conditions. For example, in Barren County, the lowest difference (20–10 °C) was 10 °C. It was reported on 18 April 2010, a dry weather day. On the other hand, the highest difference for this site was 48 °C and was reported on 11 August 2010, a humid day.

Keywords: equivalent temperature; temperature; air mass

1. Introduction

Air temperature or dry-bulb temperature has widely been used in atmospheric research to understand weather and climate variability and change. e.g., [1]. However, this measure alone does not capture the total heat content of the air because dry-bulb temperature only accounts for dry heat content and does not include moist heat [2]. As a result, we suggest that, in addition to air temperature, equivalent temperature (T$_E$) can be used for more accurate measurement of atmospheric heat content since T$_E$ represents both dry and moist heat [3–8]. In other words, this measure provides a more accurate representation of the near-surface energy budget.

Pielke Sr. et al. and Ribera et al. [2,9] demonstrated the value of T$_E$ as a measure of atmospheric heat content. Previously, Pielke Sr. [10] has shown that a 1 °C dew point temperature increase is equivalent to a 2.5 °C increase in air temperature and thus atmospheric moisture plays an important role in the calculation of atmospheric heat content. Subsequent research provided additional evidence of the role of atmospheric moisture in atmospheric heat content or T$_E$ calculation [5,7].

Near surface and tropospheric T_E for the contiguous United States using data from 1979–2005 was analyzed and results suggest that using T_E along with temperature may help to remove uncertainties in near surface and tropospheric temperature trends [5]. It is also shown that vegetation plays an important role in influencing near surface T_E [5]. Analyses of high-density meso-scale data from 33 Mesonet stations in Kentucky, USA, further demonstrated the relationship between T_E and atmospheric heat content [7]. This study in Kentucky [7] shows about 10% (14.14 g kg^{-1}) moisture contribution in the summer resulted in a T_E of 59 °C in comparison to the air temperature of 24 °C (see Figure 2a,b of [7]).

Previously, differences in near surface air and equivalent temperature trends from 1982–1997 over the Eastern U.S. were investigated [3]. It was found that overall T_E trends were relatively larger in the eastern U.S. than temperature trends [3]. These patterns, however, vary widely from site to site, so local microclimate is very important. In another study, 123 years of data for the summer season from one location in Ohio was analyzed and it reported a positive trend in T_E during the second half of the 20th century [4]. An assessment of T_E trends for seven locations over the Central U.S. found that for a majority of these locations, summer trends of T_E were positive and greater than annual trends [6]. This research in the Central U.S. [4] also demonstrated the potential use of T_E in heat wave assessment. A follow-up study, using data from four locations in Illinois, USA, found a good relationship between summer T_E hot days and antecedent 5-cm soil moisture anomalies [11]. It was reported that the highest summer T_E was strongly linked to spring soil moisture [11].

In this study, we investigate and quantify intra-seasonal and inter-annual variations of atmospheric heat content (T_E) of different air masses during the growing season in the east central USA, represented by the state of Kentucky (Figure 1).
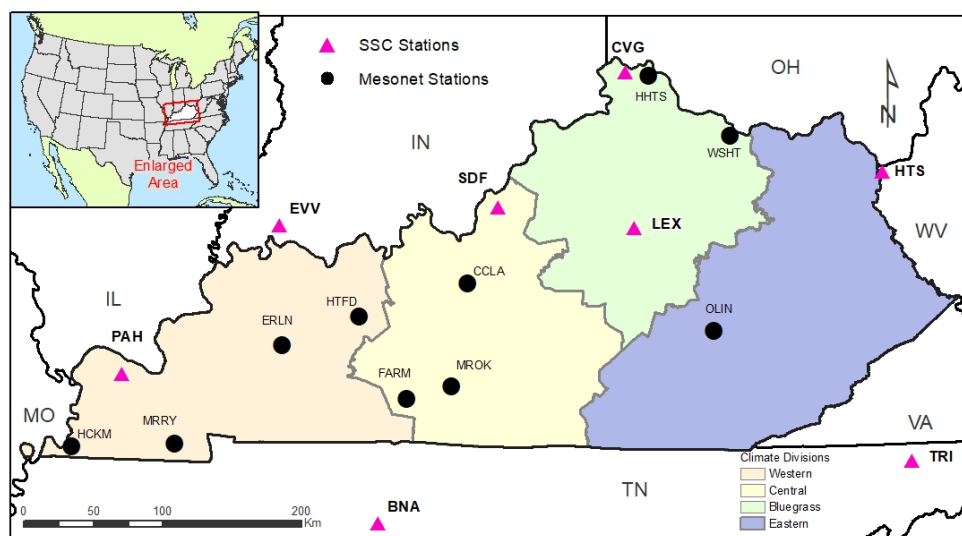

Figure 1. State of Kentucky, Spatial Synoptic Classification (SSC) Stations, and selected Kentucky Mesonet stations.

Note that the growing season also represents warm months. Kentucky was selected for several reasons. First, it provides a unique opportunity to work with a high quality T_E time series [7]. Second, this time series is derived from high-quality observations collected by the Kentucky Mesonet [12]. Kentucky Mesonet is a research grade weather and climate-observing network with redundant sensors that record high-quality, five-minute data from 72 locations. Third, this study is a natural progression of previous research efforts [7].

A study [7] on Kentucky and the east central U.S. investigated inter-seasonal and inter-annual variations of T_E at meso-scale from 2009–2014, which was the first of its kind. The time period was determined by the availability of the highest number of stations. Note that the Kentucky Mesonet started to install stations in 2007. The current study builds on the research presented in [7] and assesses

intra-seasonal variations of T_E for the growing season. Moreover, previous studies were focused on continental [3,5] and regional scales [6], while the current study focuses on meso-scales by analyzing data from a Mesonet. In addition, none of the previous studies were focused on quantifying T_E climatology related to air masses at this scale.

In the past, T_E for different meteorological seasons (spring, summer, fall, and winter) were investigated for the east-central U.S. [7], while T_E associated with different air masses during the growing season were not assessed [7]. In the current study, we investigated T_E associated with different air masses during the growing season. During this season, land surface conditions and vegetation go through distinct changes along with meteorological seasonal changes. To further capture distinct atmospheric characteristics within the growing season, we have identified three periods: early (April–May), mid (June–July), and late (August–September). Previously, T_E climatology for 33 stations/locations was developed and the current study used data from 10 of these stations (see Figure 1 in [7]). For identifying air masses, the present study used a Spatial Synoptic Classification (SSC) [13,14].

The SSC characterizes air masses based on the moisture and temperature of air. The present research quantified intra-growing season variations of T_E and SSC influences on T_E. The underlying hypothesis is that differences between T_E and T, which are largest during the growing season (see Figures 4 and 5 in [7] and Figure 2 of this paper), are directly related to the air mass types over the region and, to a lesser extent, land cover differences. The reasoning is that the characteristics of the air mass types that influence the weather at a particular location also influence the temperature and moisture content of the atmosphere, and thereby produce variations in T_E during the growing season.
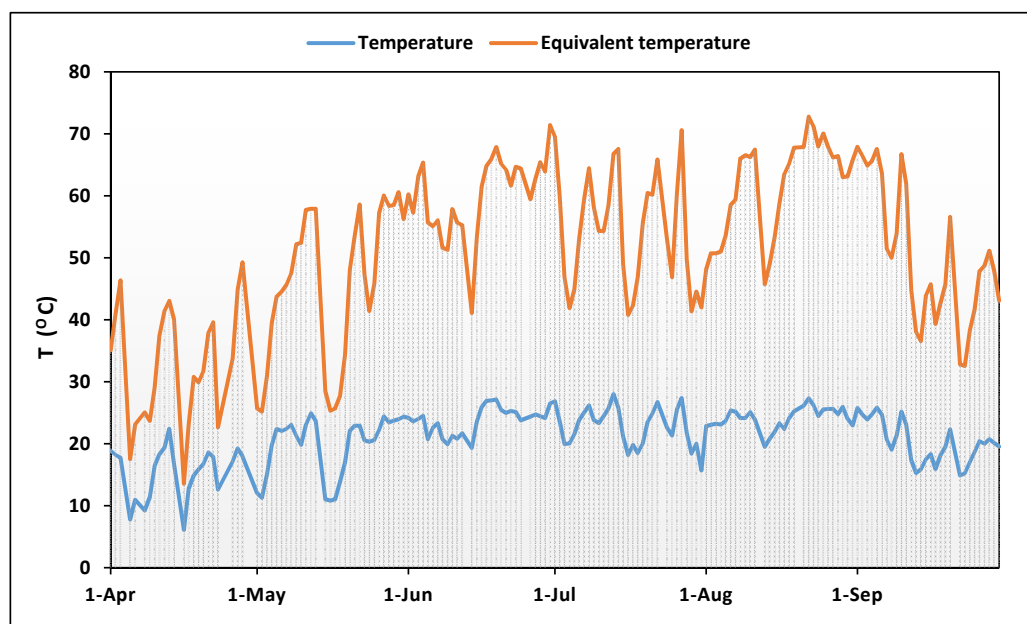
Figure 2. Temperature (T) and Equivalent temperature (T_E), for Barren County Mesonet Station, KY, in 2014.

It is expected that the moist air mass types within the growing season will have higher T_E, while the dry air mass types will have lower T_E. In addition, generally T_E would be higher compared to air temperature. Figure 2 presents T_E and air temperature from a Kentucky Mesonet station during the growing season of 2014 where T_E is consistently higher than air temperature. Day-to-day variations in T_E are largely linked to humidity of the air mass. Thus, among others, the novelty of this research lies in the fact that it quantified magnitudes of T_E for different air masses during the growing season and inter- and intra-seasonal variations of T_E. Other research findings include determination of dominant

air mass types that correspond to high and low T_E values for different years and within the growing season of the study region.

This research recognizes that land use and land cover affects the heat and moisture budgets and influences T_E. In other words, T_E at a location could be the result of large-scale moisture advection and local contribution via moisture recycling. For the latter, vegetation can play an important role by transferring moisture through evapotranspiration. However, the objective of this research is to quantify T_E for different air mass types throughout the growing season and not quantify relative contribution of large-scale moisture advection and contribution from local moisture sources.

The data and methods used in this study are described in Section 2. The results and discussion are presented in Section 3, followed by the conclusions in Section 4.

2. Methods and Data

2.1. Calculation of Equivalent Temperature

T_E was calculated utilizing the following equation [2]:

$$H = C_P T + L_V \tag{1}$$

where H is heat content, c_p is the isobaric specific heat of air (1005 J kg^{-1} K^{-1}), T is the air temperature (K), L_v is the latent heat of vaporization (2.5×10^6 J kg^{-1}), and q is the specific humidity.

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 an empirical relationship [15]:

$$e = 6.112 \exp\left[\frac{17.67\, T_d}{T_d + 243.5}\right] \tag{2}$$

From this, q is calculated as

$$q = \frac{0.622e}{P - 0.378e} \tag{3}$$

where P is the station pressure in hPa, obtained from the nearest Automated Surface Observation Systems (ASOS) stations [4].

Specific humidity can be calculated from measurements of relative humidity, dew point temperature, or wet bulb temperature [3,4]. H has units of Joules per kilogram, so, to enable comparison with air temperature, equivalent temperature in Kelvin is calculated by:

$$T_E = \frac{C_P T + L_V q}{C_P} \tag{4}$$

As well as;

$$T_E = \frac{H}{C_P} \tag{5}$$

Daily T_E averages for this research were calculated from the hourly T_E data [7].

2.2. Spatial Synoptic Classification

Unlike most existing air mass-based techniques such as the Temporal Synoptic Index (TSI), the SSC requires initial identification of the major air masses that traverse the Earth's surface, as well as their typical meteorological characteristics [16]. The SSC is a hybrid classification scheme that is based on an initial manual identification of air masses, or air mass types, followed by automated classification based on these identifications [13,16]. Note that the weather observations for the SSC come from first order stations. These stations are typically maintained by trained professionals from the National Weather Service of the USA and comparable organizations from Canada. First order stations typically use reliable instruments and are relatively well-maintained. However, they are not totally free from

some of the known challenges with instrumentation, exposure, and station siting and their influence on the data. The technique utilizes surface temperature, dew point, sea-level pressure, wind, and cloud cover to classify a given day into one of the following air mass types: dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), and moist tropical (MT). DP is a cool or cold and dry airmass and is typically associated with clear skies and northerly winds. DM signifies a mild and dry air mass. The DT air mass represents the hottest and driest conditions found at any location. The primary source region for DT is the deserts of the southwestern U.S. and northwestern Mexico. On the other hand, MP is associated with cool, cloudy, and humid weather conditions, and it is often accompanied by light precipitation. MM is warmer and more humid than MP air. MT air is warm and very humid, cloudy in winter and partly cloudy in summer. Convective precipitation is quite common in this air mass, especially in summer. MT typically forms over the Gulf of Mexico, tropical Atlantic, or the tropical Pacific Ocean. Sheridan [13] noted that for most analyses like ours, the MT+ and MT++ distinction is not required. These are subsets of the MT, and hence we grouped all of the subsets as MT air mass types. We did not use TR days because they represent days of transition from one air mass type to another, and as such, would not help with classifying the distinct air mass types.

2.3. Data Analyses

The selection of stations (Figure 1, Table 1) represents the diverse nature of the region in terms of location, geography, and length-of-time series [*cf.*, 7]. In addition, the proximity to the SSC stations, elevations, and climatic divisions contributed to the selection of the final 10 stations to ensure consistency and representativeness of results for all the Mesonet stations.

Table 1. Selected Mesonet stations and ASOS stations used for spatial synoptic classification (SSC).

County	Site ID	LATITUDE	LONGITUDE	ELEVATION (m)	SSC
Barren	MROK	37.01328	−86.106	212	BNA
Calloway	MRRY	36.61261	−88.336	173	PAH
Campbell	HHTS	39.01997	−84.475	225	CVG
Fulton	HCKM	36.57108	−89.159	105	PAH
Hardin	CCLA	37.67939	−85.979	227	SDF
Hopkins	ERLN	37.26764	−87.481	180	EVV
Jackson	OLIN	37.35629	−83.971	402	LEX
Mason	WSHT	38.62369	−83.808	277	LEX
Ohio	HTFD	37.45732	−86.855	164	EVV
Warren	FARM	36.92669	−86.465	170	BNA

Daily SSC for the growing season (April to September) were obtained from http://sheridan.geog.kent.edu/ssc.html (Note: data and metadata are available online at this website) to categorize each day by a designated air mass. There are six SSC sites within the study area (Nashville (BNA), Paducah (PAH), Lexington (LEX), Evansville (EVV), Louisville (SVF), and Covington (CVG)) (Table 1). The air mass at each site was defined as one of the following SSCs: DP, DM, DT, MP, MM and MT [13].

One-way and two-way analysis of variance (ANOVA) were used for this study. ANOVA identifies whether the means of samples chosen from three or more different populations are statistically different from each other [17–19]. Specifically, ANOVA was applied to identify whether T_E of different air masses were statistically significantly different during the growing season and whether T_E of different air masses were intra-seasonally statistically significantly different over the growing season. For this analysis, T_E was the dependent variable and the air masses and the early (April–May), mid (June–July) and late (August–September) growing seasons were the independent variables. The analyses of T_E for these three periods within the growing season provided further insight into intra-seasonal variations of T_E. The average values for T_E were calculated and analyzed for these three periods over a five-year period (1 April 2010 through 30 September 2014) and station-by-station to show the variations for each station. The number of days of each SSC within the three defined periods of the growing season for

each station were calculated to demonstrate the influence of SSC. The averages for all stations were also computed for the SSC and T_E for the five-year span. Further details can be found in Na-Yemeh [20].

One-way ANOVA for the years 2010, 2011, 2012, 2013, and 2014 for all 10 Mesonet stations was used to determine the relationship between air mass types and T_E. The hypothesis for the study can be presented as:

$H_0 : \mu_i = \mu_j = \mu_k$ The means of the samples are from the same population.

$H_1 : \mu_i \neq \mu_j \neq \mu_k$ At least one of the samples is from a different population.

Again, a two-way analysis of variance (ANOVA) was used to test for significant differences between T_E and air masses for the early (April–May), mid (June–July), and late (August–September) growing season. The two-way ANOVA thus analyzed the interactions between the two variables including intra-season months and air masses. Two-way ANOVA interactions are ideal for testing the significance of two variables [19].

3. Results and Discussions

The following sections provide overall key findings first, followed by specific periods (inter-annual, intra-seasonal, and other shorter periods).

3.1. Overall Findings

The results show that there are statistically significant differences in the means within the seasons and air mass groups (Table 2).

Table 2. One-Way Analysis of Variance for T_E by air mass types for Barren County Mesonet station for 2010.

Effect	SS	DF	MS	F	*p*-Value
Model	17,099.31	5	3419.86	35.19	0.001
Error	15,451.14	159	97.18		
Total	32,550.45	164	198.48		

SS—Sum of squares (This relates to the total variance of the observations); DF—Degrees of Freedom (Each sample has degrees of freedom equal to one less than their sample sizes, so with k samples the total degrees of freedom is k less than the total sample size: df = N - k.); MS—Mean Square (mean squares tell us if factors (treatments) are significant. The treatment mean square represents the variation between the sample means; F- is the ratio of two mean square values); and *p*-value—Statistical significance.

The two-way interactions between season and air mass are statistically significant for all five years for all locations. The two-way ANOVA suggests that interactions for T_E and intra-seasons and T_E and air masses were also statistically significant, i.e., *p*-value < 0.001 (Table 3).

Table 3. Results of Barren County two-way ANOVA for the T_E based on season and air mass classifications, including mean-square error (MS), F value, and *p*-value. In addition to an individual analysis of the three variables, the ANOVA tests two-way interactions between variables.

Source	Mean Square	F	*p*-Value
Corrected Model	2138.91	49.14	0.001
Intercept	363,404.55	8349.15	0.001
Season	5944.46	136.57	0.001
Air mass	7327.07	168.34	0.001
Season Air mass	164.14	3.77	0.001

The growing season was divided into three periods: the early, the mid and the late periods. In the early part of the growing season, the dry air masses have relatively high frequency with corresponding low mean T_E values. For example, in Barren County it ranged between 33 °C to 46 °C (Table 4).

Table 4. Average T_E for the early-, mid-, and late-growing seasons in Barren County for different years and the different air mass types.

Air Mass Types	Year	Early (°C)	Mid (°C)	Late (°C)
DM	2010	31	52	47
	2011	33	55	46
	2012	35	48	46
	2013	32	51	47
	2014	33	49	46
	Mean	**33**	**51**	**47**
DP	2010	30	-	-
	2011	26	-	31
	2012	18	-	26
	2013	22	46	43
	2014	22	43	36
	Mean	**24**	**45**	**34**
DT	2010	40	60	55
	2011	53	65	50
	2012	51	59	52
	2013	43	-	-
	2014	41	-	51
	Mean	**46**	**61**	**52**
MM	2010	50	66	58
	2011	40	61	60
	2012	40	62	59
	2013	46	59	60
	2014	53	57	56
	Mean	**46**	**61**	**59**
MP	2010	32	-	40
	2011	30	-	40
	2012	26	-	54
	2013	29	55	-
	2014	26	48	45
	Mean	**29**	**52**	**45**
MT	2010	52	68	66
	2011	54	67	58
	2012	53	66	63
	2013	50	64	62
	2014	52	63	64
	Mean	**52**	**66**	**63**

As the season transitions into the mid-season, the frequency of the moist air mass types peak (Figure 3a,b) with corresponding mean high T_E values that ranged between 52 °C to 66 °C (Table 4).

Lastly, as the season reaches its late period, the dry tropical air mass begins to increase in frequency and mean T_E values begin to lower, and this ranged between 34 °C to 52 °C (Table 4). These results are representative of other locations. In addition, for example, mean T_E for the DP air masses for early-, mid-, and late-growing season were 24 °C, 45 °C, and 34 °C, respectively (Table 4). On the other hand,

they were 52 °C, 66 °C, and 63 °C for early-, mid-, and late-growing seasons, respectively, for the MT air masses.
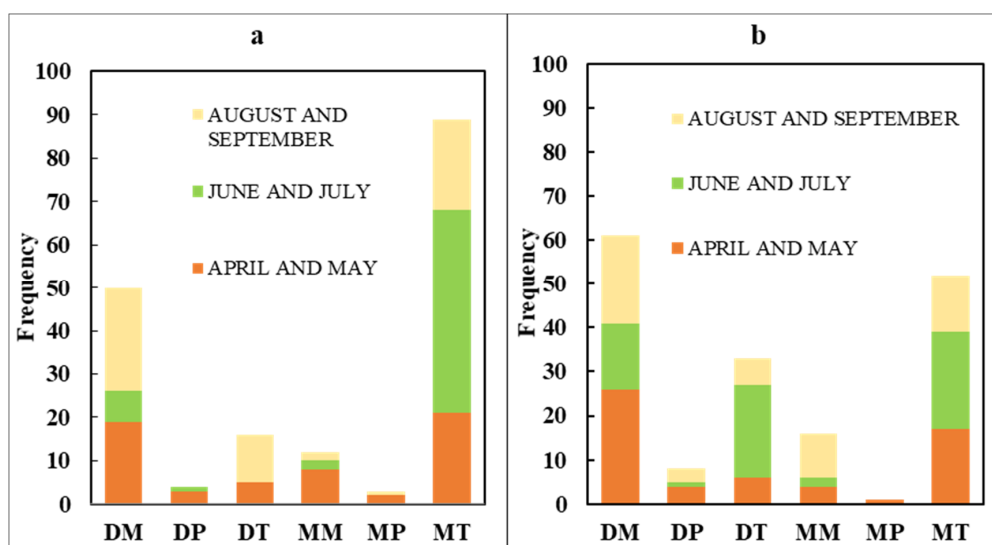

Figure 3. The frequency of air mass types for the growing season in the Fulton County Mesonet station: (**a**) 2010, and (**b**) 2012.

Additional analysis further demonstrates the influence of different air mass types on T_E values. For example, the maximum annual values of T_E for the Fulton County station for the moist tropical (MT) air mass were 81 °C, 80 °C, 75 °C, 70 °C and 74 °C from 2010 to 2014, respectively (Table 5).

Table 5. Minimum and maximum T_E for the Fulton County Mesonet station.

	2010						2011				
SSC	*Frequency*	*Mean*	*Max*	*Min*	*Median*	*SSC*	*Frequency*	*Mean*	*Max*	*Min*	*Median*
DM	50	45	66	25	46	DM	46	46	64	19	49
DP	4	34	46	25	33	DP	10	32	52	24	28
DT	16	51	69	30	56	DT	5	63	67	58	64
MM	12	51	70	34	51	MM	20	54	74	38	53
MP	3	32	37	28	30	MP	7	36	44	30	36
MT	89	67	81	41	69	MT	79	66	80	45	67
	2012						**2013**				
SSC	*Frequency*	*Mean*	*Max*	*Min*	*Median*	*SSC*	*Frequency*	*Mean*	*Max*	*Min*	*Median*
DM	61	43	67	19	43	DM	34	44	61	21	46
DP	8	26	34	18	27	DP	22	34	56	12	35
DT	33	57	69	58	41	DT	2	35	44	27	35
MM	16	52	66	35	54	MM	43	54	69	32	55
MP	1	23	23	23	23	MP	6	28	57	16	23
MT	52	62	75	44	63	MT	71	60	70	37	62
	2014										
SSC	*Frequency*	*Mean*	*Max*	*Min*	*Median*						
DM	45	45	62	22	46						
DP	23	38	53	11	44						
DT	3	39	44	32	41						
MM	15	60	69	52	61						
MP	6	32	45	25	29						
MT	74	60	74	32	63						

The DM air mass, which was commonly observed in the growing season, had the highest T_E of 66 °C, 64 °C, 67 °C, 61 °C and 62 °C, respectively, from 2010 to 2014. Calloway, Hopkins, and Ohio county stations in the Western climate division observed a similar pattern. For the Western climate division, 2010 and 2011 experienced the highest number of days with the MT air mass. The DM air

mass dominated 2012 at all four stations, whilst the moist polar generally had the lowest frequencies. Results for this climate division are comparable to the other three.

The moist air mass types (MP, MM, and MT) combined, as expected, had the highest frequency in the growing season (Figure 4, Table 5). The MM air mass recorded its highest frequency in 2013 for most stations, whilst the DM air mass types recorded relatively higher frequencies in 2012. The MT air mass type typically increases in frequency until it peaks in the mid-growing season and begins a gradual decline by the late growing season. This can be attributed to the seasonal air mass patterns and changes in the season [21]. The MT is more common because of the influx of moisture from the Gulf of Mexico, which is the primary source of MT air masses. The frequency of DM, however, begins a decline from the early growing season and is at its lowest in the mid-growing season.
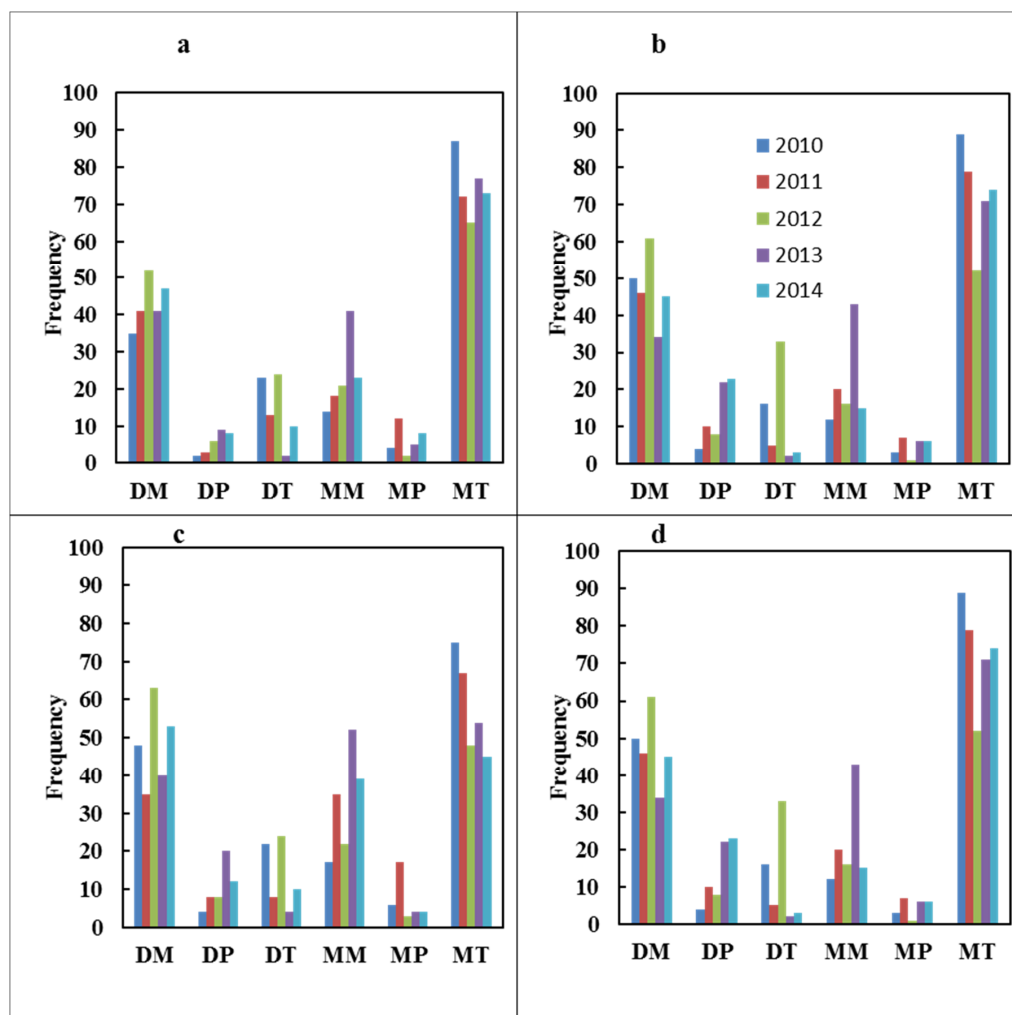

Figure 4. The frequency of air mass types for: (**a**) Barren County, (**b**) Calloway County, (**c**) Campbell County, and (**d**) Fulton County Mesonet stations for the study period.

3.2. Inter-annual Variations of the Growing Season T_E

The minimum and maximum T_E did not show high year-to-year variations for all stations for different air mass types (Figure 5a–d). For example, minimum T_E for 2010, 2011, 2012 and 2013 for the MT air mass were 40 °C, 42 °C, 42 °C and 36 °C, respectively, for the Calloway County Mesonet station. The corresponding maximum T_E for the MT air mass types for Calloway County for 2010, 2011, 2012 and 2013 were 78 °C, 81 °C, 76 °C and 71 °C, respectively, whereas minimum T_E for 2010,

2011, 2012 and 2013 for the dry polar air mass were 24 °C, 22 °C, 17 °C, and 12 °C for the Calloway County Mesonet station, respectively.
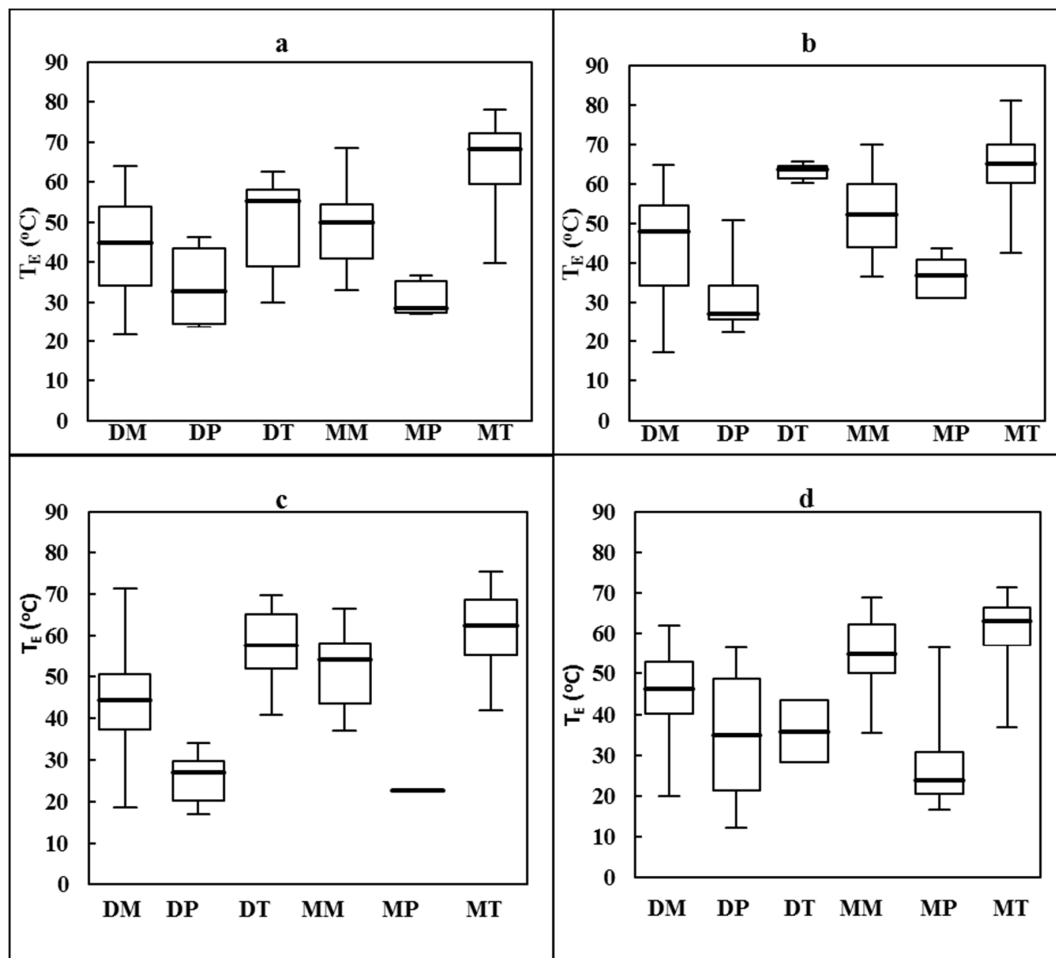

Figure 5. Box-Whisker plots of T_E for Calloway County Mesonet station: (**a**) 2010, (**b**) 2011, (**c**) 2012, and (**d**) 2013. They show maximum and minimum, median, and quartile T_E.

It is clear that the moist tropical air mass had the highest frequencies of all the air mass types for all stations for the growing season, with the exception of 2012. It appears that the 2012 drought in Kentucky was a reason for this exception. This drought event was associated with noticeable changes in air mass frequency, with a decrease in the moist air mass types and an increase in the dry air mass types. As explained earlier and illustrated in Figure 4, although Barren County showed an increase in frequency with the DM air mass from 41 days in 2011 to 52 days in 2012 and the moist tropical air mass decreased from 72 days to 63 days, it was the only location in 2012 where the moist tropical air mass exceeded the dry moderate air mass.

3.3. Intra-seasonal Air Mass and T_E Distribution

The dry air mass types had a relatively high frequency in April and May but reduced in June and July as the moist air mass peaked (Figure 3a,b and Figure 6a–d).

The frequency of the moist air mass was lower in August and September as the arrival of the dry air mass types peaked in this season (Figure 3a,b and Figure 6a–d). Calloway County, for example, experienced on average 19 days of dry moderate air mass types in April and May (not shown). This frequency was reduced to seven days in June and July and increased again to 24 days in August

and September. The moist tropical air mass, on the other hand, had a frequency of 21 days in April and May, which increased to 47 in June and July and then reduced to 21 days in August and September. By the late growing season, the influence of moisture from the Gulf of Mexico was minimized and resulted in reduction of MT air mass frequency.
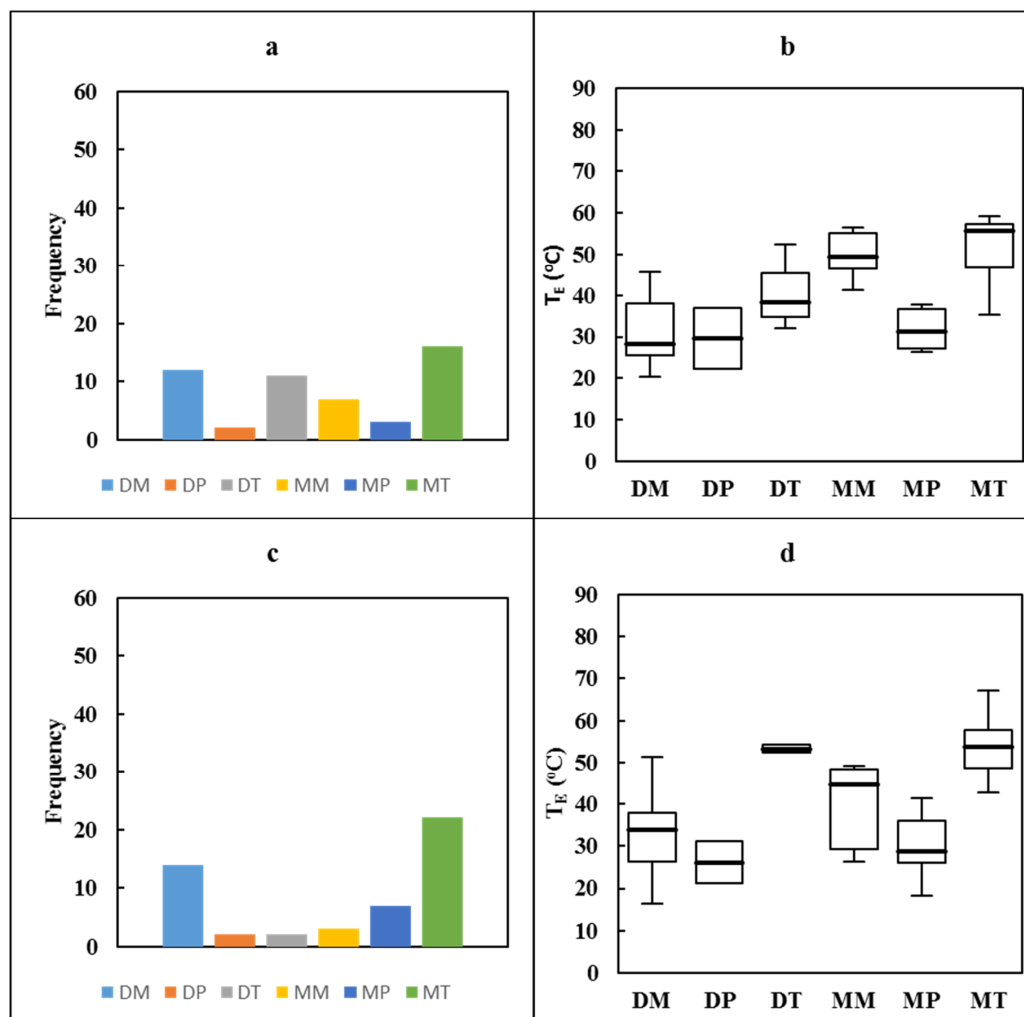

Figure 6. Distribution of air mass types and T_E for the Barren County Mesonet station for April and May: (**a**) and (**b**) 2010, and (**c**) and (**d**) 2011. Panels on the left column (Figure 6a–c) show frequency of observed air mass types during the early growing seasons of 2010 and 2011. Panels on the right (Figure 6b–d) column show distribution of T_E values for these air mass types using Box-Whisker plots. Explanation of Box-Whiskers plot is provided in the caption of Figure 5.

Hence, in April and May, the MT air mass dominated in terms of frequency and had high T_Es for the 5-year period (Figure 6a–d). For example, Barren County in 2010 and 2011 had estimated T_E ranging from 35 °C to 59 °C and 42 °C to 67 °C, respectively (Figure 6b,d). The DM air mass, on the other hand, had a relatively lower T_E for the 5-year period. In 2010 and 2011, the recorded T_E values were between 20 °C to 45 °C and 16 °C to 51 °C, respectively. In other words, from the box plots (Figure 6b,d), April and May recorded a wide range of T_E (16–67 °C in 2011) regardless of air mass type. In the early growing season, plant water usage and requirement are generally low and increase as the season progresses. In effect, evapotranspiration rates are low early in the season and gradually increase as the season progresses. Hence, T_E is generally low early in the season and increases as the growing season progresses.

In June and July, the MT air mass peaked in frequency as well as T_E for the 5-year period (Figure 7a–d). This is expected for the most part because air and dew point temperatures influence T_E. The maximum T_E was 81 °C and the minimum T_E was 51 °C for Barren County in 2011 for the MT air mass (Figure 7b,d). In the same light, the dry moderate air mass also had higher estimated values for T_E compared to April and May. For example, a maximum T_E of 63 °C and a minimum of 49 °C were estimated for the season. As compared to the early growing season where the minimum T_E was lower, the middle growing season showed relatively higher minimum T_E for prevalent air mass types. The frequency of the DP and MP air mass types was either low or nonexistent, as shown in Figure 6.
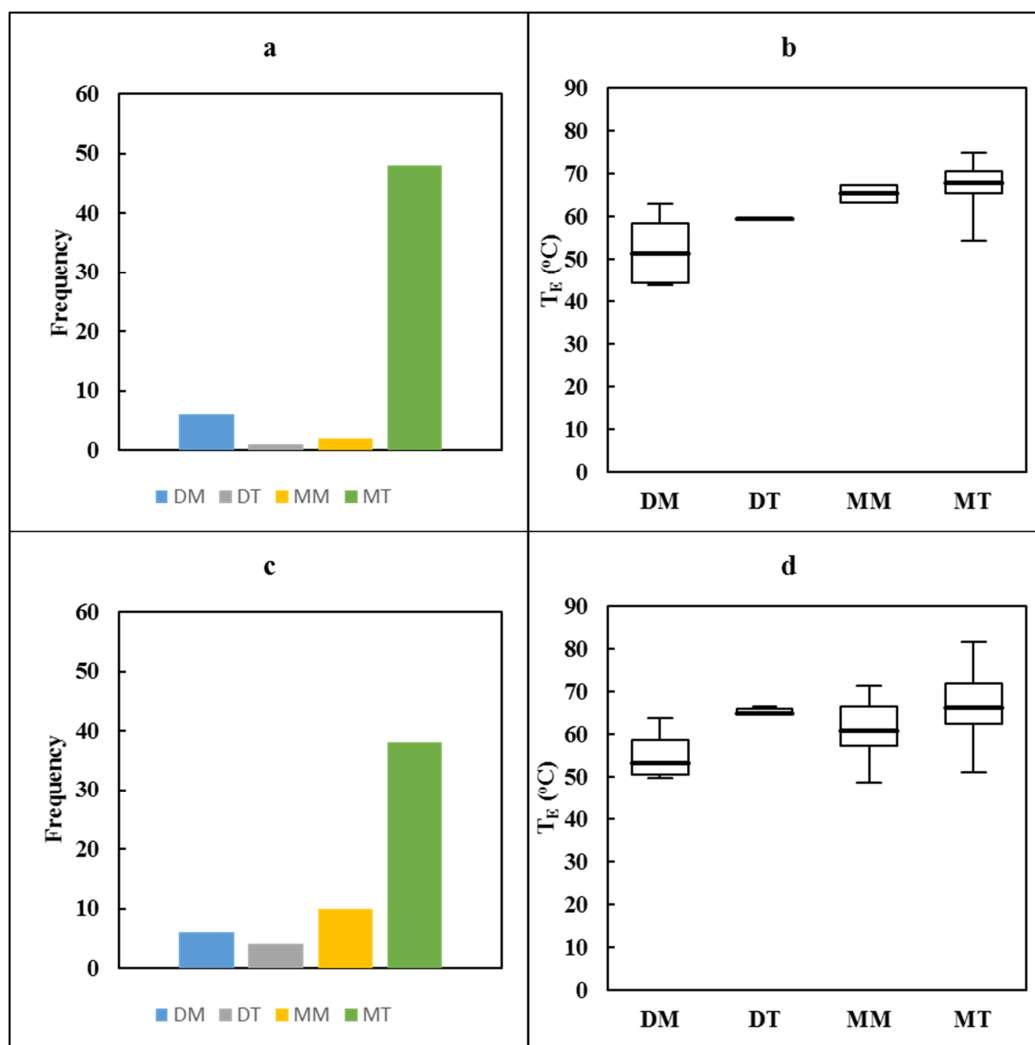

Figure 7. Distribution of air mass types and T_E for the Barren County Mesonet station for June and July: (**a**) and (**b**) 2010, and (**c**) and (**d**) 2011.

In August and September, atmospheric moisture decreases mainly due to changes in large-scale synoptic pattern and decreasing use of water by plants as they start to reach senescence and resultant lowering of evapotranspiration. The frequency of the moist tropical air mass also begins to decline as the season transitions from the middle to the late growing season (Figure 8a–d).

The frequency of dry moderate weather, however, starts to increase. The maximum and minimum T_E were 73 °C and 48 °C, respectively, in 2011 in Barren County for the moist tropical air mass. The DM air mass reported a maximum T_E of 54 °C and a minimum of 30 °C.
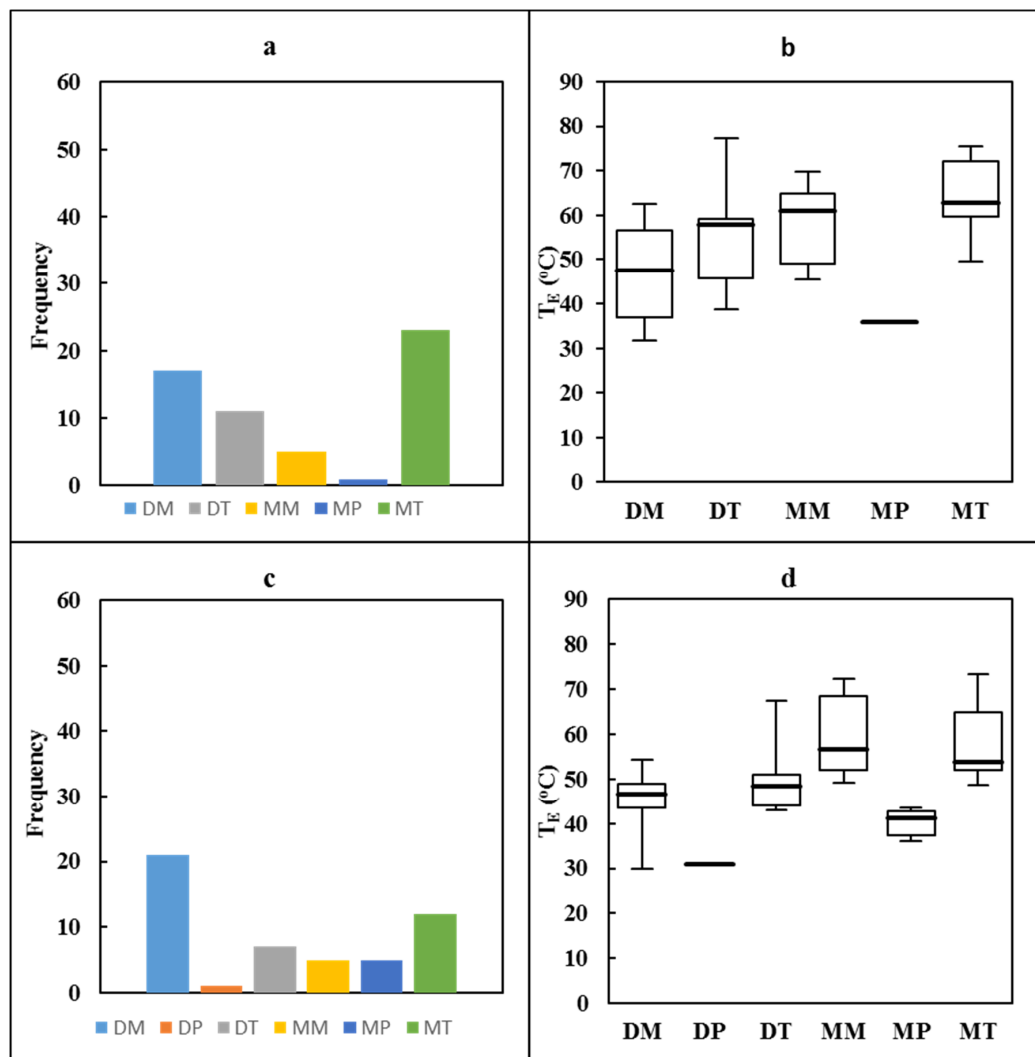
Figure 8. Distribution of air mass types and T_E for the Barren County Mesonet station for August and September: (**a**) and (**b**) 2010, and (**c**) and (**d**) 2011.

3.4. Air Mass T_E and T Differences

Results from the sections above indicate that the moist air mass types dominate during the growing season. High and low T_E correspond with moist and dry air mass types, respectively. This section examines selected days with their corresponding T_E values, air mass types, and T_E differences. The results show that the early growing season was dominated typically by dry air masses and hence low T_E values. Thus, differences between T_E and T in the early growing season were small.

Days with moist air mass types recorded a high T_E and had a corresponding high T_E-T difference for all 10 stations. In Barren County, for example, the lowest T_E-T difference was 10 °C on 18 April 2010, which was a dry weather day (T = 10 °C and T_E = 20 °C). On the other hand, the highest difference of 48 °C (T = 27 °C and T_E = 75 °C) reported on 11 August 2010 experienced a moist tropical weather event. Although land cover influences both moisture availability and temperature in the lower atmosphere and T_E is larger in areas with higher evapotranspiration rates, the biggest factor for the intra-seasonal variations in T_E is air mass contribution, as indicated in Table 6. For example, the year-to-year variations of T_E on May 1 are much greater than the station-to-station variations within a given year. This supports the understanding that the inter-annual and intra-seasonal variations in T_E can be notably influenced by air mass. This is further confirmed by the findings that the moist air

mass types commonly show large T_E-T differences. A large difference in this case suggests that there is higher contribution of moisture to atmospheric heat content.

The results presented are complimentary to the findings by [7], which quantified near-surface T_E for the spring, summer, fall, and winter seasons and assessed potential land-surface influence. The current study quantified intra-seasonal T_E variations for different air masses during the growing season and is one of the first on this topic. The findings suggest that during the growing season intra-seasonal atmospheric moistness, linked to air mass characteristics, varies from relatively dry to moist to relatively dry during the early-, mid-, and late-growing season, respectively. Hence, T_E varies also throughout the growing season from relatively low to high to relatively low, respectively.

Table 6. Daily T_E for May 1 for the 10 stations for all five (5) years.

	1 May 2010					*1 May 2011*			
Station	**Moisture content %**	**T_E**	**Diff (T_E-T)**	**Air mass**	**Station**	**Moisture content %**	**T_E**	**Diff (T_E-T)**	**Air mass**
Barren	9.08	48	29	Moist Moderate	**Barren**	8.36	45	27	Moist Tropical
Calloway	10.11	52	33	Moist Moderate	**Calloway**	9.08	46	20	Moist Moderate
Campbell	8.58	46	27	Moist tropical	**Campbell**	8.25	45	26	Moist Tropical
Fulton	10.75	56	35	Moist Moderate	**Fulton**	9.06	46	29	Moist Moderate
Hardin	9.02	47	29	Moist Moderate	**Hardin**	8.82	46	28	Moist Moderate
Hopkins	9.55	49	31	Moist Moderate	**Hopkins**	9.06	46	29	Moist Moderate
Jackson	8.45	45	27	Moist Moderate	**Jackson**	7.52	41	24	Moist Tropical
Mason	8.36	45	27	Moist Tropical	**Mason**	7.91	44	25	Moist Tropical
Ohio	9.61	49	31	Moist Moderate	**Ohio**	8.84	46	28	Moist Moderate
Warren	9.37	49	30	Moist Moderate	**Warren**	8.86	47	28	Moist Tropical
	1 May 2012					*1 May 2013*			
Station	**Moisture content %**	**T_E**	**Diff (T_E-T)**	**Air mass**	**Station**	**Moisture content %**	**T_E**	**Diff (T_E-T)**	**Air mass**
Barren	10.19	56	34	Moist tropical	**Barren**	8.19	47	26	Moist Tropical
Calloway	9.67	56	32	Moist Tropical	**Calloway**	7.85	46	25	Moist Tropical
Campbell	9.55	50	31	Moist Tropical	**Campbell**	6.47	42	20	Dry Tropical
Fulton	9.44	56	31	Moist Tropical	**Fulton**	7.93	45	25	Moist Tropical
Hardin	9.62	54	31	Moist Tropical	**Hardin**	7.41	43	23	Dry Tropical
Hopkins	9.82	56	32	Moist Tropical	**Hopkins**	7.49	45	24	Dry moderate
Jackson	9.60	53	31	Moist Tropical	**Jackson**	6.83	40	21	Dry Moderate
Mason	9.94	53	32	Moist Tropical	**Mason**	7.19	45	23	Dry Tropical
Ohio	9.46	54	31	Moist Tropical	**Ohio**	7.50	45	24	Dry Moderate
Warren	10.08	56	33	Moist Tropical	**Warren**	8.02	46	26	Moist Tropical

Table 6. *Cont.*

Station	Moisture content %	T_E	Diff (T_E-T)	Air mass
	1 May 2014			
Barren	4.55	26	14	Dry Moderate
Calloway	4.63	25	14	Dry Polar
Campbell	3.83	23	11	Dry Moderate
Fulton	4.44	26	13	Dry Polar
Hardin	4.45	25	13	Dry Moderate
Hopkins	4.43	25	13	Dry Polar
Jackson	4.72	25	14	Dry Polar
Mason	4.55	25	14	Dry Moderate
Ohio	4.54	25	14	Dry Polar
Warren	4.62	26	14	Dry Moderate

In summary, this research not only quantified T_E associated with different air masses but also provided further insight into intra-seasonal variations during the growing season. Moreover, T_E estimates and T_E-T differences provided in this research are comparable to T_E estimates provided in previous [3–8] investigations. In addition, results from this study offered an additional perspective of T_E variations, namely in meso-scale, while previous studies predominantly focused on large-scale [3,5] or a single location [2,4] assessment of T_E variations. Thus, the present research partly filled a void in the literature.

4. Conclusions

The assessment of climate variability and change has largely focused on air temperature as the primary metric [1]. Research suggests that the air temperature alone is an inadequate metric of near-surface heat content, as it does not account for the changes associated with moisture content variations. We suggest that equivalent temperature (T_E), which incorporates both the dry and moist heat content, is a better indicator of overall heat content. In this paper we investigate and quantify intra-seasonal and inter-annual variations of growing season T_E in the east central U.S. This research explains some of the causes of these variations by examining the influence of different air mass types.

Daily T_E and air mass (using the Spatial Synoptic Classification) data between 2010 and 2014 for 10 Mesonet stations were analyzed to examine how different air mass types influenced equivalent temperature. These 10 stations and their data were selected from a set of data from 33 stations. An analysis of variance (ANOVA) on all the air mass types yielded statistically significant variations among T_E values and these differences varied intra-seasonally and inter-annually. The results suggest that T_E changed under different air mass types as well as in different times of the seasons. From the results and analysis, it can be inferred that the intra-seasonal and inter-annual variations in T_E in the study region and period were influenced by the major air mass types, and there were links between changes in and magnitudes of T_E to intra-seasonal air mass differences.

Results indicated that the growing season was dominated by the MT air mass for all stations for the years 2010, 2011, 2013, and 2014. In 2012, the DM dominated the growing season for all stations except for the Barren County Mesonet station. The highest T_E values were expected to be influenced most by the MT air mass. As the season transitioned into the mid-growing season (June and July), occurrences of high T_E values corresponded with the higher frequency of moist air mass (MT) occurrences. In the late growing season (August and September), T_E values began to decline. This is mainly due to the changes in season and synoptic weather pattern and related changes in air mass types, and also due to declining plant water requirement and evapotranspiration.

Finally, differences between T_E and T in the early growing season were smaller. Days with low T_E were also characterized by dry air mass types and days with high T_E were typically moist and had a corresponding high T_E-T difference, especially in the mid-growing season. In short, based on the findings of this study [7], we suggest that future research could focus on moisture budget analysis to shed further light on the contributions of various moisture sources to T_E. In particular, future investigations may quantify relative contribution of different air masses and various types of land use land cover to T_E.

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