EC3022

Spatial and Temporal Changes in Grass-Reference Evapotranspiration across 800 US Great Plains Counties from 1968 to 2013

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Changes in reference (potential) evapotranspiration as a function of change in climate variables can substantially impact availability and utilization of water resources, which can lead to changes in agricultural operations and productivity. This Extension Circular includes scientific findings, visual interpretation, and discussion of geographic (spatial) variation and patterns of historical reference evapotranspiration across the 834 counties in the United States Great Plains. It also includes the temporal (1968–2013) trends observed in reference evapotranspiration for each county, and potential consequences and significance of these trends in the context of agricultural production and water resources in the region.

Evapotranspiration (ET) is the combined loss of water from surfaces to atmosphere through: a) evaporation of water from the soil and/or plant surfaces, and b) transpiration via stomata of the plant. ET is a critical component of the water cycle, primarily because it is usually the largest one, especially in crop production areas such as the western and Midwestern United States, where 90 percent of the precipitation received can be consumed by ET. Due to ET's relevance, importance, and use of ET in crop production, efficient irrigation management, water resources management, and environmental assessments, accurate quantification (determination) of ET is necessary so that management practices can be carried out with confidence. The most widespread approach of calculating actual crop ET (ET_a) involves the use of reference evapotranspiration (ET_{ref}) and crop coefficient (K_c) (i.e., $ET_a = ET_{ref} \times K_c$). The Nebraska Extension NebGuide G1994 *Estimating Crop Evapotranspiration from Reference Evapotranspiration and Crop Coefficients* provides detailed insights into this approach.

Reference evapotranspiration can either be measured directly using advanced evaporative flux measurement systems and more simplified tools such as atmometers (ET_{gage}™), or calculated from weather variables such as solar radiation, air temperature, relative humidity, and wind speed. For more information on ET gauges see NebGuide G1579 *Using Modified Atmometers (ET_{gage}™) for Irrigation Management*.

Since ET_{ref} is driven by a range of weather variables, any changes in weather would consequently lead to a change in ET_{ref}, too. These changes in weather can occur spatially and temporally. For more information on these effects, see Extension Circular EC716 *Long-Term (1893–2012) Changes in Air Temperature, Relative Humidity and Vapor Pressure Deficit (Atmospheric Evaporative Demand) in Central Nebraska* and Extension Circular EC715 *Climate Change Impact on Air Temperature, Daily Temperature Range, Growing Degree Days, and Spring and Fall Frost Dates in Nebraska.* As a result of these spatial and temporal changes, it is important that ET_{ref} is quantified and determined on local and time-specific scales. In some instances, users rely on long-term average ET_{ref}, which may be largely inferior to modern techniques that integrate actual weather data, atmometer data, thermal imagery, and/or other technologies, making ET_{ref} data more accurate, affordable, and available.

In irrigated agricultural production, appropriate ET_{ref} values are used to inform irrigation management decisions to meet crop water requirements. Even in rainfed or dryland fields, quantification of ET_{ref} is critical so that soil moisture can be tracked and water use vs. yield relationships can be developed. This is especially important for large scale (e.g., watershed, regional) agricultural production areas such as the Great Plains, which includes a range of climate classes that range from arid and semiarid in the west to dry subhumid and humid in the east. Moreover, these areas are home to the production of corn, cotton, wheat, soybean, sugarbeets, dry beans, proso millet, potatoes, grain sorghum, field peas, chickpeas, lentils, forage crops, and livestock. This necessitates using site-specific ET_{ref} values instead of state or regional long-term average values to accurately determine the atmospheric water demand for a given location.

The U.S. Great Plains region is geographically large, climatologically diverse, and crucial for its contribution to national agricultural production. Hence, it is important to characterize the pattern of ET_{ref} regimes in both spatial and temporal scales for the region. The spatial pattern of ET_{ref} can help to determine the water availability (in conjunction with precipitation), crop water use and aridity of a particular region. It is also important to address the pattern of ET_{ref} in a different time scale, such as annually, growing seasonally, and monthly, in order to capture temporal variability. In this publication, the crop growing season is considered to be from May 1 to September 30 regardless of geographic region. Also, the ET_{ref} in this publication refers to the grass-reference evapotranspiration.

To study the spatial and temporal trends in ET_{ref} across the Great Plains region over the 46-year period, analyses were carried out on daily datasets from more than 800 weather stations. Also, to achieve accuracy in spatial patterns, USHCN (United States Historical Climatology Network) weather stations were selected for temperature and rainfall data. ET_{ref} was calculated using an improved spatio-temporally calibrated version of the Hargreaves-Samani equation (Hargreaves and Samani 1985). This publication is based on research conducted by Kukal and Irmak (2016a and b) and reports on the ET_{ref} trends independently for all counties in the Great Plains. Since the interpretation of the data is both extensive and arduous, the ET_{ref} trends are represented using maps both spatially and temporally.

Study Region

Detailed study region characteristics are presented in Kukal and Irmak (2016a and b) and only basic information is presented here. The Great Plains region *(Figure 1)* is also referred to as the central U.S. Its boundaries extend from the Canadian border in the north to Texas in the south, Wyoming and Colorado on the west, and Iowa on the east. Specifically, the area consists of nine states (North Dakota, South Dakota, Nebraska, Iowa, Wyoming, Colorado, Kansas, Oklahoma, and Texas), which together comprise 834 counties. The total land area enclosed by these states is 890,896 mi2 (2,307,410 km^2) and lies between dense forests on the east, and mountains and deserts on the west. The common topographical characteristic of the area is vast and flat-to-rolling plains. The highest elevation throughout the region is in the Rocky Mountains in western Colorado. The lowest elevation is in the southern coastline in Texas. Temperature and precipitation have an evident north-south and east-west gradient, respectively. The long-term (1968–2013) average annual precipitation ranges from 8.5 inches in the west to 57 inches in the southeast.

Similarly, long-term (1968–2013) average growing season (May 1–September 30) precipitation varies from 4.7 inches in the west to 27.5 inches in the southeast. Average air temperature has a north-to-south increasing trend ranging from 30.2° F to 75.4° F when averaged annually, and 46.4° F to 86° C when averaged over the growing season (See the Nebraska Extension Circular EC3009 for details). Agricultural land use includes rangelands, prairies, and irrigated and rainfed farming of agronomic row crops. In the eastern parts of the region, mostly nonirrigated crop production is practiced; whereas in the western parts of the region, irrigated crop production is dominant with the major source of irrigation being groundwater from the Ogallala Aquifer.

Spatial Distribution of Annual, Growing Season, and Monthly Grass-Reference Evapotranspiration

Daily ET_{ref} at weather station sites was used to compute monthly, growing season, and annual totals of ET_{ref}. Using these estimates at over 800 sites, ET_{ref} surfaces (or maps) were developed over the region using inverse distance weighing interpolation techniques described in Kukal and Irmak (2016a). Meanwhile, statewide and county-based values were determined for inter-comparisons.

The maps for annual and growing season total ET_{ref} are shown in *Figure 2a* and *Figure 2b*, respectively. These maps, providing site-specific ET_{ref}, can be instrumental to determine average ET_{ref} amounts in any location in the region. Monthly total ET_{ref} from May to September maps are shown in *Figure 3a–e*, respectively. These maps reveal that there is a strong southwest-northeast decreasing trend in total ET_{ref} on an annual, growing season, and monthly basis. The long-term regional average ET_{ref}, when averaged across all 834 counties, was 50.7 inches for the calendar year and 31.8 inches for the growing season.

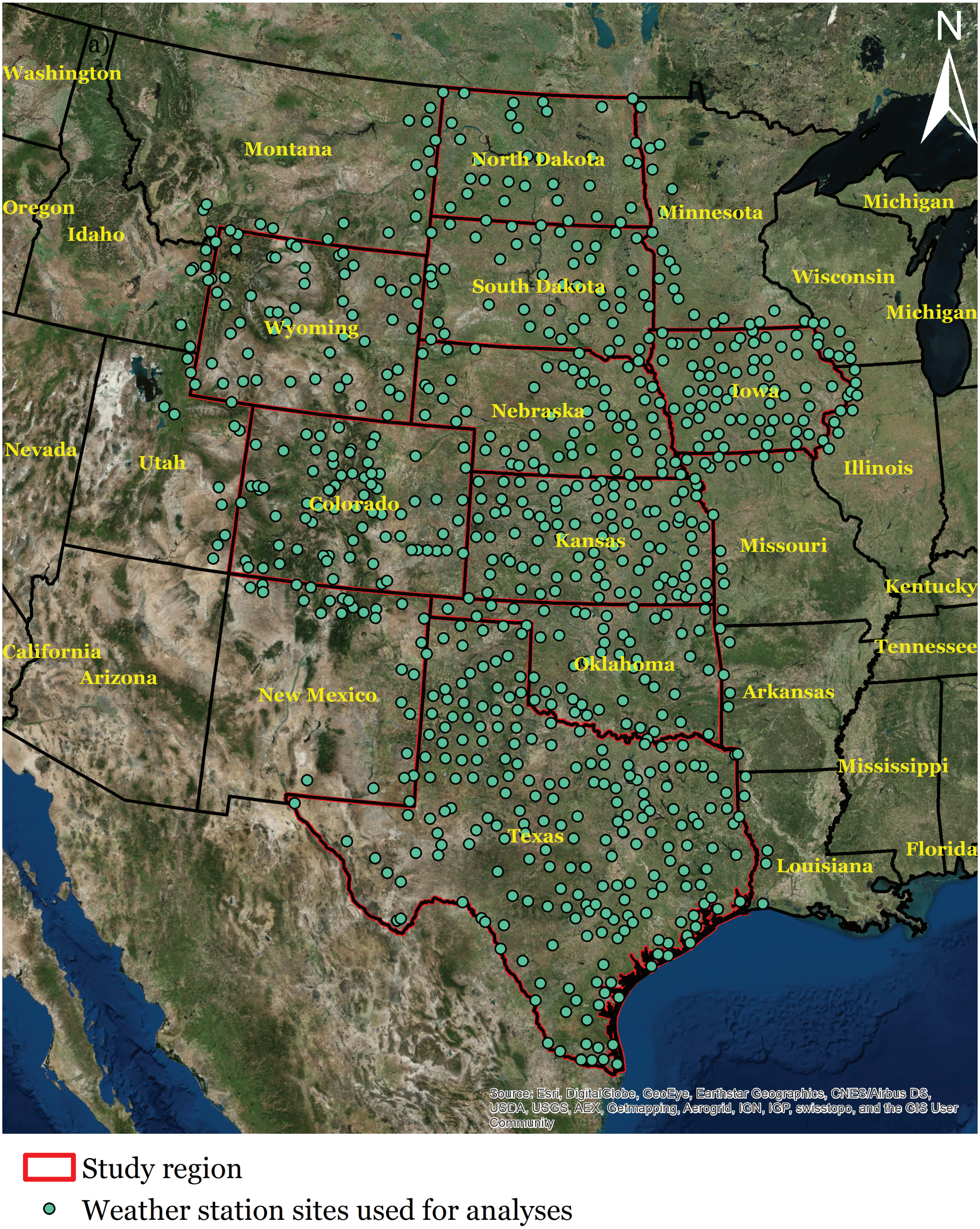

Figure 1. The study region (U.S. Great Plains) and selected weather station sites used for analyses. (Map, Kukal and Irmak, 2016 a, b).

Averaged by individual counties, the annual ET_{ref} ranges from 33.1 inches in Cavalier County, North Dakota, to 83.7 inches in El Paso County, Texas. Similarly, the growing season ET_{ref} ranges from 24 inches in Allamakee County, Iowa, to 45.9 inches in El Paso County, Texas. Statewide average ET_{ref} annual totals are highest in Texas (61.8 inches) and lowest in Iowa (38 inches). The growing season totals are also the highest in Texas (35.5 inches) and lowest in Iowa (25.6 inches). The ET_{ref} that occurs during the growing season months (May–September) contributes 66 percent of the annual ET_{ref}, when averaged across the region. This contribution of growing season ET_{ref} towards annual ET_{ref} is the highest in North Dakota (73 percent) and the lowest in Texas (57 percent). Generally, the magnitude of this contribution decreased when moving north to south. This is important to consider as the growing season ET_{ref} governs the crop water requirement of major cropping systems in the region.

Table 2 shows several statistics associated with regional and statewide annual, growing season and monthly ET_{ref}. Standard deviation (SD) is the measure of the amount of variation from the average values of ET_{ref} in each period. Higher SD indicates more variation or deviation of the ET_{ref} data point from the mean value in a given period; while the low SD indicates that the data points are close to the mean value.

Evaporative demand was highest in July during the year. This was true for the entire region as well as individual states. Within the growing season, the ET_{ref} is low in May, gradually increases until reaching the peak ET_{ref} in July, and then gradually declines until reaching the lowest value in September, as shown in *Figure 3*. The highest SD in annual and growing season ET_{ref} was observed for South Dakota, while the lowest values were observed in Colorado.

Temporal Changes in Annual, Growing Season, and Monthly Grass-Reference Evapotranspiration

Temporal trends in the annual and growing season grass-reference ET (ET_{ref}) were computed for each county in the region and the nature (whether increasing or decreasing) and statistical significance (whether a trend is large enough to be qualified as a trend by statistical definition) of the observed trends were explored. These characteristics of temporal trends for the annual, growing season, and monthly ET_{ref} are reported by maps in *Figure 4a, 4b,* and *Figure 5*, respectively. In these maps, the blue upright arrows represent increasing (positive) trends, while the red inverted arrows indicate decreasing (negative) trends. Counties with a green background indicate that the trend for the county is statistically significant at 95 percent confidence, which distinguishes them from the counties with insignificant trends (counties assigned with a white background).

The map in *Figure 4(a)* reveals that, overall, annual ET_{ref} has decreased from 1968 to 2013 over most of the region. More specifically, 62 percent of the counties (518 counties) in the region showed decreasing trends of annual ET_{ref} and 38 percent of the counties (316 counties) showed increasing trends of annual ET_{ref}. The counties that showed decreasing trends are mostly in Iowa, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas.

Out of all the counties that showed decreasing trends, the ones in eastern North Dakota and South Dakota show significant trends. However, increasing trends are observed in the western states of Wyoming and Colorado. Also, the High Plains, Trans Pecos, Low Rolling Plains, North Central, East Texas, Upper Coast, Lower Valley, Southern and Edwards Plateau regions in Texas showed increasing trends.

In Oklahoma, the Panhandle, Central, East Central, and South Central regions had increasing trends. In Kansas, the Southwest, West Central, Central, and North Central regions showed increasing trends. In addition, the Panhandle region in Nebraska; the Northwest, Southwest, and Black Hills region in South Dakota, and the Southwest region in North Dakota showed increasing trends in ET_{ref}. Out of all the aforementioned regions showing increasing trends, only the ones in Texas were statistically significant.

Similarly, growing season ET_{ref} trends were also investigated and are represented in a map in *Figure 4(b).* About 72 percent of the counties showed negative (decreasing) growing season ET_{ref} trends, which is higher than the proportion of negative trends observed in annual ET_{ref}. Interestingly, all the counties in North Dakota, South Dakota, Iowa, and Nebraska showed decreasing trends in ET_{ref}. The only increasing growing-season ET_{ref} trends observed in the region were those in Texas, Colorado, Wyoming, and southwest Kansas. However, unlike annual ET_{ref}, the increasing trends in growing-season ET_{ref} observed in the High Plains region of Texas were insignificant.

The magnitudes of these trends were also computed, although they are not represented on the maps. For annual ET_{ref}, the highest increasing trend was 0.79 inch per decade for Culbertson County, Texas, while the highest decreasing trend was 1.01 inch per decade for Dickey County, South Dakota. Similarly, for growing season ET_{ref}, the highest increasing trend was 0.67 inch per decade for Frio County, Texas, while the highest decreasing trend was 1.0 inch per decade for Dickey County, North Dakota. For annual ET_{ref}, the regional average of increasing trend was 0.23 inch per decade, whereas the regional average of decreasing trend was 0.31 inch per decade. Likewise, for the growing season ET_{ref}, the regional average of increasing trend was 0.16 inch per decade, whereas the regional average of decreasing trend was 0.30 inch per decade.

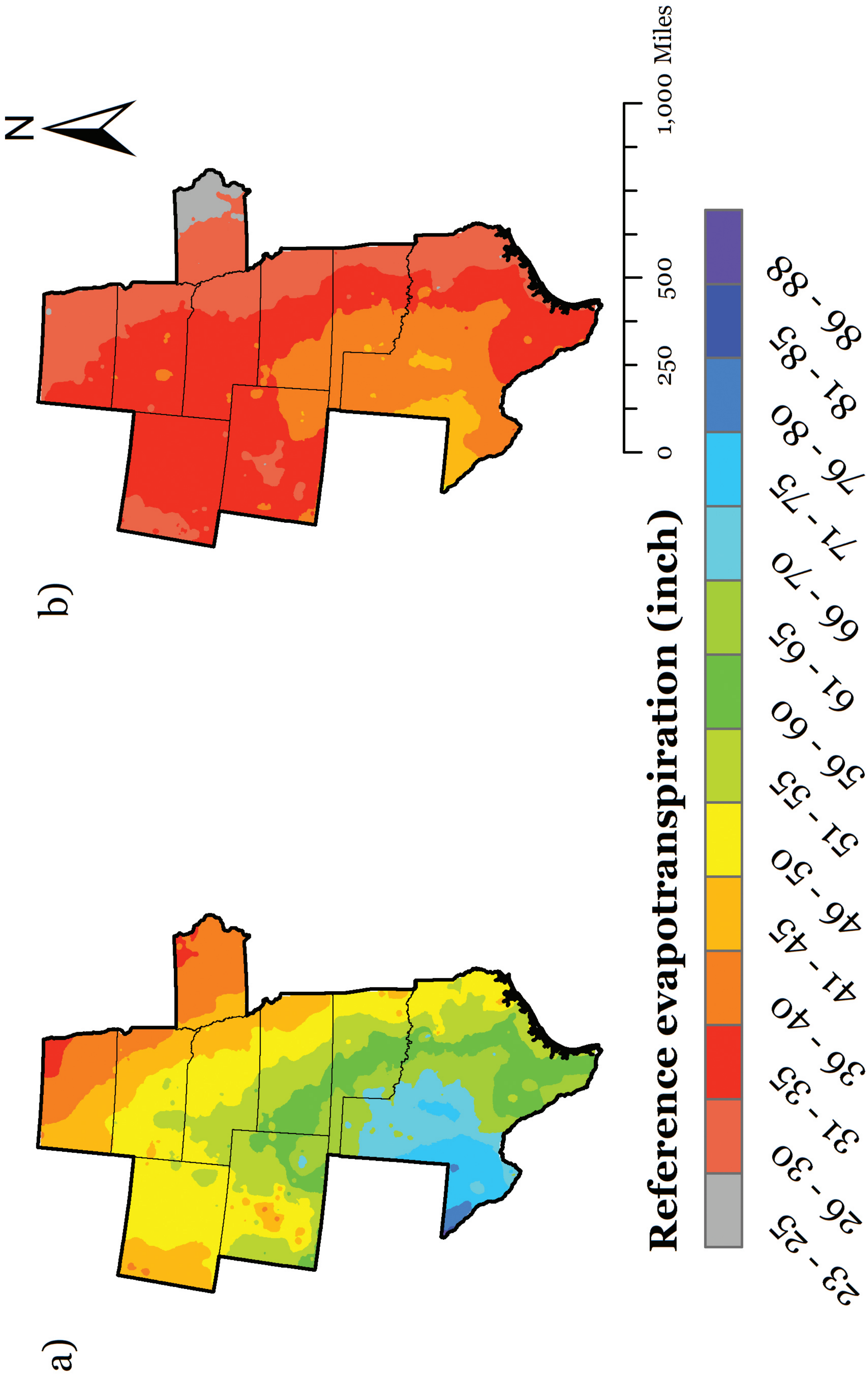

Figure 2. Spatial trends in a) annual and b) growing season grass-reference evapotranspiration (ET_{ref}) across the U.S. Great Plains.

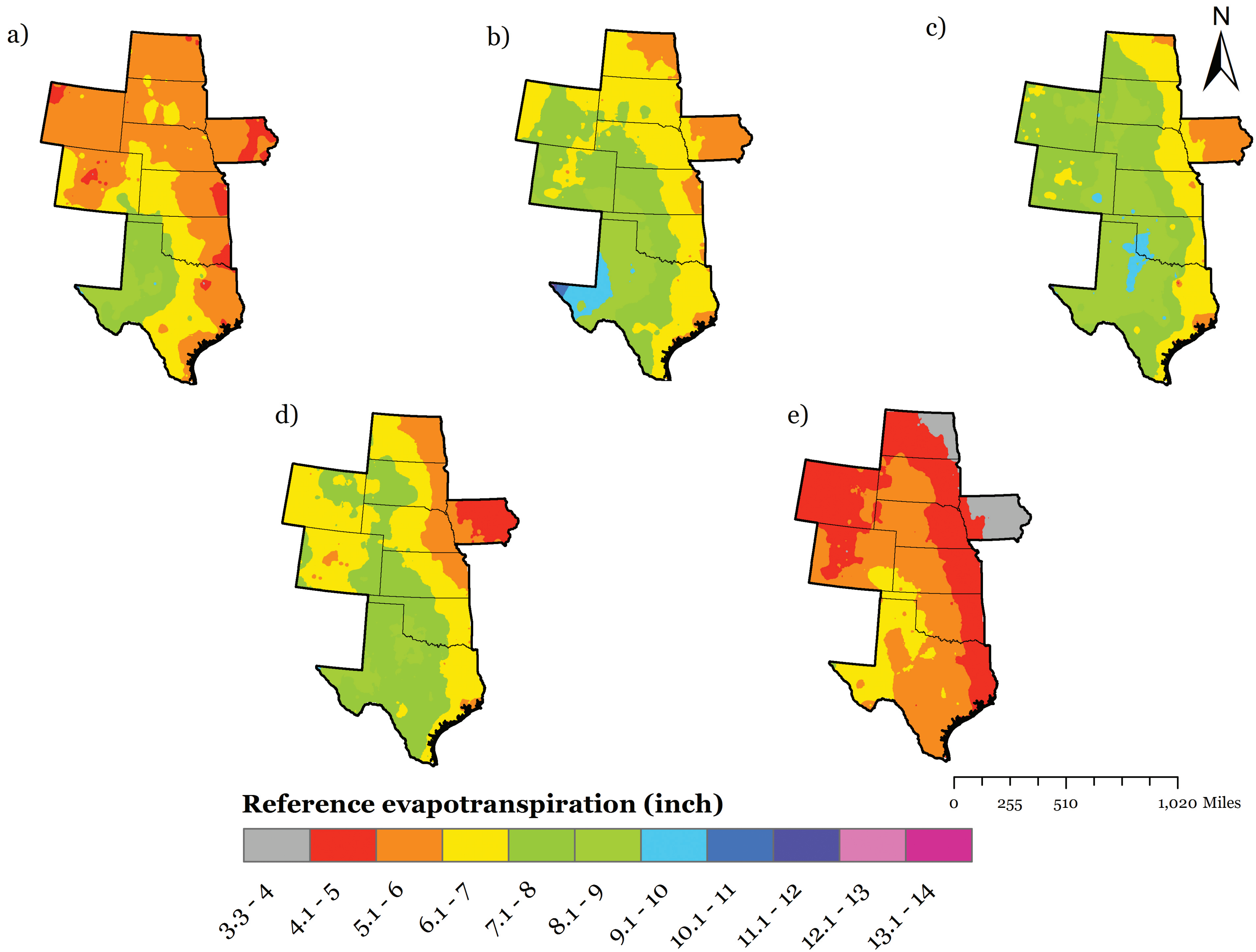

Figure 3. Spatial trends in grass-reference evapotranspiration (ET_{ref}) during a) May, b) June, c) July, d) August, and e) September across the U.S. Great Plains.

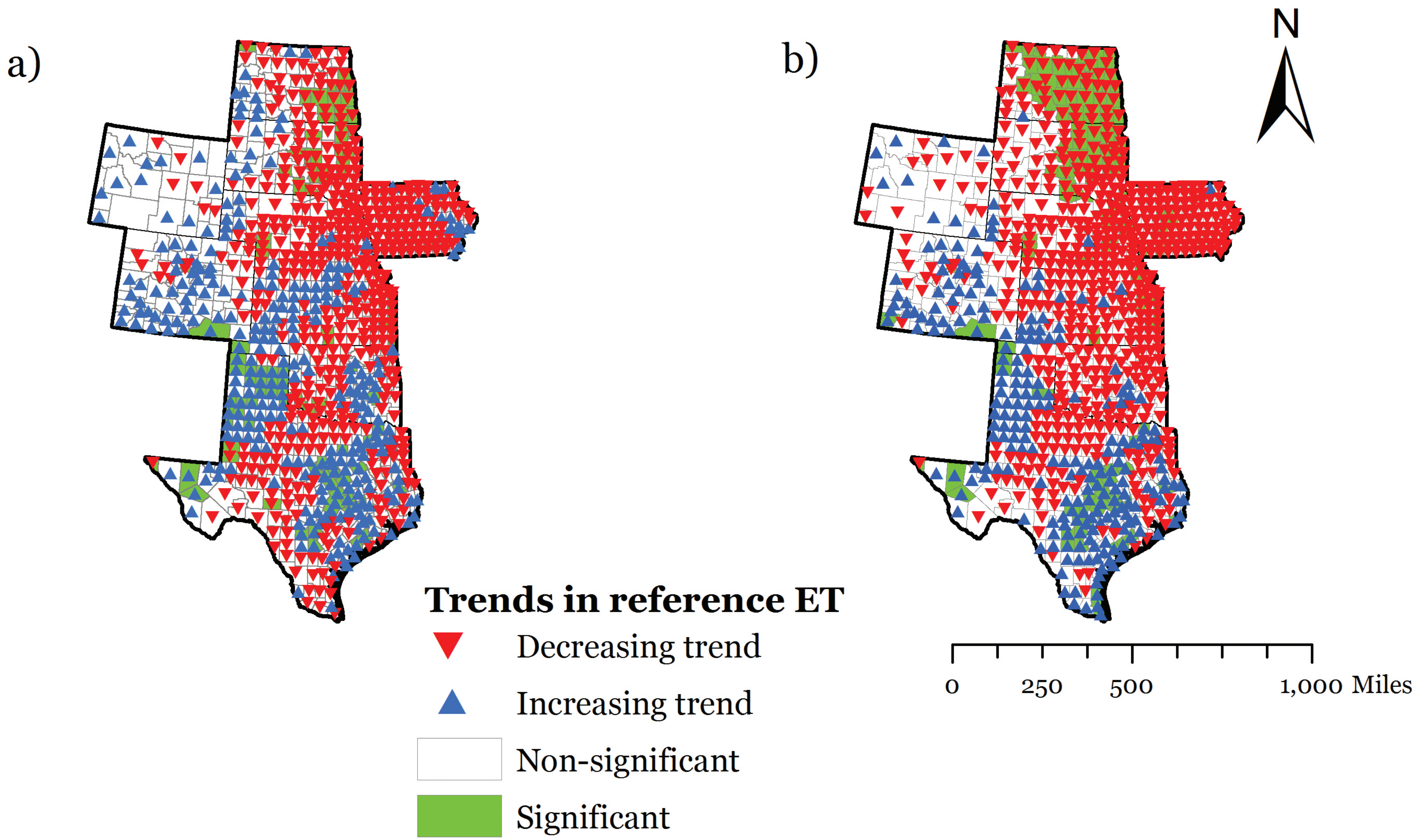

Figure 4. Temporal trends in a) annual, and b) growing season grass-reference evapotranspiration (ET_{ref}) across the U.S. Great Plains.

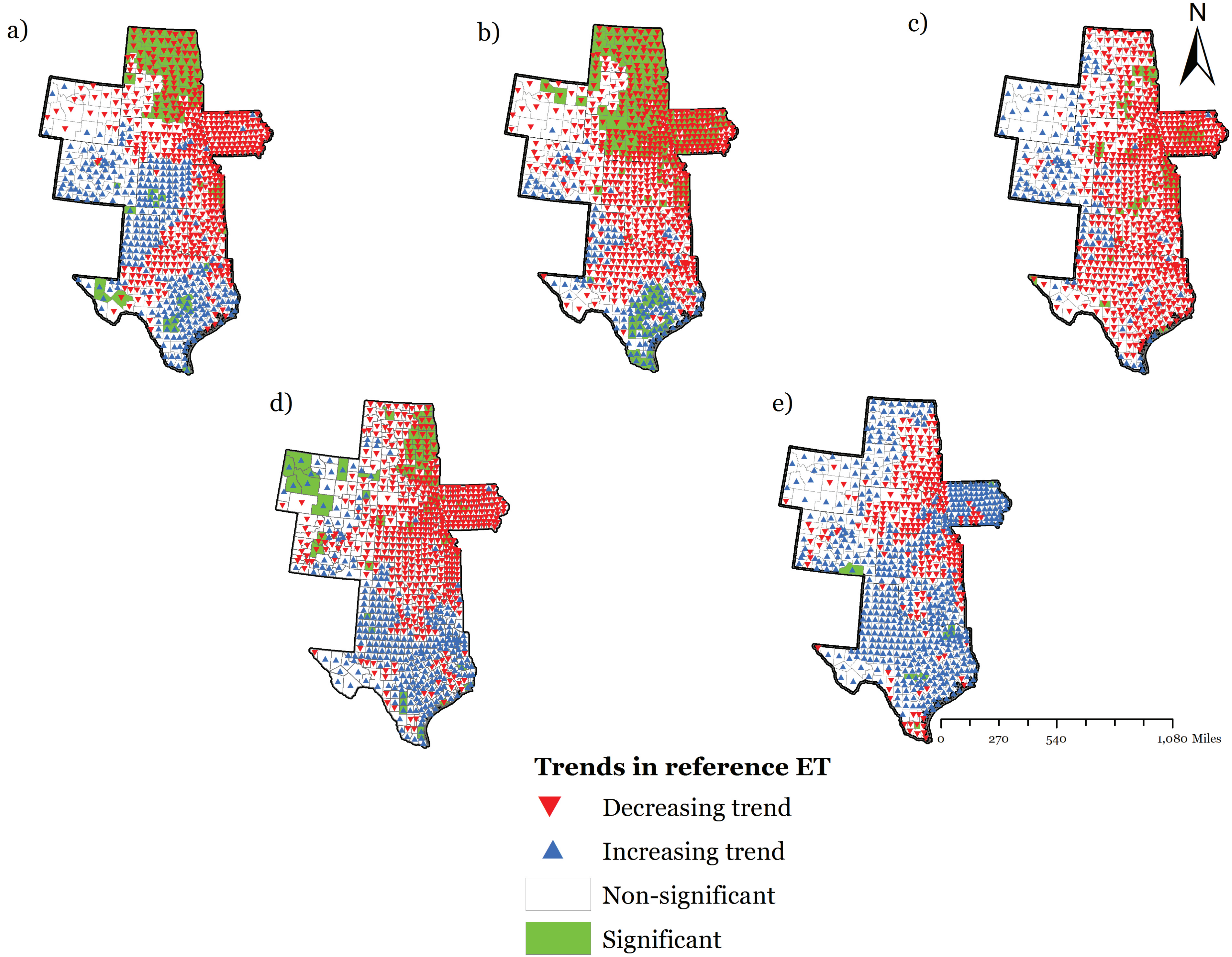

Figure 5. Temporal trends in grass-reference evapotranspiration (ET_{ref}) during a) May, b) June, c) July, d) August, and e) September across the U.S. Great Plains.

The primary reason for negative trends in ET_{ref} is a result of the negative trend in diurnal temperature range (DTR), which is discussed in detail in the Nebraska Extension Circular EC3009. The DTR is calculated as the difference of daily T_{max} and T_{min} and is used to calculate ET_{ref} in the Hargreaves–Samani equation. Detailed information and maps on spatial and temporal trends in DTR can be found in the Nebraska Extension Circular EC3009 *Observed Space and Time Changes in Air Temperatures and Daily Temperature Range for the Counties in the U.S. Great Plains*.

Temporal trends of ET_{ref} were also investigated on a monthly basis and the resulting trend maps for the individual growing season months are shown in Figure 5. The maps indicate that considerable variability in temporal trends of ET_{ref} occurring during the different months of the season. For example, counties in North Dakota and South Dakota show significant decreasing trends, which expand to counties in Nebraska, Iowa, and eastern Kansas during June. For July, the significant decreasing trends are limited to counties in southeastern North Dakota, central South Dakota, central Iowa, and eastern and south central Kansas. These significant decreasing trends again reappear in eastern North Dakota and South Dakota during August. None of the decreasing trends were significant during September. However, significantly increasing trends are primarily concentrated in Texas during May and June, and in Wyoming during August.

By observing maps in *Figure 5,* information about the county scale trends in ET_{ref} for any month can be interpreted. As an example, we chose Clay County, Nebraska, from the 834 counties in the region to extract and tabulate all the temporal trends in ET_{ref} during 1968–2013 period. Detailed information of the observed ET_{ref} trends in Clay County, Nebraska, is listed in *Table 1*. Monthly total ET_{ref} trends were negative (decreasing) for all months during the growing season. Also, the negative trends were observed for both annual total and growing season total ET_{ref}. However, none of these trends are statistically significant.

Irmak et al. (2012) also found negative trends for annual ET_{ref} in the Central Platte River Basin, Nebraska, during the period from 1893 to 2008. The site investigated by Irmak et al. (2012) is located in Merrick County and our trend maps show that negative annual ET_{ref} trends are observed for this county as well. Other similar resources that provide insights into long-term changes in ET_{ref} across Nebraska, both spatial and temporal, are:

- *Variability of Reference Evapotranspiration across Nebraska* (EC733).
- *Magnitude and Trends of Reference Evapotranspiration Rates in South Central Nebraska: Daily, Monthly, Growing Season Total, and Annual Total* (EC765).
- *Monthly, Seasonal, and Annual Spatial and Temporal Variability of Reference (Potential) Evapotranspiration across Nebraska* (EC2003).

Table 1. Temporal trends of observed monthly average ET_{ref} from 1968–2013 for Clay County, Nebraska.

Period	ET_{ref} (mm yr-1)
May	-0.01
June	-0.13
July	-0.13
August	-0.09
September	-0.01
Growing Season	-0.37
Annual	-0.25

Regional and Statewide Averages of Grass-Reference Evapotranspiration

Table 2 shows the regional and statewide averages for annual, growing season, and monthly ET_{ref} to aid the interpretation of the discussed results based on different geographic units.

Significance and Potential Implications of Reference Evapotranspiration Trends

Any changes in ET_{ref}, whether spatial or temporal, can affect the region's crop water productivity by altering the crop water requirements and crop response to atmospheric demand. The spatial distribution of ET_{ref}, along with precipitation distribution, can help us to determine whether a crop grown in a particular region would need to be irrigated, and if applicable, quantify irrigation water requirements. For instance, Iowa, which is a part of our study region even though it may not be considered part of the U.S. Great Plains, has an average (1968–2013) statewide growing season ET_{ref} of 25.6 inches. Similarly, the average precipitation received over the same period for the state is 21 inches.

By using appropriate crop coefficient (K_c) values for a crop for the region, we could compute actual crop water requirements (ET_a) and observe that average ET_a should be comparable to the rainfall received in the region. This implies that the precipitation, along with the stored soil water, should be sufficient to meet the crop water requirements most, but not all of the time). This is supported by the fact that crop production in Iowa is primarily rainfed.

Other regions, such as western Nebraska, have a greater gap between crop water requirements and precipitation, and hence the vast majority of crop production is practiced under

Table 2. Regional and statewide average annual, growing season, and monthly grass-reference evapotranspiration (ET_{ref}) (inches).

Months	Regional	ND	SD	NE	KS	CO	WY	IA	OK	TX
Monthly Means										
May	6.0	5.5	5.8	5.8	5.8	6.0	5.5	5.2	6.1	6.8
June	7.1	6.0	6.6	6.9	7.0	7.5	7.0	5.8	7.2	7.7
July	7.5	6.8	7.6	7.3	7.6	7.8	7.6	5.8	7.9	7.8
August	6.8	6.1	6.7	6.4	6.7	6.8	6.8	4.9	7.3	7.4
September	5.1	4.3	4.9	5.0	5.2	5.3	4.7	3.8	5.3	5.7
Annual										
Mean	51.1	39.2	45.2	48.1	51.1	52.2	46.0	38.0	55.1	61.8
Max	55.6	44.2	50.7	54.7	56.8	57.0	50.8	43.0	59.3	67.6
Min	47.7	35.7	40.2	43.0	46.3	49.1	41.6	33.3	51.9	58.2
SD	1.4	2.0	2.3	2.0	1.8	1.5	1.7	1.8	1.7	1.7
Growing Season										
Mean	32.4	28.8	31.5	31.4	32.3	33.3	31.5	25.6	33.8	35.5
Max	34.7	32.4	34.8	35.2	35.7	35.7	34.0	29.3	37.1	39.7
Min	30.4	25.5	27.7	28.5	29.7	31.3	28.6	22.7	31.0	32.5
SD	0.9	1.3	1.5	1.4	1.4	0.9	1.1	1.2	1.4	1.2

irrigation. In a similar manner, soil water deficit can be computed as the difference of ET_{ref} and precipitation data for each county, and information can be derived on the irrigation water needs site-specifically. Thus, the maps that were generated for this publication, and others listed in this publication, can be very useful for such analysis by practitioners and federal and state agencies concerned about changes in crop water requirements in a given geographic location in a particular state in the U.S. Great Plains.

Moreover, temporal trends, whether increasing or decreasing, have the potential to impact crop water requirements and crop success in the region. Due to the changes in meteorological variables over time, ET_{ref} can increase or decrease. This change can vary across geographic locations owing to the particular variable(s) that is affected. This is evident from our maps, which show that the temporal trends vary considerably across states and even within a state. However, a change in ET_a in a particular direction does not necessarily mean that crop water requirements change in the same direction and by the same amount. That is because numerous other factors affect the crop water requirement such as soil water availability and several other crop and management factors.

If crop water requirements increase, irrigation requirements can possibly be affected in irrigated sites, resulting in greater allocation of water towards irrigation depending upon the direction and magnitude of change in precipitation at the site. Also, an increase in crop water requirements in rainfed or dryland conditions can have negative impacts on crop yields if precipitation is insufficient at the site. Hence, accurate information about the trends that have occurred in growing season ET_{ref} is necessary to predict the trends in crop water requirements and prepare mitigation efforts for the negative impacts.

Apart from total crop water requirements during the growing season, it is important to consider ET_{ref} over relatively smaller time scales, such as months. Data presented in this publication show that the peak ET_{ref} and hence peak crop water requirement usually occurs in July, which implies that irrigation demand is the highest in July as well. Therefore, it is crucial to focus on month-specific trends in ET_{ref} during the growing season. It is clear from our analysis that the trends can vary substantially between the months in the same year. Overall, the information presented in this circular will provide insights into long-term trends and changes in atmospheric water demand or ET_{ref} in singularity. It also presents a foundation for computing crop water requirements and irrigation requirements for large scales when combined with other available resources. As a result, the user can quantify the change in current irrigation requirements and soil water deficits for various crops due to changes in climate variables, and which regions have been affected more than others and in what direction (increasing or decreasing trends).

RESOURCES

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Kukal, M., & Irmak, S. (2016a). “Long-term patterns of air temperatures, daily temperature range, precipitation, grass-reference evapotranspiration and aridity index in the USA Great Plains: Part I. Spatial trends.” *Journal of Hydrology* 542: 953–977.

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