

Potential (Reference) and Actual Evapotranspiration Trends across U.S. High Plains in Relation to Irrigation Development and Climate Change

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In agro-ecosystem-dominated regions, such as the U.S. High Plains, augmented atmospheric water vapor is, in some cases, attributed to increased actual evapotranspiration (ET_c) from irrigated surfaces as a result of increased soil evaporation and transpirative losses from the vegetation canopies through photosynthesis process. In the process of transpiration from plant canopies through stomata and evaporation from soil, water, plant, and other surfaces, water is transferred into the atmosphere in the form of very small water vapor particles (eddies), increasing atmospheric moisture content. Thus, since irrigation practices may result in increased ET_c, this would, in turn, be expected to increase atmospheric moisture content. Therefore, it is important to evaluate long-term potential changes in ET_c trends and magnitudes in the U.S. High Plains states in relation to changes in climate and irrigation practices. This Extension Circular presents the trends and magnitudes in ET_c in the High Plains region during the period from 1982 to 2008. Changes in grass-reference (potential) ET (ET_o), which is an indication of atmospheric evaporative demand and an implicit indication of the changes in climatic variables (temperature, solar radiation, wind speed, vapor pressure deficit, etc.), were also quantified from 1981 to 2009.

Irrigation practices result in significant (i.e., up to 400 percent) yield increases for many crops, and irrigated agriculture currently contributes to about 40 percent of the world's total food/fiber production on only 15-20 percent of the total cultivated land (United Nations Water Statistics, 2013). Based on 2008 data, the total irrigated land area of the world is about 806 million acres. China leads the world in terms of total irrigated land with 158 million acres. India is second with a total of 154 million irrigated acres, and the U.S. has the third place with a total of about 55 million irrigated acres (World Bank, 2013).

Irrigation development impacts surface energy balance, including actual evapotranspiration (ET_c), through modifying the available energy (solar energy) vs. ET_c partitioning of the vegetation/canopy and soil surface. Irrigation practices can alter the microclimate by changing the surface temperature, relative humidity, and vapor pressure deficit (atmospheric moisture difference between evaporating surface and atmosphere), which in turn, impacts the rate of ET_c. Vegetation plays an important role in linking the land-atmosphere interaction through the mechanistic exchange of water vapor and surface energy. Atmospheric water vapor (moisture)



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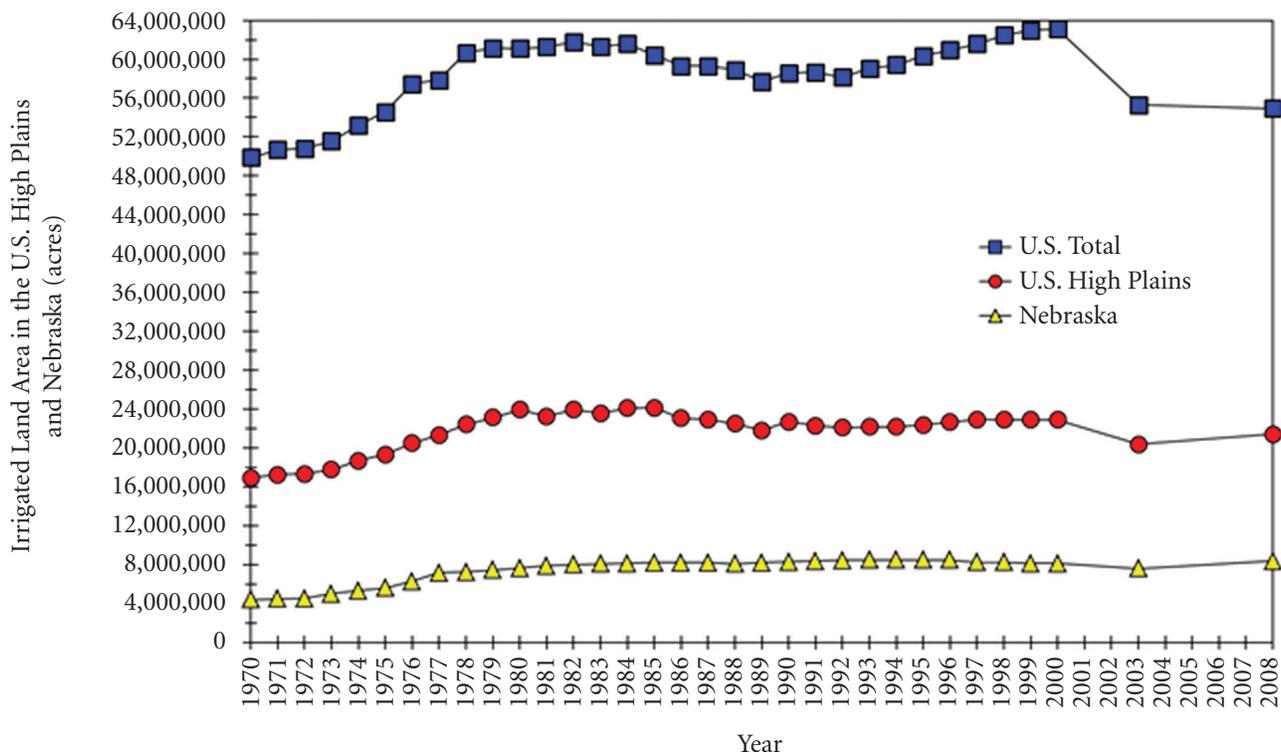


Figure 1. Changes in irrigated land area in the U.S. High Plains states and Nebraska from 1970 to 2008. Nebraska data are also included in the High Plains dataset.

has been anthropogenically altered, in part by land use/land cover changes such as conversion of natural vegetation surfaces to croplands, urbanization, irrigation practices, afforestation, and deforestation. These land use/land cover changes influence atmospheric water vapor content through modification of land surface properties and evaporation, thus impacting ETc. The term “anthropogenically” represents the influence of humans on nature, in general; the term is sometimes used in the context of CO₂ emissions released into the atmosphere from human activities, but it applies to all major human-activity impacts on the environment.

Irrigation development in the U.S. and High Plains, including Nebraska, has been dynamic in the last four decades (*Figure 1*). The U.S. has about 6.8 percent of the world’s total irrigated land. The total irrigated land area in the U.S. increased from 49.9 million acres in 1970 to 60.7 million acres in 1978 and stayed relatively constant until 1984, then declined to 58.1 million acres in 1992 and increased again to 63 million acres in 2000. The total acreage declined to 55 million acres in 2008. In the High Plains states, the total irrigated land increased from 16.9 million acres in 1970 to 24 million acres in 1980, stayed relatively constant until 1985, declined to 21.8 million acres in 1989, and remained relatively constant (with small inter-annual fluctuations) until 2008 with 21.4 million acres. Out of 13 High Plains states

considered in this publication (Colorado, Iowa, Kansas, Minnesota, Missouri, Montana, New Mexico, Nebraska, North Dakota, Oklahoma, South Dakota, Wisconsin, and Wyoming), all but five states (Colorado, Montana, New Mexico, Oklahoma, and Wyoming) exhibited an increasing trend in irrigated land from 1970 to 2008. This trend has continued in some states into the 21st century as economical profitability and other incentives of maize, soybean, wheat, and other commodity crops have led farmers to convert some of the natural vegetation surfaces into irrigated croplands. The largest decline in irrigated land from 1970 to 2008 was observed in Montana with about 1.25 million acres, and the largest increase in irrigated land was observed in Nebraska with 3.9 million acres.

There has been a gradual increase in irrigated agricultural lands in Nebraska from 4.4 million acres in 1970 to 8.5 million acres in 1996. The irrigated land area exhibited about a 1-million-acre decline from 1996 to 2003 and increased again to 8.4 million acres in 2008. Currently, Nebraska leads the nation in terms of total irrigated land. Nebraska has about 39 percent and 15 percent of the total irrigated land area of the High Plains and U.S., respectively. The dominant irrigation method (\approx 75 percent) is center pivot system, and surface/gravity (mainly furrow) irrigation method represents about 25 percent of the total irrigated area. The land area irrigated

using micro-irrigation (i.e., drip irrigation) is still a very small area, but has been increasing in the last decade.

Study Area and Data

The study region is the High Plains of the U.S. shown in *Figure 2*, which also presents the dominant land use/land cover distribution of the region. The region is geographically located in the central U.S. between dense eastern forests and the western mountains and desert landscape. The area is a flat-to-rolling plain that is predominantly agricultural lands, including rangeland, natural prairie, and irrigated and rainfed farming of row crops, primarily maize, soybean, sorghum, alfalfa, winter wheat, sugar beets, and cotton. Precipitation is limited in the western plains and increases toward the east. The average annual precipitation ranges from approximately 10.2 inches in the west to 23.6 inches in the east. Temperature has a strong north-south gradient. The climate

is influenced by the cold air fronts from Canada in the north and Rocky Mountains in the northwest and humid and warm air masses flowing into the region from the Gulf of Mexico from the south, resulting in some of the largest day-to-day, as well as diurnal, fluctuations in air temperature, creating some of the most intense air turbulence, which results in extreme weather, including severe storms and tornados (Irmak, 2010). The region is periodically affected by droughts, which likely stirred it into extensive irrigation development, starting in the 1950s.

This study (part of research reported by Mutiibwa and Irmak, 2013) used datasets obtained from several sources:

- The Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX) (Irmak, 2010), a comprehensive and expanding network of Bowen ratio energy balance systems (BREBS) and eddy covariance system (ECS) network

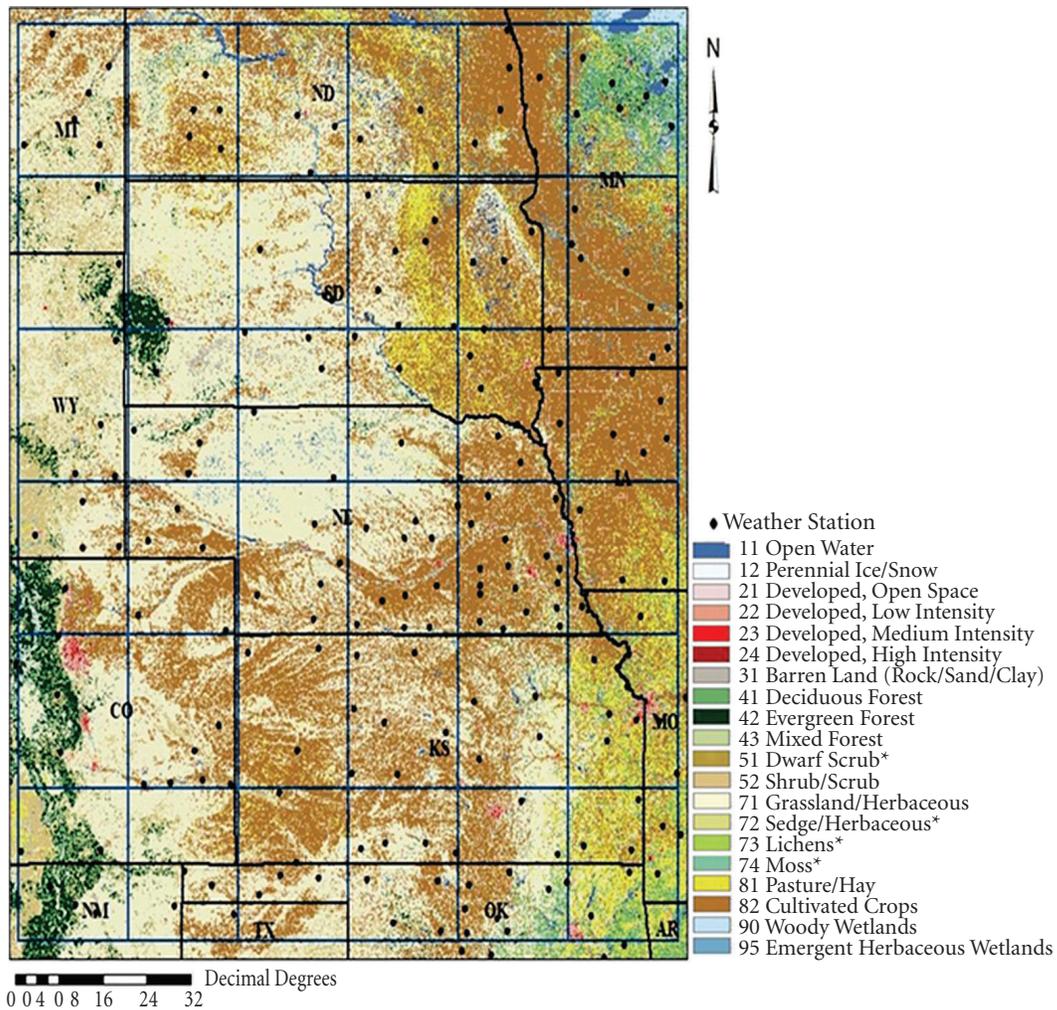


Figure 2. The U.S. High Plains region land use/land cover during 2006 (Source: National Land Cover Database) and the weather stations (black dots) used in the analyses (Source: Mutiibwa and Irmak, 2013).

that is designed to measure surface energy and water vapor fluxes, microclimatic variables, soil moisture, and plant physiological parameters for over 12 different vegetation surfaces;

- The United States Historical Climatology Network (USHCN) for the monthly temperature data of 204 weather stations across the High Plains region; and
- The normalized difference vegetation index (NDVI) measured by Advanced Very High Resolution Radiometer (AVHRR) on National Oceanic and Atmospheric Administration (NOAA) satellites.

Actual crop evapotranspiration (ET_c) was estimated using the two-step approach, in which grass-reference (potential) evapotranspiration (ET_o) was computed and adjusted to crop-specific ET_c estimates using crop coefficients (K_c) and the spatial K_c values were estimated from the model that was developed between K_c and NDVI. The temperature-based Hargreaves-Samani temperature-based equation was used to estimate reference (potential) evapotranspiration. The reason for selecting temperature-based equation was solely due to unavailability of solar radiation, wind speed, and relative humidity in all locations to use combination-based energy balance equation such as Penman-Monteith equation. The model was applied to estimate spatial K_c for the region for the growing seasons of 1981 to 2009. For more detailed information about using the two-step method for estimating ET_c from grass- and alfalfa-reference evapotranspiration see University of Nebraska–Lincoln (UNL) Extension NebGuide G1994, *Estimating Crop Evapotranspiration from Reference Evapotranspiration and Crop Coefficients* (www.ianrpubs.unl.edu/sendIt/g1994.pdf) and UNL Extension Circular EC765, *Magnitude and Trends of Reference Evapotranspiration Rates in South Central Nebraska* (www.ianrpubs.unl.edu/sendIt/ec765.pdf). The summer months studied were June, July, and August, which are considered to be the peak irrigation months. The pixel size of the spatial ET_c was 5-mile x 5-mile [pixel is a unit in remote sensing/satellite images and are composed of a matrix of picture elements or areas (pixels), which are the smallest units of an image. Image pixels are normally square and represent a certain area on an image].

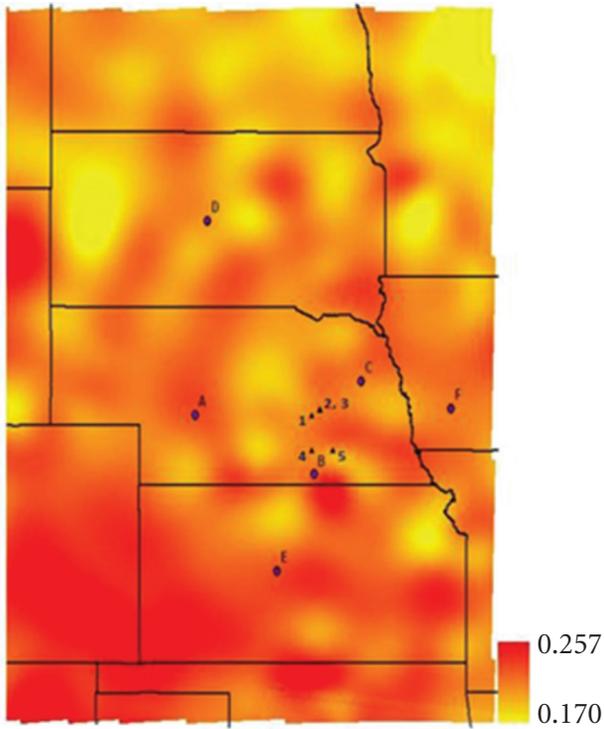
Trends in Grass-Reference (Potential) Evapotranspiration (ET_o)

The maps of monthly average ET_o at a spatial resolution of 5-mile x 5-mile grids for selected years (1982, 1990, 2002, and 2008) are presented in *Figures 3(A-L)*. ET_o over the High Plains region ranged between 0.12 in/day and 0.35 in/day. In June, ET_o appears to have an

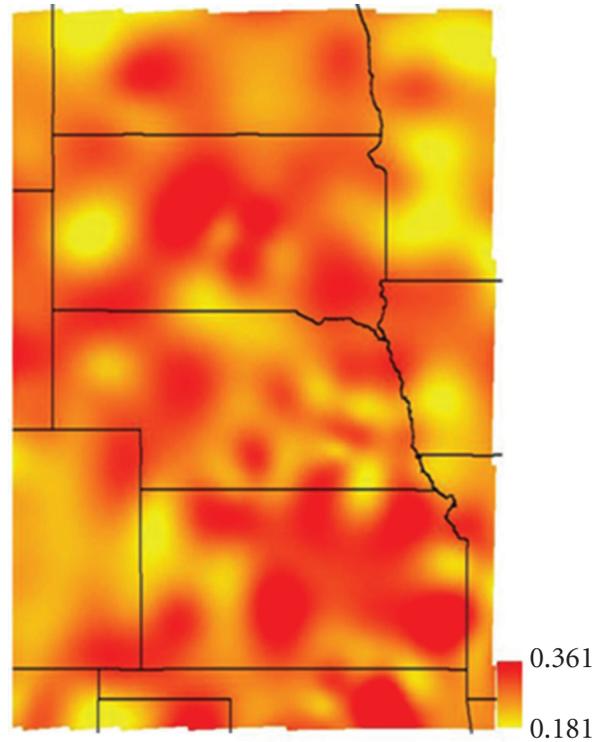
increasing north to south gradient. This could be due to the cool air masses from Canada which prevail over the Dakotas, resulting in cool temperatures, thus lowering the atmospheric evaporative demand in the northern part of the High Plains, which results in lower ET_o. For July and August, there is not a detectable trend or pattern across the region, however central and eastern Colorado show a consistent pattern of lower ET_o than other regions.

Trends in ET_o over the period from 1981 to 2009 were assessed by selecting six pixels from different locations of the region. The six pixels were selected based on land use maps of 1982, 1990, 2002, and 2008. For accurate trends in ET_o, it was important that the surface characteristics over the six sampled locations were relatively consistent over the 29 years. Thus, the primary assumption is that, over the entire study period, the land use coverage was at least 90 percent cropland. The land use maps were part of the UNL Center for Advance Land Management Information Technologies (CALMIT)-developed land cover databases. The location of the six pixels is shown in *Figure 3A*.

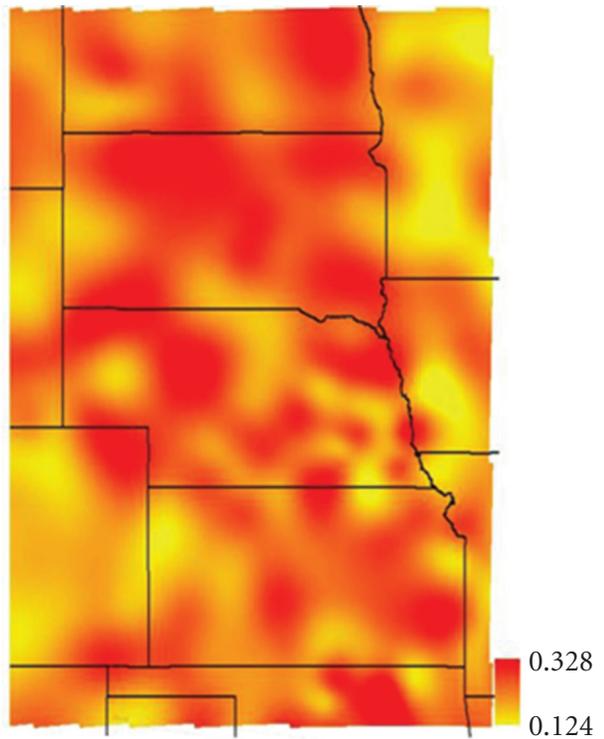
The trends of monthly average of daily ET_o (in/day) for June, July, and August are presented in *Figures 4A-4C*. With the exception of the summer of 1988, which was an extreme drought season, ET_o for June was less than July and August at all six locations (**A: west central Nebraska; B: south central Nebraska; C: northeast Nebraska; D: central South Dakota; E: west central Kansas; and F: southwest Iowa**). During the summer of 1988, monthly average temperatures of June were unusually higher than July and August average temperatures. Among all six locations shown on *Figures 4A-4C*, ET_o for June ranged between 0.17 in/day at location (C) in 1993 and 0.30 in/day at location (D) in 1988. ET_o in July ranged between 0.22 in/day in 1982 at location (D) and 0.32 in/day in 1998 at location (E). For August, ET_o range was 0.16 in/day in 1985 at location (D) and 0.30 in/day in 1983 at location (B). Location (D) in August had lower ET_o trend than any other location, which could be related to cooler temperatures in South Dakota, since it is the location furthest north. In this study, June (*Figure 4A*) depicts some of the droughts over the region, including the severe drought of 2002. The droughts of 1999-2000 showed more visible impact on August (*Figure 4C*) ET_o values. When the “average” of all years and growing seasons (June, July, and August) from 1981 to 2009 were considered, there is no evidence of increasing or decreasing trend in ET_o during the study period in the region. This could be due to the considerable fluctuation in the ET_o estimates as a result of droughts and cool summer temperatures that normalized the trends, or the number of study years may be insufficient to statistically detect significant trends in the data. However, there are



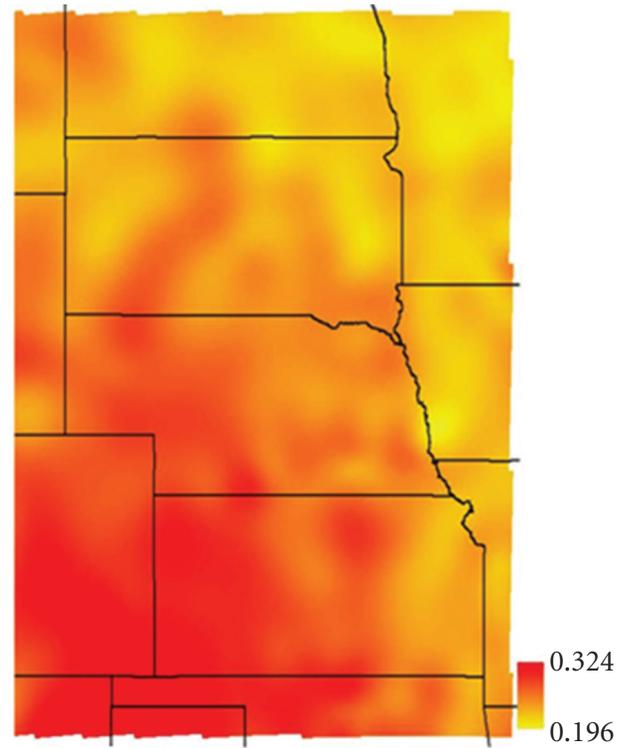
A: June 1982



B: July 1982



C: August 1982



D: June 1990

Figure 3. Monthly spatial distribution of grass-reference (potential) ETo (in/day) for June, July, and August in 1982, 1990, 2002, and 2008. Figure 3A shows the location of the five NEBFLUX BREBS flux towers and the six sampled locations (continued on the next page) (Mutiibwa and Irmak, 2013).

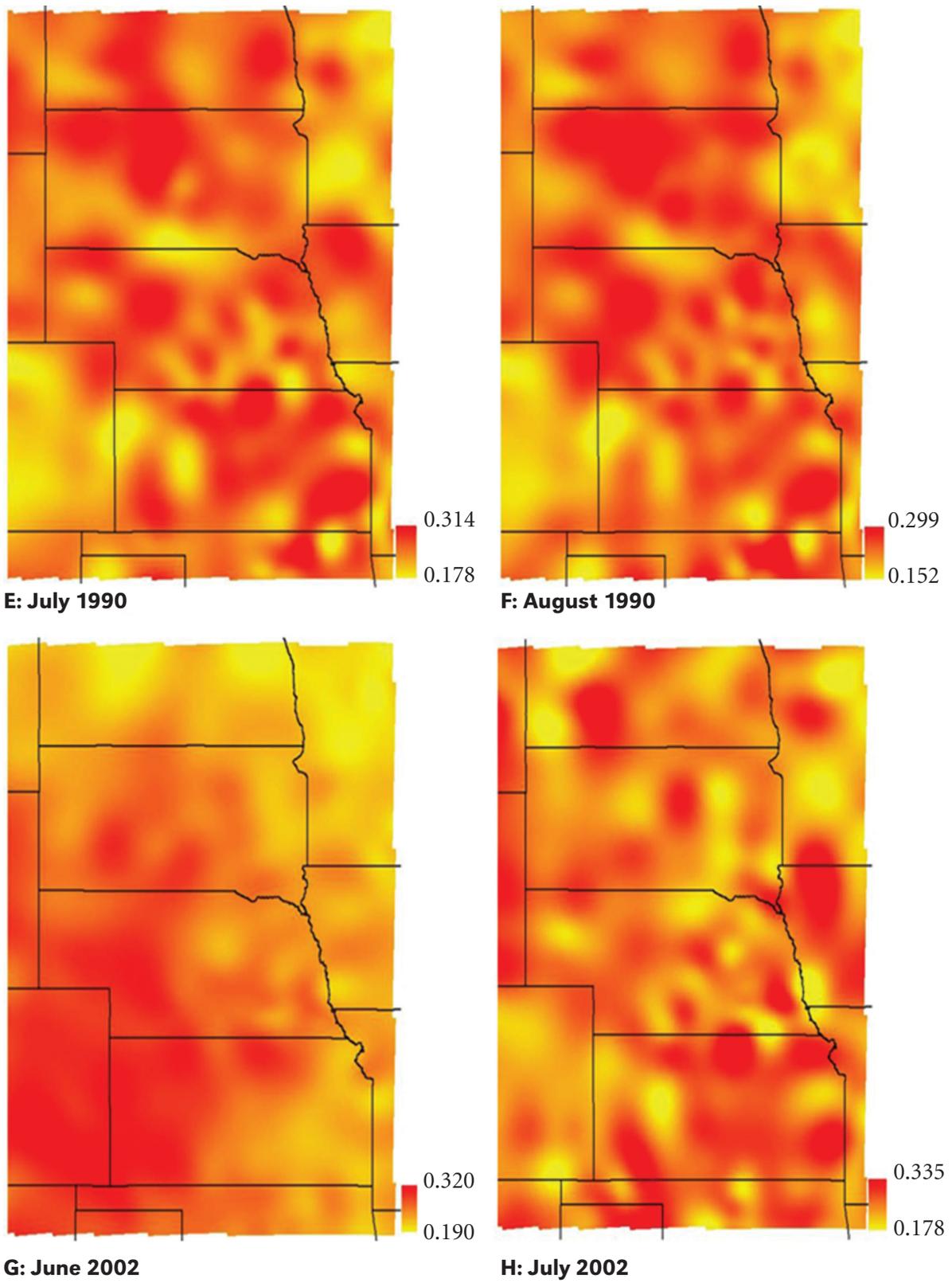
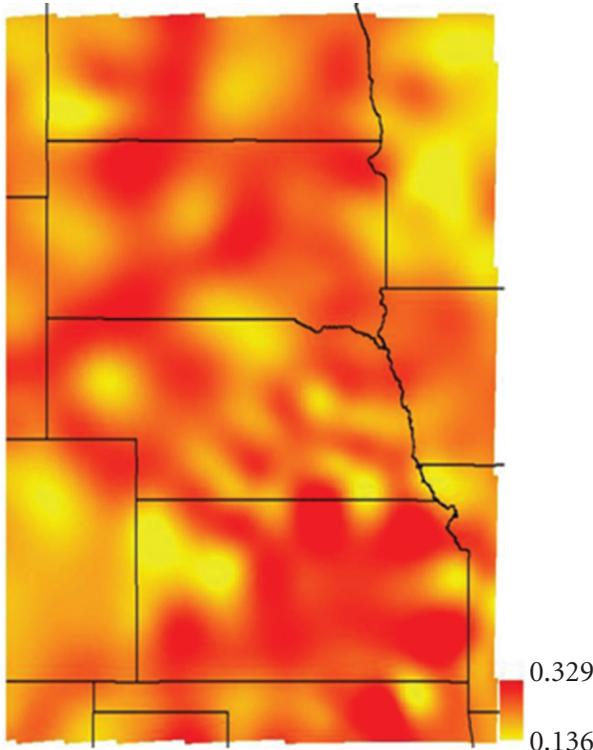
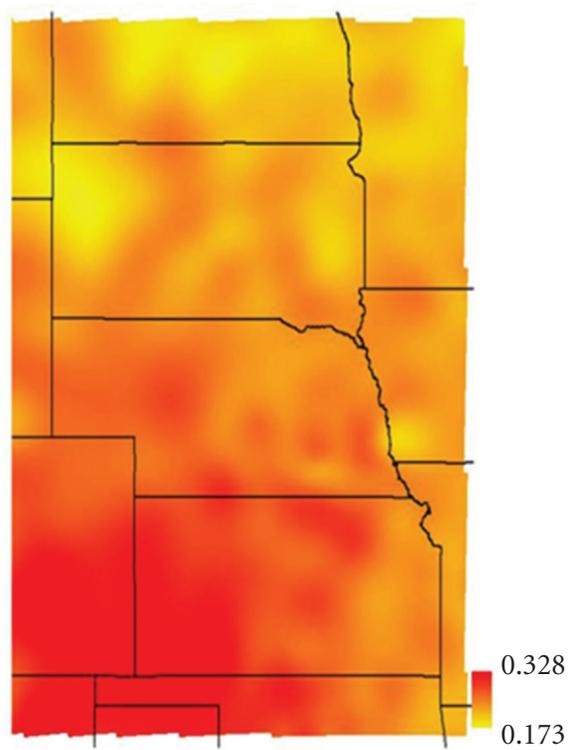


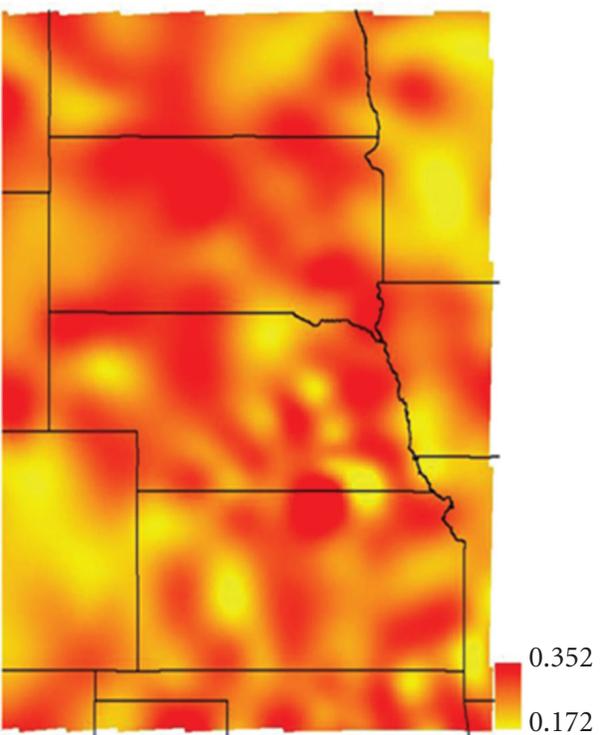
Figure 3. (Continued).



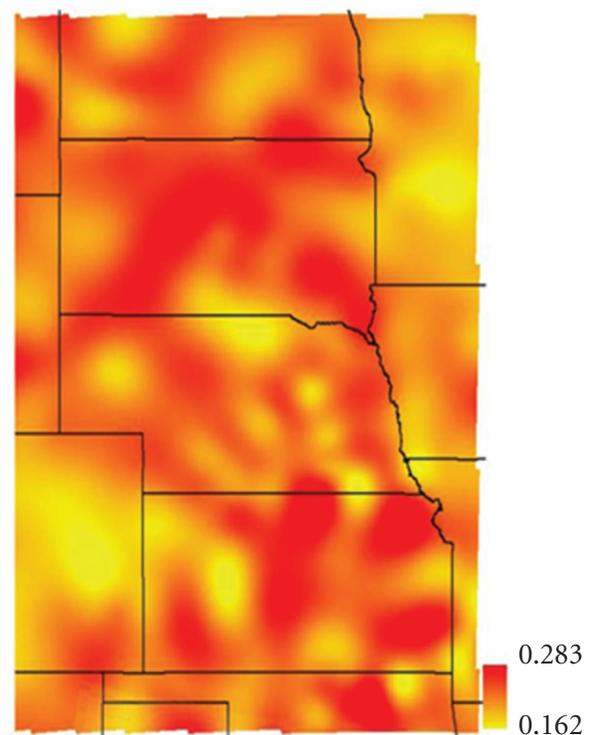
I: August 2002



J: June 2008



K: July 2008



L: August 2008

Figure 3. (Continued).

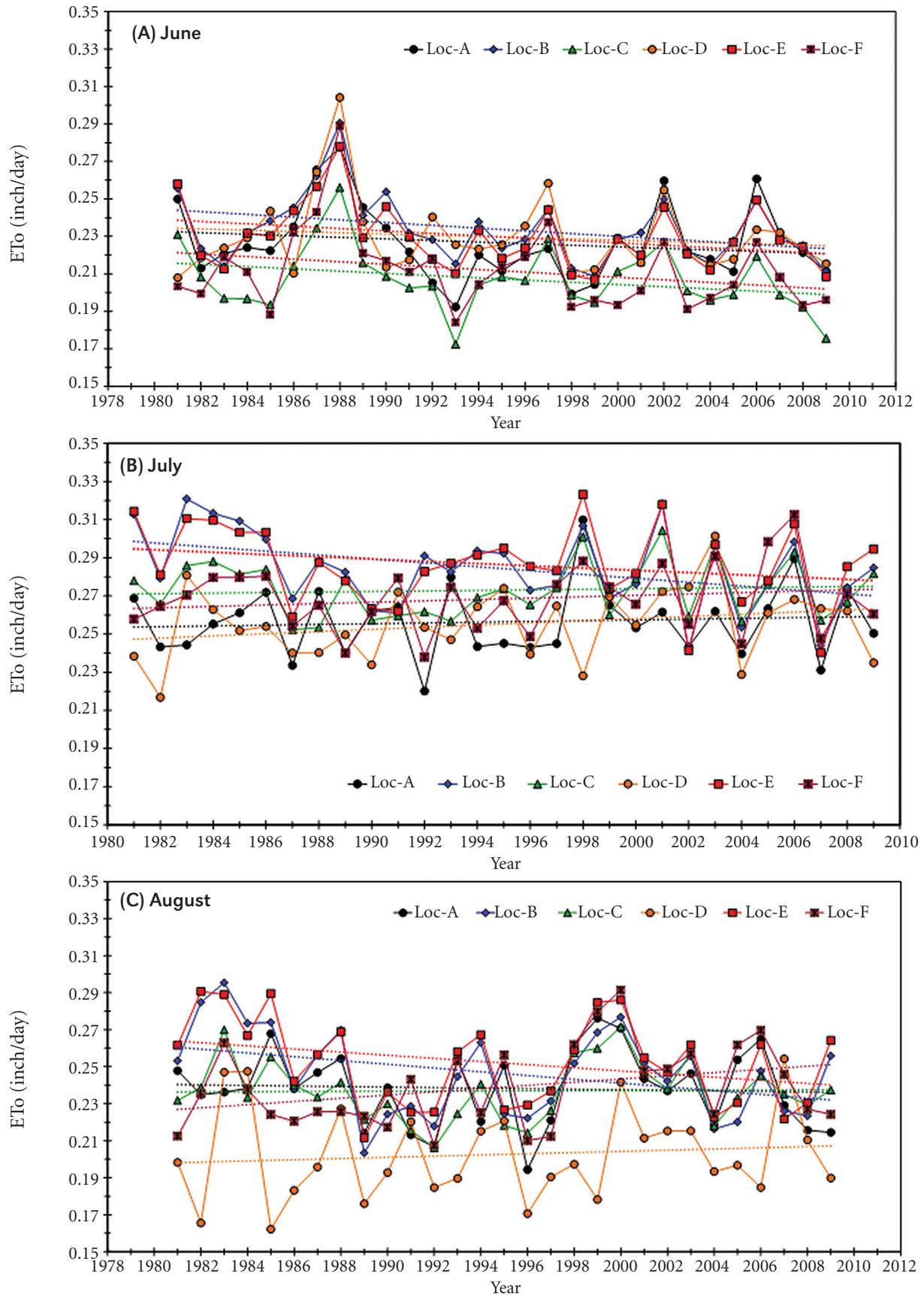


Figure 4. Time series of monthly average daily ETo from 1981 to 2009 at the six sampled locations (A: west central Nebraska; B: south central Nebraska; C: northeast Nebraska; D: central South Dakota; E: west central Kansas; and F: southwest Iowa) in the U.S. High Plains: (a) June, (b) July, and (c) August. The dashed regression lines represent the trend in ETo during the same period.

numerous periods where ETo has increased considerably such as the period from 1986 to 1988 for June, several periods between 1998 and 2006 for July, and from 1997 to 2000 for August. Also, there were several periods when substantial decreases in ETo were observed for all three months.

Spatial Growing Season Actual ET (ETc)

Trends and maps of spatial distribution of seasonal ETc in the High Plains region from 1982 to 2008 are presented in *Figure 5* for the same years as those ETo maps that were presented in *Figure 3*. The maps in *Figure 5* show that growing season ETc increases significantly from the central to eastern part of the region. The High Plains region rainfall distribution decreases from east to west. Therefore, there is more rainfed agriculture in the east than in the central and western parts of the High Plains where most of the irrigation is practiced. Due to the precipitation gradient, the natural vegetation, in most cases, is thicker and more vigorous in the east than in the west. In the High Plains region, in general, the growing season (June, July, and August) total ETc ranged from about 17 inches to approximately 31 inches per season. For the most part, eastern Colorado had the lowest growing season ETc estimates for all the study years. In *Figure 3*, the ETo maps for July and August also showed that eastern Colorado had the lowest ETo. Mutibwa and Irmak (2013) observed that eastern Colorado was also considerably cooler relative to other parts of the region studied. This was, in part, attributed to, first, the high elevation effect on temperatures in the region; the elevation of weather stations in the region were between 5,250 ft and 8,530 ft. Secondly, because of the region's location being on the foothills of the Rocky Mountains, it is subjected to periodic and severe turbulent mixings of regional air conditions from the effects of strong westerly winds over the mountain barrier. The winds are associated with a strong cold frontal passage downslope off of the mountains, thus the summer temperatures are generally cooler on the eastern slopes than other locations studied. Given that the ETo estimation procedure used in this study was temperature-based, lower temperatures results in lower ETo estimates, thus lower ETc for eastern Colorado.

The trends in the growing season ETc in the region were examined using the same six sampled locations presented in *Figure 3* (**A: west central Nebraska; B: south central Nebraska; C: northeast Nebraska; D: central South Dakota; E: west central Kansas; and F: southwest Iowa**) that were used in the discussion of ETo. Trends in the growing season ETc at the six locations were plotted on two graphs and presented in *Figures 6A* and *6B*. The

trend lines are shown on the figures as dashed regression lines. *Figure 6A* shows a general increasing trend in growing season ETc trends at all locations except west central Nebraska where ETc had a decreasing trend. Although overall trends are increasing, the slopes at Loc-D (0.051), Loc-F (0.075), and Loc-C (0.056) were not statistically significant ($p > 0.05$). However, the increasing slope at Loc-B (0.090) was significant ($p < 0.05$). *Figure 6B* shows the growing season ETc with almost no noticeable trends; the slopes at Loc-E and Loc-A were 0.019 and -0.020, respectively, both of which were insignificant. There is high fluctuation in the results due to the several droughts (1985, 1987-1989, 1999-2000, and 2002) that impacted the region in the study years, which makes statistical testing of significant trends complicated. Nevertheless, the results clearly indicate an increasing trend in ETc fluxes during the study period. By averaging slopes of the six pixels, there is an approximate increasing trend of seasonal ETc of about 0.045 inch per year during the study years. Thus, the total increase in actual crop evapotranspiration (for the June, July, and August) in the region from 1982 to 2008 is about 1.22 inches. Since no increasing trends were evident in ETo (*Figure 4*), the probable explanation for the increase in ETc trends is due to increase in irrigation practices and agronomic vegetation coverage across the High Plains region. The increase in irrigation practices, especially over the past three decades has sustained a steady increase in well-watered vegetation surface in the region that potentially increased transpirative losses and atmospheric water vapor. Thus, the observed increasing trend in ETc flux over the High Plains may not be due to increased atmospheric evaporative demand (ETo). Rather, the probable reason for the increase in ETc fluxes is increased irrigated area as rainfed croplands and/or natural grasslands are converted into irrigated croplands.

While climate change has been demonstrated through many analyses for global scales, there is lack of information and data at local and specific level regarding the magnitude and trends of change in precipitation and temperature as well as evaporative losses (ETo and ETc). Such information and data are essential for implementing effective measures to help the agro-ecosystem communities adapt and manage potential impacts of change. The climate change, in most cases, exhibits spatial and temporal dimensions. While this study indicated that the "regional average" trends did not change for ETo over the study years and increased for ETc, the study also demonstrated a significant spatial and temporal variability of impact of climatic change on ETo and ETc, illustrating considerable uncertainties/variability in the magnitudes and trends in both ETo and ETc. As seen on maps presented in *Figure 3* for ETo and *Figure 5* for ETc, there were locations where ETo actually had increas-

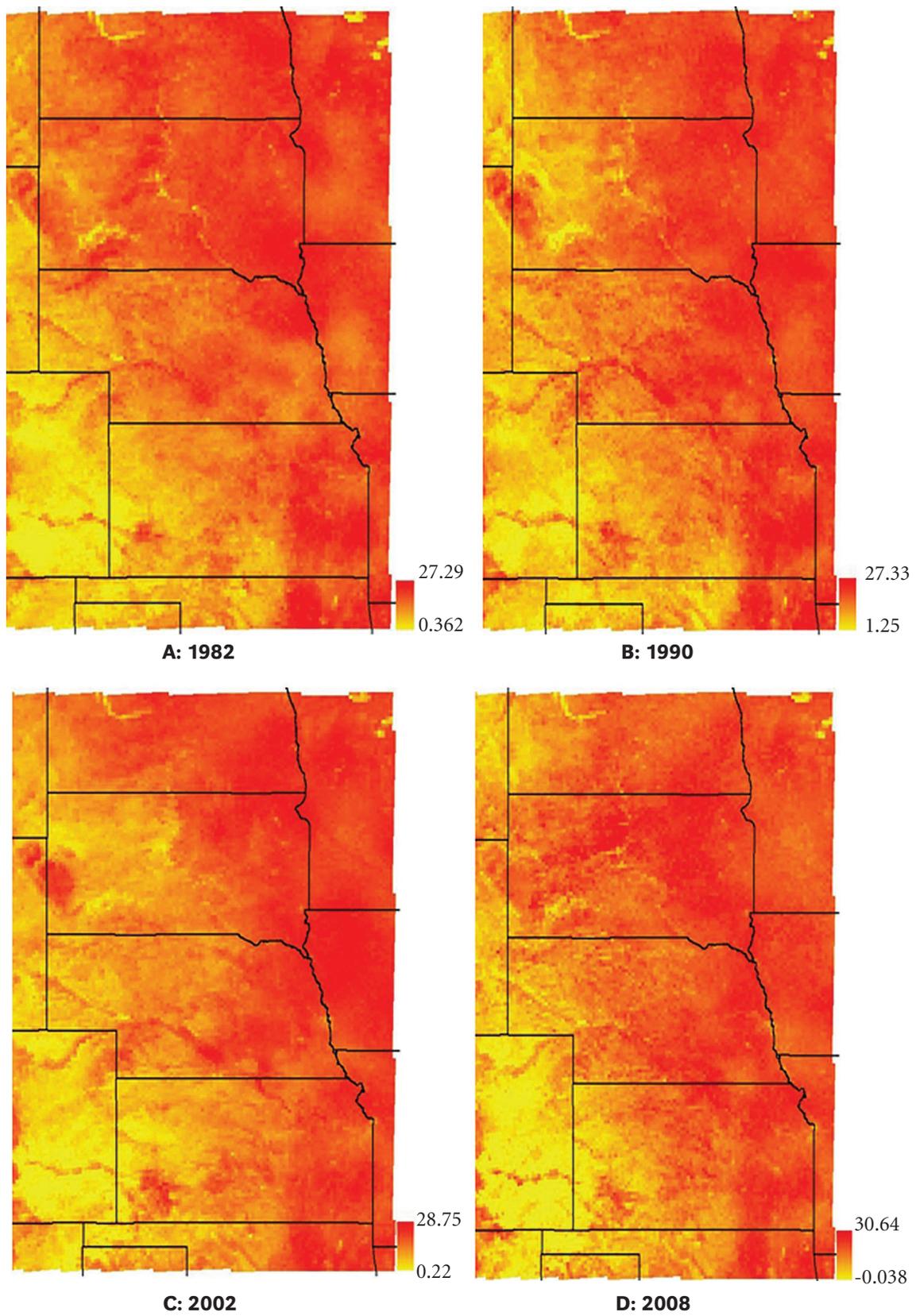


Figure 5. Spatial distribution of growing season (June, July, and August) total ETC (inches) in the High Plains for 1982 (A), 1990 (B), 2002 (C), and 2008 (D).

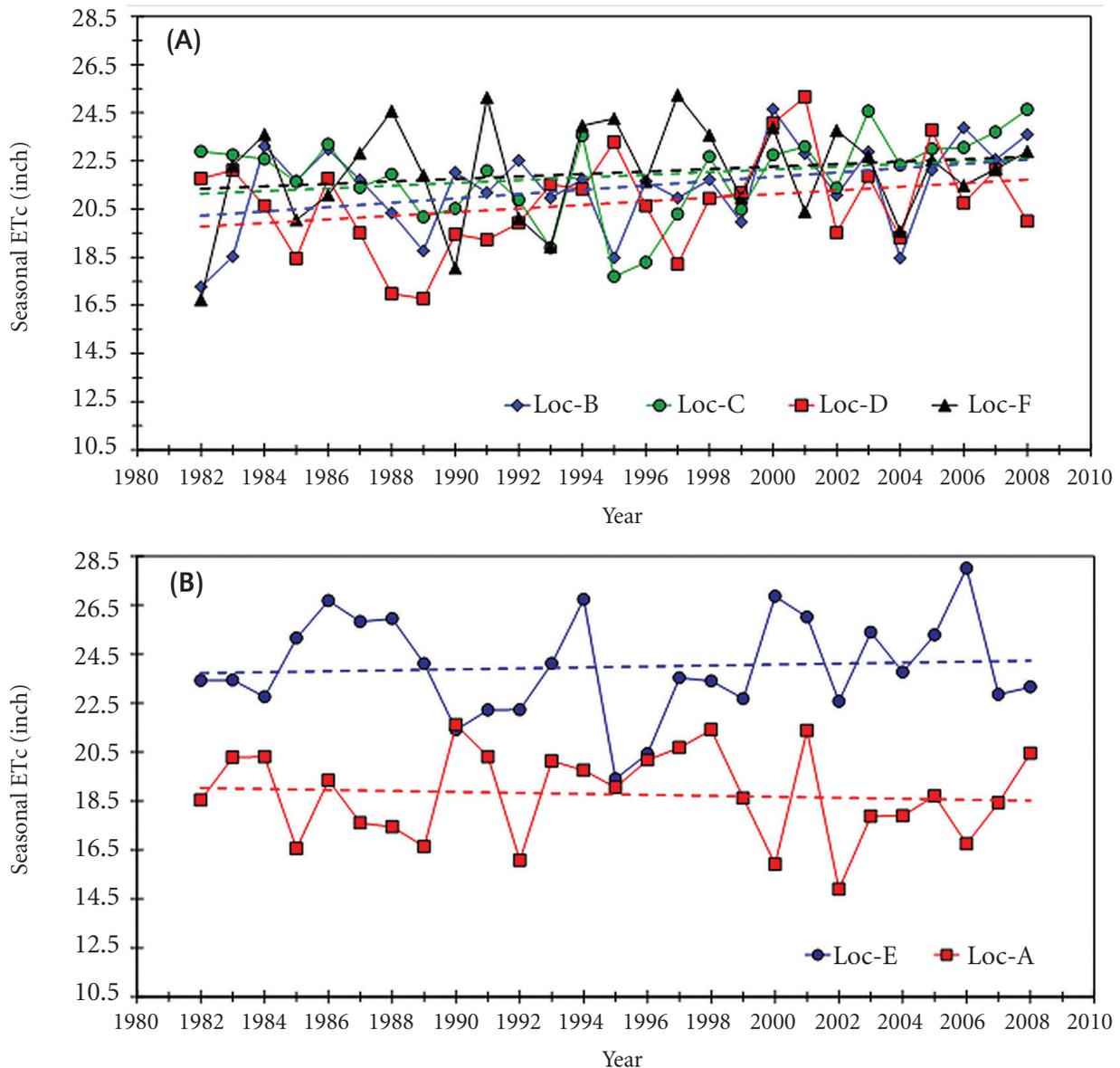


Figure 6. (A) Growing season ETc during the study period at five sample locations (A: west central Nebraska; B: south central Nebraska; C: northeast Nebraska; D: central South Dakota; E: west central Kansas) with discernible increasing trends. The dashed regression lines represent the trend in ETc during the study period (1981-2008); (B) Growing season ETc evolution during the study period at two sample locations (A: west central Nebraska; E: west central Kansas) with no discernible trends in the High Plains. The dotted lines represent the trend line in ETc during the study period (1981-2008).

ing trends [location C (northeast Nebraska), location D (central south Dakota), and location F (southwest Iowa)] and also there were locations that had decreasing ETc trends [location A (west central Nebraska), location B (south central Nebraska), and location E (west central Kansas)]. Also, there was no continuity in the trends and there were substantial inter-annual fluctuations (increase and decreases) in ETc for the same location over time. For example, in location E (west central Kansas), while seasonal ETc had a steady increasing trend overall (Figure 6B), it declined substantially from 26.7 inches in 1986 to 21.6 inches in 1990. While sea-

sonal ETc had a steady increase from 1990 to 1994 for the same location, it sharply declined by 7 inches, from 26.7 inches in 1994 to 19.4 inches in 1995. Similar increasing and decreasing trends (inter-annual variability) were observed in ETc [locations B, C, D, E, and F had increasing trend in ETc and location A (west central Nebraska) had an overall decreasing trend], emphasizing the importance of analyzing the potential impact(s) of climate change on evaporative losses, water resources, agro-ecosystem productivity, etc., for specific local conditions, because overall (regional or global) trends in change in climate variables may not be directly appli-

cable to local conditions. This impact of climate change on agro-ecosystem is not only driven by change in climatic variables, but also their interactions with the local soil, crop, irrigation, and other management practices, which exhibit substantial variation from one location to another.

It should be noted that quantification of regional changes in any climate or environmental variable, including ETo and ETc, is an extremely difficult task and requires making some assumptions. The primary assumption of this study was that the land use/land cover of the High Plains region was 90 percent cropland and this surface cover did not change significantly during the study period. However, this may not be the exact case because land use/land cover maps are not 100 percent accurate. To be able to truly quantify the changes in ETc for a specific vegetation surface, long-term measurements of actual evapotranspiration is essential. The University of Nebraska–Lincoln, Institute of Agriculture and Natural Resources has such long-term measurements of ETc and other surface energy components, as well as most of the climatic variables measurement network (Nebraska Water and Energy Flux Measurement, Modeling, and Research Network; *NEBFLUX*; Irmak, 2010) already established, with the oldest tower running on an hourly basis throughout the calendar year since August 2004.

Concluding Points:

- On all-location average basis, there is an approximate increasing trend of seasonal ETc of about 0.045 inch per year during the study years. Thus, the total increase in actual crop evapotranspiration (for the June, July, and August) in the region from 1982 to 2008 is about 1.22 inches, which is a substantial amount, especially in water-limited areas, when seasonal net irrigation water requirement of major crops (maize, soybean, sorghum, sugarbeet, wheat, edible beans, etc.) is considered.

- Increasing ETo trends found at northeast Nebraska, central south Dakota, and southwest Iowa.
- Decreasing ETo trends found in west central Nebraska, south central Nebraska and central Kansas. There was no annual continuity in the trends and there were substantial inter-annual fluctuations (increase and decreases) in ETo over time.
- Impact of climate change on agro-ecosystem is not only driven by change in climatic variables, but also their interactions with the local soil, crop, irrigation and other management practices, which exhibit substantial variation from one location to another, emphasizing the need to study climate change impact(s) on specific location rather than on a global, continental, or regional scale, when determining the climate change impact on agriculture and natural resources.

Resources

Irmak, S. 2010. Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (*NEBFLUX*). *Transaction of the ASABE* 53:1097-1115.

Global Inventory Modeling and Mapping Studies (GIMMS): http://gcmd.nasa.gov/records/GCMD_GLCF_GIMMS.html.

Mutiibwa, D., and S. Irmak. 2013. AVHRR-NDVI-based crop coefficients for analyzing long-term trends in evapotranspiration in relation to changing climate in the USA High Plains. *Water Resources Research* 49(1): 231-244. doi:10.1029/2012WR012591.

The United States Historical Climatology Network (USHCN): <http://www.ncdc.noaa.gov>.

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