MAPPING SPATIALLY INTERPOLATED PRECIPITATION, REFERENCE EVAPOTRANSPIRATION, ACTUAL CROP EVAPOTRANSPIRATION, AND NET IRRIGATION REQUIREMENTS IN NEBRASKA: PART I. PRECIPITATION AND REFERENCE EVAPOTRANSPIRATION

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Mapping Spatially Interpolated Precipitation, Reference Evapotranspiration, Actual Crop Evapotranspiration, and Net Irrigation Requirements in Nebraska: Part I. Precipitation and Reference Evapotranspiration

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Abstract. *Precipitation and reference evapotranspiration are two important variables in hydrologic analyses, agricultural crop production, determining actual crop evapotranspiration and irrigation water requirements, and irrigation management. Both variables vary in space and time, and the weather networks that measure or quantify and report both variables are too sparse for practical applications by water resources planners, managers, and irrigators. Long-term (1986-2009) average annual (January to December), seasonal (growing season, May to September), and monthly (May, June, July, August, and September) precipitation and Penman-Monteith-estimated alfalfa-reference evapotranspiration (ET_{ref}) were spatially interpolated and mapped for all 93 counties in Nebraska using the spline interpolation technique in ArcGIS. Precipitation gradually increased from the western part and southwest corner (zone 1) to the eastern part (zone 4) of the state. Long-term average county annual precipitation ranged from 325 to 923 mm, with a statewide mean of 581 mm. The long-term average seasonal precipitation showed a similar trend as the annual precipitation and ranged from 215 to 601 mm, with a statewide average of 380 mm. Based on the annual average precipitation data, there was an approximately 30 mm decrease in precipitation for every 40 km from east to west. Seasonal and annual precipitation were inversely proportional to elevation with high coefficients of determination (R^2 = 0.94 for annual and R^2 = 0.88 for seasonal). Annual precipitation decreased between 18 and 131 mm for every 100 m increase in elevation. Seasonal precipitation decreased between 11 and 72 mm for every 100 m increase in elevation. The long-term statewide average annual ET_{ref} was 1,400 mm, with significant differences across the state: 1,662 mm (zone 1), 1,542 mm (zone 2), 1,350 mm (zone 3), and 1,285 mm (zone 4). The statewide long-term average seasonal ET_{ref} was 883 mm, with a maximum of 1,087 mm and minimum of 684 mm. The maximum monthly ET_{ref} of 268 mm was observed in July, and the minimum value of 12 mm was observed in December. The annual ET_{ref} increased by 47 mm for every 100 m increase in elevation, and the seasonal ET_{ref} increased by 29 mm for every 100 m increase in elevation. Spatially interpolated maps of precipitation and ET_{ref} can provide important background information and physical interpretation of precipitation and ET_{ref} for climate change studies in the region, which can lead to the ability to take proactive steps to balance water supply and demand through various available methods, such as changing cropping patterns to implement cropping systems with lower water demand, reduced tillage practices to minimize unbeneficial water use (soil evaporation), implementing newer drought-tolerant crop hybrids and cultivars, implementing deficit irrigation strategies, and initiating and deploying more aggressive and effective irrigation management programs.*

Keywords. *Precipitation, Reference evapotranspiration, Spatial interpolation, Spline.*

Population increase and the decrease in availability of freshwater supplies for agricultural production have created an essential need for effective management of limited water resources while increasing agricultural productivity. Reducing unbeneficial water use in agricultural fields through precise water resource planning, management, and allocation will aid in achieving this goal. In dealing with irrigation management, water resource planners and managers often face the following questions: how much water is needed for irrigation? What crop types would be most feasible and economical to produce in a given area to sustain agricultural productivity by having a balance between the availability and use of water resources? Addressing these and similar questions requires quantification, evaluation, and understanding of precipitation and crop water demand, which drive sustainable assessments and development of water resources. Quantification of crop water use on large scales plays an important role in accomplishing the aforementioned tasks. Among several alternatives, crop water demand (actual crop evapotranspiration) for a specific crop can be estimated by multiplying reference evapotranspiration (ET_{ref}) with appropriate

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crop coefficients. Both precipitation and ET_{ref} vary in space and time, causing variability in irrigation requirements. Therefore, it is important to quantify and evaluate the spatial distribution of precipitation and $ET_{ref,}$ and the consequent change in irrigation water requirements for various crops. The main objective of proper quantification of irrigation water requirements is to provide plants with sufficient water at the right time to prevent the stress that may cause yield reduction and reduced yield quality. The required timing and amount of irrigation is primarily governed by the prevailing weather conditions, including precipitation, as well as type of crop, stage of growth, soil moisture condition, soil type, management practices, and other factors. Thus, studying the spatial interpretation of climate variables to aid in better assessment and management of water resources is becoming increasingly important around the world as well as in heavily irrigated areas of the U.S., including Nebraska.

Precipitation and ET_{ref} usually display very complex spatial and temporal patterns. When large-scale application of precipitation and ET_{ref} data in agricultural irrigation and crop productivity is concerned, the values of these two critical climate elements cannot be measured at all points across the landscape. In most cases, weather stations that record precipitation and all the primary weather variables required to estimate ET_{ref} (solar or net radiation, maximum and minimum air temperature, maximum and minimum relative humidity, and wind speed) are not nearly dense enough to be able to use the precipitation and ET_{ref} information for locations that are far from the weather stations. For example, as of August 2011, the High Plains Regional Climate Center (HPRCC) operated approximately 65 automated weather stations, scattered throughout Nebraska, that record precipitation and the necessary variables for ET_{ref} calculation (fig. 1). However, with 3.6 million ha of irrigated land, the density of the HPRCC weather stations in Nebraska is approximately one weather station per 55,300 ha, which is not enough to accurately represent the precipitation and ET_{ref} that occur in locations that are far from weather stations. Thus, spatial interpolation techniques must be used to estimate the values in areas where measurements are not available.

Spatial interpolation estimates an unknown value of a variable (e.g., precipitation and ET_{ref}) at some point where measurements are not available by using known measurements obtained at a set of sample locations (weather stations) (Kyriakidis and Goodchild, 2006). With the advances in geographic information systems (GIS), numerous spatial interpolation methods have been applied to create continuous surfaces of climate variables at various spatial and temporal scales. Many of the interpolation techniques are referred as deterministic and geostatistical interpolation methods. Deterministic interpolation methods, such as inverse distance weighting (IDW) (Willmott and Matsuura, 1995; Dodson and Marks, 1997) and spline (Hulme et al., 1995), estimate the value at a point from values recorded at

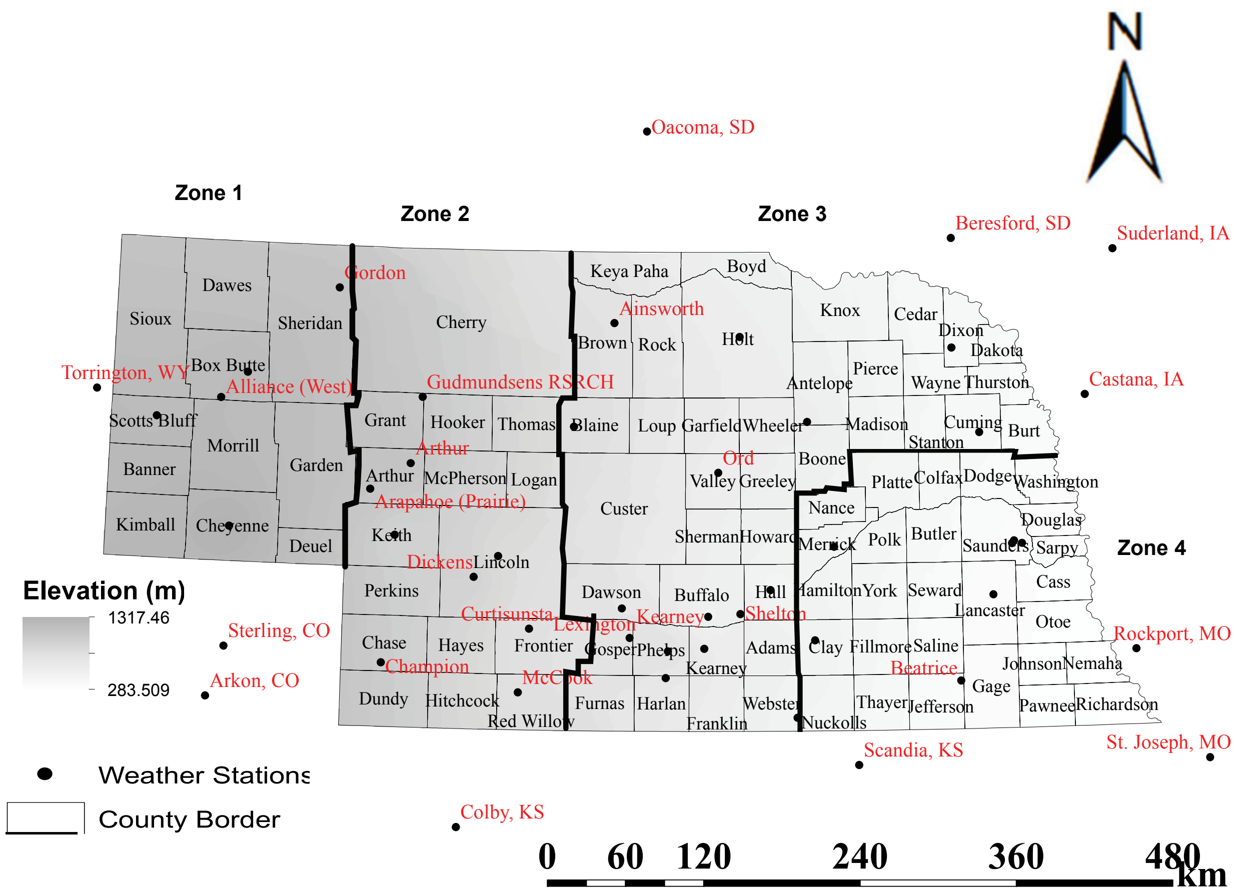

Figure 1. Point locations of the High Plains Regional Climate Center (HPRCC) automated weather stations used to run the interpolation technique (i.e., radial basis function, RBF) and the four climatic zones. Gray scale indicates elevation above mean sea level.

neighboring points (Kurtzman and Kadmon, 1999). Geostatistical interpolation methods, such as kriging (Holdaway, 1996; Hudson and Wackernagel, 1994; Hammond and Yarie, 1996), are based on statistical models that include autocorrelation. Many studies also account for topography, cloudiness, longitude and latitude, general atmospheric circulation patterns, and urbanization to improve the accuracy of interpolation of climate surfaces (grids) (Li et al., 2006; Courault and Monestiez, 1999; Jones et al., 1999; Creech and McNab, 2002; Goodale et al., 1998; Daly et al., 1994). For example, Goovaerts (2000) showed significant improvement in predicting continuous surfaces of mean monthly and mean annual rainfall when elevation was incorporated into the analyses. A similar observation was made by Hevesi et al. (1992) after comparing multivariate geostatistics results for rainfall interpolation (which included elevation as covariate) with six other interpolation techniques. Li et al. (2006) found that variables such as latitude, longitude, elevation, and distance from sea were important predictors of seasonal temperature in the Zhejiang province of China. Vicente-Serrano and Cuadrat (2003) compared diverse interpolation methods in Spain. The best results were obtained with regression-based modeling for both temperature and rainfall. Ninyerola et al. (2000) used multiple regressions with latitude, solar radiation, and cloudiness factor as independent variables for climatological modeling of temperature. Collins and Bolstad (1996) compared eight interpolation techniques for temperature estimation across two regions (eastern and western North America), maximum and minimum air temperature, and three temporal scales (ten-year mean, seasonal mean, and daily). Irmak et al. (2010) used the inverse distance weighted, spline, and kriging techniques to study the spatial variability of climate variables (maximum and minimum air temperature, and seasonal and annual precipitation) in Nebraska.

Mardikis et al. (2005) evaluated four interpolation methods concerning their suitability for spatial prediction of long-term monthly mean daily ET_{ref} in Greece. They studied ordinary kriging (OK) and inverse distance squared (IDS) and the incorporation of elevation data into the interpolation processes. The modified methods were named residual kriging (RK) and gradient-plus-inverse distance squared (GIDS) and showed that the incorporation of elevation significantly improved the performance of all interpolation methods. They concluded that all methods performed satisfactorily and while no method exhibited consistently superior performance in all months, in general, the GIDS and RK methods were superior to the other methods. Martinez-Cob (1996) also used three interpolation methods (ordinary kriging, co-kriging, and modified residual kriging) to interpolate long-term mean total annual ET_{ref} and long-term mean total annual precipitation in a mountainous region in Spain. They found that estimates at validation stations were in good agreement with observed values for all three interpolation methods, although the modified residual kriging estimates of long-term mean total annual precipitation (APRE) were slightly worse than the estimates obtained with the other two methods. At grid points, estimates were improved by co-kriging by about 11.5% and 8.4% compared with ordinary kriging and modified residual kriging, respectively. Likewise, co-kriging was superior for interpolation of APRE in terms of errors obtained at validation stations. At grid points, co-kriging reduced estimation uncertainty by 18.7% and 24.3% compared with ordinary kriging and modified residual kriging, respectively, whereas modified residual kriging, in general, did not improve ordinary kriging results. Computed estimation error variance values indicated that modified residual kriging would reduce estimation uncertainty in areas where very few weather stations are available for interpolation.

Considering the extensive water withdrawal for irrigation and the significant agricultural production activities in Nebraska, and given the limited number of weather stations that provide precipitation and ET_{ref} data to farmers, water management agencies, crop consultants, and irrigation districts, spatial interpolation of precipitation and ET_{ref} and maps showing magnitudes of these two critical variables would be very useful and contribute to improving the assessment, planning, allocating, and managing of water resources for agricultural production, ecological functions, and hydrologic water balance analyses. The main objective of this study was to quantify and map monthly (May, June, July, August, and September), seasonal (May to September), and annual precipitation and ET_{ref} for all 93 counties in Nebraska using the spline interpolation technique. The performances of the spline and kriging methods were compared for interpolating monthly, seasonal, and annual precipitation and ET_{ref}. Based on the results of the comparisons, a decision was made about which interpolation method to use in this study. Part II of this study (Sharma and Irmak, 2012) uses the spatially interpolated precipitation and ET_{ref} data to estimate, spatially interpolate, and map long-term average actual crop evapotranspiration (ET_a) and net irrigation requirements for irrigated maize and soybean across all 93 Nebraska counties. Thus, Part I (this article) prepares basic ground work and analyses to estimate ET_a to quantify spatially interpolated net irrigation requirements to improve irrigation management and water resource balance analyses.

Materials and Methods

Study Area

The study was conducted for the entire state of Nebraska. Historical weather data on a daily time step were obtained from the automated HPRCC weather stations throughout the state and in surrounding states, and the data were processed to calculate the mean monthly values of meteorological variables. The climate data were imported to ArcGIS software (ver. 10, ESRI, Redlands, Cal.) for the exploratory spatial analysis. The spline method was used to estimate the spatial distribution of precipitation and reference evapotranspiration across the state. Nebraska has 93 counties located between latitude 40° to 43° N and longitude 95° 19′ to 104° 3′ W, with a population of 1,796,620 and a population density of about nine people per km^2. The total area of the state is approximately 200,356 km^2, making it the 16th largest state in U.S., with the state average

elevation of 793 m above mean sea level. The highest point in the state is Panorama Point (1,653 m above mean sea level), and the lowest point is 256 m above mean sea level at the Missouri River in southeastern Richardson County. The major river basins in the state are the Missouri, Niobrara, Platte, and Republican rivers. The state comprises Universal Transverse Mercator (UTM) zones 13, 14, and 15. In this study, for the GIS analyses, UTM zone 14 was used because more than 80% of the state area is within this zone. Because of its latitude and interior continental location, Nebraska has wide climatic seasonal variation, with warm summers (Strahler and Strahler, 1984) and extremely cold winters. The continental climate of Nebraska is mainly divided into two regions: the eastern and central parts of the state are humid/subhumid continental climate, and the western third has a semiarid/arid climate. The state experiences a wide range of seasonal variation in temperature and precipitation. The weather in the region is influenced by cold, dry continental air masses from Canada during winter and warm, moist air from the Gulf of Mexico during summer. The highest wind speed usually occurs from January to late May and early June, with daily average wind speed showing significant fluctuation, ranging from 2 m s^{-1} to over 8 m s^{-1}. The lowest wind speeds usually occur in the summer months. Summer months are usually hot and humid, averaging 24°C in July, but hot and dry winds often drive summer temperatures above 32°C (Irmak, 2010). Nebraska's ground and surface water resources are regulated by the Nebraska Department of Natural Resources and 23 Natural Resources Districts. Nebraska is one of the leading farming and ranching states in the U.S. There are 138 soil series and many soil types and phases, which further differentiate the soil series in the state. Of these 138 soil series, 17 soil series constitute about 49% of the land area (NRCS-USDA web soil survey, http://websoil survey. nrcs.usda.gov/app/HomePage.htm).

Nebraska soils have been grouped by their similarities and differences related to the soil's position on the landscape. These groupings are called "associations." Each soil in the state belongs to one or more of the 44 soil associations. The dominant soils in the study area are broadly classified into four soil types: Valentine sand, Holdrege silt loam, Nora fine silt loam, and Sharpsburg silt loam, with field capacities of 0.09 to 0.10 m^3 m^{-3}, 0.29 to 0.31 m^3 m^{-3}, 0.25 to 0.26 m^3 m^{-3}, and 0.33 to 0.34 m^3 m^{-3}, respectively, and permanent wilting points in the range of 0.04 to 0.05 m^3 m^{-3}, 0.17 to 0.18 m^3 m^{-3}, 0.13 to 0.15 m^3 m^{-3}, and 0.27 to 0.29 m^3 m^{-3}, respectively. Regional differences in environmental characteristics with the combined effects of climatic conditions, soil, and topographic characteristic divide Nebraska into three broad environmental regions: the east is characterized by relatively high precipitation with superior soils rich in organic matter and is generally very favorable for crop production and relatively high agronomic productivity; the central part is generally characterized by flat topography and moderate precipitation supplemented with irrigation (Searcy and Longwell, 1964); and the western part has the least precipitation and soils with the lowest potential for agronomic productivity as compared with the central and eastern parts.

State Climatic Zones

To study climate associations, to quantify precipitation and ET_{ref}, and to analyze the association of water requirements (Sharma and Irmak, 2012) with precipitation, ET_{ref}, and the environmental heterogeneity across the state, it was necessary to discretize the study area into different regions (zones). The state is subdivided into four management zones, which are presented in figure 1. Regional differences in environmental characteristics, with the combined effects of climatic conditions, soil, and topographic characteristics, characterize these zones (table 1).

Environmental Variables

Daily climate data from 1986 to 2009 were obtained from 50 weather stations of the HPRCC automated weather data network (AWDN) (fig. 1). Fifty of the 65 weather stations had the long-term (1986-2009) climate data that were needed for this study. To increase the climatic data density and robustness of the analyses, some stations outside Nebraska, also part of the HPRCC-AWDN, were used to interpolate weather data across the boundaries of Nebraska counties. In the analysis, 38 AWDN stations in Nebraska, two in Colorado, three in Kansas, three in South Dakota, two in Missouri, and two in Iowa were used. Point coverage of the ground-based meteorological stations was created in ArcGIS. The locations (longitude and latitude) of the weather stations and the climate data were imported into Geodatabase. The climate data were then explored using ArcGIS Geospatial analyst preceding interpolation. Precipitation data were derived from daily weather observations for the period 1986 to 2009, originating from 50 weather stations. Analyses were conducted for the typical growing season (1 May to 30 September). The growing season precipitation was calculated and averaged across the observation period.

Daily climate data from the automated weather stations were used to calculate daily ET_{ref}. Mean monthly maximum and minimum air temperatures were calculated from ob-

Table 1. Climatic regions (zones) and counties included in each zone.

Zone	Region	Counties
1	Panhandle	Banner ,Box Butte, Cheyenne, Deuel, Garden, Kimball, Morrill, Scottsbluff, Sheridan, Sioux, Dawes
2	West-central	Arthur, Cherry, Grant, Hooker, Logan, McPherson, Thomas, Chase, Dundy, Frontier, Hayes, Hitchcock, Keith, Lincoln, Perkins, Red Willow.
3	East-central	Antelope, Boone, Burt, Boyd, Cedar, Cuming, Dakota, Dixon, Knox, Madison, Pierce, Stanton, Thurston, Wayne, Buffalo, Custer, Dawson, Greeley, Hall, Howard, Sherman, Valley, Adams, Franklin, Furnas, Gosper, Harlan, Kearney, Phelps, Webster, Keya Paha, Brown, Rock, Holt, Blaine, Loup, Wheeler, Garfield
4	Southeast	Butler, Colfax, Dodge, Douglas, Hamilton, Lancaster, Merrick, Nance, Platte, Polk, Sarpy, Saunders, Seward, Washington, York, Cass, Clay, Fillmore, Gage, Jefferson, Johnson, Nemaha, Nuckolls, Pawnee, Richardson, Saline, Thayer, Otoe.

Table 2. Summary of climate parameters.

Parameters	Unit	Description
Growing season precipitation	mm	Long-term mean precipitation between the beginning and end of the growing season
Daily air temperature	°C	Daily average air temperature between the beginning and end of the growing season
Daily wind speed	m s^{-1}	Daily average wind speed between the beginning and end of the growing season
Daily solar radiation	MJ m^{-2} d^{-1}	Daily average solar radiation between the beginning and end of the growing season
Daily relative humidity	%	Daily average relative humidity between the beginning and end of the growing season

served daily series. Table 2 describes the environmental variables required for the calculation of net irrigation requirement and ET_{ref}.

Penman-Monteith Reference Evapotranspiration Equation

In the Great Plains, nearly 90% of precipitation returns to the atmosphere as ET_a (USGS, 2000). Thus, ET_a is an important driving force in the hydrological cycle of the region and is highly variable in space and time because of the variability in climate, land use, soil, and management practices. Direct measurement of ET_a is an expensive and difficult task, and other more practical approaches have been developed to estimate ET_a rates of various crops. For example, the two-step approach of adjusting ET_{ref} by a crop-specific coefficient (K_c) (i.e., $ET_a = K_c \times ET_{ref}$) is one of the simplified approaches that is practiced by irrigators, technicians, and water resource managers. The ET_{ref} was calculated on a daily time step using the Penman-Monteith (PM) (Monteith, 1965) equation with a fixed surface resistance of 45 s m^{-1} and fixed plant height (0.50 m) for a alfalfa-reference surface (Irmak et al., 2012; ASCE-EWRI, 2005). The concept of ET_{ref} has aerodynamic resistance and canopy resistance parameters standardized and integrated into the equation. Thus, the ET_{ref} equation and associated equations for calculating aerodynamic and bulk surface resistance are combined and condensed into a single equation that is applicable to both grass and alfalfa surfaces by changing standardized constants (Irmak et al., 2006, 2008; Irmak and Irmak, 2008; Irmak et al., 2012). The form of the PM equation (Irmak et al., 2012; ASCE-EWRI, 2005) used on a daily time step is:

$$\mathrm{ET_{ref}} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{C_n}{T+273} u_{2(e_s - e_a)}}{\Delta + \gamma\left(1 + C_d u_2\right)} \qquad (1)$$

where

ET_{ref} = alfalfa-reference evapotranspiration (mm d^{-1})

R_n = net radiation at the reference surface (MJ m^{-2} d^{-1})

G = soil heat flux density (MJ m^{-2} d^{-1}, assumed to be zero for daily time step)

T = mean daily air temperature at 2 m height (°C)

u_2 = mean daily wind speed at 2 m height (m s^{-1})

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

$e_s - e_a$ = vapor pressure deficit (kPa)

Δ = slope of the saturation vapor pressure curve (kPa $°C^{-1}$)

γ = psychrometric constant (kPa $°C^{-1}$)

C_n = numerator constant that changes with the reference crop (1,600 for alfalfa-reference)

C_d = denominator constant that changes with the reference crop (0.38 for alfalfa reference).

Interpolation Techniques

The predicted values of climate variables based on 24 years of historical data were computed using the spline and kriging interpolation methods. For comparison of the performance of both methods, the interpolation techniques were evaluated based on the root mean square difference (RMSD) and coefficient of determination (R^2) using number of observations ($N = 50$). The spline and kriging interpolation methods, in conjunction with cross-validation, were used and their performances were compared. For both techniques, interpolations with ten neighboring stations with a minimum of seven stations were tested. The spline method was used to estimate the spatial distribution of precipitation and ET_{ref} across Nebraska. The method is a deterministic interpolation method that fits a mathematical function through input data to create a smooth surface. It can generate accurate surfaces from only a few sampled points (Anderson, 2002). The spline functions allow users to decide between smooth curves or tight straight edges between measured points. In the interpolation, each station is omitted, in turn, from the estimation of the fitted surface, and the mean square error (MSE) is calculated. This is repeated for a range of values of a smoothing parameter, and the value that minimizes the MSE is used to provide the optimum smoothing. This process is referred to as minimizing the generalized cross-validation. In our analyses, a regularized spline was selected because it creates a smoother surface closely constrained with the sample data range. The following form of the spline function (Franke, 1982) was used:

$$S\left(x, y\right) = T\left(x, y\right) + \sum_{j=1}^{N} \lambda_j R\left(r_j\right) \qquad (2)$$

where T is the constant trend, r_j is distance from point (x, y) to the jth point, R is a weighted function of the distance between the interpolated point and the jth data point (j =1, 2, 3,..., N), and N is the number of known points. For the regularized spline, T and R are defined as:

$$T\left(x, y\right) = a_1 + a_2 x + a_3 y \qquad (3)$$

$$R\left(r\right) = \frac{1}{2\pi}\left\{\frac{r^2}{4}\left[\ln\left(\frac{2}{2\pi}\right) + c - 1\right] + \tau^2\left[K_o\left(\frac{r}{\tau}\right) + c + \ln\left(\frac{r}{2\pi}\right)\right]\right\} \qquad (4)$$

where τ is a weight parameter of the third derivatives of the surface in the curvature minimization expression, r is the distance between the point and the sample, K_o is a modified

Bessel function, and c is a constant (0.577215). Coefficients a_1, a_2, and a_3 in equation 3 are found by the solution of a system of linear equations. The weight parameter (τ) was optimized using ArcGIS, indicating the smoothness of the interpolant; the higher the weight, the smoother the output surface is (Mitas and Mitasova, 1988).

Zonal statistics were used to calculate the precipitation values for each county. The zonal statistics tool (Spatial Analyst tool of ArcGIS ver. 10) calculates statistics on the value of a raster (cell size: 1,000 m × 1,000 m) within the zone of another dataset. Each county statistic was calculated from the precipitation and evapotranspiration rasters using all of the Nebraska counties defined by name (string attribute field) of the county feature class based on the precipitation value from precipitation raster dataset. The zonal statistic tool summarizes the value of the precipitation raster within the county and reports the result as mean, maximum, minimum, and range values. Some studies have used zonal statistics for computing the average elevation, aspect, slope (topographic attributes), and normalized difference vegetation index (NDVI) (Bakhsh and Kanwar, 2004; Sharma et al., 2011), and others have used zonal analysis to calculate the crop yield for different grids (Kulkarni et al., 2008).

The same analyses were repeated using kriging to interpolate precipitation and ET_{ref}. Unlike spline interpolation, kriging is based on a statistical model that includes autocorrelation, i.e., the statistical relationship among the measured points. This is because geostatistical techniques (kriging) not only have the capability of producing prediction surfaces, but they also provide some measure of the accuracy of the prediction (Merino et al., 2001). It was not practical to use more than six or seven neighboring weather stations for interpolation because of the large distance between the ground-based automated weather stations. In kriging, the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. The kriging tool fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. It is a multi-step process and includes exploratory statistical analysis of the data, variogram modeling, creating the surface, and (optionally) exploring a variance surface. Kriging is most appropriate when it is known that there is a spatially correlated distance or directional bias in the data. It is often used in soil science and geology. Kriging weights the surrounding measured values to derive a prediction for an unmeasured location. The formula for kriging interpolation is formed as a weighted sum of the data:

$$\hat{Z}(s_o) = \sum_{i=1}^{N} \gamma_i Z(s_i) \qquad (5)$$

where

$Z(s_i)$ = measured value at the ith location

γ_i = unknown weight for the measured value at the ith location

s_o = prediction location

N = number of measured values.

In kriging, the weights are based not only on the distance between the measured points and the prediction location, but also on the overall spatial arrangement of the measured points. To use the spatial arrangement in the weights, the spatial autocorrelation must be quantified. Thus, in ordinary kriging, the weight γ_i depends on a fitted model to the measured points, the distance to the prediction location, and the spatial relationships among the measured values around the prediction location. Thus, the spline and kriging methods were used for interpolation of precipitation, and spline interpolation alone was used for interpolating other environmental variables and precipitation, and ET_{ref} maps were created for the entire state.

Results and Discussion

The statistical measures used to compare the performance of the spline and kriging techniques were based on the cross-validation predictions from 50 AWDN weather stations (table 3). The R^2 and RMSD values for monthly, seasonal, and annual precipitation and ET_{ref} for the spline and kriging interpolation are presented in table 3. The highest R^2 value between observed and interpolated data was observed in May (0.82 for spline and 0.80 for kriging) and November (0.81 for both techniques), while the lowest R^2 value for both techniques was observed in January (0.41 for spline and 0.37 for kriging). Similar results were found for ET_{ref}, with the highest R^2 value between observed and interpolated data observed in November (0.83 for spline and 0.82 for kriging) and the lowest R^2 value for both techniques observed in October (0.47 for spline and 0.46 for kriging). A negligible difference in RMSD was observed among the annual, seasonal, and monthly (January to December) data for both techniques (table 3). The greatest RMSD for precipitation and ET_{ref} for individual months was in July (16 mm for both techniques) and September (22 mm and 23 mm for spline and kriging, respectively). The lowest values were usually observed in winter months. On an annual basis, the spline method had about 5 mm and 6 mm less RMSD than kriging for precipitation and ET_{ref}, respectively. While the R^2 and RMSD values were similar for both techniques, the performance of spline was slightly better than kriging; therefore, this method was used for interpolation of other environmental variables.

Table 3. Coefficient of determination (R^2) and root mean square difference (RMSD) between observed and interpolated monthly, seasonal (1 May to 30 September), and annual precipitation and reference evapotranspiration for spline and kriging interpolation computed from cross-validation of AWDN weather stations.

Period	Precipitation				Alfalfa-Reference Evapotranspiration (ET_{ref})			
	R^2		RMSD (mm)		R^2		RMSD (mm)	
	Spline	Kriging	Spline	Kriging	Spline	Kriging	Spline	Kriging
January	0.41	0.37	4.2	4.5	0.59	0.61	8.8	8.6
February	0.66	0.67	3.8	3.8	0.74	0.77	6.3	5.9
March	0.59	0.55	8.1	8.7	0.63	0.64	10.0	9.9
April	0.67	0.73	8.2	7.6	0.59	0.65	9.3	6.8
May	0.82	0.80	9.0	9.6	0.78	0.81	13.1	13.0
June	0.60	0.50	11.2	12.8	0.61	0.55	12.9	13.8
July	0.42	0.45	16.1	15.5	0.69	0.68	16.2	16.3
August	0.67	0.72	12.2	11.1	0.63	0.69	20.8	21.8
September	0.72	0.70	8.5	8.8	0.68	0.64	22.3	23.4
October	0.52	0.50	9.7	10.1	0.47	0.46	14.1	13.5
November	0.81	0.81	4.6	4.5	0.83	0.82	5.6	5.2
December	0.78	0.80	3.1	2.9	0.75	0.76	4.5	3.9
Seasonal	0.85	0.86	33.8	31.9	0.66	0.67	48.8	51.5
Annual	0.88	0.90	50.9	45.5	0.67	0.67	75.4	69.2

Mapping Spatial Distribution of Precipitation

Long-term (1986-2009) average annual, seasonal (growing season), and monthly (May, June, July, August, and September) precipitation means exhibited very similar spatial patterns (fig. 2). The descriptive statistics for mean monthly, seasonal, and annual precipitation data are presented in table 4. Precipitation gradually increased from the southwest corner (zone 1) to the eastern part (zone 4) of the state (figs. 1 and 2). Nebraska usually receives most of its precipitation in the spring and summer (April to September). The mean precipitation peaks in May (92 mm) and gradually decreases toward September (55 mm), with a maximum of 144 mm in Douglas County and minimum of 52 mm in Scottsbluff County. The maximum and minimum precipitation in September was 88 mm in Nemaha County and 30 mm in Scottsbluff County. The two major agronomical row crops that are grown in Nebraska, and in other Midwestern states, are maize and soybean. Both crops are typically planted in late April to early and mid-May and emerge within 7 to 10 days under normal weather, soil temperature, and adequate soil moisture conditions. In the western portion of the state, because winter/spring precipitation is lower than in the eastern portion, the crop water use from winter/spring precipitation is also usually lower. However, in the drier western parts of the state, shorter-season crops are planted, and the planting date is typically earlier than in the central and eastern parts. The statewide long-term average annual precipitation ranged from 325 to 923 mm, with a mean of 581 mm (fig. 2a). In the western half of the state, precipitation is usually a significant limiting factor for crop production. The annual average precipitation in zone 3 is 592 mm, with the maximum of 717 mm in Burt County and minimum of 496 mm in Dawson County. Zone 3 is a heavily irrigated part of the state. Approximately 75,000 of the 110,000 active irrigation wells are located in this zone (USDA-NASS, 2007), and about 60% of the total 60,000 to 65,000 center-pivot irrigation systems are located in zone 3. Based on the annual average precipitation data, there is an approximately 30 mm decrease in precipitation for every 40 km from east to west. There is also a gradual trend of decreasing precipitation from south (maximum of 932 mm in Nemaha County, zone 4) to north (maximum of 717 mm in Burt County, zone 3) along the eastern edge of the state (fig. 2a).

The statewide long-term average seasonal precipitation showed a similar spatial trend as the annual precipitation (fig. 2b). Average county precipitation ranged from 215 to 601 mm, with a statewide average of 380 mm. Seasonal and annual precipitation were both inversely proportional to elevation. This is usually attributed to a high correlation between precipitation and elevation. From figures 1 and 2, it is clear that, as the elevation increases, precipitation decreases from east to west. On a given slope, climatological precipitation increases with elevation (Alter, 1919; Barrows, 1933; Spreen, 1947; Schermerhorn, 1967; Hibbert, 1977; Smith, 1979). This phenomenon, commonly called the orographic effect, has been shown in many other cases worldwide (e.g., Henry, 1919; Hutchinson, 1968). Air masses generally produce more precipitation when lifted over a higher elevation. However, the inverse precipitation vs. elevation correlation observed in this study is more likely a result of the combination of elevation decreasing toward the east, since Nebraska is located on the eastern (leeward) side of the Rocky Mountains and the distance from the major moisture source (the Gulf of Mexico) decreasing toward the southeast.

Table 4 shows the statistical attributes of the annual, seasonal, and monthly precipitation. Monthly maximum and minimum precipitation ranged from 17 to 144 mm and from 4 to 57 mm, respectively, with minimum values observed in January and maximum values in May and June (table 4). The standard deviation (SD) of daily precipitation increased gradually from January toward the summer months, peaked at 20 mm in May, and decreased again gradually toward November and December. The coefficient of variation (CV) showed an opposite trend to SD and was highest during winter months and lowest in the summer. The monthly minimum precipitation showed the highest CV, reaching about 42.5% during winter. Higher statewide variation was observed for higher values of seasonal and annual precipitation mean. On the other hand, CV increased from the western part to the eastern part of the state, indicating a higher degree of spatial pattern in precipitation from west to east. This might be due to the fact that the

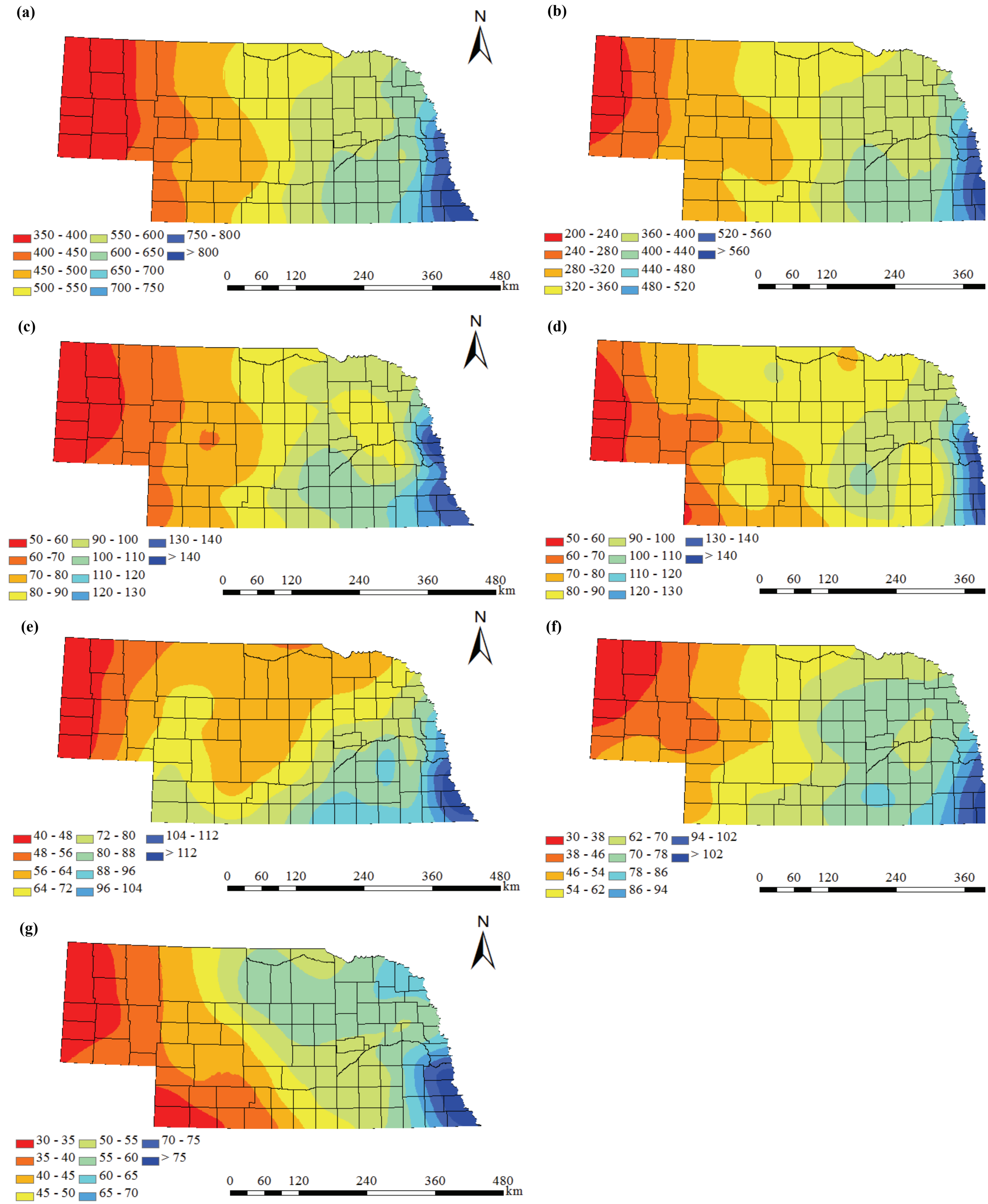

Figure 2. Spatial variation of long-term (1986-2009) average (a) annual, (b) seasonal, (c) May, (d) June, (e) July, (f) August, and (g) and September precipitation (mm) across Nebraska.

western parts of the state (Panhandle and Sand Hills) are low-pressure areas with low precipitation. When a low-pressure air mass moves in from the northwest from the Rocky Mountains region, it is usually followed by a cold front, but it seldom brings precipitation to the western part of the state (Hall, 1938). Zone 4 had higher SD and CV values for both seasonal and annual precipitation than the other zones, and zone 2 had the lowest SD and CV values,

Table 4. Descriptive statistics for mean monthly (statewide), seasonal (statewide and zone-wise), and annual (statewide and zone-wise) precipitation (mm) of all 93 counties ($N = 93$) for the observation period (1986-2009) across Nebraska (SD = standard deviation and CV = coefficient of variation).

Period		Precipitation (mm)				CV
		Mean	Max.	Min.	SD	(%)
Monthly	January	10	17	4	3.5	34.1
	February	15	25	7	4.4	30.1
	March	35	59	14	11.3	32.5
	April	63	91	39	13.1	20.7
	May	92	144	52	20.4	22.2
	June	89	138	57	16.3	18.3
	July	77	124	42	17.0	22.2
	August	68	113	30	16.2	23.8
	September	55	88	30	13.6	24.8
	October	46	80	26	12.9	27.8
	November	24	41	10	8.3	34.1
	December	12	25	5	5.1	42.5
Seasonal	Statewide	380	601	215	78.7	20.7
	Zone 1	253	289	215	24.9	9.9
	Zone 2	318	337	296	12.5	3.9
	Zone 3	384	451	331	26.5	6.9
	Zone 4	461	601	391	64.0	13.9
Annual	Statewide	581	923	325	132.7	22.8
	Zone 1	369	409	325	28.7	7.8
	Zone 2	461	503	424	25.4	5.5
	Zone 3	592	717	496	49.5	8.4
	Zone 4	719	923	621	95.8	13.3

indicating the lowest precipitation variability. Statewide average SD and CV values were greater than the values for individual zones.

The zone-wise monthly county variations in precipitation are represented by box-and-whisker plots in figure 3. The mean monthly values for zone 1 varied from 5 mm (January) to 66 mm (June), with a maximum monthly value of 78 mm (June) and minimum of 4 mm (January) in Sheridan and Dawes counties, respectively. A similar annual distribution was observed for zone 2, with the mean precipitation varying from 7 mm (January) to 77 mm (June). The maximum precipitation of 86 mm (June) and minimum of 5 mm (December) were observed in Cherry and Arthur counties, respectively. For central and eastern Nebraska (zones 3 and 4), the mean monthly precipitation varied from 10 mm (January) to 94 mm (May) and from 14 mm (January) to 112 mm (May) for zones 3 and 4, respectively. The maximum of 115 mm (Burt County) and 144 mm (Douglas County) and minimum of 7 mm (Keya Paha County) and 13 mm (Nuckolls County) were observed for zones 3 and 4, respectively.

Mapping Spatial and Temporal Distribution of Reference Evapotranspiration

Spatial distributions of long-term average annual, seasonal, and monthly ET_{ref} for all counties are presented in figure 4. Variation of the meteorological variables caused the annual, seasonal, and monthly variation of ET_{ref} in different zones. The statistics for ET_{ref} are presented in table 5. There was a gradual decrease in ET_{ref} totals from the western to the eastern part of the state. The statewide long-term average annual ET_{ref} value was 1,400 mm, with substantial differences across the state: 1,662 mm (zone 1), 1,542 (zone 2), 1,350 (zone 3), and 1,285 mm (zone 4). The minimum (1,025 mm) and maximum (1,751 mm) annual ET_{ref} values were observed in Kimball (zone 1) and Washington (zone 4) counties, respectively. There was an approximately 726 mm difference in the annual ET_{ref} amounts between the western and eastern parts of the state (fig. 4a). In the southeast (Cass and Otoe counties), there was a small patch of high ET_{ref} values. This might be an artifact of the inter-

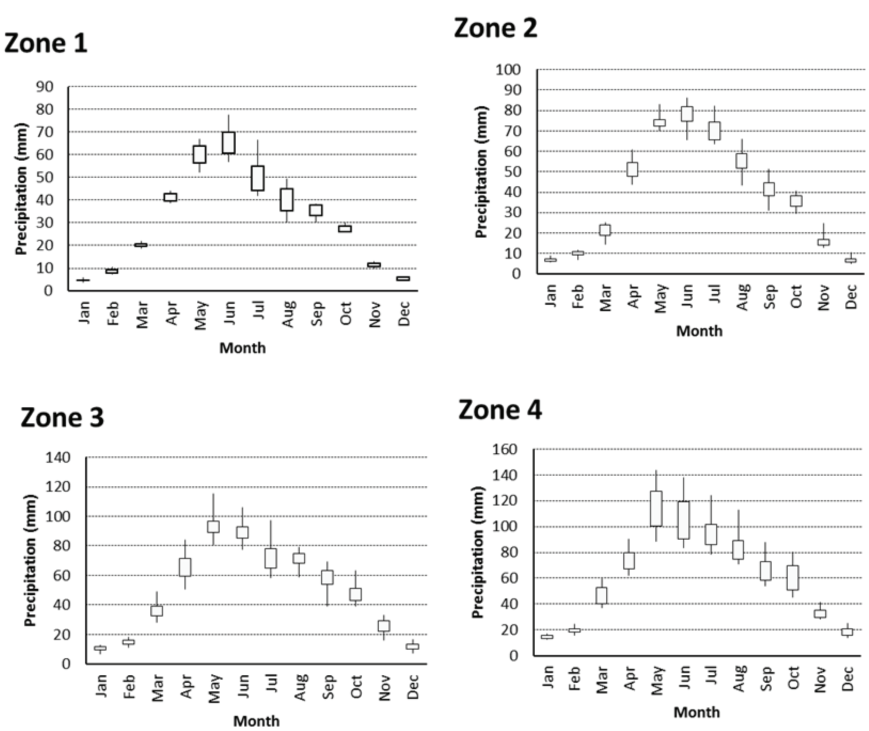

Figure 3. Box-and-whisker plots for long-term (1986-2009) average monthly precipitation (January to December) for zones 1, 2, 3, and 4 across Nebraska.

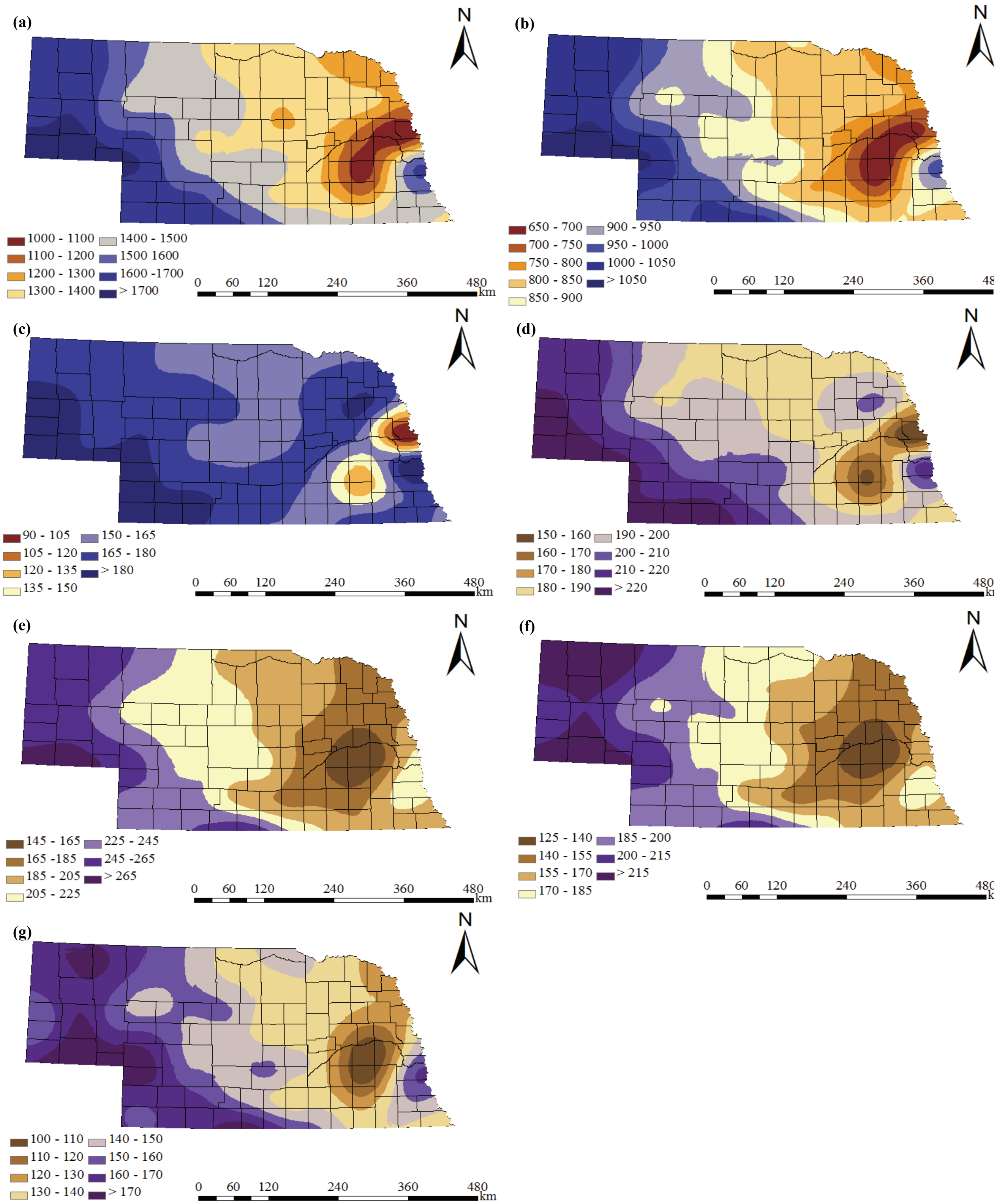

Figure 4. Spatial variation of long-term (1986-2009) average (a) annual, (b) seasonal, (c) May, (d) June, (e) July, (f) August, and (g) September ET_{ref} (mm) across Nebraska.

polation procedure. A total of seven weather stations located in and around the urban areas (Lincoln, Omaha, and Rockport) were used to interpolate ET_{ref} for that location. Thus, since ET_{ref} values were generally higher for these urban stations than for stations in rural areas, the ET_{ref} values that were interpolated for Cass and Otoe counties were also high. The seasonal total ET_{ref} showed similar patterns as the annual ET_{ref} (fig. 4b).

The statewide long-term average seasonal ET_{ref} value was 883 mm, with a maximum of 1,087 mm and a mini-

Table 5. Descriptive statistics for statewide mean monthly, seasonal (statewide and zone-wise), and annual (statewide and zone-wise) alfalfa-reference evapotranspiration (ET_{ref}, mm) of all 93 counties (N = 93) for the observation period (1986-2009) across Nebraska (SD = standard deviation, and CV = coefficient of variation).

Period		Alfalfa-Reference Evapotranspiration (ET_{ref}, mm) Mean	Max.	Min.	SD	CV (%)
Monthly	January	41	67	18	9.8	24.0
	February	49	72	28	9.7	20.0
	March	93	115	64	12.5	13.5
	April	136	171	90	13.1	9.6
	May	169	197	91	16.4	9.7
	June	196	232	149	17.3	8.8
	July	204	268	146	28.3	13.9
	August	171	231	123	25.9	15.1
	September	144	183	101	18.2	12.7
	October	102	128	67	13.2	12.9
	November	59	82	26	10.2	17.4
	December	37	61	12	9.8	26.2
Seasonal	Statewide	883	1087	684	96.0	10.9
	Zone 1	1043	1087	989	27.8	2.7
	Zone 2	967	1040	893	47.3	4.9
	Zone 3	860	1004	772	48.0	5.6
	Zone 4	805	952	684	71.1	8.8
Annual	Statewide	1400	1751	1025	165.8	11.8
	Zone 1	1662	1751	1568	58.7	3.5
	Zone 2	1542	1668	1395	84.2	5.5
	Zone 3	1350	1586	1169	84.5	6.3
	Zone 4	1285	1557	1025	147.2	11.5

mum of 684 mm observed in Cheyenne and Seward counties, respectively. The maximum CV of 8.8% was observed in zone 4, and the minimum of 2.7% occurred in zone 1, indicating the high seasonal variability in ET_{ref} in the eastern part of the state. The SD increased from January-February to summer and decreased again toward November-December, with CV having an opposite trend. Similar to the observations for precipitation, the SD and CV values for ET_{ref} increased from zone 1 to zone 4.

Table 5 shows the descriptive statistics for ET_{ref}. The long-term average monthly ET_{ref} values varied from 37 mm in December to 204 mm in July. The maximum monthly value of 268 mm was observed in July, and the minimum value of 12 mm was observed in December. The SD reached a maximum of 28.3 mm in July and a minimum of 9.8 mm in December and January. The CV reached its maximum (26.2%) during December and minimum (8.8%) during June, which indicates that the relative spatial variability of ET_{ref} during winter was almost twice as large as during late summer. The annual distribution of the long-term average monthly ET_{ref} in zones 1 to 4 can be observed from the box-and-whiskers plots in figure 5. Relatively high solar radiation and wind speed, low relative humidity, and low precipitation that result in high vapor pressure deficit are the main causes of the high ET_{ref} in zone 1 as compared with the other zones during the growing season (fig. 6).

Relationships of Elevation vs. Precipitation, Elevation vs. ET_{REF}, and Precipitation vs. ET_{REF}

It was previously shown that seasonal and annual precipitation was inversely proportional to elevation. To further analyze these relationships, the correlation between station elevation vs. seasonal (May to September) and annual (January to December) precipitation and ET_{ref} for all 93 counties are presented in figures 7a and 7b. The relationships between elevation and seasonal and annual precipitation were described by power functions, and the ele-

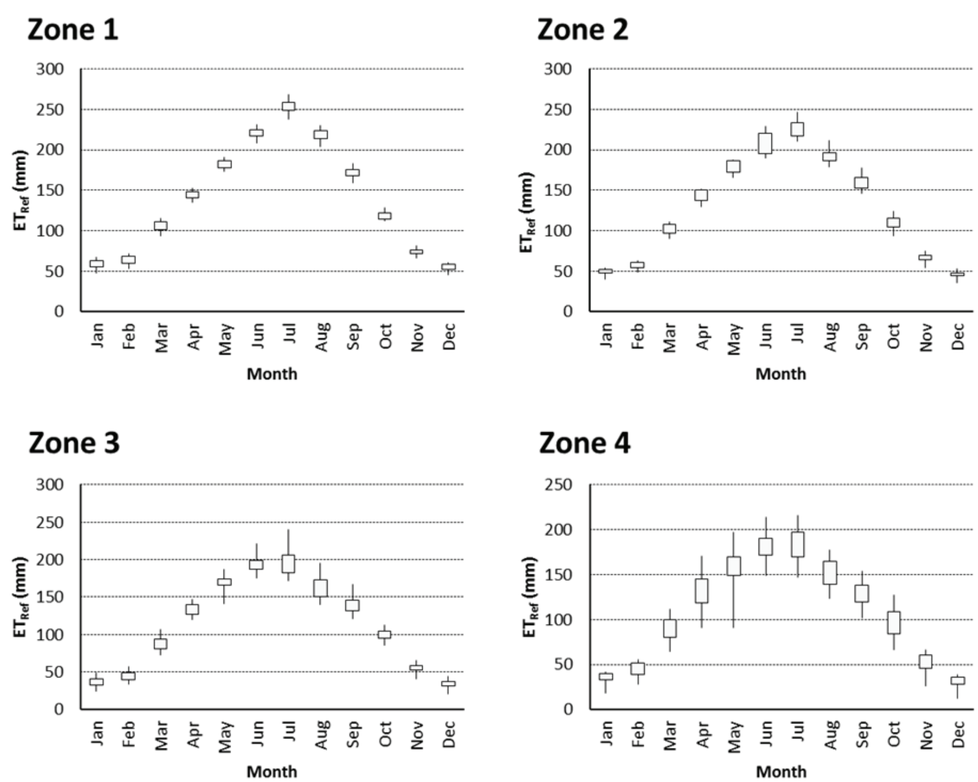

Figure 5. Box-and-whisker plots for long-term (1986-2009) average monthly alfalfa-reference evapotranspiration (ET_{ref}) from January to December for zones 1, 2, 3, and 4 across Nebraska.

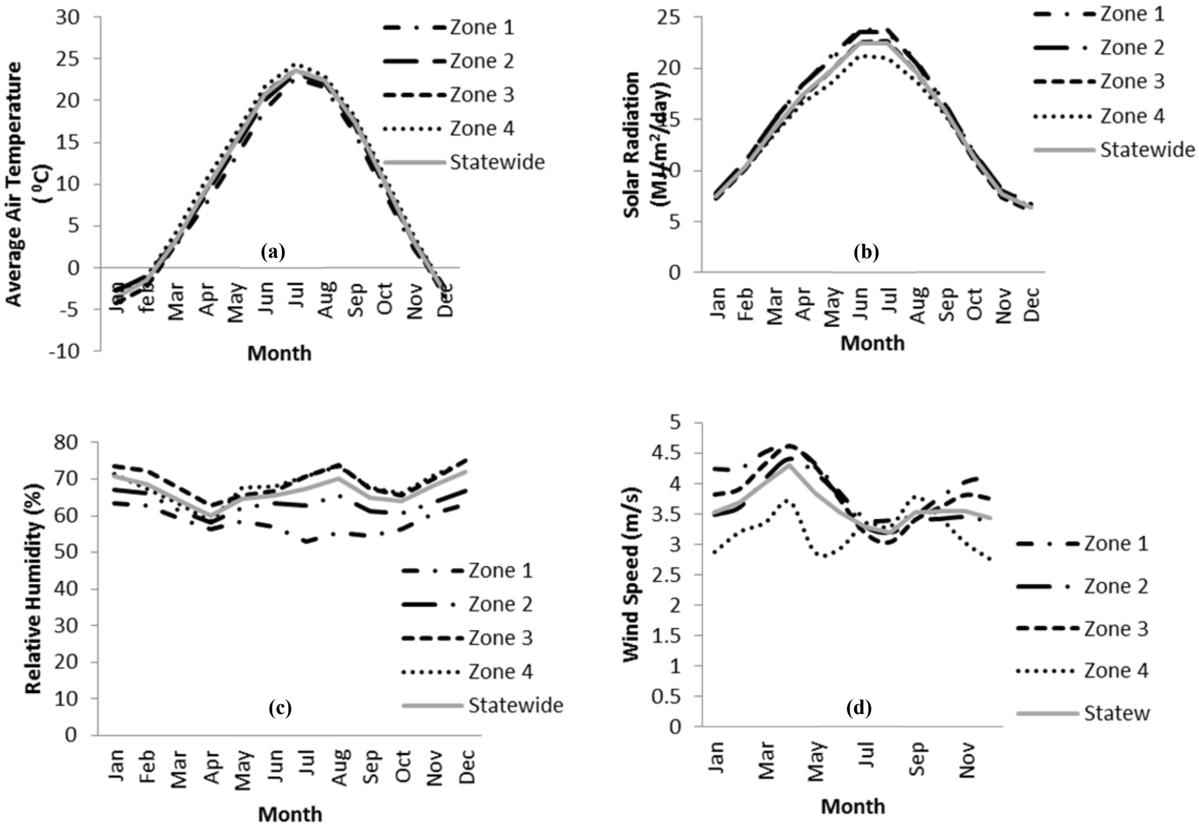

Figure 6. Long-term (1986-2009) average monthly variation of average (a) air temperature, (b) solar radiation, (c) relative humidity, and (d) wind speed across four zones in Nebraska.

vation vs. ET_{ref} relationship was explained by a linear regression. There was a very strong correlation between both seasonal and annual precipitation vs. elevation. The coefficient of determination was stronger for annual (R^2 = 0.94) than for seasonal (R^2 = 0.88) precipitation. The exponent of the annual precipitation power function (-0.5751) was 1.15 times smaller than for seasonal precipitation (-0.4989), and annual precipitation had 2.5 times greater slope than seasonal precipitation. In both cases, there was a gradual decrease in precipitation with increase in elevation (i.e., from eastern to western Nebraska). For counties that had lower elevation (i.e., between 300 and 450 m), which are mostly located in the southeast, there was a more rapid decrease in both seasonal and annual precipitation with increase in elevation as compared with the other counties. The most southeastern counties (Richardson and Nemaha) had the lowest elevation (302 and 305 m, respectively) and the greatest seasonal and annual precipitation (920 and 593 mm for annual and seasonal precipitation for Nemaha County; 923 and 601 mm for seasonal and annual precipitation for Nemaha County). The least annual precipitation was in Scottsbluff County (325 mm), which had the highest elevation (1,214 m). The same county also had the least seasonal precipitation (215 mm) (fig. 7a). The annual precipitation decreased between 18 and 131 mm for every 100 m increase in elevation. The seasonal precipitation decreased between 11 and 72 mm for every 100 m increase in elevation.

The relationships between annual and seasonal ET_{ref} vs. elevation were weaker than the precipitation relationships but were still moderately correlated to elevation, with R^2 = 0.61 and 0.68 for annual and seasonal ET_{ref}, respectively (fig. 7b). The correlation was weakest for the counties at lower elevation (i.e., <400 m). Opposite to the trends observed for precipitation vs. elevation, the annual ET_{ref} increased by 47 mm for every 100 m increase in elevation, and the seasonal ET_{ref} increased by 29 mm for every 100 m increase in elevation. Vanderlinden et al. (2008) found a similar correlation between annual ET_{ref} and elevation for Andalusia (Spain), with an R^2 of 0.76 (pooled data for coastal and inland locations), and they explained the relationship with a quadratic polynomial function, with decrease in ET_{ref} with increase in elevation for the Mediterranean climate. They observed that the relationship between ET_{ref} and elevation was linear in winter months, but in the summer (e.g., July) the curve flattened toward lower elevations, when the coastal observations were excluded. The R^2 ranged from 0.78 in the spring and autumn to 0.46 in the summer. We observed a gradual decrease in the ratio of annual and seasonal precipitation to annual and seasonal ET_{ref} (fig. 7c) from western to eastern Nebraska, with the annual ratio ranging from 0.20 in the west to 0.77 in the east, with a statewide average of 0.43. Similarly, the ratio of seasonal precipitation to seasonal ET_{ref} ranged from 0.21 in the western part of the state to 0.71 in the east, with a statewide average of 0.44. Thus, on a statewide average basis, the annual and seasonal precipitation can only meet 43% to 44% of the annual and seasonal ET_{ref}. The relationship between

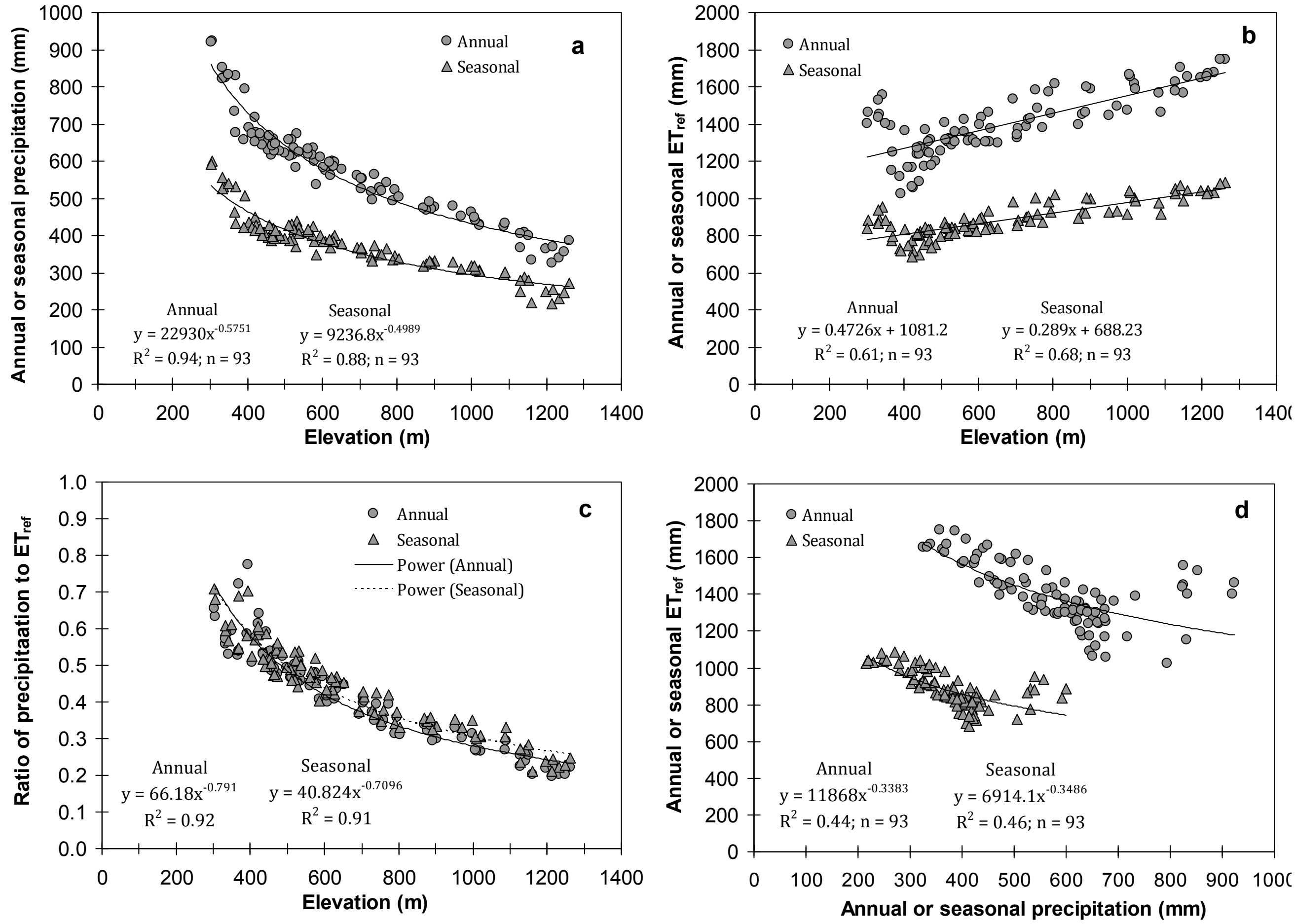

Figure 7. Relationship of (a) elevation vs. annual and seasonal precipitation, (b) elevation vs. annual or seasonal alfalfa-reference evapotranspiration (ET_{ref}), (c) elevation vs. ratio of annual or seasonal precipitation to annual or seasonal ET_{ref}, and (d) annual or seasonal precipitation vs. annual or seasonal ET_{ref} for all 93 counties in Nebraska.

annual and seasonal precipitation vs. ET_{ref} (fig. 7d) was weak, but there is a general increase in both ET_{ref} with increase in elevation. The weak correlation is caused by the counties (Cass, Richardson, Otoe, Nemaha, Pawnee, Sarpy, and Johnson; fig. 1) that are located in the eastern part of the state at elevations lower than 400 m. In this part of the state, although annual and seasonal precipitation is high, ET_{ref} is also high, which forces the correlation between the two variables to be weak.

SUMMARY AND CONCLUSIONS

Long-term (1986-2009) average annual (January to December), seasonal (growing season, May to September), and monthly (May, June, July, August, and September) precipitation and Penman-Monteith-estimated alfalfa-reference evapotranspiration (ET_{ref}) were spatially interpolated and mapped for all 93 counties in Nebraska using the spline interpolation technique in ArcGIS. The state was divided into four climatic zones that have significantly different climatic characteristics, ranging from semi-arid in the western part (zone 1) to humid/subhumid in the southeastern part (zone 4). Annual, seasonal, and monthly precipitation means exhibited similar spatial patterns. Precipitation gradually increased from the southwest corner (zone 1) to the eastern part (zone 4) of the state. The long-term seasonal precipitation showed a similar spatial pattern as the annual precipitation. The monthly minimum precipitation showed the greatest coefficient of variation (CV), reaching about 42.5% during the winter months. On an annual basis, greater statewide variation was observed for higher values of seasonal and annual mean precipitation. On the other hand, CV increased from the western part to the eastern part of the state, indicating a higher degree of spatial pattern in precipitation from the west (drier) to the eastern part (subhumid). Based on the annual average precipitation data, there was an approximately 30 mm decrease in precipitation for every 40 km from east to west. There was a very strong correlation between both seasonal and annual precipitation and elevation, and the correlation was stronger for annual (R^2 = 0.94) than for seasonal (R^2 = 0.88) precipitation. In both cases, there was a gradual decrease in precipitation with increase in elevation (i.e., from eastern to western Nebraska). The relationship between annual and seasonal ET_{ref} vs. elevation was weaker than the precipitation relationship, but both ET_{ref} values were still moderately correlated to elevation, with R^2 = 0.61 and 0.68 for annual and seasonal ET_{ref}, respectively.

Overall, the maps of precipitation and ET_{ref} presented in

this study can provide invaluable large-scale information to water management policy and decision-makers, as well as for hydrologic analyses and water resource planning and management in statewide and county-scale watersheds, because spatial distributions of annual, seasonal, and monthly values of precipitation and ET_{ref} are important driving forces in various aspects of the hydrological cycle. In wet seasons, ET_{ref} provides an upper limit for the actual evapotranspiration. In dry seasons and water-limited areas, ET_{ref} is an indication of atmospheric evaporative demand for actual crop evapotranspiration. Thus, it can be used as an indication of the upper limit of water loss from a watershed. Combining the spatial distribution maps of ET_{ref} with the spatial distribution of precipitation can provide an important background and physical interpolation for climate change studies in the region. These maps can also be used to evaluate areas where the differences in water supply and use are increasing so that priority areas can be identified for closer monitoring, which will lead to the ability to take proactive steps to balance water supply and demand through various available methods, such as changing cropping patterns to implement cropping systems with lower water demand, reduced tillage practices to minimize unbeneficial water use (soil evaporation), implementing newer drought-tolerant crop hybrids and cultivars, implementing deficit irrigation strategies, and initiating and deploying more aggressive and effective irrigation management programs. After spatially interpolating precipitation and ET_{ref} for large scales, the next step is spatial interpolation of actual crop evapotranspiration (ET_a) and net irrigation requirements of various crops, which can further enhance water balance analyses, assessments of availability and actual consumption of water resources, and aid in in-season irrigation management decisions. The spatial interpolation of actual crop evapotranspiration (ET_a) and net irrigation requirements is presented in Part II of this study (Sharma and Irmak, 2012).

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