Basic Meteorological Data Derived 30-year Normals (1981–2010) of Actual Evapotranspiration Rates in Nebraska, USA

Bulletin 8 (New Series)

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ABSTRACT

Evapotranspiration (ET) is an important bio-physical process that plays a pivotal role in climate formation for the entire globe and --from an agriculturalist point of view-- it also regulates the surface temperature of crops thus protecting them from overheating and cellular damage in hot weather. With the latest advances in hydrological research, 30-year normals (1981 – 2010) of monthly and annual ET rates across Nebraska were derived from basic meteorological data (i.e., air-, dew-point temperature, wind, and net surface radiation) without the customary calibration of any model parameters. The annual state-wide ET rate of 21.6 in (548 mm) is within 0.5% of the water-balance derived (i.e., precipitation less runoff) value of 21.65 in (550 mm).

INTRODUCTION

Long-term and/or state-wide to continental-scale ET rates cannot be derived by direct flux measurements using Bowen-ratio (e.g., Billesbach and Arkebauer, 2012) or eddy-covariance (e.g., Landon et al., 2009) techniques since such approaches have been in existence only for the last several decades and/or are usable only at the plot-scale. Therefore in the past, actual ET rates were typically obtained through soil-moisture budgeting (Thornthwaite and Mather, 1955). Even today this is the standard practice in Land Surface Models (Sheffield et al., 2012) that provide latent (*LE*) and sensible (*H*) heat fluxes between the surface and the ambient atmosphere for climate model applications. Soil moisture budgeting however requires detailed information on a) soil type and its related physical properties such as porosity, thickness, layering, hydraulic conductivity; b) depth to groundwater; c) vegetation cover such as the type of vegetation, rooting depth, leaf area index, and; d) land use. The larger the area in question, the larger the degree of necessary generalization in these parameters, and therefore the less reliable the resulting estimates become. As an alternative, there exists an exciting, fast developing but yet largely underemployed technique that works at a regional scale and requires only basic meteorological measurements.

The complementary relationship (CR) of evaporation (Bouchet, 1963; Brutsaert and Stricker, 1979; Morton, 1983; Szilagyi and Jozsa, 2008; Brutsaert, 2015; Szilagyi 2015; Szilagyi et al., 2016, 2017) connects actual ET rates to the state of the lower atmosphere by realizing that over a suitable time-period and horizontal extent (scale) the two are linked together. According to Morton (1983), the shortest time-interval the CR can routinely be applied is about 5 days. Also, studies by Davenport and Hudson (1967) and Lang et al. (1974) demonstrated that adjustment of atmospheric moisture content to the underlying latent heat source takes place within a kilometer (roughly 2/3 of a mile) horizontally. The temporal and spatial resolution of the data applied in this study meet these prerequisites by their monthly time-step and the employed 32-km North American Regional Reanalysis (NARR, Mesinger et al., 2006) net radiation (R_n) and 4-km Parameter-Elevation Regressions on Independent Slopes Model (PRISM, Daly et al., 1994, 2008) air- (T_a), dew-point temperature (T_d), and wind (u) data. The T_d values were only available as 30-year monthly normals at the time of this study therefore all other variables were averaged the same way for the 1981 – 2010 period. As a result, trend-analysis of the variables is not made possible by the data. For a state-wide validation of the ET rates, long-term mean annual water balance ET was derived as the difference of PRISM precipitation (P) and United States Geological Survey's (USGS) 8-level Hydrologic Unit Code (HUC8) runoff (Q) data averaged over the state for the 1981 – 2010 time period.

METHODS

By the latest advances in CR-research (Brutsaert, 2015; Szilagyi et al., 2017) actual ET can be obtained as

$$ET = E_p \left(\frac{E_{pmax}-E_p}{E_{pmax}-E_w}\frac{E_w}{E_p}\right)^2 \left(2 - \frac{E_{pmax}-E_p}{E_{pmax}-E_w}\frac{E_w}{E_p}\right) \quad (1)$$

where E_p is the ET rate of a small wet patch, given by the Penman equation (1948)

$$E_p = \frac{\Delta(T_a)}{\Delta(T_a)+\gamma} R_n + \frac{\gamma}{\Delta(T_a)+\gamma} f_u \left[e^*(T_a) - e^*(T_d)\right] . \quad (2)$$

Here $\Delta(T_a)$ is the slope of the saturation vapor pressure (e^*) curve at T_a, γ [= $c_p p$ / $(0.622L)$] the psychrometric constant, where c_p is the specific heat of air at constant air pressure (p), L is the latent heat of vaporization ($2.47 \cdot 10^6$ J kg^{-1}at 15 °C) for water, and the net radiation at the surface, R_n, is specified in water depth per unit time (i.e., mm d^{-1}). f_u is an empirical wind function, traditionally written as $f_u = 0.26(1 + 0.54u_2)$, where u_2 is the mean horizontal wind speed in m s^{-1}, measured at 2 m above the ground, and e^* is specified in hPa. Notice that i) $e^*(T_d)$ equals actual vapor pressure, e_a, and; ii) $e^*(T_a) - e_a$ is called the vapor pressure deficit, *VPD*. The wet-environment ET rate, E_w, in (1) is obtainable by the Priestley-Taylor equation (1972) as

$$E_w = \alpha \frac{\Delta(T_w)}{\Delta(T_w)+\gamma} R_n \quad (3)$$

where T_w is the wet-environment air-temperature and α is the Priestley-Taylor coefficient. T_w is the temperature the air cools down by unimpeded evaporation of the environment on a regional scale under the prevailing R_n and wind conditions. The value of α is 1.13 (Szilagyi et al., 2017) for the conterminous US employing the current data sets. T_w can be derived from the implicit equation of the ratio of sensible and latent heat fluxes written for a small wet patch (Szilagyi and Jozsa, 2008) as

$$\frac{H}{LE} \approx \frac{R_n - E_p}{E_p} \approx \gamma \frac{T_{ws} - T_a}{e^*(T_{ws}) - e^*(T_d)} \quad (4)$$

where T_{ws} is the wet-surface temperature, a good proxy for T_w as long as $T_{ws} < T_a$. Finally, E_{pmax} is the dry-environment E_p rate, estimated by (2) with $e_a = 0$ and $T_a = T_{dry}$, the latter calculated as (Szilagyi et al., 2017)

$$T_{dry} = \frac{e^*(T_{wb})(T_a - T_{wb})}{e^*(T_{wb}) - e_a} + T_{wb} \quad (5)$$

where T_{wb} is the wet-bulb temperature, derivable from the implicit equation containing T_a and T_d as (Monteith, 1981)

$$\gamma \frac{T_{wb} - T_a}{e^*(T_{wb}) - e^*(T_d)} = -1 . \quad (6)$$

Eq. (1) has been applied for the conterminous US (Szilagyi et al., 2017) with data specified above. The below results are a subset of that study.

RESULTS AND DISCUSSION

Long-term mean annual ET rates in Nebraska are displayed in Fig. 1. Generally, ET rates decline from east to west by almost 50% in accordance with precipitation (Fig. 2). The highest rates, in excess of 26 in (660 mm), are found in the extreme south-east part of the state, mostly due to the abundance of precipitation, while the smallest values, less than 16 in (406 mm), are found in the panhandle region, due to the lack of ample moisture.

Within-year, monthly distribution of the ET rates is depicted in Figs. 3 - 4 and in Table 1. As seen, warming-up of the state from its winter freeze, and with it, greening of the land in close linkage with ET rates, spread from south-east toward north-west, to reach a longitudinal distribution by July. Drop in ET rates follows an opposite course (i.e., starts in the north-west and spreads to the south-east) in the second half of the year (Fig. 4).

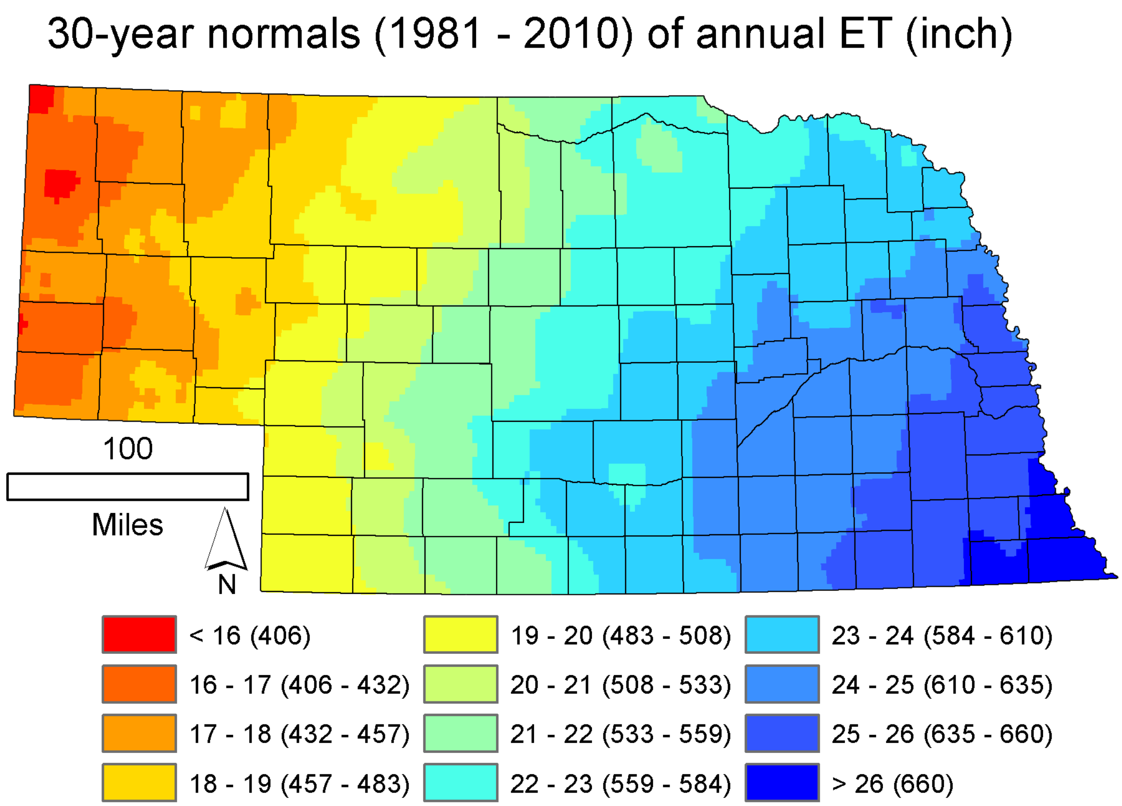


Figure 1. Annual ET rates in Nebraska. State-wide mean is 21.6 in (548 mm).

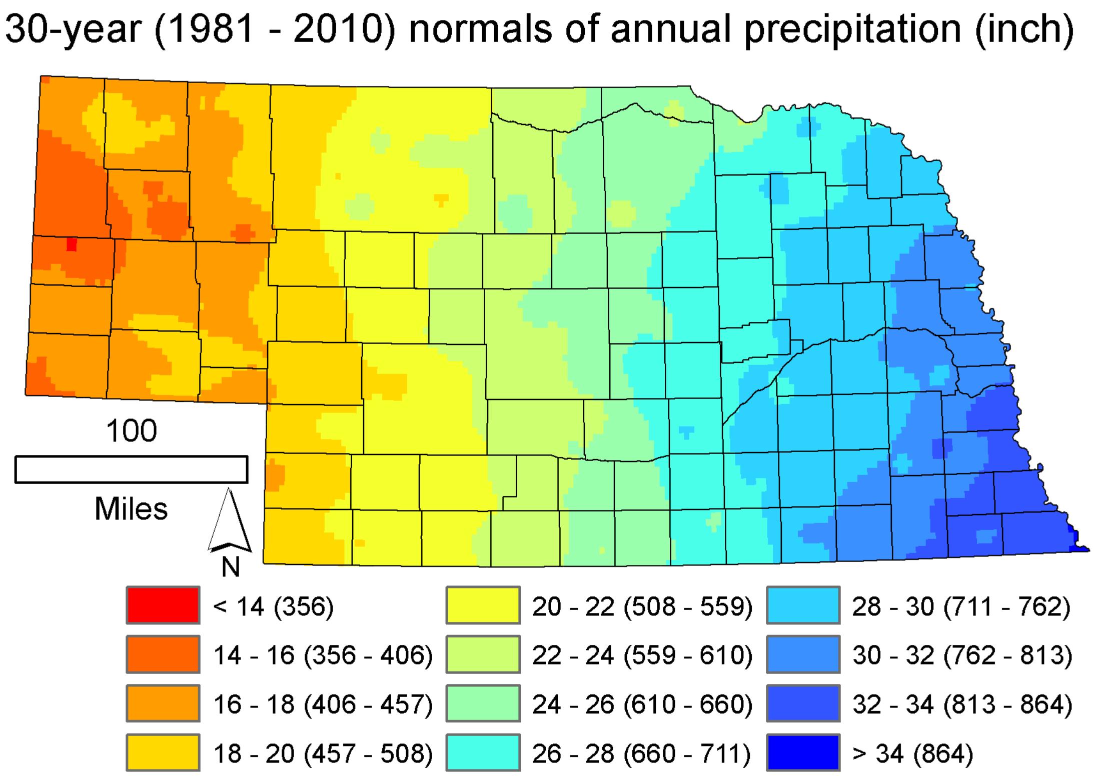
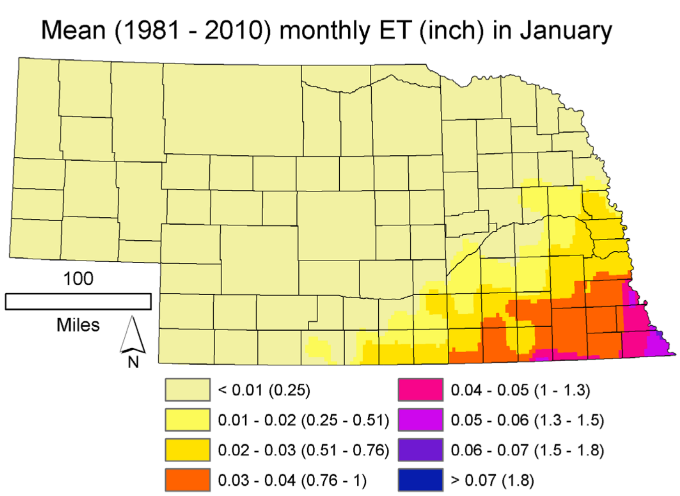


Figure 2. Annual precipitation rates in Nebraska. State-wide mean is 23.65 in (601 mm).



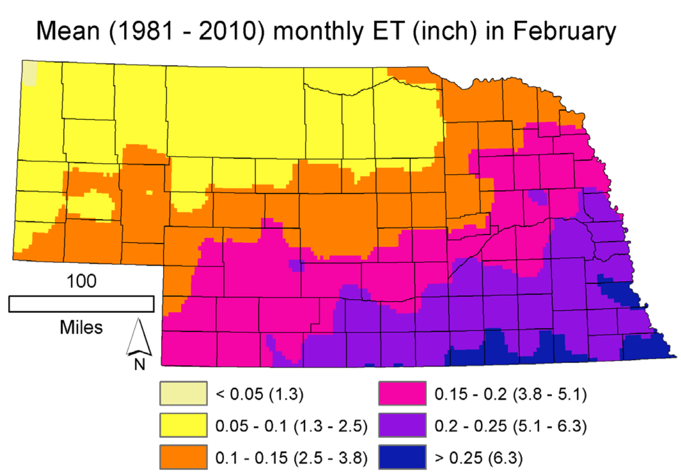


Figure 3. Monthly ET rates in the first half of the year in Nebraska. The values in parenthesis are in mm.
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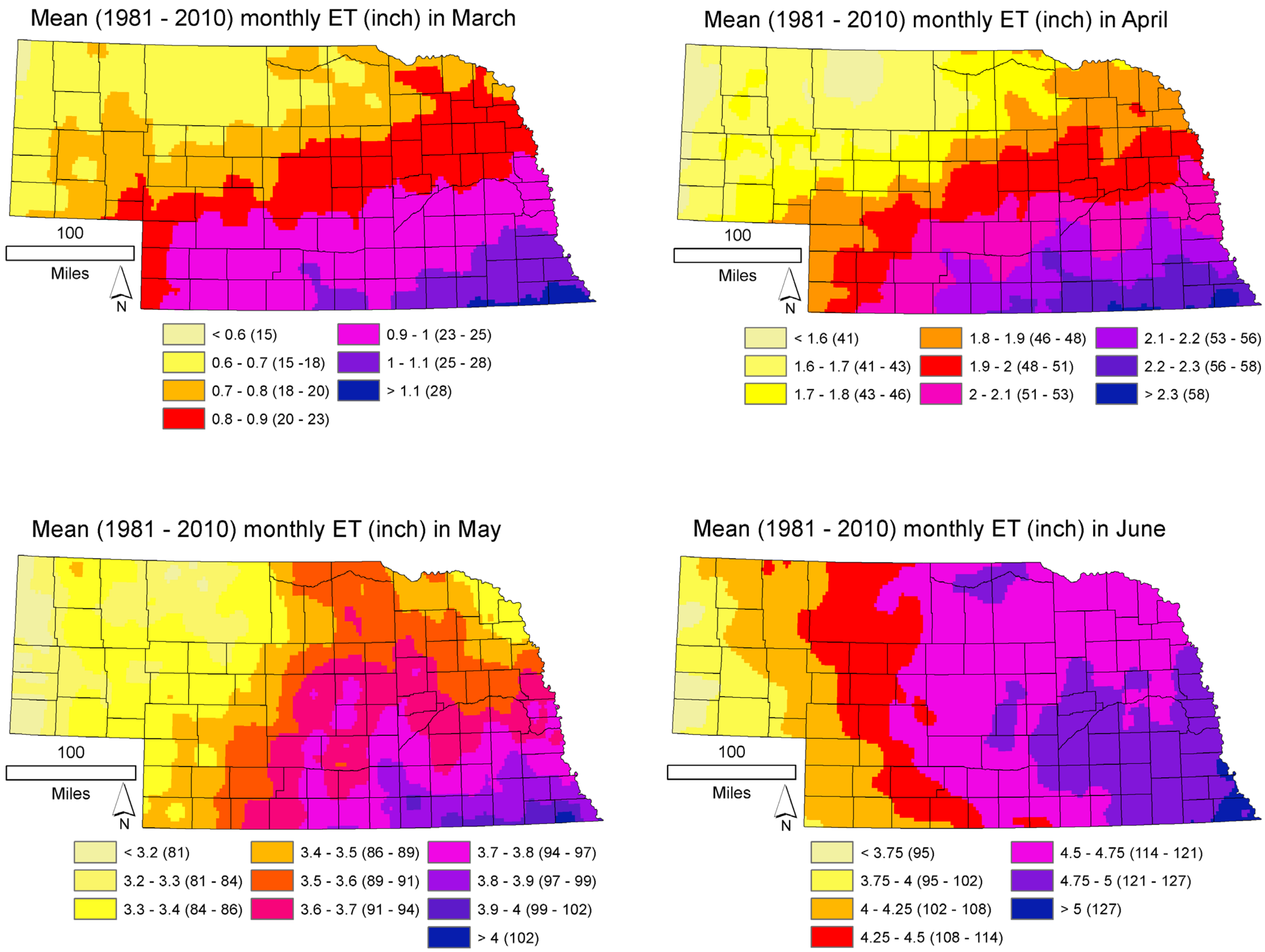

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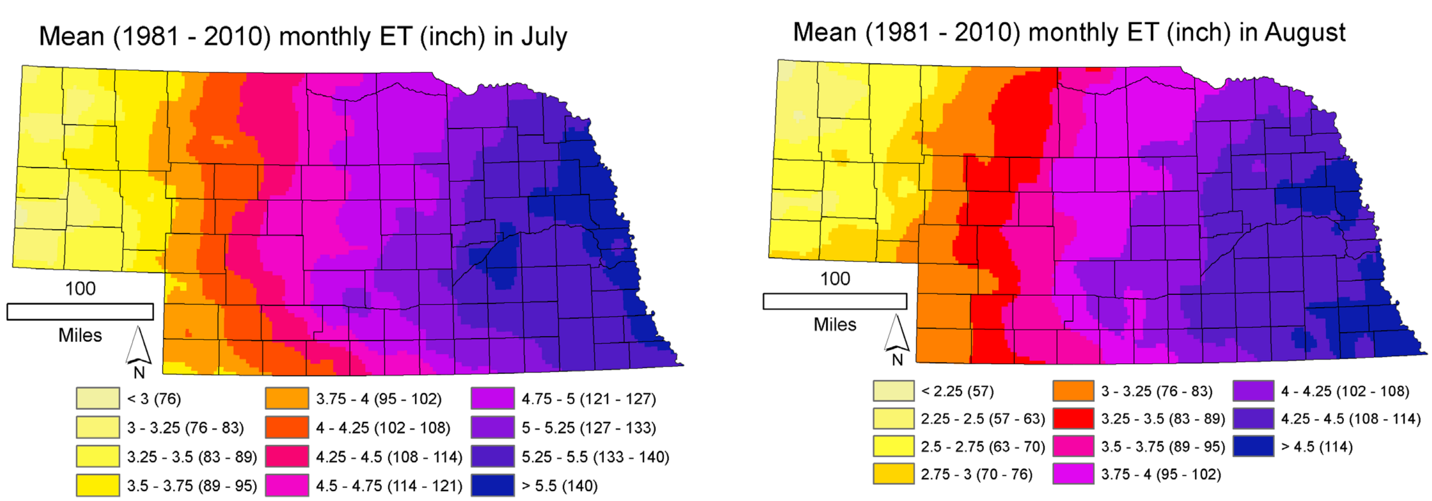

Figure 4. Monthly ET rates in the second half of the year in Nebraska. The values in parenthesis are in mm.
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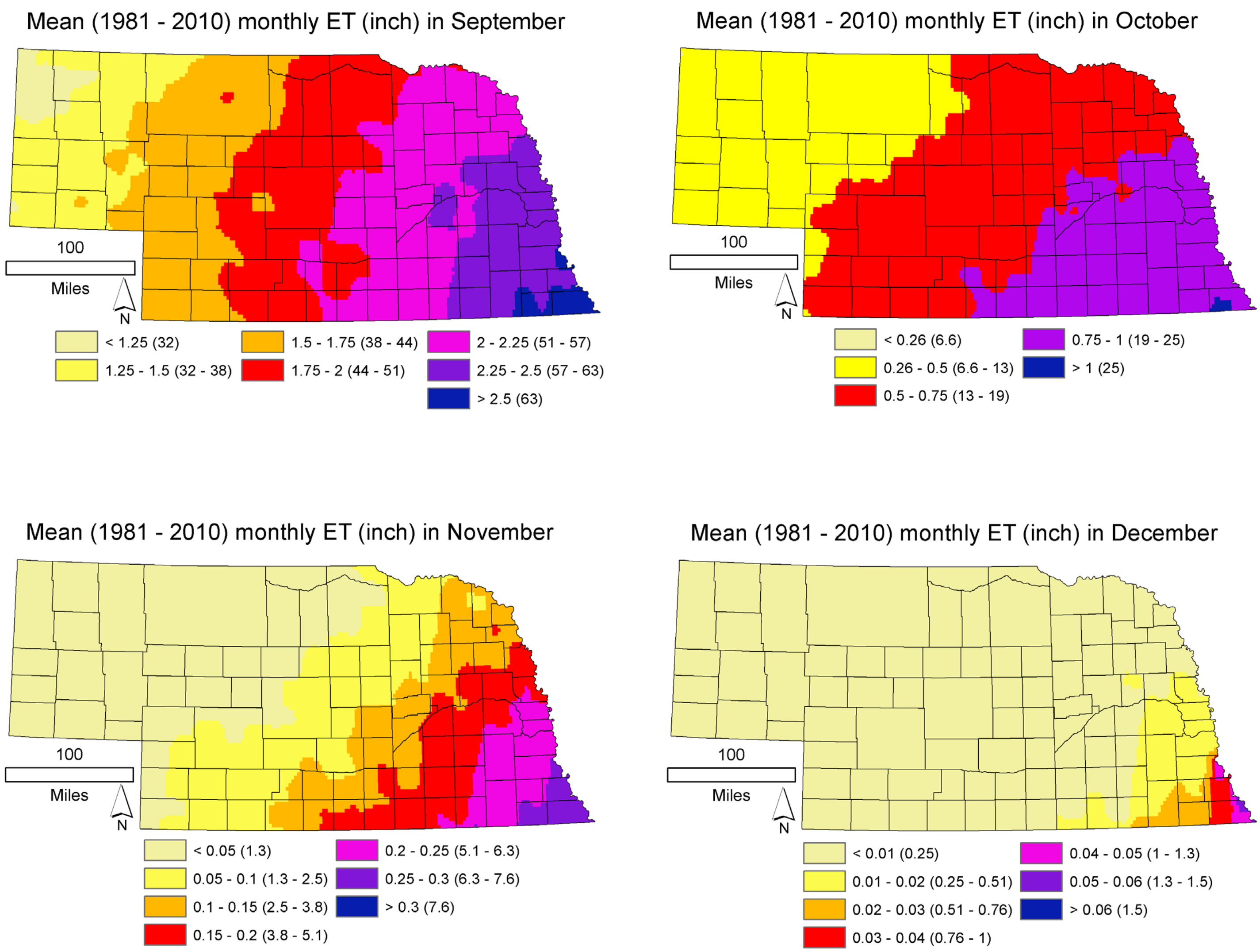

Figure 4. Monthly ET rates in the second half of the year in Nebraska. The values in parenthesis are in mm.

Table 1. Distribution of state-wide monthly ET rates (in) within the year (1981 – 2010).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
ET (mm)	0.006 (0.15)	0.14 (3.6)	0.83 (21)	1.88 (48)	3.5 (89)	4.48 (114)	4.56 (116)	3.66 (93)	1.86 (47)	0.6 (15)	0.08 (2)	0.003 (0.08)	21.6 (548)

As precipitation rates follow a similar spatial distribution as ET rates (Fig. 2), a more meaningful picture of ET activity emerges by normalization with *P*, displayed in Fig. 5. In areas with less than 21 in (533 mm) of annual precipitation, ET rates often exceed precipitation (turquoise to blue colors). This can only happen on a regional scale if ET is boosted by either ground- and/or surface water in areas of e.g., large (or many small) lakes and wetlands or artificially, as irrigated areas (Fig. 6).

Of course, irrigation always enhances ET rates (Kustu et al., 2011), but when precipitation rates are high enough, the ET gains will not become as easily identifiable as when they exceed precipitation rates in drier regions. The third bull's eye from the left (Fig.

5) in the panhandle region in Sheridan County does not correspond to any irrigated areas in Fig. 6, but the region, together with the northern part of Garden County south of it, contains one of the densest distribution of inter-dunal lakes in the Sand Hills of Nebraska. Other parts of the Sand Hills, where lakes are less abundant or absent, evaporate way below the precipitation rate due to the high infiltration rates of the sandy soils.

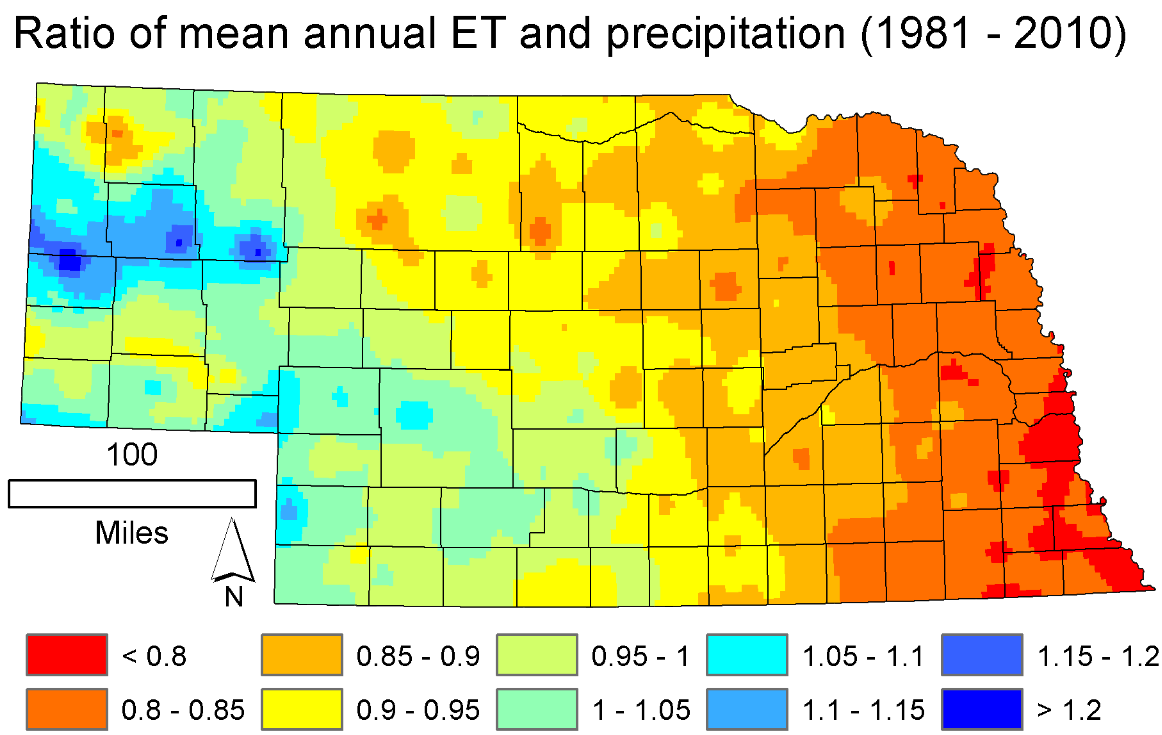

Figure 5. ET to precipitation (P) ratios in Nebraska. State-wide mean is 91%.

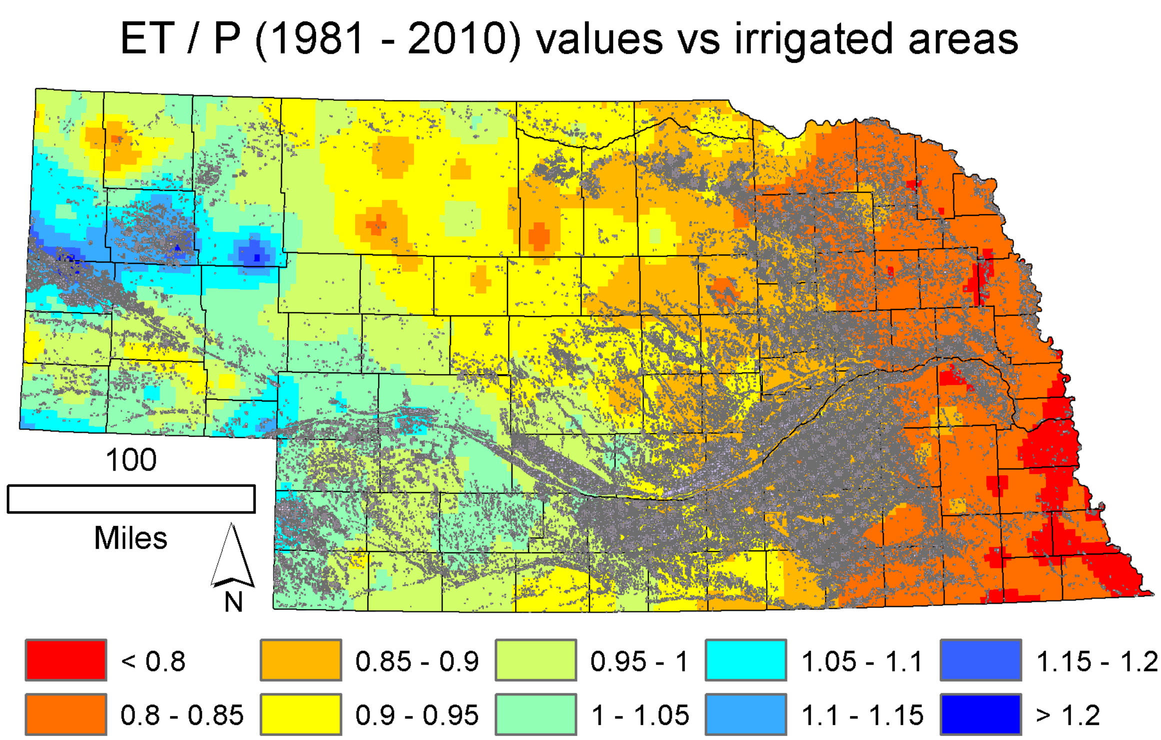

Figure 6. Distribution of irrigated areas in Nebraska in 2005 (after Dappen et al., 2012a,b), overlain the ET to P ratios.

The state-wide average of the ET to P ratios is 91%, which means that about 9% of the precipitation [i.e., 2.1 in (53 mm)] the state received between 1981 and 2010 left its boundaries, which is very close to the USGS measured runoff [2.01 in (51 mm)] for the same time period, and this accuracy was achieved without any calibration whatsoever in Eq. (1). The same ratio was estimated as 95% by Szilagyi (2013) for the 2000 – 2009 period using different data sets, such as the 1-km Moderate Resolution Imaging Spectroradiometer (MODIS) surface temperature data, available only after 2000. The difference in the ratios (i.e., declining runoff) may be attributed to increases in irrigated areas and water volumes between the two periods, among many other possible factors, such as climatic and/or anthropogenic by origin.

CONCLUSIONS

Recent advances in hydrologic research made the derivation of accurate, actual ET rates possible, here at a monthly time step, from routinely obtained meteorological data without resorting to any land use, vegetation cover or soil moisture information.

The 30-year normals of monthly and annual ET rates across Nebraska may serve as base values in the coming decades of climate variability and the ensuing adaptation in land-use change.

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