THE ATMOSPHERIC DEMAND FOR MOISTURE IN THE GREAT PLAINS

Raquel Dominguez[1,2], Ryann Wakefield[3], Jordan Christian[3], Jeff Basara[4]

[1]National Weather Center Research Experiences for Undergraduates Program
Norman, OK, USA
[2]Western Kentucky University
Bowling Green, KY, USA
[3]University of Oklahoma, School of Meteorology
Norman, OK, USA
[4]University of Oklahoma, School of Civil Engineering and Environmental Science
Norman, OK, USA

ABSTRACT

Changes in the demand for moisture by the atmosphere can significantly impact the vulnerability of ecosystems to drought. Between arid and humid regions lies a transition zone where a significant gradient in aridity also exists. This aridity gradient can shift depending upon changes in precipitation and atmospheric demand. Thus, we employ a metric known as the aridity index which is defined as the ratio of precipitation to potential evapotranspiration (PET), where PET represents the atmospheric demand for moisture. The aridity index allows for identification of climatological patterns in atmospheric demand and any deviations from those patterns. The individual components of aridity, which are precipitation and PET, were also analyzed to better understand which variable contributed to changes in aridity. Using reanalysis and observational data, this study focused on the Great Plains of the United States, which is a climatological transition between arid and humid climates. We found the gradient becomes weaker with time across the Great Plains. The trends found using North American Regional Reanalysis data were compared to observations by calculating aridity using Oklahoma Mesonet data, and these trends could have significant implications for agricultural practices and drought management on the Great Plains.

1. INTRODUCTION

In recent years, there has been increasing interest in changes to aridity within the climatological record. Observing shifts in aridity, precipitation, and potential evapotranspiration over different temporal scales will allow us to identify changes in aridity and its associated impacts within the Great Plains. Any trends within the Great Plains have potential ramifications such as impacts to food production in a region (Skaggs and Irmak 2012). Further, changes in aridity can influence not only food production, but ecosystems, hydrology, and vulnerable vegetation life overall. For this reason, it is important to understand temporal variation in aridity and other related variables.

The aridity index can be defined as the amount of moisture delivered to the surface in contrast to the amount of moisture that is being demanded from the atmosphere.

[1] *Corresponding author address:* Raquel Dominguez, c/o CAPS, 120 David L. Boren Blvd. Suite 2500, Norman OK 73072. Email: raquel.maritza@hotmail.com.

Specifically, aridity index is composed of two variables: precipitation and potential evapotranspiration (PET). PET is the evapotranspiration shown in fig 1a, that would occur from a well vegetated surface when moisture supply is not limiting. Temperature, wind speed, vapor pressure deficit, and net incoming radiation are variables that affect PET, and as such, they also influence the aridity index. Moreover, examining variables such as precipitation and PET individually is instrumental in understanding the variation of aridity that occurs within the Great Plains.

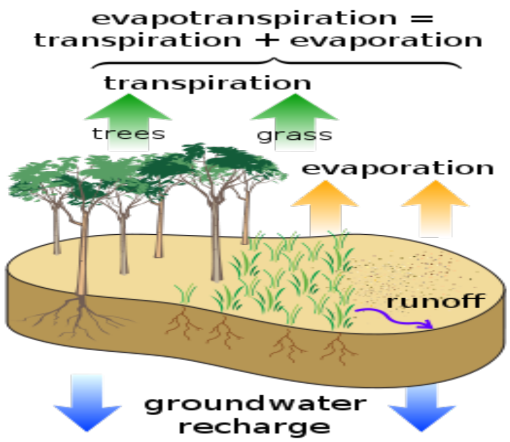


Figure 1a.) represents how evapotranspiration is the process of transpiration from agriculture and evaporation from water sources in an area.

The differences in aridity across the Great Plains is partly caused by differences in moisture transport from the Gulf of Mexico into the Great Plains via the low-level jet (Higgins et al. 1999). As a result, eastern portions of the Great Plains experience greater transport of moisture, resulting in greater annual precipitation. However, in the western Great Plains, southwesterly flow is deficient of significant moisture, resulting in lower annual precipitation (Seager et al. 2018a). Seager et al. (2018b) used the North American Land Data Assimilation System version 2 (NLDAS-2) to show that the projected cross-continental increase in PET causes aridity to increase more in the east than in the west. Furthermore, CMIP5 climate model projections have also suggested that there has been an eastward movement of given aridity values (Kukal and Irmak 2016A; Seager et al. 2018B).

The purpose of this research is to:

- Verify aridity index values produced by the North American Regional Reanalysis (NARR) by comparing these values to aridity index computed from Mesonet data.
- Confirm whether the aridity gradient is shifting using different observational and reanalysis datasets than the original study.
- Identify the dominant driver (precipitation versus PET) associated with this shift.

2. METHODS

2.1 Data

The NARR is subject to extensive quality assurance reviews and incorporates a variety of observational platforms from geostationary satellites, surface stations, and aircrafts (Mesinger et al. 2006). The NARR has a spatial resolution of 32 km per grid point or 0.3° at the lowest latitude and a temporal resolution of 3 hours. Three hourly data is aggregated to obtain monthly sums of precipitation and PET, and these monthly values were used for this particular study. NARR estimates of PET are derived utilizing The Modified Penman Scheme from Marht and EK (1984). Precipitation assimilations with the NARR were found to be very successful as it produced values quite similar to the precipitation inputs (Bukovsky and Karoly 2006). To validate the NARR's representation of aridity index and its component variables, comparisons of these variables were made with observations of precipitation and PET from the Oklahoma Mesonet. Mesonet sites that had continuous data from 2000-2015 were used for these comparisons. To sufficiently evaluate the diverse climate regimes of Oklahoma, one

Mesonet site from each of the nine climate divisions was selected. Results from this analysis are presented in section 3.

2.2 Study Period & Domains

The Great Plains lies within a natural transition zone between arid and humid regions, making the region a prime area to study aridity changes. Therefore, the study focused on aridity within the Continental United States (CONUS), with a specific focus on the Great Plains. This region covers 30% of the CONUS and accounts for 2,307,410 km^2 total (Kukal and Irmak 2016B). The NARR's portion of the analysis was completed for the time-period of 1979-2018. Due to limits in temporal coverage from the Mesonet, only the time period 2000-2015 was studied when comparing Mesonet and NARR data.

2.3 Statistical Analysis

To maintain consistency with previous work (Seager et al. 2018a,2018b), aridity index was calculated using the UNESCO (1979) method as seen in equation 1. This quantifies the amount of precipitation received with respect to evaporative demand at the surface, yielding a numerical index that defines the aridity of the region. With this definition, lower values of the aridity index indicate an arid climate where precipitation cannot meet atmospheric demand for moisture. Higher values indicate a more humid climate and suggest that the surface is receiving enough moisture to balance evaporative demand. Since precipitation and PET are measured in the same units, it is important to note that aridity index is a unit-less quantity.

Aridity Index =

$$\boxed{Aridity\ Index = \frac{Precipitation}{PET}} \qquad (1)$$

The annual aridity index was computed to provide a base state climatology within the CONUS. Annual means were also computed for precipitation and PET to assess which variable has the greatest contribution to the observed patterns in aridity climatology. In addition, the standard deviation was taken for the same variables to observe the base state variability within the CONUS.
Monthly means and standard deviations of each variable were also computed to investigate the seasonality of aridity, and whether the relative contributions of precipitation and PET to aridity also have seasonal variability. Lastly, monthly and annual trends were computed using least squares linear regression to determine whether spatial patterns of aridity are changing across the Great Plains. A classification chart seen in Table 1, with aridity index representing values ranging from 0.05 as hyper arid to 0.65 as hyper humid was utilized to further specify how aridity index defines a region's atmospheric climate.

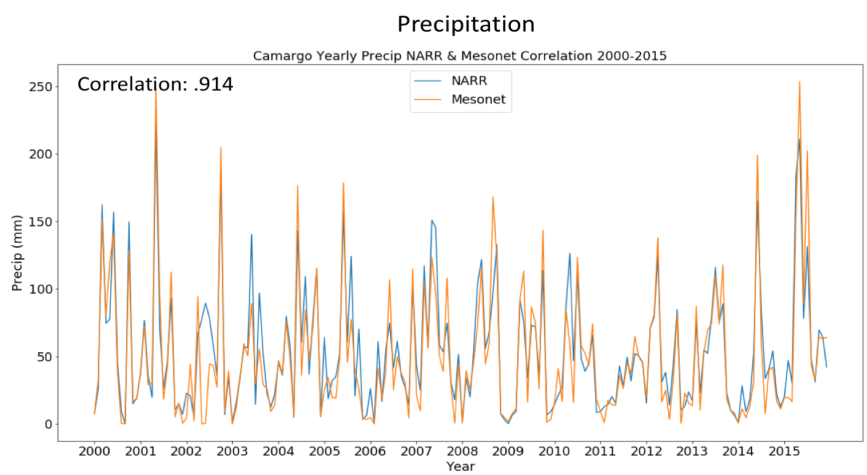
CLASSIFICATION	ARIDITY INDEX
AI < 0.05	Hyper-arid
0.5 < AI < 0.2	Arid
0.2 < AI <0.5	Semi-arid
0.5 < AI <0.65	Semi-Humid
0.65 < AI > 0.75	Humid
AI > 0.75	Hyper-humid

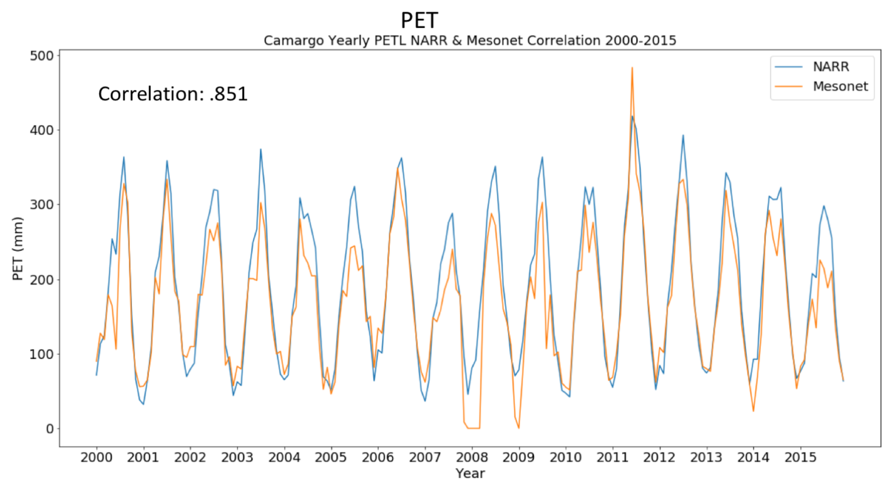
Table 1 is the classification scale that indicates the climate of a region depending on the aridity index value.

3. RESULTS

To investigate the reliability of the NARR, correlation coefficients were computed. Results showed high correlation between Mesonet and NARR data for precipitation, PET, and aridity, with all coefficients ranging from 0.7-0.96. Only one correlation coefficient was found to be less than 0.80 which was PET at Mt. Hermen. Throughout the examination of the correlations, it was discovered that the western divisions of Oklahoma had the overall best agreement with the NARR. For example, Camargo, a western division, had correlations coefficients consisting of 0.91 for precipitation, 0.93 for PET, and 0.86 for aridity as shown in figures. However, Pryor, an eastern division, had correlation coefficients of 0.89 for precipitation, 0.85 for PET, and 0.80 for aridity as shown in figure 3. The largest differences within the correlations were seen in PET between the western and eastern divisions. For example, for PET Mt. Hermen, an eastern division, had a correlation coefficient of 0.70, and Goodwell, a western division, had a correlation coefficient of 0.82, which further confirms that the western divisions generally have best agreement within these variables. Despite this, the overall agreement within all variables showed high correlation, with only one coefficient being under 0.80, thus confirming the NARR's reliability and accuracy of precipitation, PET, and aridity.

Figure 2 Displays Camargo's mesonet coefficients with the NARR for Precipitation, PET, and aridity.





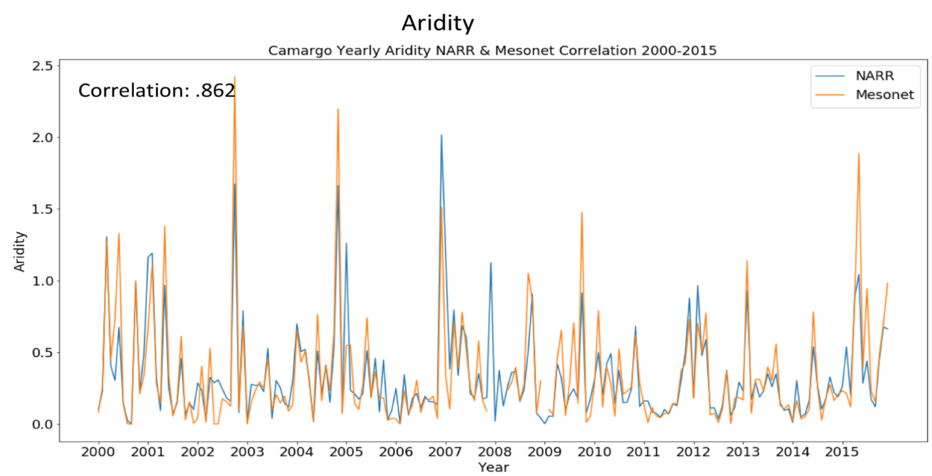
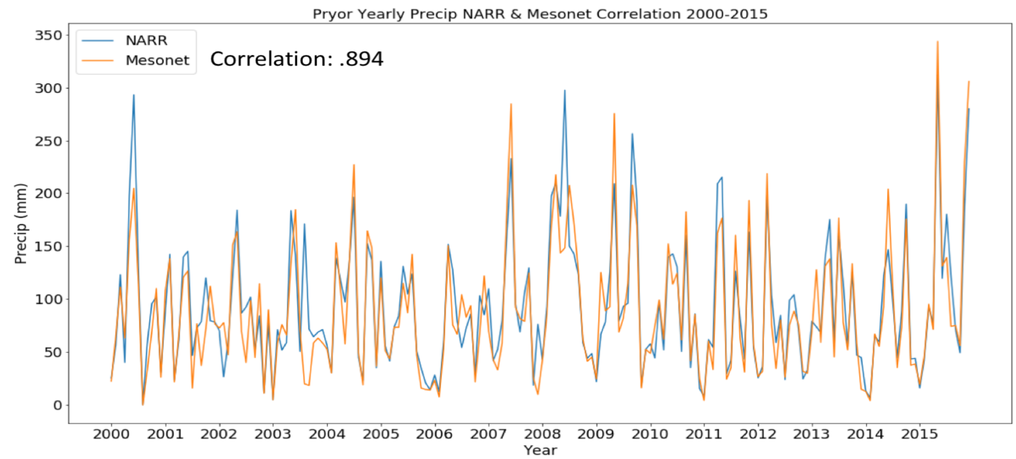
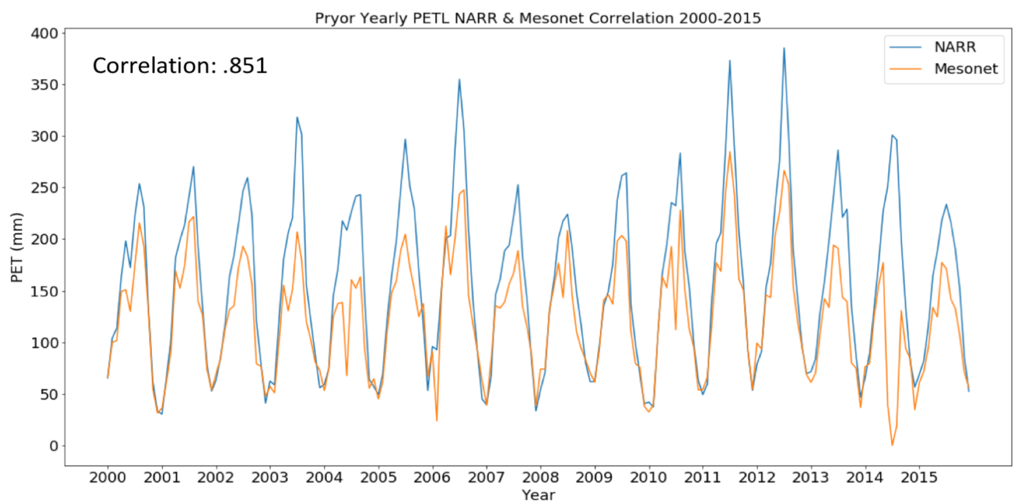


Figure 3 Displays Pryor's mesonet correlation coefficients with the NARR for precipitation, PET, and aridity

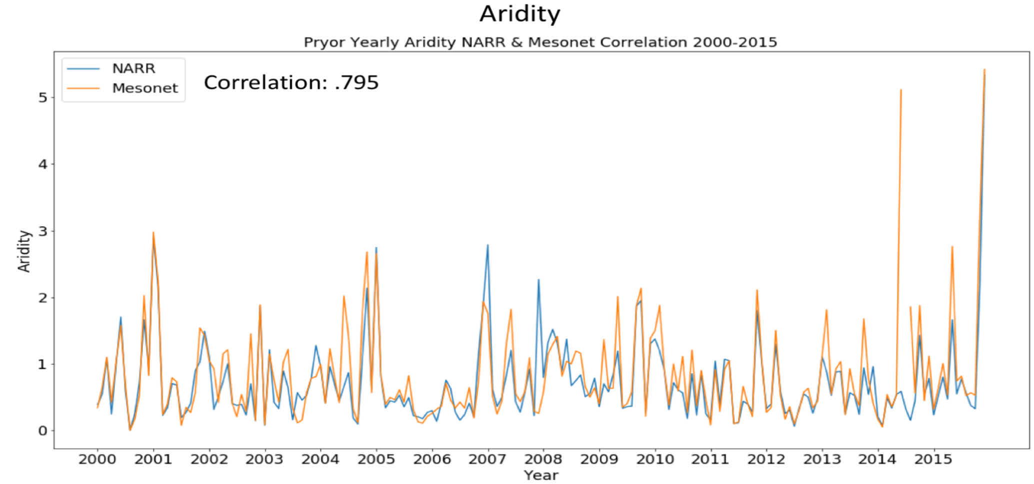
Precipitation



PET



Aridity



Using NARR, it was observed that while given aridity values were consistently shifting year to year on an annual timescale, there was no distinct shift in the gradient of aridity, but rather this gradient appeared to become more diffuse on an annual climatological record as seen in figure 2, contrary to Seager et al. 2018B findings. This suggests that eastern regions are becoming more arid, and western regions are becoming more humid. It is important to note that there is a zonal precipitation gradient across the

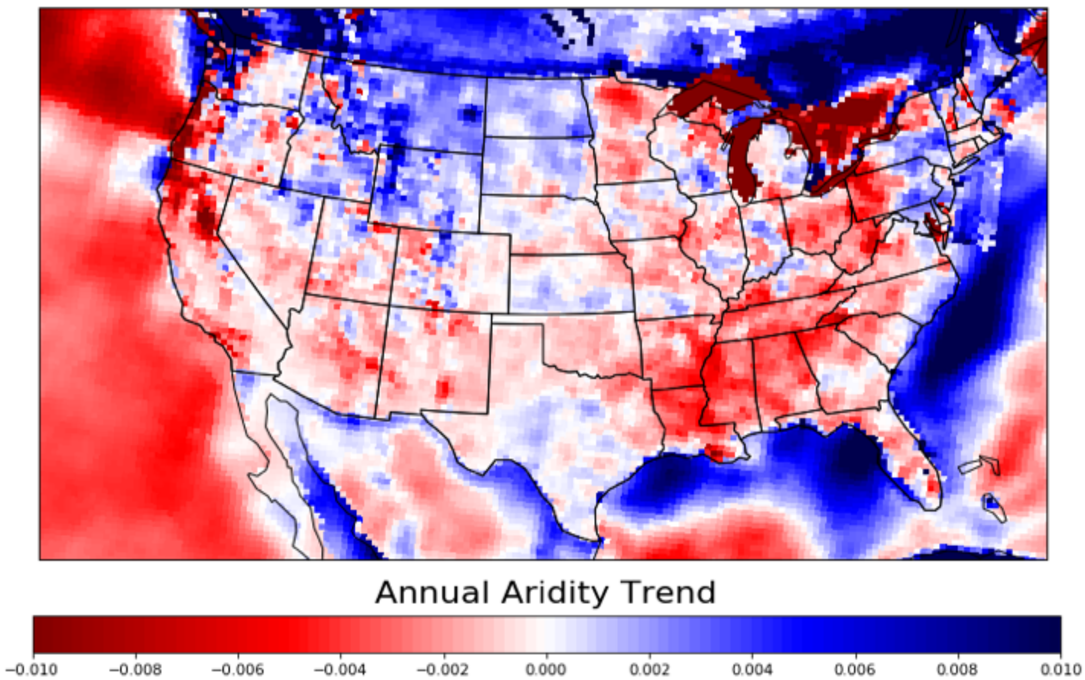


Figure 4 displays the diffusion of the aridity gradient with dryness decreasing in the east and decreasing in the west.

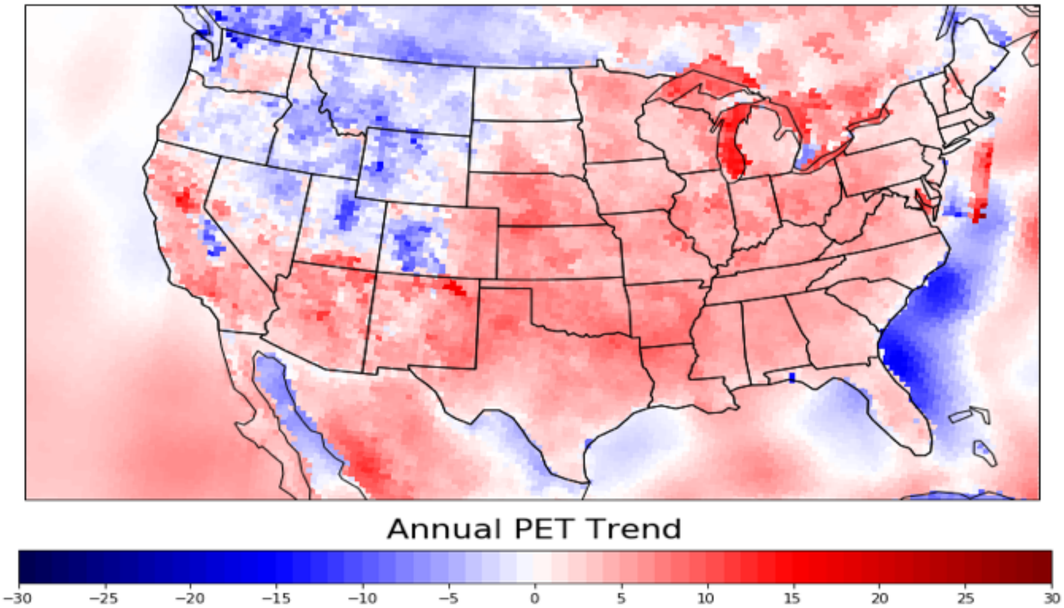


Figure 5 displays that PET is increasing throughout the majority of the great plains and showing an increase in PET more so in the east than in the west.

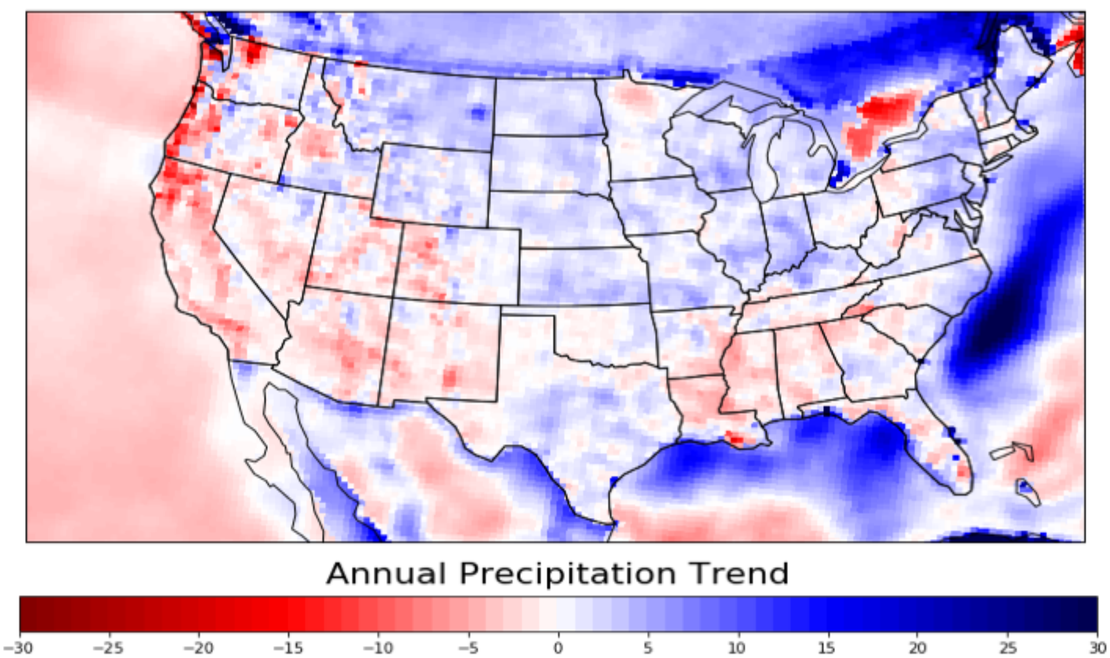


Figure 6 displays that precipitation is increasing in the west and decreasing throughout the eastern Great Plains.

CONUS with western regions receiving 163 mm, to eastern regions receiving 1,486 mm during the growing season (Kukal and Irmak 2016A). This west to east increase in precipitation and increase in aridity in the eastern regions of the Great Plains could imply that PET is increasing at a rate that surpasses that of precipitation. While this is possible, the annual plots of precipitation and PET suggest that both variables hold equal dominance over the aridity index on an annual timescale. This can be seen in figure 3 and 4 as both precipitation and PET values work together to impact aridity. Among climatological calculations of aridity index, precipitation, and PET were examined within an identical climatological record for comparison to aridity. Within the monthly trends, all variables displayed highly variable spatial patterns. While this variability was prominent, monthly trends within precipitation and aridity resembled a strong similarity. Figure 5 show that dry aridity index values stay to the southern portion of the Great Plains from May-June. In June, these values shift to the northern portion of CONUS, and show high spatial variability from August-October. Precipitation also resembles this as seen on figure 6, with low precipitation values in the southern Great Plains from May-June that shift to the north in July, then proceed to express high variability from August-October. It is important to note that although variation was high within aridity and precipitation from August-October, both of these variables displayed the same patterns within this variability over CONUS. However, in PET, higher values indicating drier climate also stay to the southern portion of the Great plains from May-June as seen in figure 7, but do not display the northward shift that were seen in precipitation and aridity. Differences in the variation from August-October of PET from precipitation and aridity were also observed. Although PET has a great impact on aridity, precipitation mirrored patterns shown in aridity accurately. Although precipitation is highly variable across time and space, it displays dominance over aridity within a monthly climatological record.

4. CONCLUSIONS

Overall, it was shown that NARR provides a representative estimation of PET and precipitation temporal patterns when compared to the Oklahoma Mesonet. Given this information, there is greater confidence in the overall trends in aridity presented in this study. While NARR estimates of PET had better agreement with Mesonet estimates in some locations than others, this does not impact the overall trends observed. It may however introduce some biases in the annual means, but the primary objective of this study was to identify trends. NARR data indicates that the aridity gradient is diffusing over the Great Plains rather than shifting toward the east. Precipitation and PET were analyzed within the same climatological record to identify relative contributions of

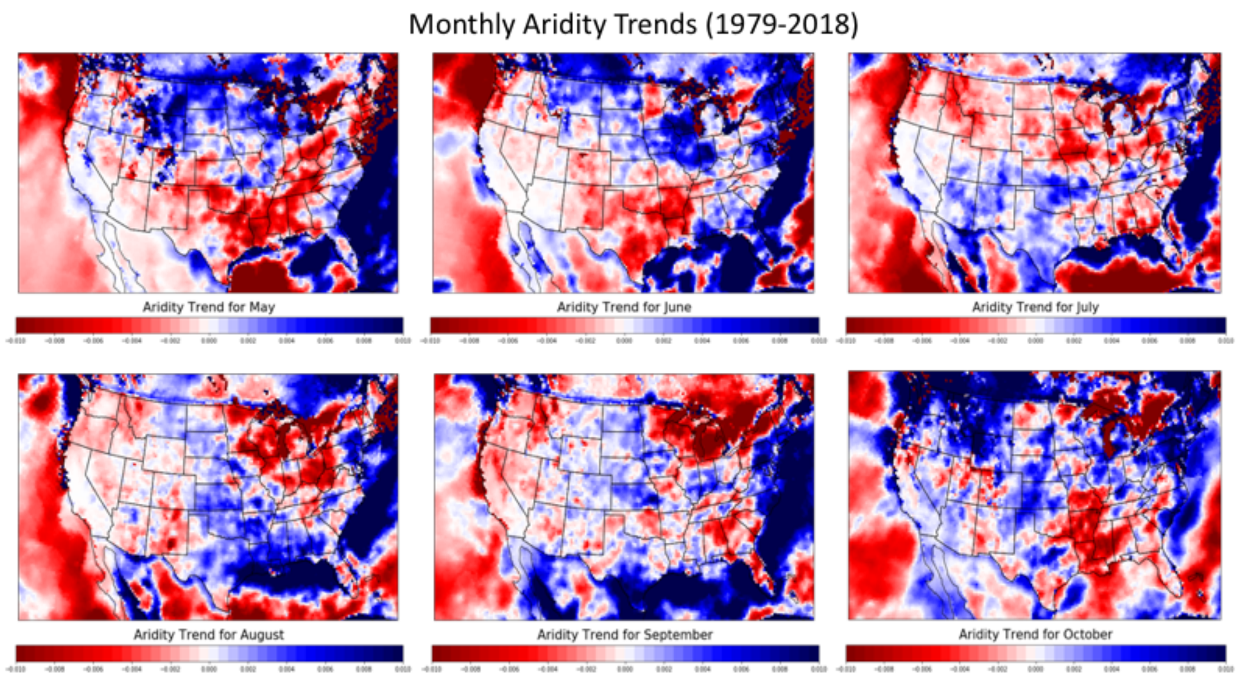


Figure 7 displays monthly aridity trends on a climatological record, with low aridity index values staying to the southern Great Plains from May-June, moving to the northern Great Plains by July, and behave disorderly from August-October.

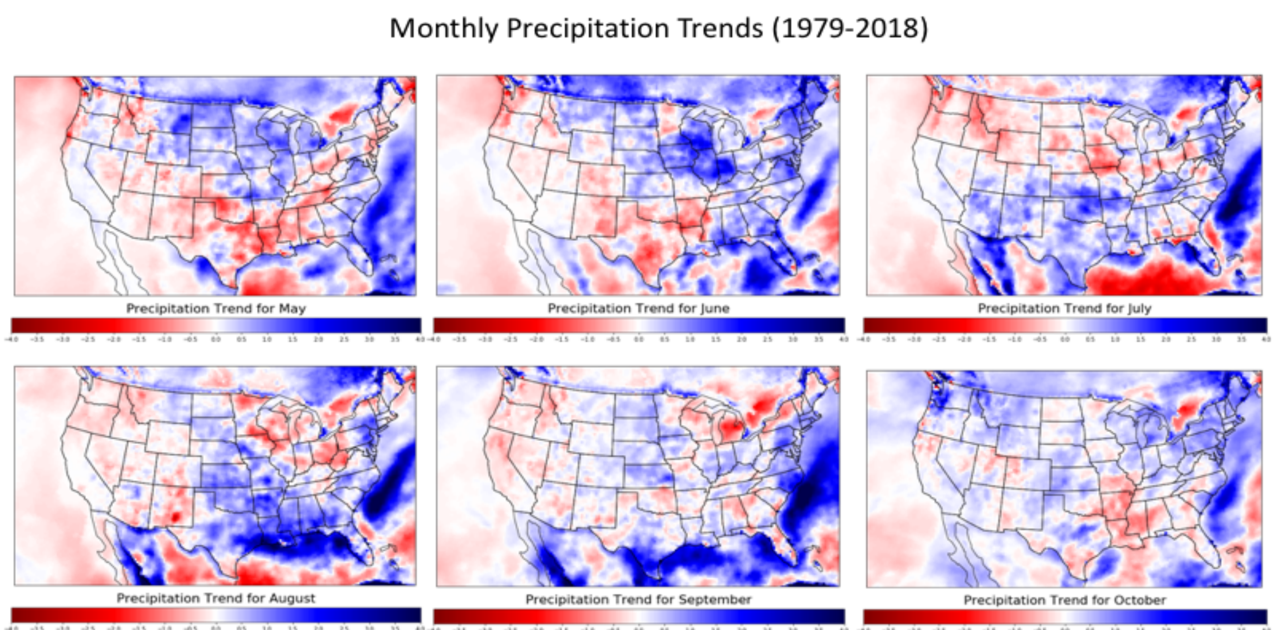


Figure 8 displays monthly precipitation with less precipitation to the southern portion of the Great Plains from May-June, moving to the northern Great Plains by July, and shows the same disorderly pattern from August-October.

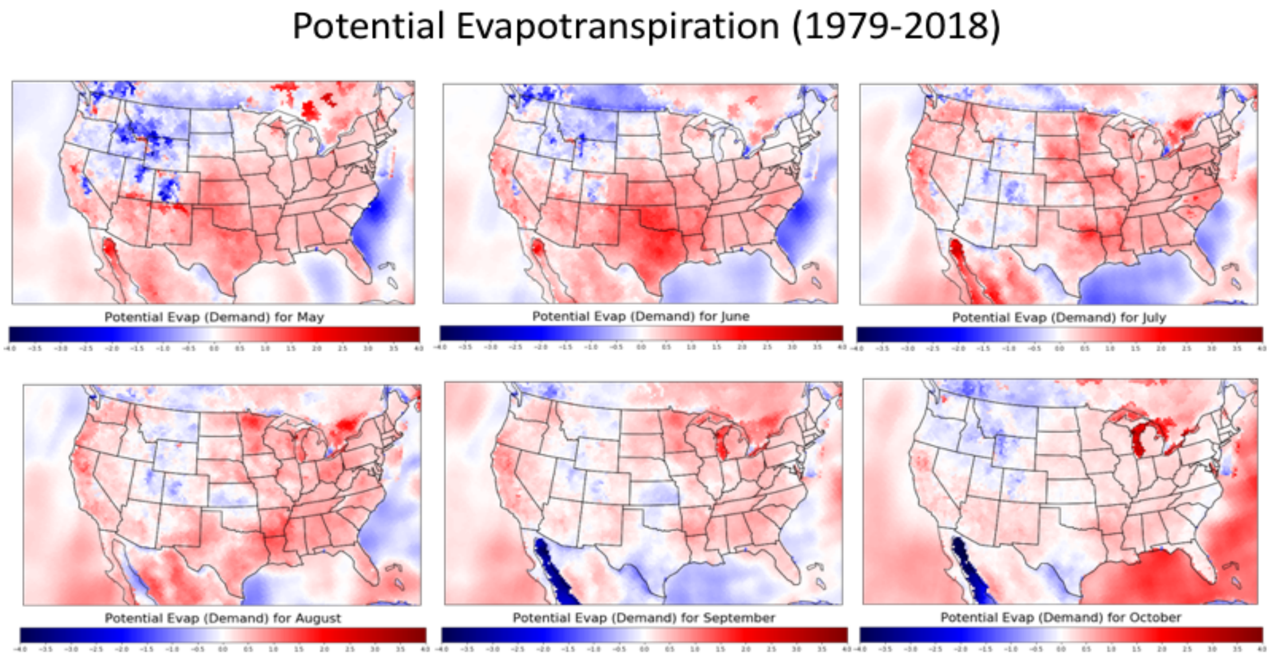


Figure 9 shows high PET values to the southern Great Plains, indicating dry weather from May-June, however these values do not display the northern shift that were present in precipitation and aridity. PET is seen to increase throughout the majority of CONUS on a monthly scale.

these variables to aridity. Although this diffusion of the aridity gradient on an annual timescale differs from recent publications, it provides us with additional insight into how complex aridity can be within differing datasets. These results also highlight how fluctuating variables such as precipitation, the dominant variable of aridity within a monthly record, has a large impact on climate within shorter timescales but holds less influence within an annual timescale.

In future work, it would be beneficial to detect a pattern within PET to see if it is truly increasing at a faster rate than precipitation and thus causing the east to become more arid. Examining the drivers of precipitation variability at a monthly scale would aid in understanding aridity's behavior throughout time and space. Determining how pluvial and drought periods affect aridity on a short-term scale would also be beneficial to explore.

Other important variables to explore include those which contribute to changes in PET such as net incoming radiation, temperature, wind speed, etc. This study focuses primarily on the CONUS, but it would be valuable to extend this research beyond North America, especially to other semi-arid regions of the world. Lastly, examining the correlation with other surface observation networks within the CONUS would be useful for additional confirmation of NARR reliability.

6. ACKNOWLEDGMENTS

I would like to thank my mentors, Ryann Wakefield and Jordan Christian for being hands on and guiding me through my REU journey. Whether it was science, code, or even life questions you both have been more than kind with your responses. CHEWe lyfe forever!

Appreciation is extended to Daphne LaDue as well as the NWC REU selection committee for allowing me to participate in this internship for the summer.

This material is based upon work supported by the National Science Foundation under Grant No. AGS-1560419.

7. REFERENCES

Kukal, M., and S. Irmak. “Long-Term Patterns of Air Temperatures, Daily Temperature Range, Precipitation, Grass-Reference Evapotranspiration and Aridity Index in the USA Great Plains: Part I. Spatial Trends.” *Journal of Hydrology*, vol. 542, 9 June 2016, pp. 953–977., doi:10.1016/j.jhydrol.2016.06.006.

Kukal, M., and S. Irmak. “Long-Term Patterns of Air Temperatures, Daily Temperature Range, Precipitation, Grass-Reference Evapotranspiration and Aridity Index in the USA Great Plains: Part II. Temporal Trends.” *Journal of Hydrology*, vol. 542, 9 June 2016, pp. 978–1001., doi:10.1016/j.jhydrol.2016.06.008.

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P.C. Shafran, W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E.H. Berbery, M.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.,* 87, 343–360

Seager, R., N. Lis, J. Feldman, M. Ting, A.P. Williams, J. Nakamura, H. Liu, and N. Henderson, 2018: Whither the 100th Meridian? The Once and Future Physical and Human Geography of America’s Arid–Humid Divide. Part I: The Story So Far. *Earth Interact.,* **22**, 1–22, https://doi.org/10.1175/EI-D-17-0011.1

Seager, R., J. Feldman, N. Lis, M. Ting, A.P. Williams, J. Nakamura, H. Liu, and N. Henderson, 2018: Whither the 100th Meridian? The Once and Future Physical and Human Geography of America’s Arid–Humid Divide. Part II: The Meridian Moves East. *Earth Interact.,* **22**, 1–24

Illston, B.G., J.B. Basara, C.A. Fiebrich, K.C. Crawford, E. Hunt, D.K. Fisher, R. Elliott, and K.Humes, 2008: Mesoscale Monitoring of Soil Moisture across a Statewide Network. *J. Atmos. Oceanic Technol.,* **25**, 167-182, https://doi.org/10.1175/2007JTECHA993.1

Illston, B. G., Basara, J. B. and Crawford, K. C. (2004), Seasonal to interannual variations of soil moisture measured in Oklahoma. Int. J. Climatol., 24: 1883-1896. doi:10.1002/joc.1077