THE EFFECTS OF ANTECEDENT SOIL MOISTURE ANOMALIES
ON TORNADO ACTIVITY IN THE UNITED STATES

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ABSTRACT

Recently there has been increased interest in the ability to forecast severe weather events on a seasonal scale. Being able to forecast events such as the April 2011 outbreak could have beneficial impacts such as increased preparedness at the Federal and local level as well as greater public awareness. To better forecast tornadoes on a seasonal scale, we must first look at the underlying factors that influence the inter-annual variability of both tornado locations and intensity. Soil moisture has been shown, on regional scales, to have an effect on moisture within the boundary layer, and therefore, the potential for deep convection. Previous studies have examined relationships between factors related to soil moisture such as precipitation and evapotranspiration and their effects on tornado climatology at the local and regional scale. This study examined the relationship between antecedent soil moisture and tornado activity in five regions within the United States east of the Rocky Mountains, using two approaches. The first approach used fall and winter soil moisture anomalies as a predictor for spring tornado activity while the second looked at the six months preceding each month in the year. In addition, we also assessed the reliability of our modeled soil moisture dataset by comparing it to the high-resolution Oklahoma Mesonet observational network.

1.INTRODUCTION

Motivation

In recent years, there has been an increased interest in seasonal forecasting of extreme weather events. S.1331, the Seasonal Forecasting Improvement Act, a bill proposed by the senate in May 2015 seeks to improve seasonal forecasting of extreme events from droughts to tornadoes, and to encourage better communication of such forecasts (cite the actual website with the bill from Washington post article).

Brooks et al. (2003) noted that severe weather, and in particular, tornado climatologies can be useful to multiple public service sectors including weather forecasters, emergency managers, insurance companies, and the general public. It is therefore important to gain a better understanding of factors that affect the seasonal and annual variation of tornado activity in the United States.

Even with advances in tornado detection, and public awareness, we are still unable to prevent all deaths related to tornadoes (Ashley, 2007). Being able to create a seasonal forecast for tornadoes, especially for large outbreak years such as 2011, could be critical to saving lives, and enhancing public preparedness and awareness months in advance of such a threat.

Objective

Our study seeks to examine whether or not a relationship exists between soil moisture anomalies and tornado activity in the United States. Soil moisture, in addition to vegetation type, has been shown to regulate heat and moisture fluxes within the planetary boundary layer, hence influencing the thermodynamic structure of the atmosphere (Hanesiak et al., 2009; Raddatz, 1998; Basara and Crawford, 2002; Raddatz and Cummine, 2003; Koster et al., 2004; Raddatz, 2006).

Wei (1995) discusses the critical link between soil moisture and the atmosphere, as the near surface soil moisture is an important component for sensible and latent heat exchange with the atmosphere. It has been suggested that soil moisture is linked to the

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planetary boundary layer through vegetation (Hanesiak et al., 2009). Basara and Crawford (2002) through the use of field measurements at the Norman, Oklahoma Mesonet site, demonstrated a linear relationship between root zone soil water and atmospheric parameters such as sensible heat flux, latent heat flux, and mixing ratio, implying the importance of soil moisture and atmosphere interactions.

The relationship between evapotranspiration and planetary boundary layer moisture was demonstrated by Raddatz and Cummine (2003) when examining how the development of local crops varied on an inter-annual and seasonal scale in the Canadian prairies and how these variations influenced convection. They note that evapotranspiration is limited by the amount of soil moisture available in the soil, and therefore evapotranspiration can be assumed to be a reflection of soil moisture levels. They determined that crop maturity varied on an annual scale, where peak evapotranspiration was measured by looking at peak fractional consumptive use for the crops. This peak in evapotranspiration increased specific humidity within the boundary layer, which increased the amount of buoyant energy for deep convection, thereby potentially triggering development of tornadic thunderstorms. When the authors looked at a drought year, (e.g. 1988), peak crop development, peak evapotranspiration, and peak tornado days all occurred earlier. During a cooler, wetter year, (e.g. 1993), peak crop development occurred later as well as peak tornado days.

Shepherd et al., (2009) used antecedent precipitation departures as a predictor for spring (March through June) tornado activity in the southeastern United States, particularly Georgia. Their findings suggested a positive correlation existed between antecedent fall-winter drought and the subsequent spring decrease in tornado days. The authors concluded that future work should look at whether or not the relationships they identified existed at other times of the year.

The studies mentioned demonstrate an indirect relationship between soil moisture and tornado activity in two distinct regions of North America. This suggests that antecedent soil moisture may have a seasonal scale effect on the following tornado season, though few studies have looked at this relationship on both a large spatial and temporal scale. Because of this we are motivated to examine soil moisture as a direct predictor of tornado activity throughout the United States east of the Rocky Mountains.

2. DATA AND METHODS

Study Area

We focused on the region east of the Rocky Mountains and divided it into four smaller regions(i.e.Northern Plains, Southern Plains, Northeast, Southeast)

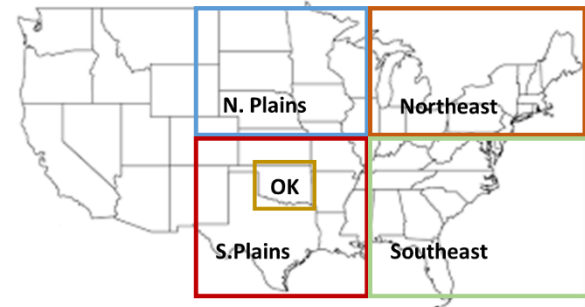and a fifth sub-region in Oklahoma. The regions are divided as shown in Figure 1 and Table 1.

Figure 1: Focus regions for analysis

Table 1: latitudes and longitudes for the regions of focus

REGION	NORTH LAT	SOUTH LAT	WEST LON	EAST LON
NORTHERN PLAINS	49°N	40°N	105°W	90°W
SOUTHERN PLAINS	40°N	25.5°N	105°W	90°W
NORTHEAST	49°N	40°N	90°W	72°W
SOUTHEAST	40°N	25.5°N	90°W	72°W
OKLAHOMA	34°N	37N	100°W	95°W

Data

Tornado data was acquired using the Storm Prediction Center's severe weather database from which tornado days and tornado counts for all tornadoes rated E(F1) or greater within each region were calculated, for each month from 1954 through 2013. Individual tornadoes were considered to be those that have their own unique tornado number within the database. Tornado days were calculated by finding only the days with tornadoes greater than or equal to a rating of E(F1). We chose to examine tornado days in addition to tornado counts, because tornado days provide a more reliable measure of tornado activity. (Raddatz and Cummine, 2003)

Soil Moisture data was provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ at 0.5° grid spacing. To calculate soil moisture, a land surface model using equation (1) is integrated forward in time and space to generate monthly soil moisture values for each grid point. The variable w represents soil moisture and P is observed precipitation. E represents evaporation and is estimated from observed temperature, while R is runoff which is estimated based on tuning the model to small river basins in eastern Oklahoma, which results in an implied soil column of 1.6 meters (Huang et al 1996, Fan and van den Dool 2004). We used both calculated values from 1953 to 2014, and long term monthly mean values calculated from the period 1981 to 2010.

$$\frac{dw}{dt} = P - E - R, \qquad (1)$$

Soil moisture departures were calculated for each grid point at each month in time using the following equation:

$$departure = 1 + \left(\frac{obs - LTM}{LTM}\right) \times W, \qquad (2)$$

where "*obs*" is the CPC calculated soil moisture value at a particular grid box at a particular time, "*LTM*" is the monthly long term mean within the grid space, and "*W*" is the weighting factor to account for the decrease in grid box area with increasing latitude. W is is calculated using the latitude in radians (lat):

$$W = [\cos(lat)]^{1/2} \qquad (3)$$

Departure values less than one are considered drier than average while departure values greater than one are considered wetter than average. We then calculated the average departure over the entirety of each region for each month in the data set to give us regional soil moisture departures.

Experiment 1

Our first experiment used similar time periods as Shepherd et al (2009) but used antecedent soil moisture instead of rainfall, in each of the five regions. We looked at fall and winter months (September through February) preceding the spring tornado season months (April through June). Average soil moisture departures over the entire region were calculated by summing the regional soil moisture departures for the fall-winter period and dividing by six. Tornado days and tornado counts were then summed for the 3-month tornado season and divided by three to provide tornado counts per month, and tornado days per month. This was done for years 1953-2013 where 1953 was the first year for soil moisture since the fall-winter season began in September 1953, and 1954 was our first year for tornado data since the tornado season occurred in the following spring of 1954. We conducted a least squares linear regression, and all correlation coefficients were calculated at the 95% significance level.

Experiment 2

The second experiment looked at 6-month antecedent soil moisture as a predictor for 1 month tornado activity, for each month in the year. For example, June tornado activity would be predicted using average soil moisture values from the preceding December through May, and July tornado activity would be calculated using average soil moisture values from the

preceding January through June. We generated scatter plots of tornado days versus soil moisture and tornado counts versus soil moisture over the entire time period for each month.

Correlation coefficients (r), and percent of variance (r^2) were also calculated for each month in each region. Monthly time-series for the magnitudes of both of these parameters were plotted for each region to identify seasonal patterns in soil moisture and tornado relationships.

Validation Procedure

Once we examined soil moisture as a predictor for tornado activity, we examined how well the CPC soil moisture dataset represented reality. The Oklahoma region we analyzed was selected specifically for this purpose. The Oklahoma mesonet presents a unique opportunity to compare in situ soil moisture observations to the modeled soil moisture values from the CPC. Oklahoma's large range in annual rainfall (Figure 2) allows for comparison of the CPC modeled soil moisture to observed soil moisture in both wet and arid regions.
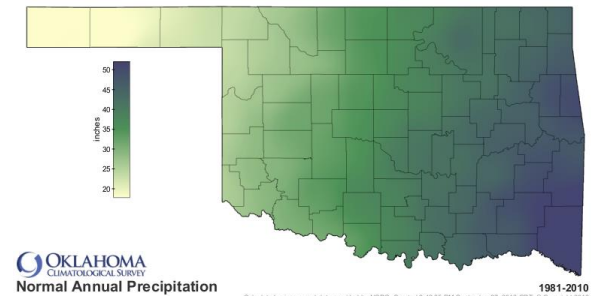

Figure 2: Annual Precipitation in Oklahoma.

Source: Oklahoma Climatological Survey

The deepest soil moisture measurement for the Oklahoma Mesonet is 80 cm Plant Available Water while the CPC soil moisture is a 1.6 m deep bucket model. This means that the two measurements are not directly comparable in terms of magnitude, but their co-variability and trends can indicate whether the CPC is able to reproduce the behavior of observation.

For this comparison we did not calculate departures, but instead looked at the observed values in the Mesonet case and the modeled values in the CPC case. The time period for the validation experiment was from 2000-2015 to ensure the greatest amount of Mesonet station coverage with respect to soil moisture (Brad Illston, personal communication). A complication that arose with looking at the deepest soil moisture depth, was the reliance on measurements at shallower depths to acquire measurements at the

deepest depth. If the sensor failed to take measurements at a level shallower than 80 cm, then data were unavailable for the 80 cm depth.

A point—by—point comparison was performed using the center point of each CPC grid box, and locating the nearest Mesonet station to that center point. Dates missing observational data at the Mesonet station were eliminated for both the Mesonet dataset and the CPC dataset. A lag correlation was performed on the CPC dataset after removing points in which data was missing. The lag correlation was computed as follows:

$$Lag(L) = cor(var_{(t0,t-L)}, var_{(t0+L,t)}) \qquad (4)$$

where L is lag 1, lag 2, etc., and *var* is the variable we are examining. In our case *var* was the CPC soil moisture dataset. For example, to calculate lag 1, the case where L=1, we conducted a Pearson product-moment correlation given by:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \qquad (5)$$

where *x* represents all of the CPC soil moisture values through the second to last value (*t-L*). This is the first array that we are comparing. The second array of values represented by y is the second value in the set (*t0+L*) through the last value in the set (*t*). The correlation between the two arrays is computed as in equation 5. This was performed until the lag correlation coefficient was less than 0.25. To calculate degrees of freedom, the sample size was divided by the number of lags with correlations greater than 0.25.

Using the degrees of freedom we found from the autocorrelation, we conducted a least-squares linear regression on the two data sets to find the correlation coefficient, percent of variance, and p-value. This was performed for every grid box and its nearest Mesonet station within Oklahoma, including the panhandle.

3. RESULTS

For experiment 1, when comparing 6-month fall-winter soil moisture departures to spring tornado days, we found statistically significant correlations at 95% confidence interval, in three of our regions. It is interesting to note the positive correlation between soil moisture departures and tornado days in the Southeastern United States (Figure 3d), but a negative correlation in the Northern Plains and Oklahoma (Figure 3a and Figure 3e respectively). These results certainly merit further investigation into the physical mechanisms causing an opposite relationship in the Plains to the Southeast. Another interesting result was the fact that Oklahoma showed a significant negative correlation between soil moisture and tornado days, while the Southern Plains as a whole, which also contains Ok-

lahoma, had a statistically insignificant positive correlation (Figure 3b). The Northeastern United States also showed a statistically insignificant positive correlation (Figure 3c).
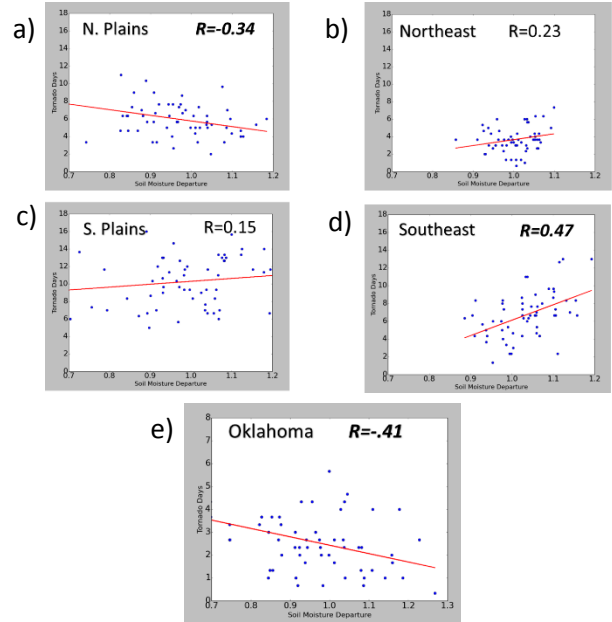

Figure 3: September through February average antecedent soil moisture (x-axis) as a predictor of average April through June tornado days per month (y-axis). a) Northern Plains, b) Southern Plains c) Northeast, d) Southeast e) Oklahoma

When the same experiment was conducted using fall-winter soil moisture departures as a predictor for tornado counts, there were no statistically significant relationships at the 95% confidence level (Figure 4). Oklahoma showed the most substantial negative correlation between tornado counts and soil moisture as we expected, though the correlation was only significant at a 94% confidence level. In the southeastern region, we have one significant outlier, which was attributed to the 2011 tornado season.
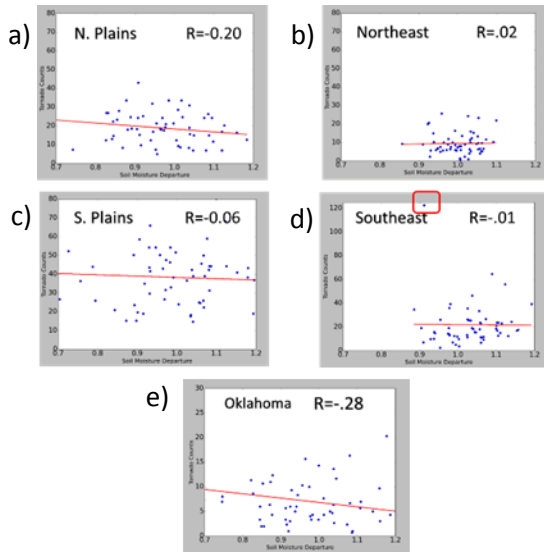
Figure 4: September through February average antecedent soil moisture (x-axis) as a predictor of average April through June tornado counts per month (y-axis). a) Northern Plains, b) Southern Plains c) Northeast, d) Southeast e) Oklahoma

We hypothesized that this outlier was preventing us from seeing the positive correlation we were expecting to see. In the absence of the outlier, a trend of increasing tornado days with increasing soil moisture departures is apparent, though the line of best fit does not match this (Figure 5a). After removing the outlier, the linear regression was performed once again, and resulted in a positive correlation (Figure 5b). The correlation was barely insignificant at the 94% level, when the criteria for significance was 95%, but these results were more consistent with those of the experiment with tornado days in the southeast.
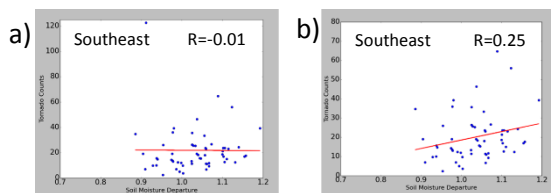

Figure 5: September through February average antecedent soil moisture (x-axis) as a predictor of average April through June tornado counts per month (y-axis). a) Southeast before removing outlier b) Southeast after removing outlier

For the second experiment, which looked at 6-month antecedent soil moisture as a predictor for 1 month tornado days and tornado counts, there was more consistency in the behavior of the two predictands (tornado days and tornado counts). For tornado days as the predictand, the percent of variance (r^2) explained by soil moisture departures was between 10% and 25%.
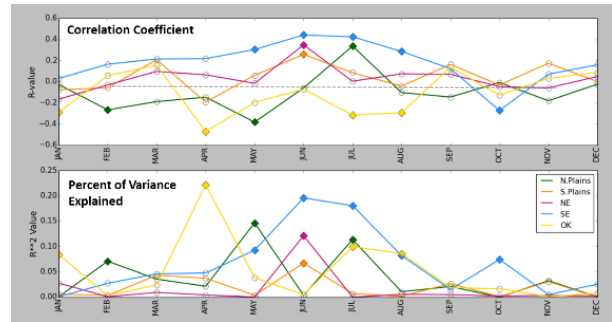

Figure 6: Correlation coefficient (top) and percent of variance explained (bottom) for six month antecedent soil moisture anomalies as predictor for one month tornado days in each region.

As in the first experiment, our most impressive result for the second experiment occurred in the southeastern region (Figure 6: blue line). Correlations became more positive during the warm season, with May through August having positive and statistically significant correlations. October was anomalous with a negative correlation, though we believe this may be attributed to influence of tropical cyclones on tornado activity in this region. The rest of the months did not have a statistically significant correlation in the southeast.

The northern plains region (Figure 6: green line) behaved as expected with a statistically significant negative correlation in May. A surprising finding was that the correlation became positive and statistically significant in July. This did not appear in the first experiment because only tornado days within the time period of April to June were examined, and the antecedent months had been held constant as September through February, whereas the antecedent months for only the month of July were January through June. This finding suggests the need for future study regarding which physical processes may be controlling the soil moisture and tornado days relationship. The significant negative correlation for the month of February was ignored due to small sample size. Few tornadoes occur during this month in the northern plains, and therefore it is difficult to assume any relationships from this point.

Oklahoma also demonstrated a significant negative correlation between soil moisture and tornado days in April, July and August. The correlations in May and June were also negative, though not significant, and future work could examine why the relationship in these two months is not as strong (Figure 6: yellow line).

The northeast and southern plains region only had one statistically significant correlation for the entire year, and there was no clear trend in the data points to suggest the existence of a minor relationship (Figure 6: pink line and orange line respectively).

The tornado counts and soil moisture relationship in the second experiment was again, not as strong as the relationship between tornado days and soil moisture, though the overall behavior and trends of the original regions were similar. Between 10% and 20% of the variance in tornado counts could be explained by soil moisture in the statistically significant cases, though there were fewer significant points (Figure 7).
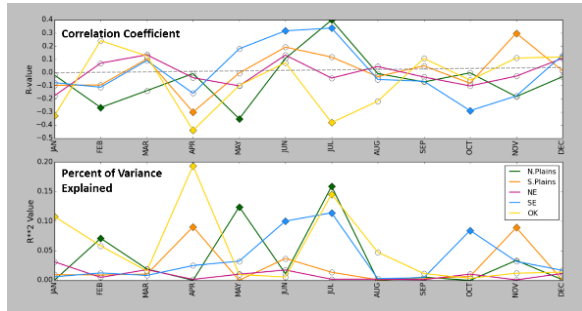

Figure 7: Correlation coefficient (top) and percent of variance explained (bottom) for six month antecedent soil moisture anomalies as predictor for one month tornado counts in each region.

June and July were the only warm season months in the southeast (Figure 7: blue line) to have a significant correlation between tornado counts and soil moisture, and the correlation coefficient curve peaks more sharply for warm season tornado counts than it does for warm season tornado days in the southeast. The negative correlation in October also exists when we look at tornado counts versus soil moisture.

The northern plains (Figure 7: green line) also shows a negative correlation between tornado counts and soil moisture in May, with a positive correlation in July, confirming further investigation into the mechanisms causing this result for both tornado days and tornado counts is necessary. The negative correlation in February was ignored again despite its statistical significance due to small sample size.

Oklahoma (Figure 7: yellow line) had more fluctuations in the correlation coefficient curve with two statistically significant negative correlations in April and July. The negative correlations are not maintained in the months between April and July, which we expected since the negative correlation between fall-winter soil moisture and spring tornado days in the first experiment for Oklahoma was statistically insignificant, yet still negative.

Both the northeast and southern plains (Figure 7: pink line and orange line respectively) had only one statistically significant point, and no distinguishable pattern in the correlation coefficient curve to conclude the existence of a relationship.

Mesonet vs. CPC Comparison

It was concluded that relationships between tornado activity and soil moisture existed in the southeast, the northern plains and Oklahoma, however, it is necessary to also test the quality of the CPC soil moisture data set to examine how well it reflects reality. The Oklahoma Mesonet provides a unique opportunity to acquire observed soil moisture data at a high resolution to compare to the modeled CPC soil moisture dataset.

A point by point comparison was performed between the central point of each 0.5° grid box, and the nearest Mesonet station to that point. After finding the nearest points, it was clear that the Mesonet spacing matched the spacing of the grid boxes well as we can see in figure 8.
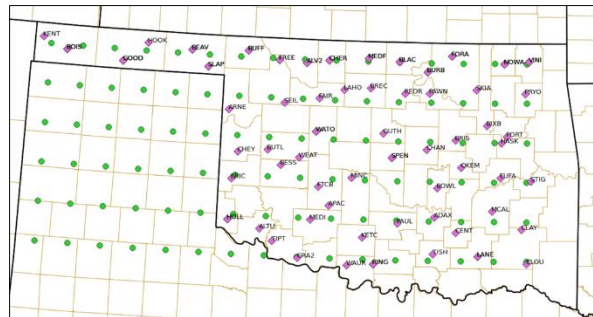

Figure 8: Mesonet stations are represented with diamonds and the center of each grid box is represented by the filled circles.

Because of a lack of soil moisture observations at the most shallow depths at some Mesonet stations, some grid boxes did not have data for comparison, though overall, the results produced a strong representation of how well the CPC modeled reality within Oklahoma. It was assumed that despite the different measurements between the two data sources, similar behavior should be exhibited if the CPC dataset does represent soil moisture variability well.

The grid boxes which did have Mesonet data for comparison all had statistically significant positive correlations. Eastern and Central Oklahoma had the strongest correlations between Mesonet data and CPC data with many of the grid boxes at a confidence level greater than 99.5%. The Mesonet station at Arnett, which represents a 99.5% confidence level has a correlation coefficient of 0.57, while the Mesonet station at Cheyenne, which represents the 95% confidence level has a correlation coefficient of .40 (Figure 9).

Statistical significance decreases slightly for grid boxes in the panhandle, though they are still statistically significant at a 95% level or above. This may imply that the CPC soil moisture performs better in wet-

ter regions, and a decrease in performance in drier regions. It would be useful to compare the CPC dataset to regions beyond Oklahoma, but a lack of high resolution observation networks limits the ability to perform this analysis.
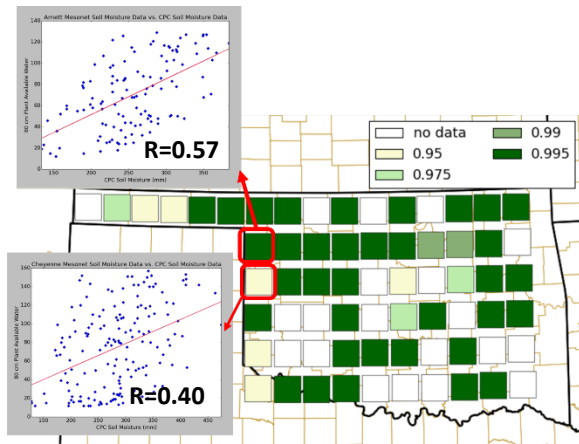

Figure 9: CPC grid boxes color coded by statistical significance. White boxes are the grid boxes for which there was no soil moisture data at the nearest Mesonet station. The scatter plots show the linear regression and data points for the Mesonet measurement of Plant Available Water at 80 cm (on the y axis) vs. CPC Soil Moisture in mm (on the x axis). The top scatterplot is the Mesonet station at Arnett, and the bottom scatter plot is the Mesonet station at Cheyenne.

4. DISCUSSION

Oklahoma demonstrated a negative correlation between antecedent soil moisture departures and tornado days despite its location within the Southern Plains, which demonstrated a statistically insignificant positive correlation. One theory is that the Southern Plains behave differently within its subregions, where the area nearest to the Gulf of Mexico may behave more like the Southeast, hence our positive correlation, while areas further from the Gulf may exhibit behavior more similar to that of the Northern Plains and Oklahoma. This would need to be examined in future work where each of the four main regions examined in this study could be subdivided into smaller regions. It would also be useful to consider soil moisture departures in adjacent regions to determine if there is a spatial relationship and if there is some influence from local advection.

One limitation to examining smaller regions would be sample size, especially in regions that do not experience a large number of tornadoes annually. This is why we chose to examine 4 larger regions in this initial analysis. It would be useful, as mentioned above, to subdivide the southern plains region into smaller regions. It would be easier to subdivide this specific

region due to a larger sample size, as this region sees a significant number of tornadoes each year.

Future analyses could also divide the overall region east of the Rocky Mountains into smaller regions based on seasonality of tornado season. Brooks et al. (2003) found Texas panhandle to have the strongest seasonality with a near 70% chance that the peak day for tornado activity will occur within a 20 day window. When progressing further south and east, there is a greater variation in the date of maximum tornado activity, while to the north, the maximum date is more seasonal. We hypothesize that seasonality may also influence how much influence soil moisture may exert on tornado activity. A highly seasonal region may be driven more by the synoptic scale patterns while a more variable region could see greater influence from smaller scale processes such as the influence of soil moisture on triggering convection.

The strong relationship between the CPC soil moisture dataset and the Oklahoma Mesonet soil moisture observations suggests that further analysis on larger scales with the CPC dataset will model reality well.

We are limited by a lack of high resolution soil moisture observations (Koster et al., 2004), and based on the findings in this study, it is possible that the CPC dataset will perform slightly worse in regions drier than the Oklahoma panhandle.

Future Directions

In an ideal world we would conduct a comparison within 0.5° grid boxes of soil moisture and tornado data, but due to our 60 year dataset, we are limited by sample size. Future work will also need to look more closely at the physical processes driving the relationships observed within the northern plains region. It would be useful to determine why increased soil moisture increases tornado days and counts in late summer, but decreases tornado days and counts in the spring.

It is important to note the impacts of these findings for seasonal forecasting. While there is much to be investigated, these findings imply that soil moisture could be used as an additional variable for predicting seasonal tornado forecasts. The April 2011 outbreak did not adhere to the relationships found in the southeast, as it was a significant outlier, suggesting that large outbreaks may be more synoptically driven.

Because large outbreaks may be synoptically driven, it could also be useful to look at the relationship between soil moisture and non-outbreak tornado days. Eliminating days with significant synoptic influence and reanalyzing the data could provide some insight into whether soil moisture has a more robust effect on tornado activity, in the absence of large scale dynamics.

5. ACKNOWLEDGMENTS

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