USING SOIL MOISTURE AS A PREDICTOR FOR SPRING CONVECTION WITHING THE STATE OF MISSOURI

A Thesis Presented to the Faculty of the Graduate School at the University of Missouri

In Partial Fulfillment of the Requirements for the Degree

Master of Science

by

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The undersigned, appointed by the dean of the Graduate School, have examined the

thesis entitled

USING SOIL MOISTURE AS A PREDICTOR FOR SPRING CONVECTION

WITHIN THE STATE OF MISSOURI

Presented by Corey Clay,

a candidate for the degree of Master of Science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Professor Anthony Lupo

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Professor Christopher Wikle

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ABSTRACT

Previous studies have shown that increased soil moisture can affect the overlying water vapor in the atmospheric boundary layer (ABL), potentially moistening this layer. Increased buoyancy can create more turbulence and in turn, be more conducive for severe weather. Because of the position of Missouri within the center of the United States, many factors come together to create a wide variety of weather. This position also puts the state in a transition zone, meaning both dry soils and wet soils can lead to convection. This research will attempt to show how the amount of soil moisture can be an indicator for tornado, hail, and wind activity within the state of Missouri.

This study will have three main components and will focus on the period from 1980-2018 time period. The first part will use April-June soil moisture anomalies to see if there is a correlation to severe activity for the corresponding months. The second part will use soil moisture anomalies for the months of January-March to find a relationship to severe weather for the following April-June months. The third experiment will use soil moisture anomalies from September-February to assess the potential correlation to severe convection to the following April-June months. Synoptic maps, in conjunction with the ENSO phenomena, will be utilized to understand what other mechanisms may be attributing to the increase/decrease in storm reports within the state. Finally, a spectral analysis by using Fourier transforms will be conducted to see the interannual variability with respect to severe convection and soil moisture.

Results showed statistical positive significance comparing April-June soil moisture with April-June tornado and wind activity. Some positive and statistical negative significance was seen with the January-March soil moisture comparison to the following April-June severe weather reports. However, no statistical significance was found within the September-February soil moisture comparison to the following April-June severe weather reports. Most of the statistically significant correlations were noticed in south central Missouri, both positive and negative. Some variability was observed with ENSO years and tornado activity, indicating that the synoptic setup may play more of a role than soil moisture. La Niña was also found to produce more tornadoes even though drier conditions were evident during this period. Overall, southern Missouri was shown to be more conducive for severe weather, mainly tornado and wind events.

CHAPTER 1. INTRODUCTION

1.1 Purpose

There are many known mechanisms which contribute to convection (Newton 1963, Brooks and Craven 2002, Kim et al. 2003, Sherburn et al. 2014, 2016) but little is known of the importance of soil moisture and how much or little it contributes to storm development. Moisture is one of the most important factors, as buoyancy enables a parcel to accelerate through the atmosphere (Rasmussen and Blanchard 1998). The more moisture that is added to the atmosphere, the more buoyant a parcel will become. Therefore, it is reasonable to assume moisture within soil can, at least in some part, contribute to the overlying moisture content within the atmosphere above (Siqueira et al. 2009, Ek 2004). The question then becomes whether enough of the moisture within the soil can be evaporated to make an overall difference to the quantity of moisture within the atmosphere directly above or downwind of the area when accounting for advective properties. The purpose of this research is to identify if there is a correlation between soil moisture and convection within the state of Missouri and within each of the six climate divisions in the state.

1.2 Background

Since the state of Missouri lies within the middle of the United States, it is influenced by weather systems from several areas: storm systems flowing over the Rocky Mountains to the west, cool and northerly flow from Canada, and moist southerly flow from the Gulf of Mexico (Andresen 2012). The unique position of Missouri also puts the western half state in a narrow transition zone, meaning both dry soils and wet soils can lead to convection. The eastern half of the state has shown to have more of a positive feedback effect with soil moisture (Findell and Eltahir 2003b). This is shown in Fig. 1 below. Furthermore, within the state, there is the Ozark Plateau. This region extends from northern Arkansas into southwest, central, and eastern Missouri (Fig. 2). There have been some cases where this terrain can affect weather in and around the region, such as flash flooding and the January 12-14, 2007 ice storm. Doug Cramer (National Weather Service Springfield, MO -personal communication) mentioned how the plateau allowed cold air to be dammed up along the plateau causing colder temperatures to occur. Higher winds can also be funneled into the area when there is southeasterly flow (Kielman 2016).

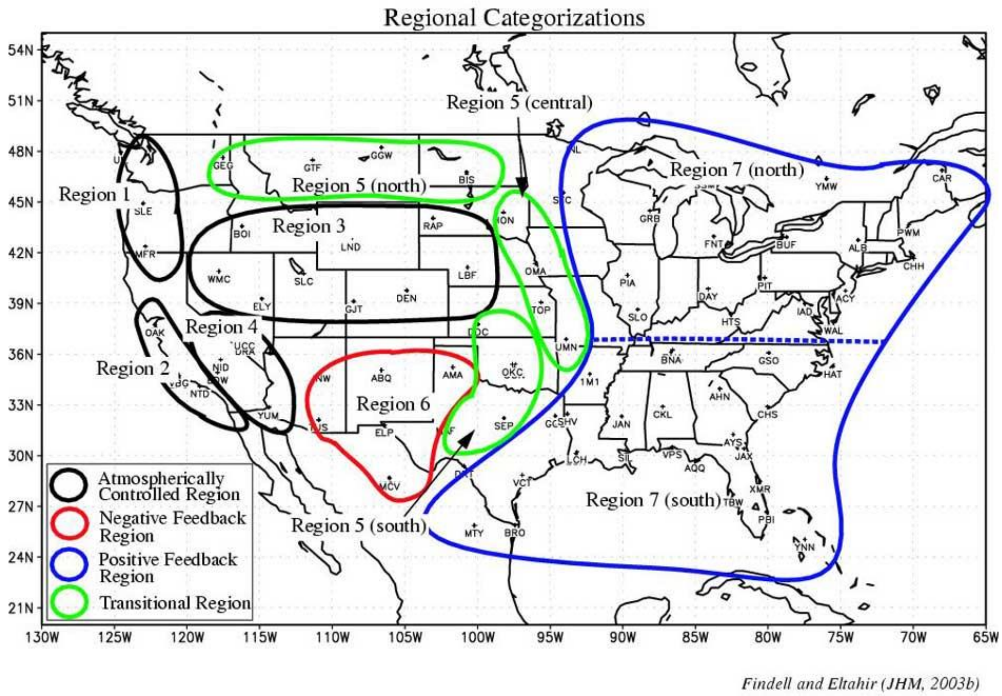


Fig. 1. The areas where feedbacks occur across the U.S. The eastern half of Missouri lies within the positive feedback region, while the western half is within the transitional zone. Credit: Findell and Eltahir (2003b).

The plateau, along with the position of Missouri in the transition zone, makes the state an interesting place to study convective storms and how the presence of soil moisture can lead to enhanced or decreased severe potential.

Fig. 2. Location of the Ozark Plateau. Credit: Dey et al (2020).

1.2.1 Positive Feedback Process

Soil moisture is important for many reasons. Not only is it crucial for the survival of all living organisms, but soil moisture information is also useful for reservoir management, crop yield and drought forecasting, and scheduling of irrigation routines. Beyond this, soil moisture becomes an important factor for hydrometeorology and short-term severe weather forecasting. It is well known that the amount of moisture within the soil can alter the temperature within the boundary layer directly above. Studies have shown (Mintz 1984, Beljaars et al. 1996, Eltahir 1998) that large-scale wet and dry regions can lead to a positive feedback process. Examples include the drought of 1988 and the floods of 1993. A report by the Illinois State Water Supply (Hollinger et al. 1992) states that the large-scale drought which occurred in Illinois during the year 1988 was reinforced by drought conditions that were already present, and therefore, caused a positive feedback process within that region.

Also stated, within the report, was how the drought was self-perpetuating by means of the Bowen Ratio, $B = \frac{sensible\ heat\ flux}{latent\ heat\ flux}$. This definition is important because it indicates how much energy is used to heat the environment and how much is used for evaporation. The ratio will be low when there is more ground moisture and more evaporation taking place. It will be higher if there is more dry soil and there is a more sensible heat flux. Overall, this definition gives a net radiation of the atmosphere (the balance of incoming and outgoing radiation at the top of the atmosphere). Eltahir (1998) hypothesized that the changes in the amount of sensible heat (SH) and latent heat (LH) flux can alter the characteristics of the boundary layer such as the temperature, moisture, and radiation which can lead to increased rainfall. Beljaars et al. (1996) further attested to the idea of a positive feedback process by use of a land surface model. They were able to show that the floods of 1993 along the Mississippi River were possibly enhanced by previous precipitation. In addition, Mintz (1984) concluded with a study suggesting that precipitation tends to increase as the evaporation rate increases. Thus, a positive feedback process occurs. An illustration of a positive feedback loop is below in Fig. 3, as shown in the work by Eltahir (1998).

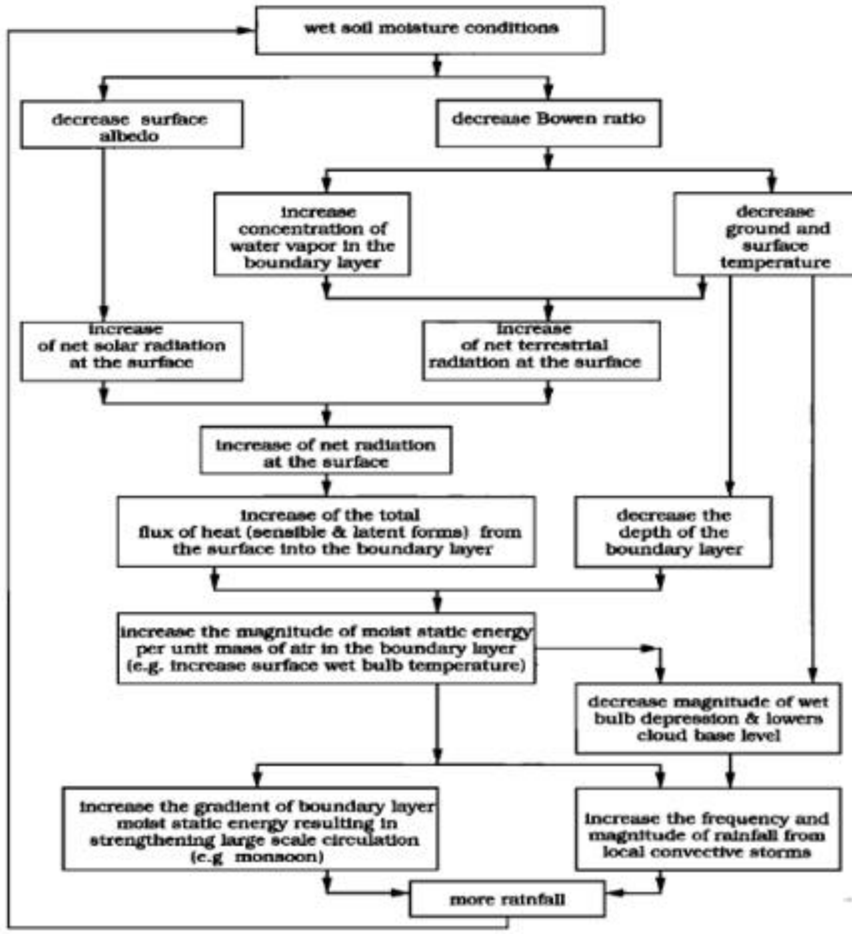


Fig. 3. Positive feedback loop presented by Eltahir (1998).

As mentioned above, the amount of soil moisture can also increase or decrease the amount of sensible heat (SH) and latent heat (LH) flux. Fig. 4 gives a graphical depiction of this. Within the figure, a moist area (purple) is compared to a dry area (yellow) in a volumetric soil sample. As expected, SH is highest with the dry area and LH is highest with the wet area. Also, of note is how the temperature with the dry area, both ground and at 2 meters, are as much as 5°C warmer.

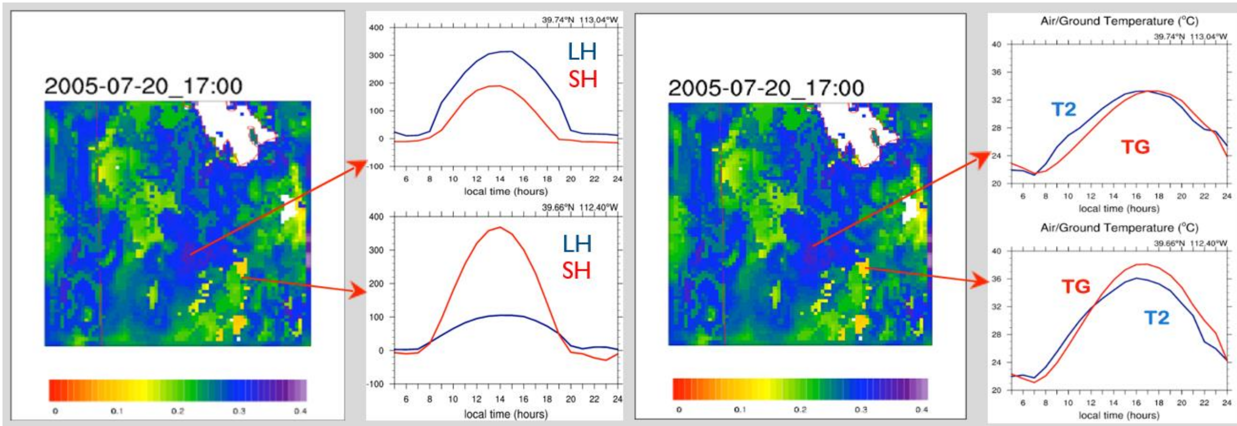


Fig. 4. Left- A graphical depiction of how dry ground versus wet ground affects sensible heat and latent heat. Right- A graphical depiction of how wet and dry ground influences the temperature at 2m above the surface and the surface. The yellow pixels indicate dry soil while the purple indicates moist soil. Credit: Andrea Hahmann, ATEC Forecaster's Conference (2005).

1.2.2. How Soil Conditions Lead to Convection

Both dry soils and wet soils can lead to increase in convection, but which one is more important? This is one question which this paper will try to address. As shown in Fig. 5, dry soil will create more turbulence and instability as the surface warms. Wet soil will cause more evaporation and thus, more buoyancy as parcels are able to quickly ascend through the atmosphere. The evaporation from wet soils act as a sink for sensible heat and therefore, more surface energy is able to be converted into latent heat release. Moistening of the planetary boundary layer can also lower the lifted condensation level, enabling clouds to form easier.

SH and LH can greatly influence the amount of instability within the atmosphere, and thus enhance the severe weather potential, if all other severe weather parameters are optimal. It has been shown that soil moisture tends to minimize the temperature spread

(Fischer et al. 2007, McCorcle 1988). During the day, evaporational cooling from the surface acts to suppress the temperature. Thus, a cooler airmass is present than would otherwise be. The opposite occurs during the overnight hours as latent heat release keeps the air warmer. Fischer et al. (2007) showed that by decreasing soil moisture content by 25% in the spring, temperatures in the summer can increase by as much as 2°C. On the other hand, McCorcle (1988) showed that an increase in soil moisture from 25%-75% can decrease the temperature by more than 5°C. Fig. 3 accurately depicts the different amounts of sensible and latent heat flux, along with turbulence between the soil types.

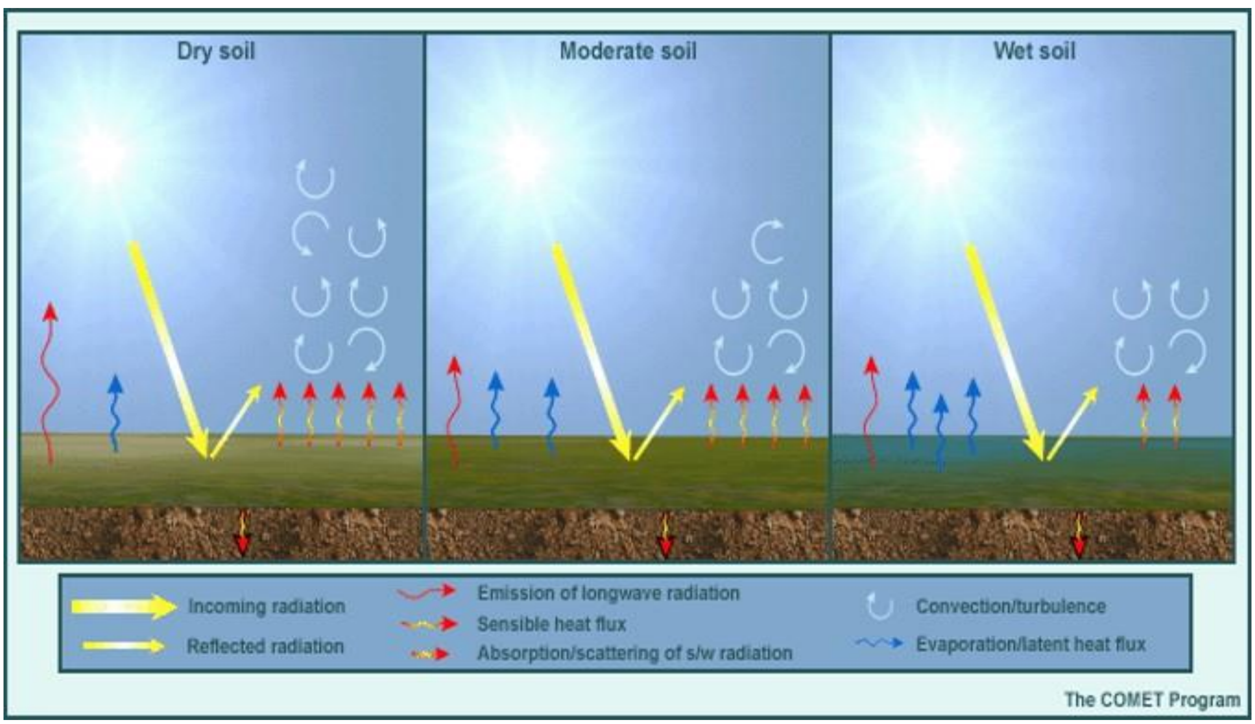


Fig. 5. A graphical depiction of how sensible heat flux and latent heat flux changes from dry to wet soil. Credit: Comet, 2009.

Since dry soil leads to higher sensible heating, a deeper boundary layer can be established which can make the LFC more attainable (Findell and Eltahir 2003a). Findell and Eltahir (2003a) modeled what conditions would look like over wet and dry soils. A sounding was derived from one of their simulations and is shown in Fig. 6. As shown, a deeper boundary layer is notable in the dry soil sounding (Fig. 6b). Also, of interest, is the higher convective inhibition (CIN) within the dry sounding, as compared to the wet soil sounding (Fig. 6a). More convective available potential energy (CAPE) is evident in the moist sample, as well. This is intriguing as more instability (CAPE) would be expected with a drier soil sample since there would be stronger surface heating. CIN can prevent air parcels from accelerating upward which can suppress convection, much like the lid on a pressure cooker. CAPE, on the other hand, is the amount of energy available for air parcels as they are lifted from the surface. More CAPE indicates more unstable conditions for convective activity. Another simulation modeled what the outcome of the different types of convection would be over wet and dry soils (Fig. 7). In this simulation, less convective triggering potential and more low-level moisture is needed over wet soils to achieve better chances for rain. The opposite is true over dry soils.

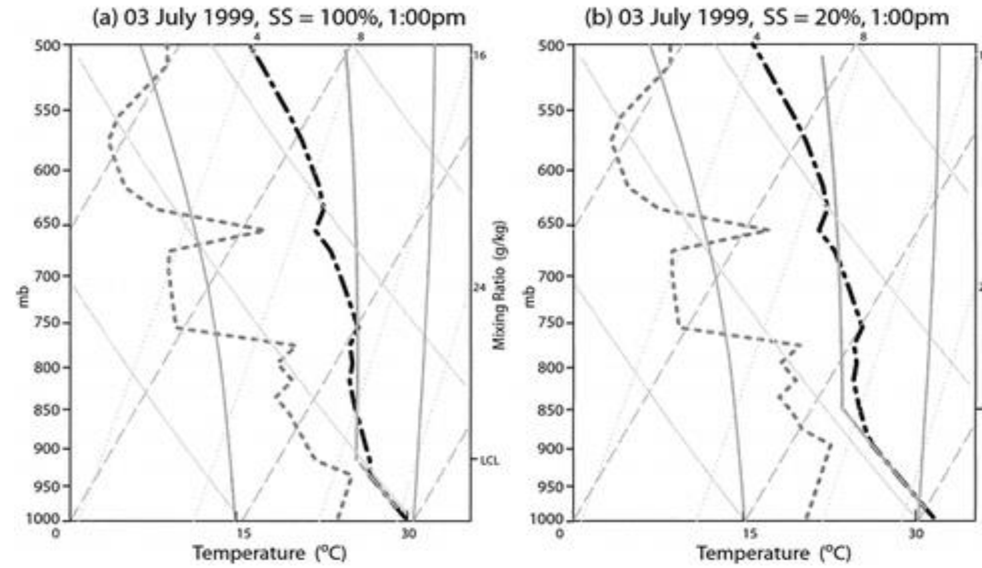


Fig. 6a. Left- vertical profile of the atmosphere. Dark long-dashed line is the temperature; light-dashed line is the dewpoint; short-dashed lines are mixing the mixing ratio; light long-dashed line are constant temperature; light solid line is the dry adiabat; medium solid lines are the moist adiabats. The path of the parcel is shown here as it follows a dry adiabat from the surface until it reaches its LCL and then follows a moist adiabat. Fig. 6b. Right- same as in 6a. Credit: Findell and Eltahir (2003a).

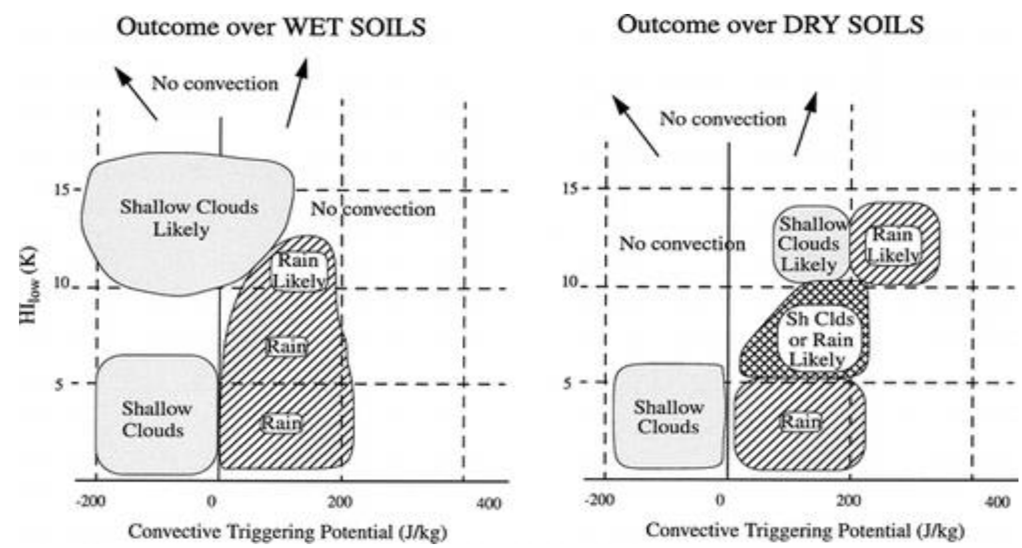


Fig. 7. HI(low) is the low-level humidity index. An index used to calculate the sum of the dew point depression at 950-hPa at 850-hPa. Convective Triggering Potential is the sum of the area between the environmental temperature and the moist adiabat originating at 100-hPa and concluding at 300-hPa. Coupled together, these indexes give a representation the types of convection above wet and dry soils. Credit: Findell and Eltahir (2003a).

1.3 Additional Previous Work

A study by Frye and Motte (2010) from 1998-2004 further explored the idea of instability and its relation to soil moisture. Their study focused on parts of Texas, Oklahoma, and Kansas and examined parameters such as CAPE, Lifted Index (LI), and CIN. Also examined was how the low-level jet (LLJ), combined with soil moisture, can increase/decrease these parameters. They looked at four types of days: NoLLJ/SB (no LLJ with synoptically benign days), NoLLJ/SP (no LLJ with synoptically primed days), LLJ/SB (LLJ with synoptically benign days), and LLJ/SP (LLJ with synoptically primed days). SP were days in which lapse rates were > 6°C km^{-1}, where SB were days in which lapse rates were < 6°C km^{-1}. Their results are shown below in Fig. 8.

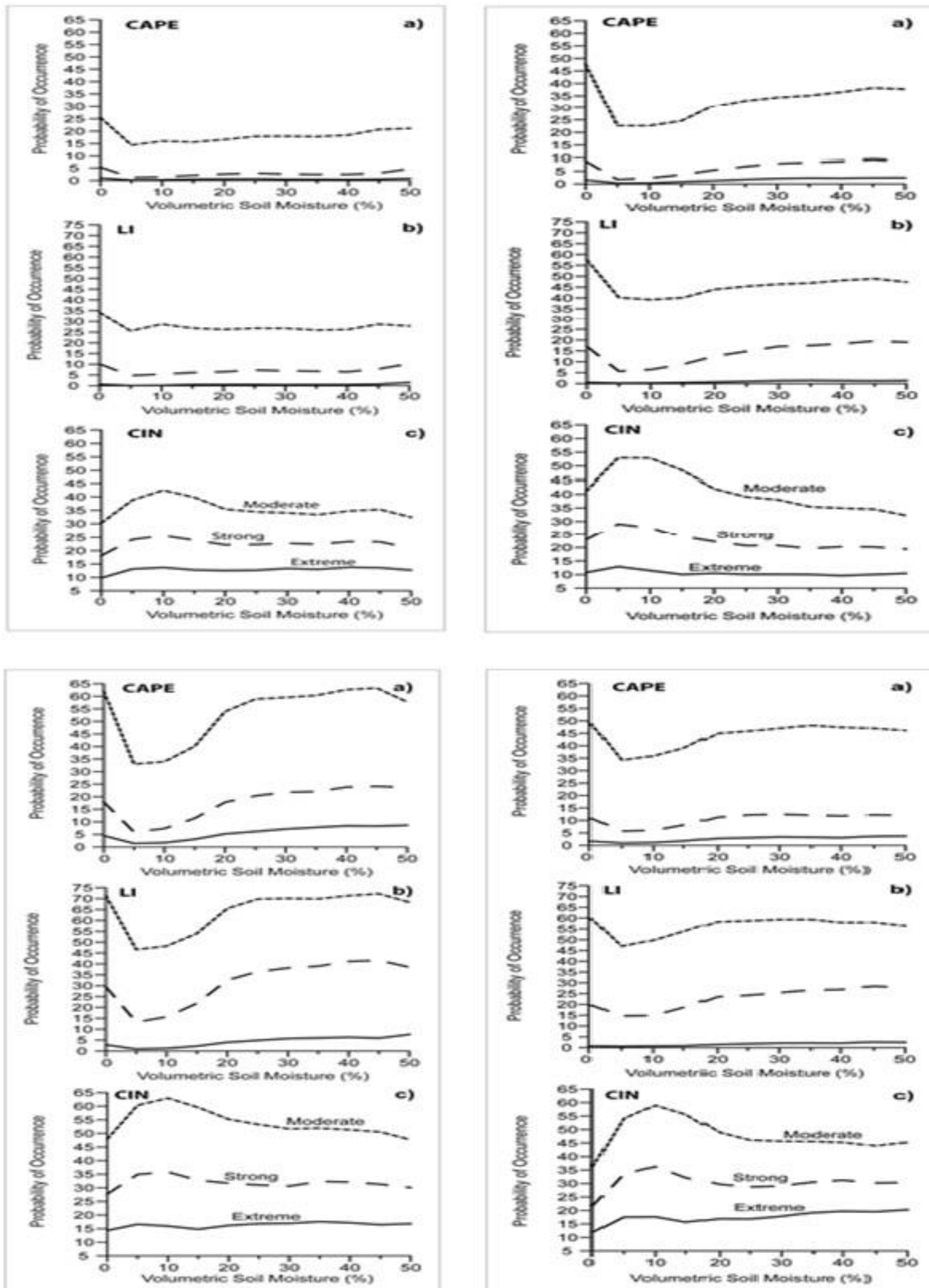


Fig. 8a. Top Left- NoLLJ/SB days. Fig. 8b. Top Right- NoLLJ/SP days. Fig.8c. Bottom Left- LLJ/SB days. Fig. 8d. Bottom Right- LLJ/SP days. Extreme (solid line) parameters are as follows: CAPE > 3500 J/kg, LI < -10°C, and CIN < 101 J/kg. Strong (long-dashed lines) parameters are as follows: CAPE 2500-3500 J/kg, LI -6-(-10°C), and CIN -51-(-101 J/kg). Moderate (short-dashed lines) parameters are as follows: CAPE 1000-2500 J/kg, LI -3-(-6°C), and CIN 21-(-51 J/kg). Credit: Frye and Mote (2010).

They concluded that as the volumetric soil moisture increases, after about 5%, the atmosphere is more likely to become destabilized with the highest instability occurring at completely dry soil. As shown in Figs. 8c and 8d, the LLJ plays an important role in convection, possibly transporting soil moisture. Soil moisture also increased whenever an LLJ was present. In addition, their study showed that a stable atmosphere was generally over wetter soils, as compared to dry soils (Fig. 9).

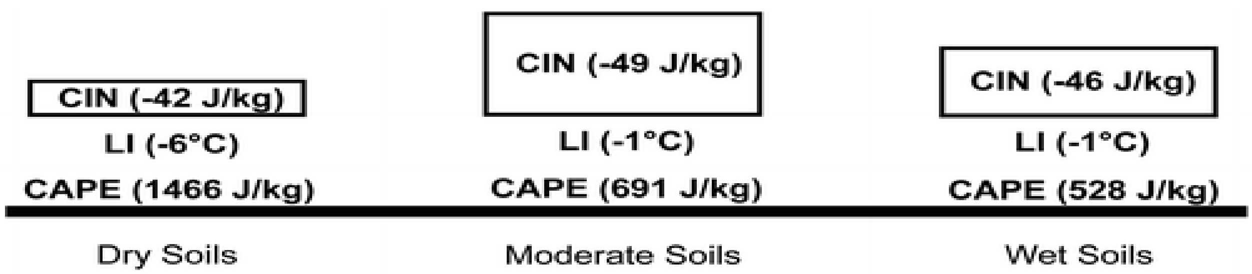


Fig. 9. Instability parameters over dry, moderate, and wet soils. As shown, more stable conditions are present over wetter soils. This does not account for an LLJ. Credit: Frye and Mote (2010).

Another LLJ case study (McCorcle 1988) tested to see if dry conditions can lead to the enhancement of the jet activity over the Southern Plains and east of the Rocky Mountains. Prior to the 48-hour study, little rainfall occurred. A test was performed over a homogenous soil type where three experiments were executed: one for dry soil (η = 0.1), near saturation (η = 0.75), and complete saturation (η = 1.0). Within this test, it was concluded that the amplitude of the diurnal wind decreases with the wetter soil. Furthermore, the saturated soil indicated a 40% reduction of the jet speed, as compared to that over the dry soil sample. The results are shown in Fig. 10.

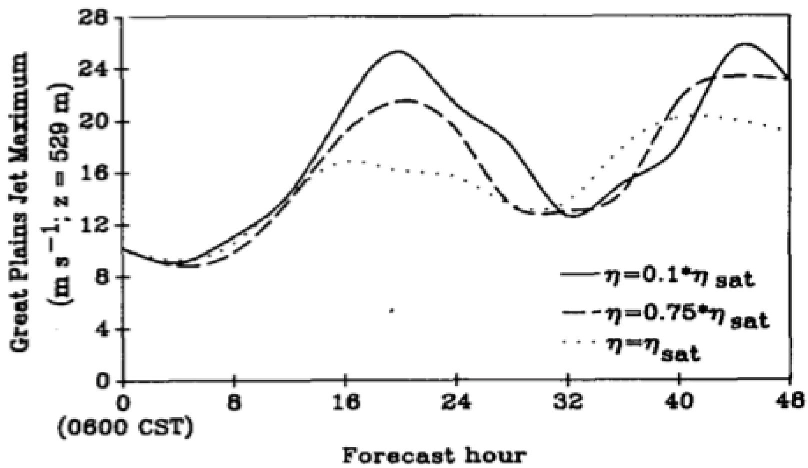


Fig. 10. Amplitude of the soil types in relation to the jet maximum speed with respect to time. Complete saturation is the short-dashed line, near saturation is the long-dashed line, and dry soil is the solid line. Credit: McCorcle (1988).

Also compared were the vertical velocities over the different soil types (saturated, near saturated, and dry). The results are shown in Fig. 11. This suggests that dry soils over the Southern Plains and east of the Rocky Mountains may enhance convergence and contribute to the strength of the LLJ.

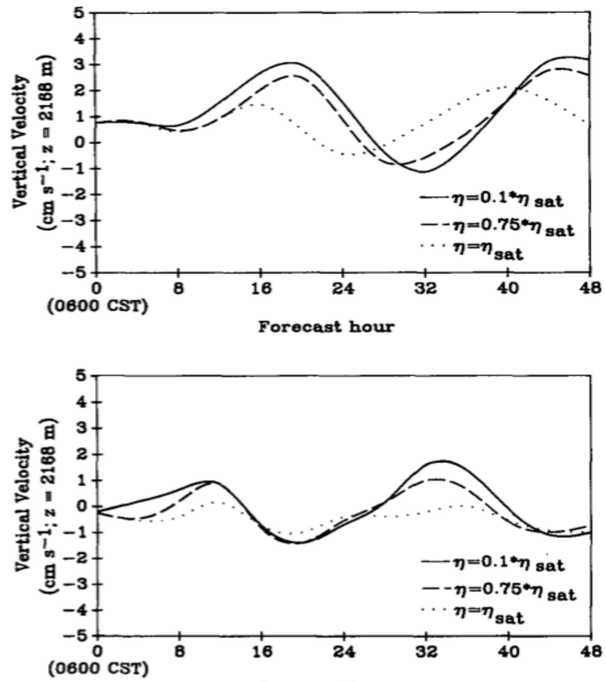


Fig. 11. Amplitude of the soil types in relation to the vertical velocity with respect to time. Complete saturation is the short-dashed line, near saturation is the long-dashed line, and dry soil is the solid line. Missouri is on top, while Colorado is on bottom. Credit: McCorcle (1988).

These studies appear to show that while dry soils may enhance severe weather, wet soils may overall contribute more to precipitation.

One last study, which will be the basis for this research, is from Wakefield et al. (2015). This study examined the effects of six-month (September-February) antecedent soil moisture departure on tornado activity (April-June) within the Central and Southern Plains from 1954-2013. All tornado counts and days that were used within this period were > E(F0). They looked at 5 regions: Southeast, Northeast, Southern Plains, Northern Plains, and Oklahoma (which lies within the Southern Plains region). Fig. 12 shows the study area.

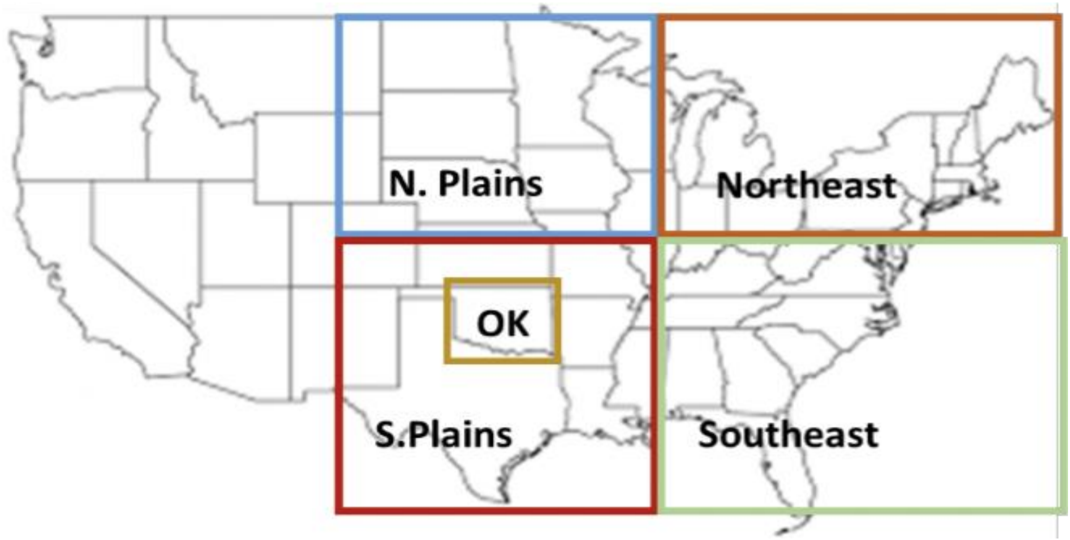


Fig. 12. The study area from Wakefield et al. (2015).

For tornado days, they found statistically significant correlations at the 5% (Type 1 error) level, by performing a least squares linear regression, in three of five regions. These included the Northern Plains, Southeast, and Oklahoma. The Northern Plains and Oklahoma exhibited a negative correlation, meaning increased soil moisture decreased tornado days or vice versa, while the Southeast showed a positive correlation (Fig. 13). They chose to look at tornado days, in addition to tornado counts, because tornado days gives a more accurate depiction of tornado activity (Raddatz and Cummine 2003).

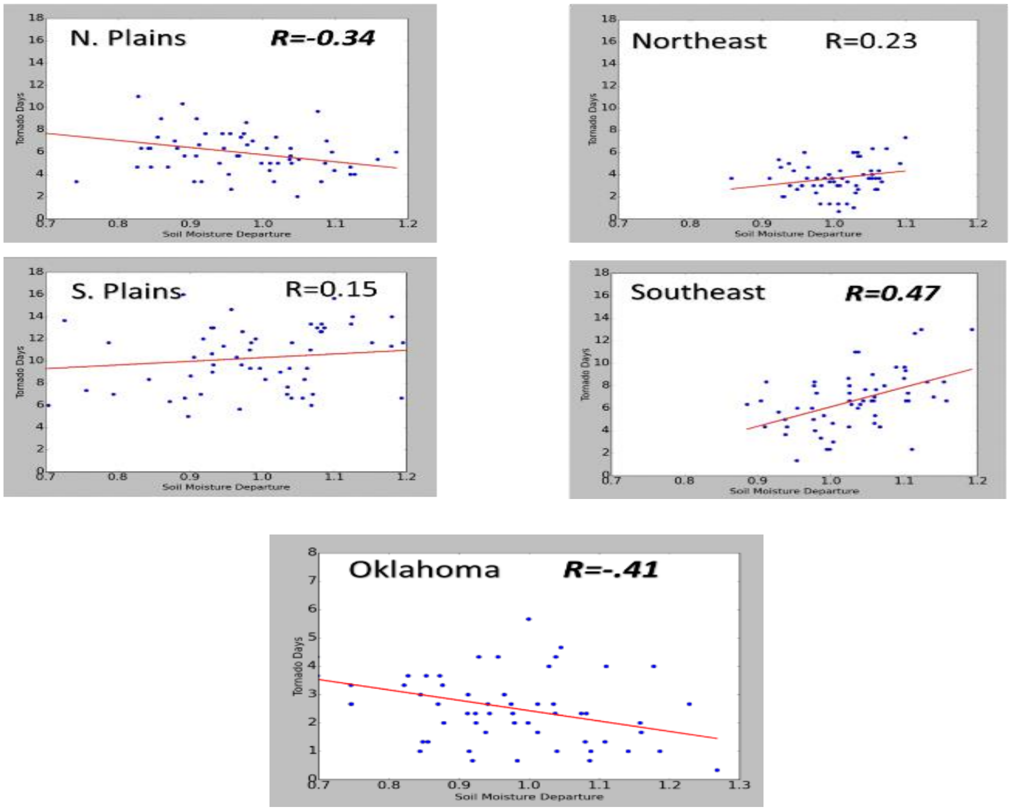


Fig. 13. Correlations between soil moisture departure and tornado days for the five regions. Credit: Wakefield et al. (2015).

For the tornado counts, no statistically significant correlations were discovered at the at the 5% (Type I error) level (Fig. 14). Although, after removing the significant outlier in 2011, the Southeast had a significant correlation at the 10% level ($p \leq 0.10$) (Fig. 15).

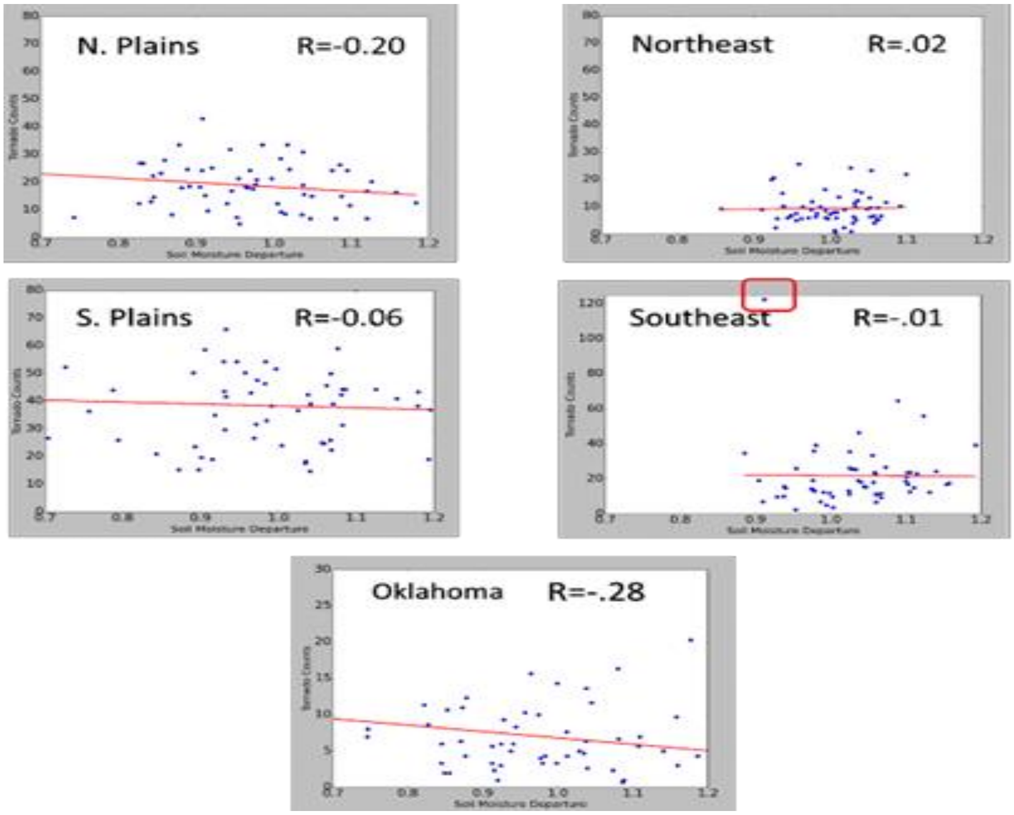


Fig. 14. Correlations between soil moisture departure and tornado counts for the five regions. Credit: Wakefield et al. (2015).

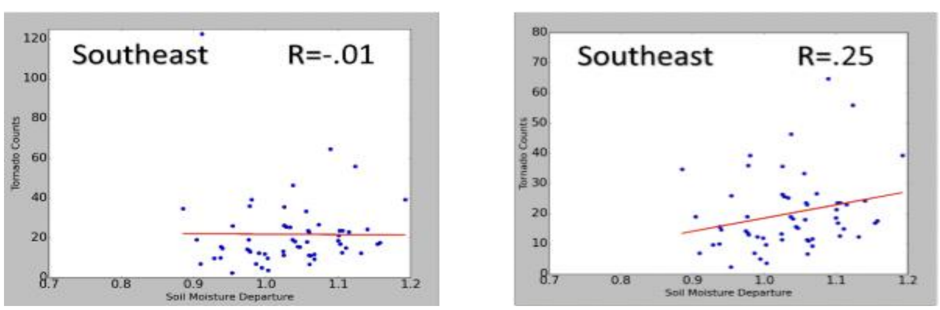


Fig. 15. Correlation between soil moisture departure and tornado counts for the Southeast with the 2011 outlier removed (right) and before it was removed (left). Credit: Wakefield et al. (2015).

It was concluded that areas within the Southern Plains may behave differently, depending on the location. For example, areas near the Gulf of Mexico may exhibit behavior more like the Southeast, whereas areas farther from the Gulf of Mexico may be more like

Oklahoma and the Northern Plains. Interestingly, despite Oklahoma's location within the Southern Plains region, it behaved more like the Northern Plains region.

1.4 ENSO Impacts on the Midwest

It is believed that the El Niño Southern Oscillation (ENSO) may influence the weather in the Midwest. ENSO is a natural cycle that occurs over the tropical Pacific Ocean basin on a 2-7-year cycle (Hanley et al. 2003) and lasts 12-18 months (Lupo et al. 2012a). It is characterized by the warming and cooling of the sea surface temperatures (SST) within the tropical Pacific Ocean basin. During El Niño, trade winds (easterlies) weaken around the equator in the western Pacific as high pressure starts to form over this area, while low pressure forms over the eastern Pacific. The weakening of these winds causes warm water to migrate eastward from the west. Upwelling from within the depths of the ocean which usually transports cooler water to the western areas of North and South America is subsided. This allows the SST to rise in these areas.

El Niño is known to bring above average temperatures to the United States during the winter and can suppress tropical storm formation in the Atlantic. La Niña does just the opposite (McPhaden 2002). According to NOAA, El Niño brings wet weather to the southeast and western California during the spring months (Fig. 16). This can be used to compare with the results section of this research.

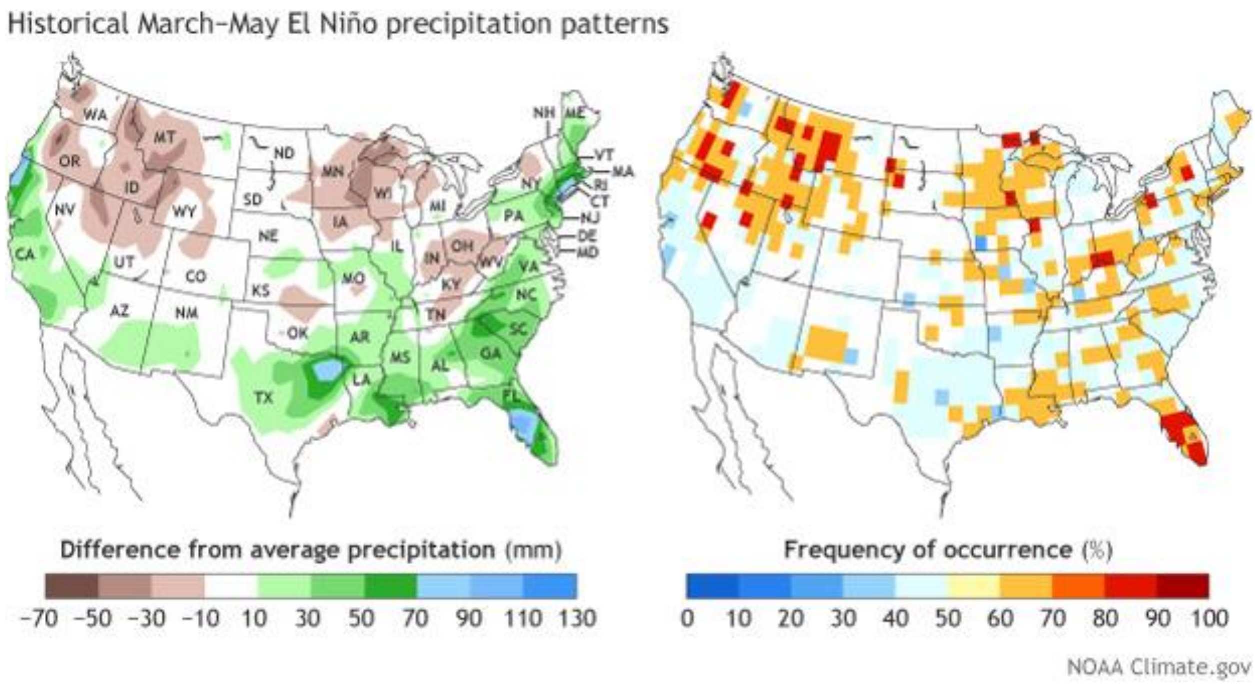


Fig. 16. Historical spring precipitation within the United States through 2015. Credit: Lindsey (2015).

Many definitions are used to define what constitutes an El Niño or La Niña year. For the purpose of this research, the Japan Meteorological Association (JMA) definition will be used to classify ENSO events since it is the most widely used and most accepted (Lupo et al. 2012a). Within this definition, ENSO events (El Niño, La Niña, neutral) are classified on a five-month continuous SST departure from the mean. These SST anomalies lie within the region of 4°N-4°S, 150°W-90°W in the tropical Pacific Ocean basin. To be considered an El Niño year, there must be six consecutive months where SST are ≥ 0.5°C. La Niña years are those where SST are < -0.5°C and neutral conditions are those between the two values. ENSO events must include the months of October, November, and December. The ENSO year is considered to run from October to the following September (Birk et al. 2010).

Several studies have attempted to show how ENSO affects the Midwest. Lupo et al. (2007) used a Fourier analysis and showed significant variability around the 3, 6, and 20-year mark when looking at temperature and precipitation for Columbia, Missouri. Hu et al. (1998) also had similar results for the Midwest region. These results are consistent with the ENSO cycle, especially the 3 and 6-year cycle. When looking at tornadoes and their relationship to ENSO, Bove (1998) showed that there was a decrease in the number of tornadoes in Tornado Alley during the February-July El Niño periods. Browning (1998) indicated that northwest Missouri has an increase in tornadoes during La Niña years. He also found that windstoms and hailstorms increased during El Niño years. For the results, a comparison of the number of storms in Northwest Missouri (from SPC) to the El Niño/La Niña years was made. This is similar to the methods that will be used within this research (Section 2). Akyuz et al. (2004) also showed an increase in tornadic events within the central Plains during La Niña years. Their study focused on those greater than E(F1). Marzban and Schaefer (2001) showed a small, but significant correlation between SST anomalies in the Pacific Ocean and tornadoes in the United States. Their results showed a negative correlation between SST and the frequency of tornadoes and tornado days. Cooler SST (La Niña) seemed to have a higher number of tornado counts and days.

1.5 Objectives

The goal of this research is to expand the Wakefield et al. (2015) study and apply some of the same methods to the state of Missouri. By using previous results, this research can be used to further correlate soil moisture to convective properties. To achieve this, the following objectives are defined:

- Compare April-June soil moisture anomalies with April-June (in-season) tornado, wind, and hail data.
- Compare 3-month antecedent (January-March) soil moisture anomalies with in-season tornado, hail, and wind data.
- Compare 6-month antecedent (September-February) soil moisture anomalies with in-season tornado, wind, and hail data.
- Analyze synoptic charts to look for convergence or moisture advection for wet and dry periods.
- See how the interannual variability of ENSO affects tornadoes and soil moisture within the state by using a Fourier analysis and synoptic charts.

CHAPTER 2. DATA AND METHODS

2.1 Data

2.1.1 Soil Moisture and Composite Maps Data

The soil moisture data which was used for this research was obtained through the National Centers for Environmental Prediction's (NCEP) National American Regional Reanalysis (NARR) database (*provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at https://psl.noaa.gov/)* at a resolution of 0.3 × 0.3 degrees. NARR uses the NCEP Eta Model at a 32 km resolution with 45 layers. This model is used in conjunction with the Regional Data Assimilation System (RDAS), which assimilates precipitation.

The Time frames of April-June, January-March, and September-February were chosen, for reasons explained more fully in the following chapters and sections. Using this database, several other composite maps can also be made with many different parameters. Composites, other than soil moisture anomalies, that were made for this research include: 300-hPa vector winds and heights; 500-hPa vector winds and heights; 700-hPa omega, specific humidity, heights and vector winds; 850-hPa vector winds, heights, and specific humidity; MSLP, latent and sensible heat flux, 2-m relative humidity, 2-m temperature, lifted index, 2-m dew point, moisture availability, and surface CAPE. These parameters were chosen to determine if there is also a correlation between the synoptic setup, along with soil moisture, and will be analyzed in chapter 8. Also in this chapter, ENSO years will be compared with some of the composite maps and Fourier transforms will be performed to further understand the correlation between the interannual variability and severe weather/soil moisture.

2.1.2 Storm Data

The storm data, which contains tornado, hail, and wind, was collected through the Storm Prediction Center's (SPC) database. This data includes all tornado counts and tornado days within the state of Missouri with the years 1980-2018 from the months of April-June. This time period was chosen because those years before 1980 are not available within the NARR database. This period should be enough to see if there is a correlation between soil moisture and severe convection. The monthly time frame was decided upon for a couple reasons. First, it matches up with the research by Wakefield et al. (2015). Second, this is when most tornadoes occur during the spring. Long and Stoy (2014) suggests peak tornado season in tornado alley occurs May 19th. Therefore, a month and a half before and after seems reasonable. Tornadoes used are those which contained their own unique tornado number within the database. Any tornadoes that were crossovers into Missouri from another state were not included. Tornadoes which originated within Missouri and traveled to another state were included since this research is focused on the origins of convective activity. However, convection that originated in Missouri and then produced a tornado in another state were not included. This is because it was difficult to discern which tornadoes in neighboring states originated in Missouri from importing the data alone. Previous radar data and analysis was needed to distinguish between convective activity, which because of time constraints for this research, was not able to be performed. The same issue was seen for the individual climate divisions within the state. Also, any storm reports (tornadoes, hail, wind) that had coordinates in another state (after importing the data in ArcMAP 107.1) but had a state identity of Missouri were dismissed. Upon collecting the data, there were a handful of tornadoes that were duplicated (same starting latitude and longitude coordinates). These were removed. Since there were many more hail and wind reports, duplicated reports were not analyzed. It is important to note that wind and hail events can be reported with proximity to each other and potentially within the same storm. Therefore, it becomes difficult to discern between separate events. The first few years of wind and hail data were analyzed to see if there were any duplicate reports, and none were found. Ultimately, it was concluded that there were far too many reports for duplicates to make a significant difference.

Tornado data was categorized with all tornado counts, tornado counts > E(F0), all tornado days, tornado days > E(F0), weak, and strong tornadoes. Weak tornadoes were considered those with E(F0) and E(F1) strength. Strong were those with strengths between E(F2)-E(F5). Tornado counts and days > E(F0) were mostly used within this research. Hail data was categorized with all hail reports, reports with magnitude < 1.25 in., and hail with magnitudes ≥ 1.25 in. Wind data was categorized with all wind reports, reports with a magnitude < 60 kts, and those with magnitudes ≥ 60 kts. It was noticed that many wind reports of zero exists within the SPC database. This suggests that there are several unknown wind events. Since it was difficult to establish the strength of the wind, these reports were recorded as zero for this paper. Therefore, it is better to use “total wind reports” for comparison.

2.2 Methods

2.2.1 Storm and Soil Moisture

Once the storm data was downloaded from SPC’s database by csv format, it was imported into a geographic information system (GIS) program called ArcMap. GIS is useful for analyzing geographic data as it is displayed on a map. In this research, it was used as a way to calculate storm and moisture data in several ways, but mainly averages within regions. It is also useful to physically see the differences when portrayed geographically. Furthermore, ArcMap is user friendly as it allows NetCDF (files which contain meteorological variables) files to be easily imported, which happens to be the format of the composite maps from the NARR database.

For the soil moisture data, composite maps were generated through the NARR database. These maps were imported into ArcMap 10.7.1 for an easy to read layer. The soil moisture data was converted to raster layers through the “make NetCDF raster layer” function. Once within ArcMap, only the data confined to Missouri was used. For the averages of the soil moisture anomalies within the state and the six climate divisions (shown in Fig. 18), the function “extract by mask” within the spatial analyst section of Arc Toolbox was used. Extract by mask is useful for inputting raster layers and features and then outputting a raster layer by combing the two inputs and can be used for statistical analysis (ESRI). In this case, the first input raster layer was the soil moisture anomalies and the second input was the shapefile feature of the state or climate division upon which was being correlated. Combining these two inputs produced a raster layer which can then be used to find maximums, minimums, standard deviations, and averages of the data. The figure below (Fig. 17) shows what this function looks like when it is applied. The shape of the mask is the same but shifted slightly. The values do not seem to be affected by this shift.

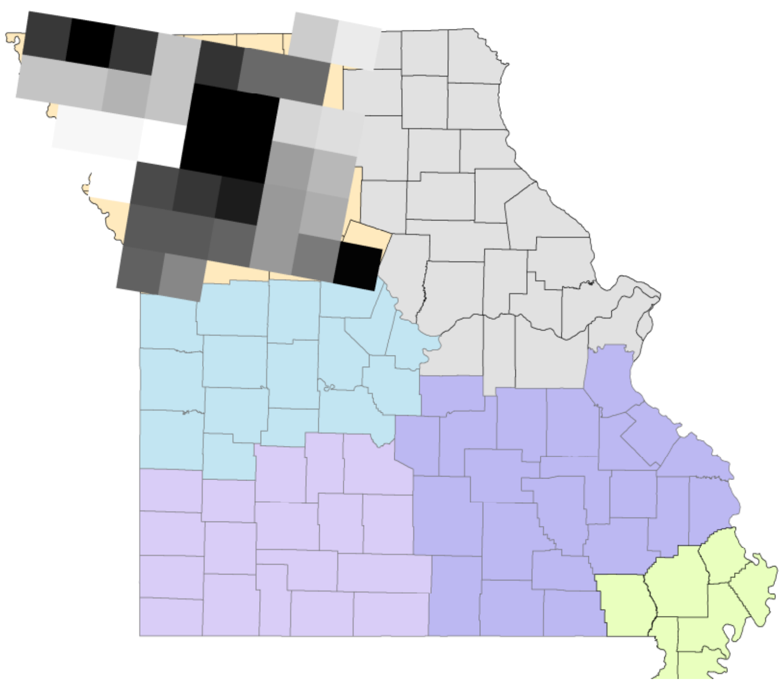


Fig. 17. An example of a mask environment setup for division 1. Produced through ArcMap 10.7.1.

The spatial join function within the overlay section of Arc Toolbox was used to find the number of storm reports for each of the six climate divisions. Three experiments were performed and are detailed within the following sections.

2.2.2 Fourier Transforms

To find a correlation between ENSO and severe convection/soil moisture, Power spectra were generated from the soil moisture and tornado data from which total tornado days and counts were used. After the mean was removed, Fourier transforms were constructed to analyze the wavelengths using Mathcad software. Fourier transforms converts Cartesian coordinates to wave space which is useful for wave analysis to study cyclical periods. In this case, the interannual cycle was analyzed to see if it may be affecting severe convection or soil moisture amounts. The observed wave spectrum can then be compared against white and red noise spectra to determine statistical significance (Wilks 2006). White noise represents a null hypothesis for a test statistical where no specific wavelengths can dominate, and red noise represents a null hypothesis for a statistical test where smaller wave numbers can naturally dominate (Wilks 2006). Significant periods were found by dividing peak waves by the number of years. For instance, on the total tornadoes graph (section 8.2, Fig. 54b), the peak wave number 4 was divided by 39 to give a value of 9.8 year, meaning this peak can be expected to occur approximately every 10 years. The power spectra of tornadoes/tornado days were also compared to the power spectra of April-June soil moisture anomalies against the white noise continuum to see if there is any coherence between the two. Coherence is useful to find significant peaks between two variables. If peaks are present, there is a correlation between the two, and the higher the peaks, the stronger the correlation.

2.2.3 First Experiment

The first experiment compared April-June soil moisture anomalies with April-June convective storm (tornado, hail, and wind) reports. This time period was chosen to see if there is a correlation between in-season soil moisture and in-season storm reports. To find a correlation, the Pearson Correlation Coefficient was used (Asuero 2006), where x and y are the comparison values, and $\bar{x}$ and $\bar{y}$ are their corresponding mean values.

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

To test the significance of the Pearson Correlation Coefficient, the following t-test equation was used (Illowksi 2015), where N = number of years and r = correlation coefficient.

$$t = \frac{r}{\sqrt{\left[\frac{1-r^2}{N-2}\right]}}$$

Soil moisture anomalies are the departure from the 30-year climatological average (1981-2010) and have the units kg/m^2. For this experiment, all tornado counts > E(F0), all tornado days > E(F0), weak tornadoes (E(F0)-E(F1)), and strong tornadoes (E(F2)-E(F5)) were compared with soil moisture anomalies for the state of Missouri. Tornado counts and days > E(F0) were mostly used within this paper. In order to keep consistent with the Wakefield et al. (2015) paper. Additionally, weaker tornadoes have been shown to not accurately represent the number of tornadoes, due to be overestimated, especially within large population centers. Higher end tornadoes are more faithfully reported (Akyuz et al. 2004, Anderson 2007). The three experiments in this research only used this criterion of tornadoes > E(F0). The tornado categories were calculated with a linear least squares regression. In the results section, a p-value of .10-.05 is colored in blue (R value) and those with a p-value ≤ 0.05 are colored in red (R value). From here on, any correlations with a p-value of 0.1-0.05 will be labeled as "$p \leq 0.10$" level. The same was done with correlations $p \leq 0.05$. In addition, all wind reports, those with a magnitude of < 60 knots (kts), and those with a magnitude of ≥ 60 kts were used. As far as hail, all reports, those with a magnitude < 1.25 inches (in.), those with a magnitude ≥ 1.25 in. were included. The climate divisions do not include the different categories of the storm reports. They only include tornado counts > E(F0), tornado days > E(F0), total hail counts, and total wind counts. All categories of the varying magnitudes were only included when the storm reports were compared with the whole state, not within the individual climate divisions. This is because when comparing the state moisture with the above categories of the severe storms, there is more data. There is not enough data when broken down to be compared with individual regions. The climate divisions within the state of Missouri are displayed below in Fig. 18. Division 1 (Northwest Prairie) is in the northwest part of the state, Division 2 (Northeast Prairie) is in the northeast part of the state, Division 3 (West Central Ozarks) is in the west central part of the state, Division 4 (West Ozarks) is in the southwest part of the state, Division 5 (East Ozarks) is in the south central to southeast part of the state, and Division 6 (Bootheel) is in the far southeast part of the state.

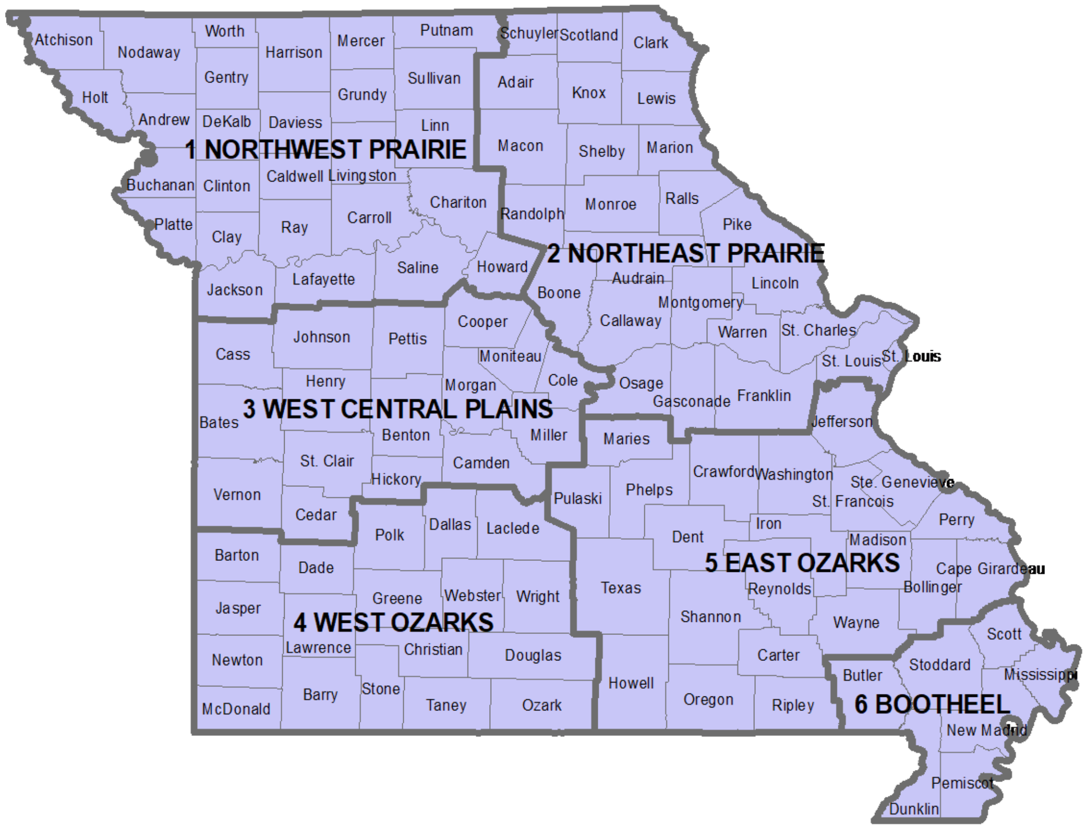


Fig. 18. A map of the six climate divisions within Missouri, as identified by the National Oceanic and Atmospheric Administration (NOAA). Produced through ArcMap 10.7.1.

2.2.4 Second Experiment

The second experiment analyzed the 3-month (January-March) soil moisture anomalies to the following April-June severe storm reports. Much like the previous experiments, the state of Missouri was compared along with its climate divisions. The varying magnitudes (categories) of the storms were only analyzed for the state, not for the climate divisions. In addition to the Wakefield et al. (2015) chosen antecedent time period, this period was chosen to see if soil moisture closer to the tornado season may be more of a factor as a predictor to severe convection.

2.2.5 Third Experiment

The third experiment that was performed analyzed the correlation between the 6-month (September-February) antecedent soil moisture anomalies to the following April-June severe storm reports. The same procedure as in section 2.2.1 was followed. These months were chosen so the results could be compared with that of the Wakefield et al. (2015) paper.

CHAPTER 3. FIRST EXPERIMENT RESULTS

3.1 Soil Moisture Analysis

The first part of this experiment analyzed the soil moisture trends for the April-June (in-season), January-March (3-month antecedent), and September-February time frames (6-month antecedent). These time periods were chosen because these are what were used within the three main experiments (in-season moisture, 3-month, 6-month soil moisture comparison to severe storm reports). Trends over the 39-year period was analyzed to see the difference over time during the above time frames.

The graph in Fig. 19a shows the soil moisture anomalies within a time period of 1980-2018 from September-February (green line), January-March (purple line), and April-June (red line). Interestingly, and somewhat expectedly, the soil moisture peaks and valleys between the three lines line up close to one another. The only obvious exception to this is the year 1990 where the January-March period has a valley, while the April-June period has a peak. Also, the overall trend is that the soil moisture is decreasing over time for all three periods. The average soil moisture anomaly for the January-March time frame was -13.14 kg/m^2 with a standard deviation of 76.27 kg/m^2. September-February time frame had a soil moisture anomaly average of -12.29 kg/m^2 with a standard deviation of 54.91 kg/m^2. April-June had an average soil moisture anomaly of -13.58 kg/m^2 with a standard deviation of 76.64 kg/m^2. The major wet anomalies for the January-March period were the years 1983, 1994, 1999, 2005, 2010, and 2016. The minor peaks were 1985, 1991, 1997, 2002, and

2013. Major dry anomalies for this time included 1981, 1990, 1996, 2000, 2007, 2011, and 2014. The minor valleys included 1984, 1992, 1998, 2003, and 2011. The major wet anomalies for April-June were the years 1983, 1994, 1999, 2008, and 2010. Minor peaks for this time were 1990, 2002, 2005, 2013, and 2016. The major dry anomalies were the years 1981, 1992, 2000, 2006, and 2014; while the minor valleys were 1989, 1997, 2003, 2009, and 2012. As far as the September-February time frame, the major wet anomalies were 1986, 1995, and 2010. The minor peaks were 1984, 1999, 2005, and 2016. Looking at the major dry anomalies for this time period, the years were 1990, 2000, 2006, and 2014; while the minor valleys were 1985 and 1997. Major peaks/valleys are those which exhibit large rises/falls. Minor peaks/valleys are those which exhibit small rises/falls.

Figs. 19b-d compares all six of the climate divisions to the three time periods. The climate divisions further indicate the decreasing soil moisture trend. The wettest divisions for all the periods was division 6 in the southeast part of the state. The driest was division 3 in the west-central part of the state. For a better look, Appendix A shows the individual climate divisions for each of the three periods.

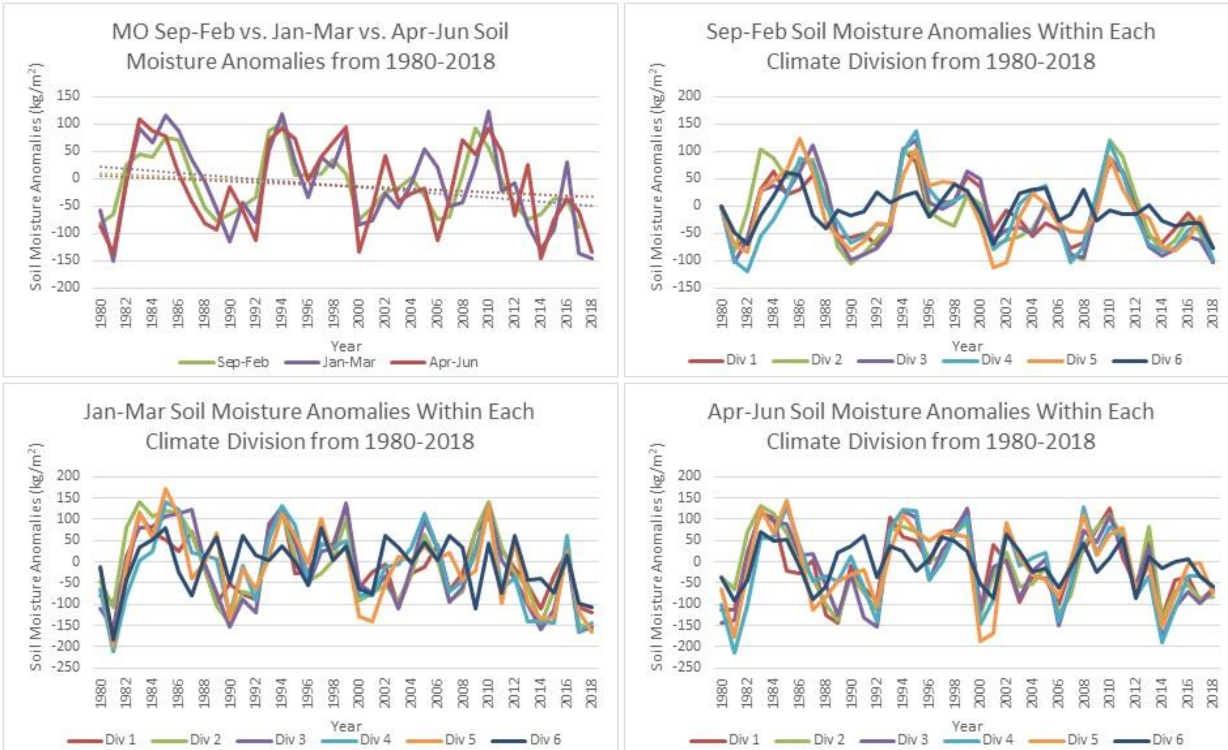


Fig. 19a. Top Left- Comparison of Sep-Feb (green line), Jan-Mar (purple line), and Apr-Jun (red line) soil moisture anomalies for the study period (1980-2018). Fig. 19b. Top Right- Sep-Feb soil moisture anomalies within each climate division. Fig. 19c. Bottom Left- Same as b, but comparing Jan-Mar soil moisture anomalies. Fig. 19d. Bottom Right- Same as b and c, but for Apr-Jun soil moisture anomalies. An overall drier trend can be seen within these graphs, along with distinct peaks and valleys.

3.2 Tornado Analysis

3.2.1 Tornado Counts

The April-June tornado counts were divided by the total numbers, > E(F0), E(F0)-E(F1), and > E(F1). As expected, these all closely line up with one another and decrease in numbers with increasing strength. The overall trend shows an increase in overall tornado counts and days with magnitude, except for E(F2)-E(F5). These show a slight decrease in both numbers and counts within the state (Fig. 25a). The largest increase was those in the

E(F0)-E(F1) range. This is most likely due to population growth and the increase in technology over the years. Some noticeable peaks include the years 2003 (largest at 83 total counts) and the infamous outbreak of 2011 (64 counts). Both 1988 and 1992 recorded zero total tornadoes which also happen to be El Niño years. While analyzing tornado days, 1988, 1992, and 2007 all reported zero tornado days > E(F0). 2007 also happened to be an El Niño year. The average counts of tornadoes per year over the 39-year period was 23, while the average tornado counts > E(F0) was 10.4.

Fig. 20a shows the tornado counts and their magnitudes. The tornadoes within each climate division are also illustrated in Fig. 20b (all counts) and 20c (counts > E(F0)). As previously mentioned, tornado magnitudes for the climate divisions were not included in the study, only those with magnitudes > E(F0). However, all tornado counts along with counts > E(F0) were included within this section as a comparison between the two and to see the trend over the 39-year study period. The only division which saw a decrease in total tornado counts was division 3 which also happens to be the driest. When looking at tornado counts > E(F0), divisions 1, 3, and 6 saw a decrease. Division 1 had the highest average number of total tornadoes per year at 4.6, while division 6 had the lowest at 2.2. This is expected since division 6 is much smaller than the other divisions. Not including division 6, division 3 had the lowest number with 3.6. Regarding tornado counts > E(F0), division 4 had the highest at 2.3 counts per year. The lowest (not including division 6 which had an average of 0.8 counts) was division 3 at 1.5 counts. For a better look, Appendix B.1 shows the individual climate divisions for total tornado counts and those > E(F0).

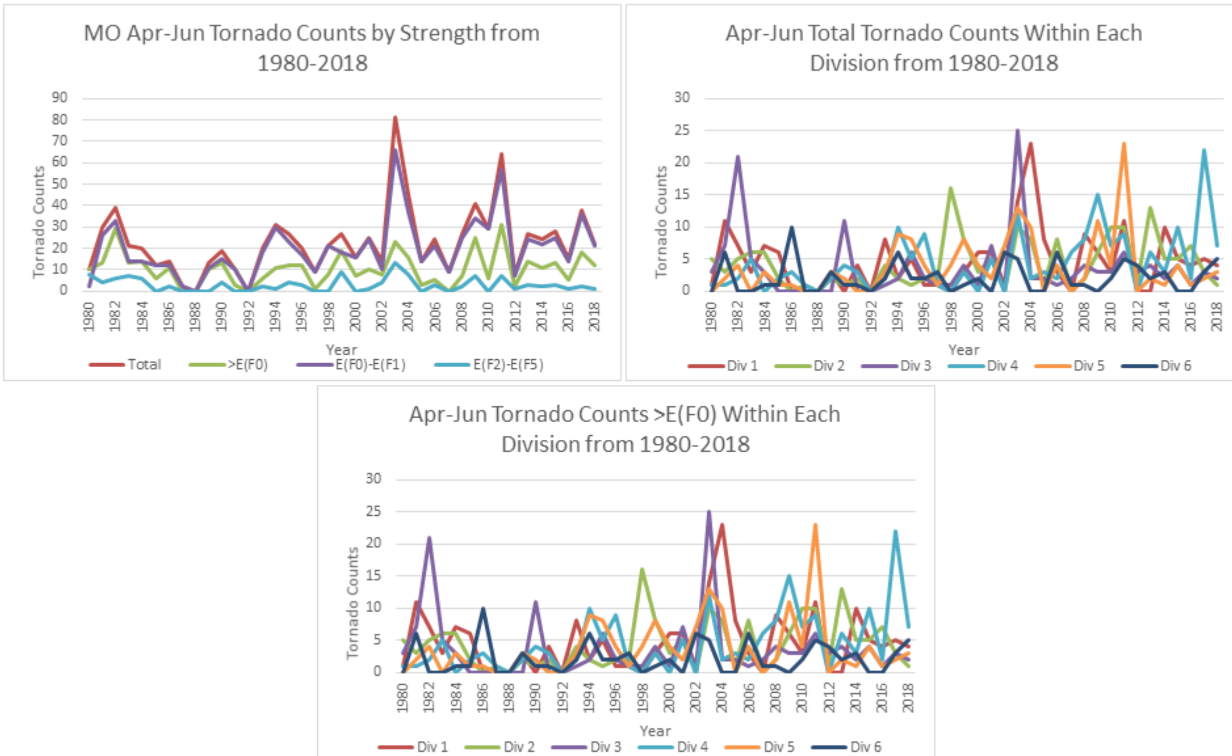


Fig. 20a. Top Left- April-June total tornado counts (red line), tornado counts > E(F0) (green line), tornado counts E(F0)-E(F1) (Purple line), and tornado > E(F1) (blue line) from 1980-2018. Fig. 20b. Top Right- Total tornado counts within each climate division for the study period: division 1 (red), division 2 (green), division 3 (purple), division 4 (blue), division 5 (orange), division 6 (dark blue). Fig. 20c. Bottom- Same as 20b, but with tornado counts > E(F0). An increase in tornado counts within the state is evident. Div. 1 had a decrease in total tornado counts. Divs. 1, 3, and 6 saw a decrease in counts > E(F0).

3.2.2 Tornado Days

As in section 3.2.1, April-June tornado days were also divided into total numbers, > E(F0), E(F0)-E(F1), and those greater than E(F1). Much like the tornado counts, the tornado days exhibited the same behavior (Fig. 21a). The largest peak was in the year 2011 with the total tornado days, > E(F0), and E(F0)-E(F1). The year 2011 had a total of 17 tornado days and 11 days > E(F0). The range of E(F2)-E(F5) had several peaks over the course of the 39-year period. These can be seen in Fig. 21a. Interestingly, the 2003 year, which had the most tornado counts (81), only had 8 tornado days, 4 of which were > E(F0). The average tornado days per year over the 39-year period was 7.7, while the average tornado counts > E(F0) was 4.4.

Tornado days within each climate division are illustrated in Fig. 21b (all days) and Fig. 21c (days > E(F0)). As in section 3.2.1, those with magnitudes > E(F0) and all tornado days (for comparison) are only included for this part of the research. None of the divisions saw a decrease in total tornado counts. Although, division 3 only saw a very slight increase. Like tornado counts > E(F0), tornado days of the same magnitude saw a decrease in divisions 1, 3, and 6. The highest number of tornado days was in divisions 1 and 4 with 2.4 days per year. The lowest (besides division 6 which had an average of 1.3 days) was division 3 at 1.7 days. Regarding tornado days > E(F0), the highest was division 2 at 1.3 days, while the lowest (not including division 6 which had 0.6 days) was division 3 at 0.9 days. This is somewhat expected. For a better look, Appendix B.2 shows the individual climate divisions for total tornado days and those > E(F0). These numbers are relatively low with both tornado days and counts > E(F0), and therefore, statistical analysis became a challenge.

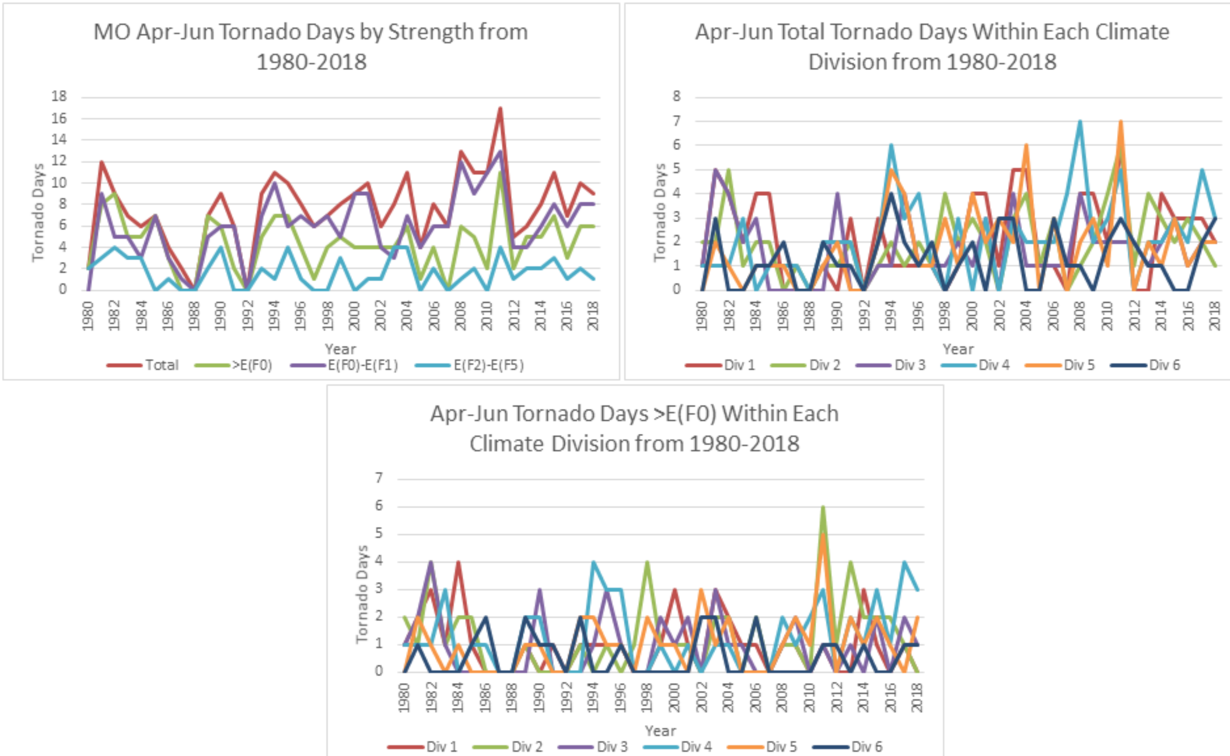


Fig. 21a. As in Fig. 20, except for tornado days. An increase in tornado days within the state is evident. Divs. 1, 3, and 6 saw a decrease in tornado days > E(F0).

3.3 Hail Analysis

Hail reports for the April-June time frame were divided into three categories: all hail reports, hail reports < 1.25 in., and hail reports ≥ 1.25 in. As with the tornado analysis, hail reports also maxed out in 2003 and 2011. Several other peaks are seen at the years 2004, 2006, and 2008 (Fig. 22a). The year with the highest number of hail reports was in 2011 with 934. The year with the smallest number of reports was 1980 with 36. However, this is likely not accurate because of poor reporting and a smaller population density at the time. The average number of reports for the 39-year period was 270. Since the year 2000, there have been an average of 413 reports per year.

The same trend within the state reports can also be seen within the climate divisions (Fig. 22b). Division 2 had the highest number of hail reports with 308 in the year 2011. Division 5 had the lowest with 7 reports in 2012 (excluding division 6). Division 1 had the highest total yearly average of 65.5 reports. Excluding division 6 (which only had 9.5 reports per year), the lowest yearly average was found in division 5 with 38.5 reports. A further look between the six climate divisions can be found in Appendix C.

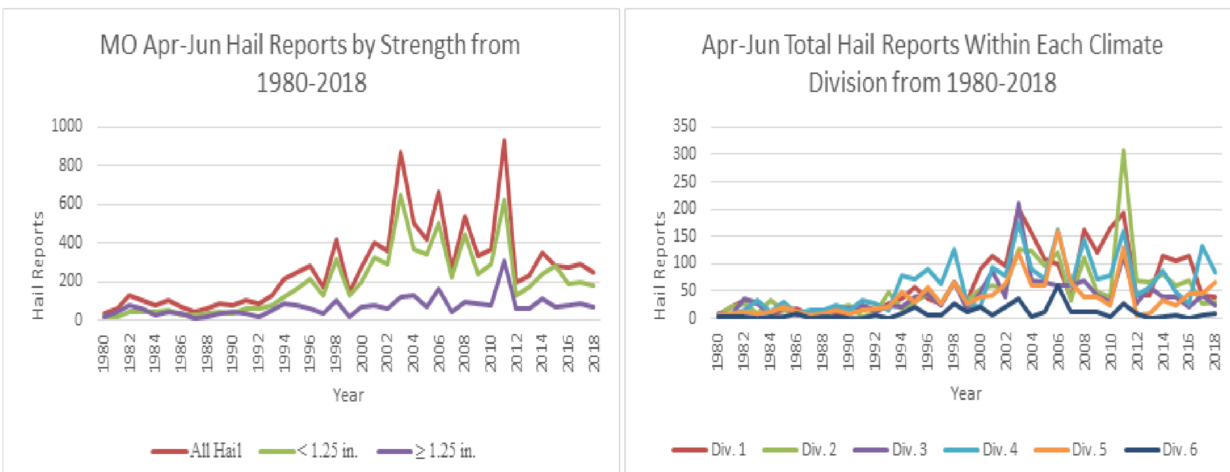


Fig. 22a. Left- April-June hail reports per year for all hail reports (red line), hail reports < 1.25 in. (green line), and hail reports ≥ 1.25 in. (purple line). Fig. 22b. Right- April-June all hail reports for each climate division: division 1 (red line), division 2 (green line), division 3 (purple line), division 4 (light blue line), division 5 (orange line), division 6 (dark blue line). An increase in hail reports is evident within the state and its climate divisions. Peaks are seen in 2003 and 2011.

3.4 Wind Analysis

Wind reports for the April-June time frame were also divided into three levels (Fig. 23a): all wind reports, wind reports < 60 kts, and wind reports ≥ 60 kts. Noticeable peaks are evident in the years 1982, 1995, 1998, 2000, 2004, 2008, 2011, 2013, and 2017. The year with the highest total wind reports was 2011 with 425, while the year with the least number of reports was 1986 with 27. Much like the hail and tornado reports, this is likely not accurate. Since 1995, the lowest number of reports was 67 in 2012 (lowest since 1992). This is interesting since it is the year right after the highest number was reported. Another unique aspect was in the year 2003 when the number of reports ≥ 60 kts was greater than the < 60 kts reports. The average number of reports for the 39-year period was 170.1. Since 2000, the average was 245.9.

When analyzing the six climate divisions (Fig. 23b), the same trend is seen. The division with the highest average of wind reports was division 4 with 40.1. This division also had the highest yearly number of 131 in 2008. The smallest number of reports on average was division 3 with 24.4 (division 6 had an average of 9, but like the tornado and hail reports, it does not give a true representation because its small size). A further look at the individual climate divisions can be found in Appendix D.

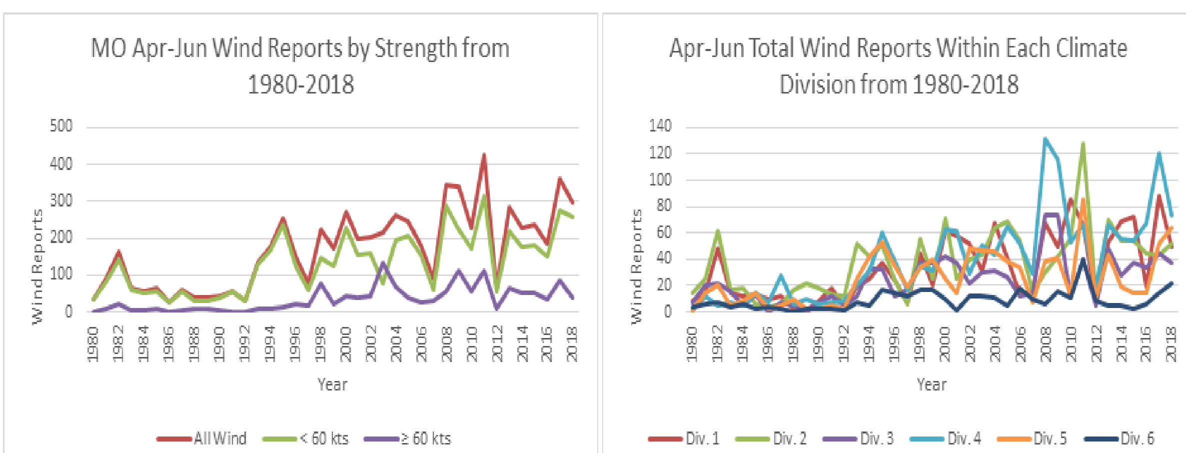


Fig. 23a. Left- April-June wind reports per year for all wind reports (red line), wind reports < 60 kts (green line), and wind reports ≥ 60 kts (purple line). Fig. 23b. Right- April-June all wind reports for each climate division: division 1 (red line), division 2 (green line), division 3 (purple line), division 4 (light blue line), division 5 (orange

line), division 6 (dark blue line). An increase in wind reports is evident within the state and its climate divisions. Large peaks are seen in 2011 and 2017.

3.5 State In-Season Soil Moisture Compared with In-Season Tornado Counts

When comparing in-season soil moisture anomalies to in-season tornado counts within the state, there was a positive correlation (Figs. 24b-d) for all levels (> E(F0), E(F0)-E(F1), and E(F2)-E(F5)). Soil moisture and tornado counts > E(F0) and the soil moisture and tornado counts E(F2)-E(F5) showed significant positive correlations ($p \leq 0.10$). What is interesting is the soil moisture was decreasing during this time, but the categories of tornado counts > E(F0) and tornado counts E(F0)-E(F1) were increasing. The tornado counts E(F2)-E(F5) was slightly decreasing. Even though it appears there is a negative correlation, there is a positive correlation because the peaks and valleys line up more consistently.

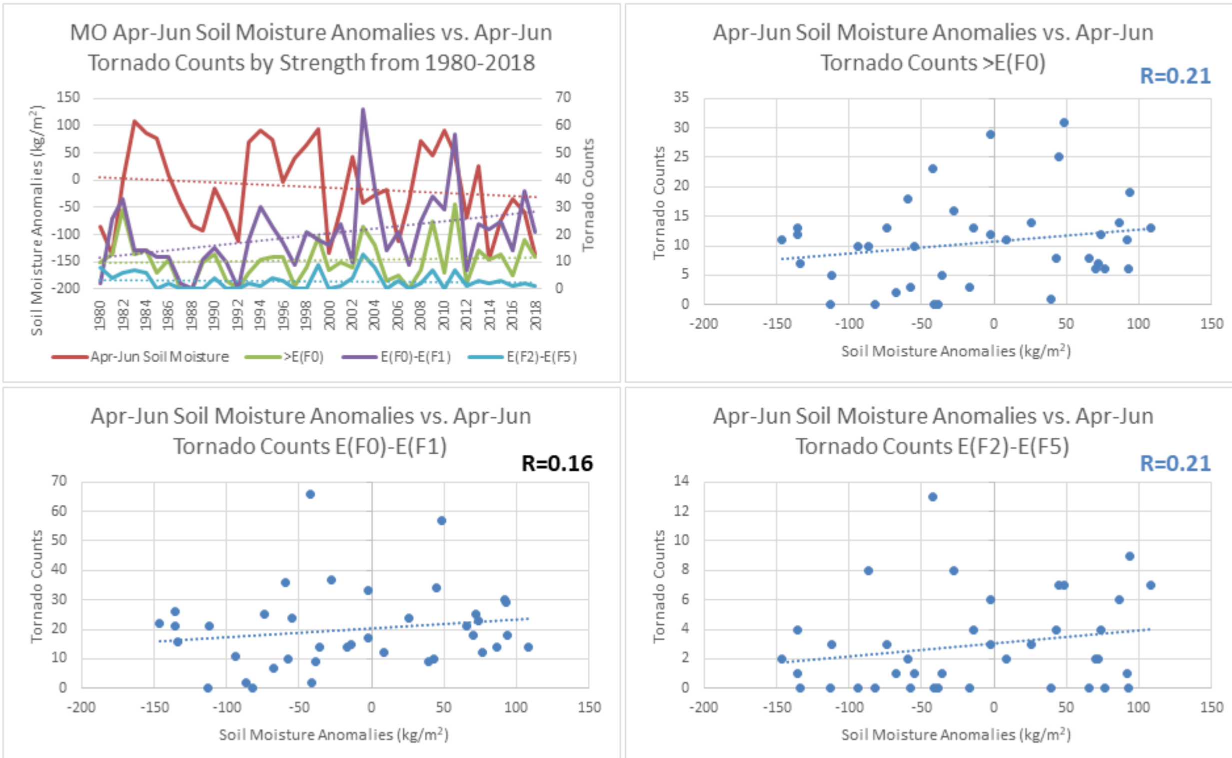


Fig. 24a. Top Left- April-June soil moisture anomalies (red line) compared with April-June tornado counts > E(F0) (green line), tornado counts E(F0)-E(F1) (purple line), and tornado counts E(F2)-E(F5) (blue line). Fig. 24b. Top Right- April-June soil moisture anomalies versus April-June tornado counts > E(F0). Fig. 24c. Bottom Left- Same as in 24b, but for tornado counts E(F0)-E(F1). Fig. 24d. Bottom Right- Same as in previous graph, but for tornado counts E(F2)-E(F5). Significant positive correlations ($p \leq 0.10$) are seen in Figs. 24b and 24d.

3.6 State In-Season Soil Moisture Compared with In-Season Tornado Days

When comparing the in-season soil moisture anomalies with in-season tornado days > E(F0), tornado days E(F0)-E(F1), and tornado days E(F2)-E(F5), only the tornado days E(F0)-E(F1) had a significant correlation ($p \leq 0.10$) (Fig. 25c). Although, all categories showed positive correlations (Figs. 25b-d). Since soil moisture was generally decreasing and tornado activity was increasing, the peaks and valleys lined up closely causing the positive correlations. It is important to remember that there may be other factors contributing to the increase in tornadic events. One could be the population growth and better reporting. Other factors may include synoptic variables.

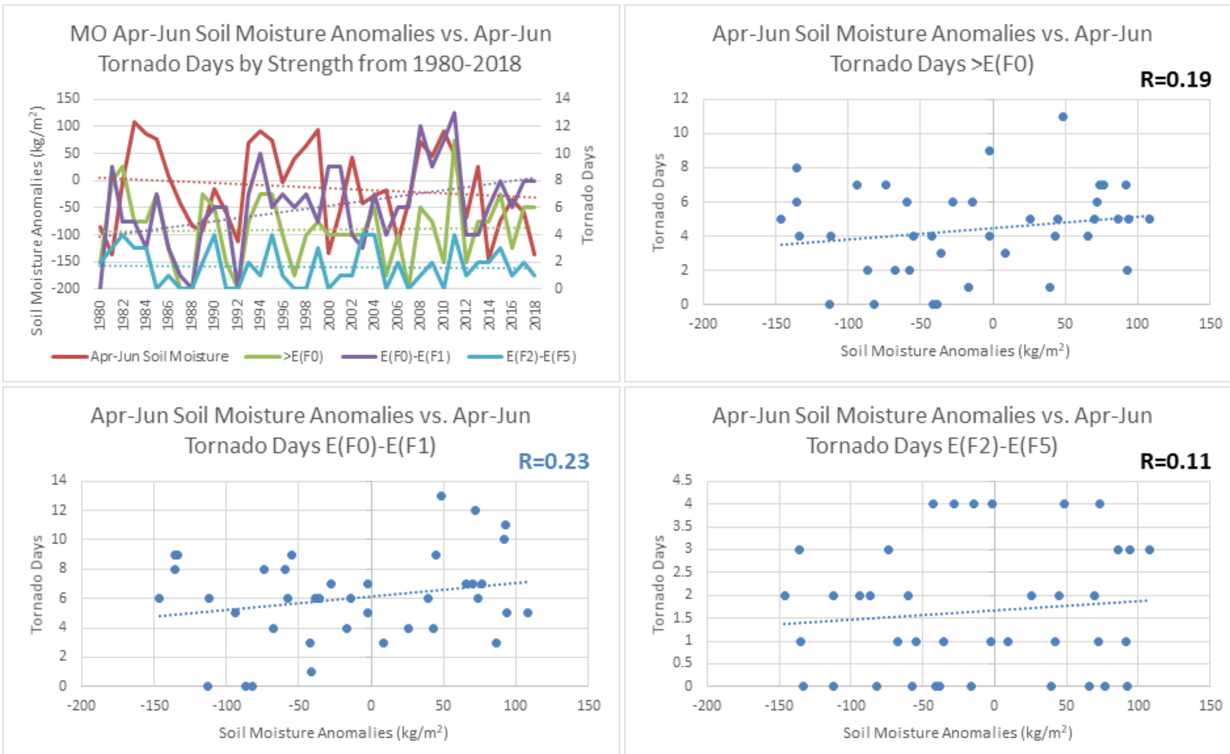


Fig. 25a. As in Fig. 24, except for tornado days. A significant correlation ($p \le 0.10$) is seen in Fig. 25c.

3.7 Divisional In-Season Soil Moisture Compared with Divisional In-Season Tornado Counts

The divisional in-season soil moisture anomalies are compared with the divisional in-season tornado counts in Fig. 26. The following divisional comparisons do not account for advection of environmental air from other areas. Therefore, only direct comparisons within the divisions are made. Also, as mentioned previously, only severe reports that occurred within the division in question are included. Within the six climate divisions, divisions 2 and 5 showed significant positive correlations ($p \leq 0.05$). Divisions 3 and 4 also showed slight positive correlations, although not statistically significant. Divisions 1 and 6, which are in the opposite parts of the state, indicated non-significant negative correlations.

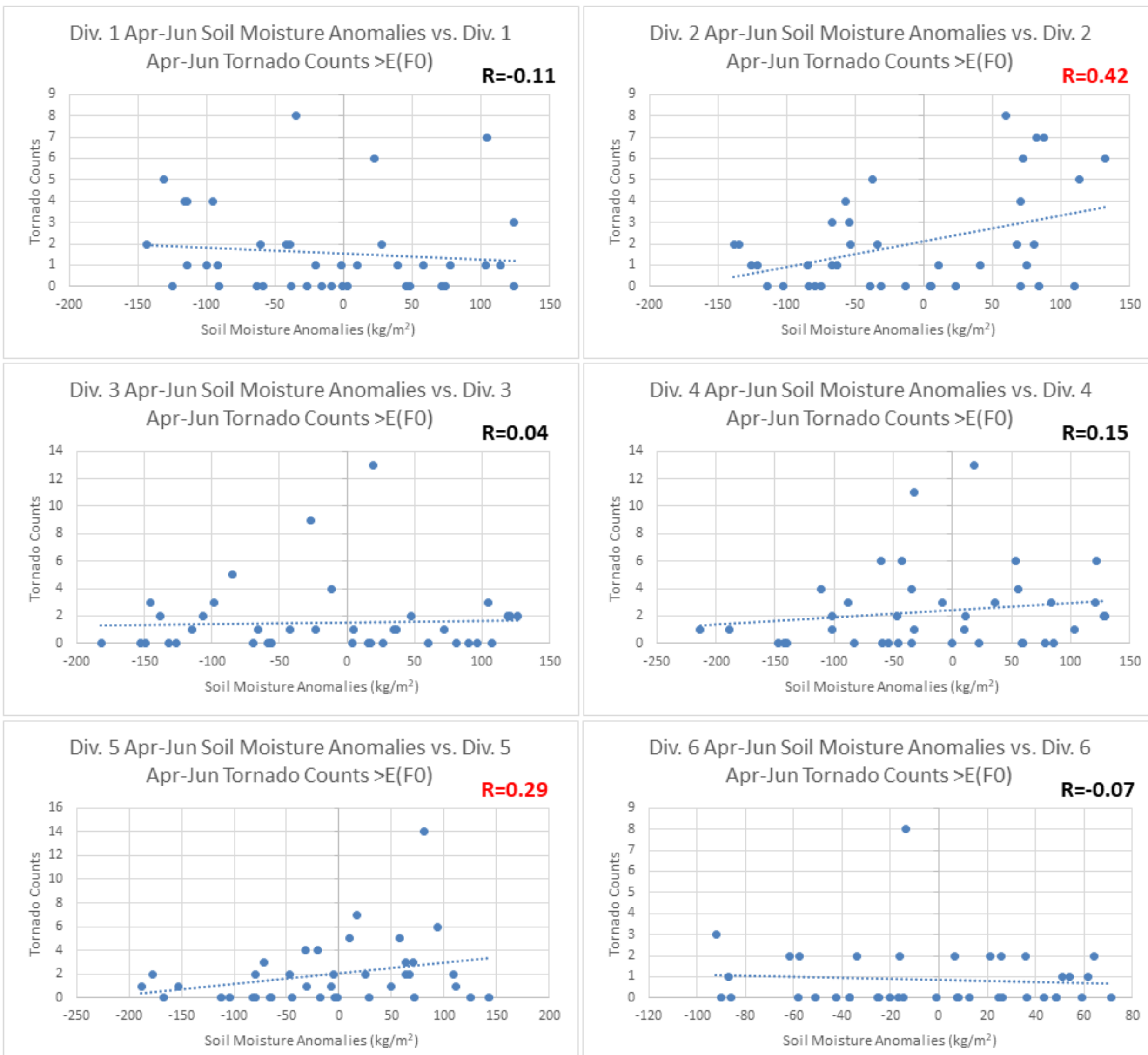
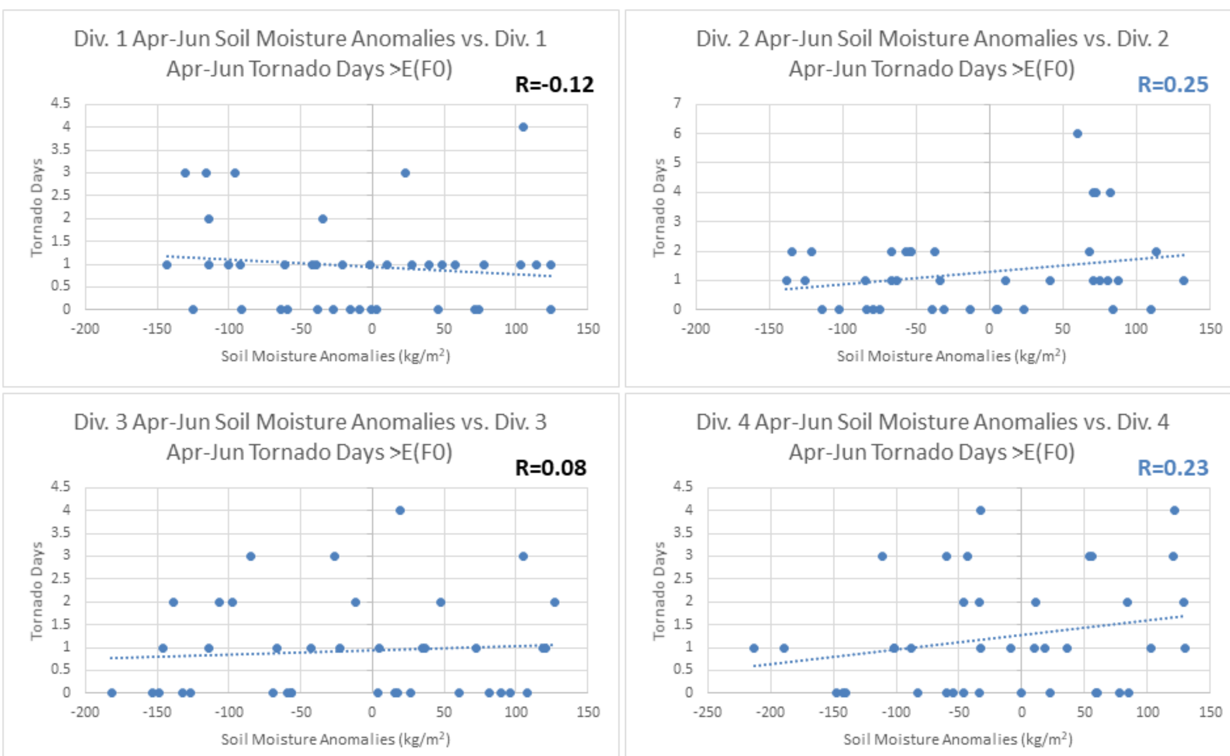


Fig. 26a. Top Left- Division 1 April-June soil moisture anomalies compared with division 1 April-June tornado counts > E(F0). Fig. 26b. Top Right- Same as in 26a, but for division 2. Fig. 26c. Middle Left- Same as previous graphs, but for division 3. Fig. 26d. Middle Left. Same as in previous graphs, but for division 4. Fig. 26e. Bottom

Left- Same as in previous graphs, but for division 5. Fig. 26f. Bottom Right- Same as in previous graphs, but for division 6. Divisions 2 and 5 saw significant positive correlations (p ≤ 0.05).

3.8 Divisional April-June Soil Moisture Compared with Divisional Tornado Days

The divisional in-season soil moisture anomalies are compared with the divisional in-season tornado days in Fig. 27. Within the six climate divisions, divisions 2, 4, and 5 all showed significant positive correlations ($p \leq 0.10$). Divisions 3 and 6 also showed slight positive correlations, although not statistically significant. Division 1 was the only one to indicate a negative correlation and it was not statistically significant.



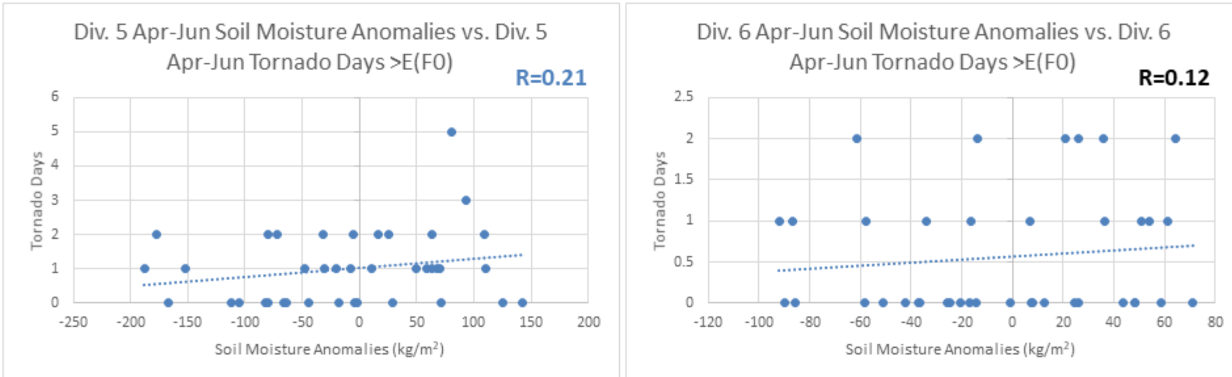


Fig. 27. As in Fig. 26, except for tornado days > E(F0). Divisions 2, 4, and 5 had significant positive correlations (p ≤ 0.10).

3.9 State In-Season Soil Moisture Compared with In-Season Hail Reports

The state in-season soil moisture anomalies are compared with in-season all hail reports, hail reports < 1.25 in., and hail reports ≥ 1.25 in. below in Fig. 28. All had slightly positive correlations, but none were statistically significant.

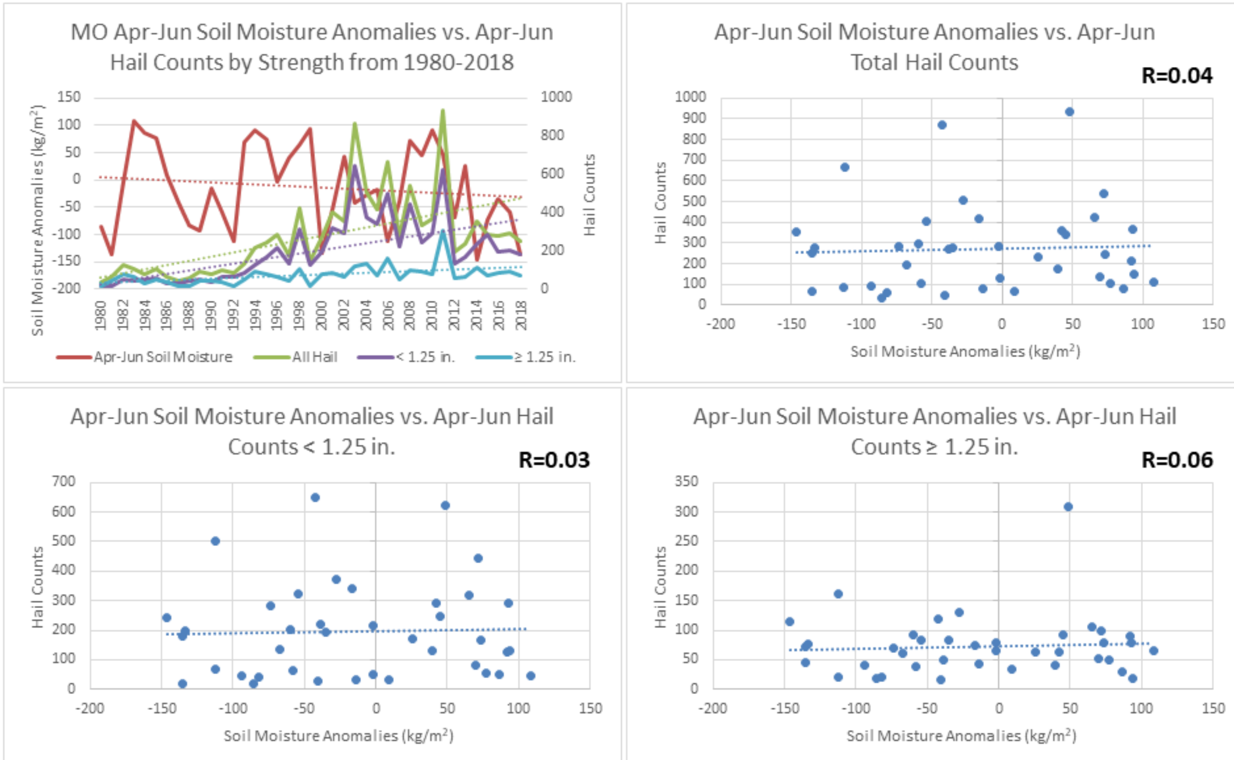


Fig. 28a. Top Left- April-June soil moisture anomalies (red line) compared with April-June all hail reports (green line), hail reports < 1.25 in. (purple line), and hail reports ≥ 1.25 in. (blue line). Fig. 28b. Top Right- April-June soil moisture anomalies versus April-June total hail reports. Fig. 28c. Bottom Left- Same as in 28b, but for hail reports < 1.25 in. Fig. 28d. Bottom Right- Same as in previoud graph, but for hail reports ≥ 1.25 in. No statistical significance was seen.

3.10 Divisional In-Season Soil Moisture Compared with Divisional In-Season Hail Reports

The divisional in-season soil moisture anomalies are compared with the divisional in-season hail reports in Fig. 29. Within the six climate divisions, divisions 1, 2, 4, and 5 showed positive correlations, but none were statistically significant. Divisions 3 and 6 showed slight negative correlations.

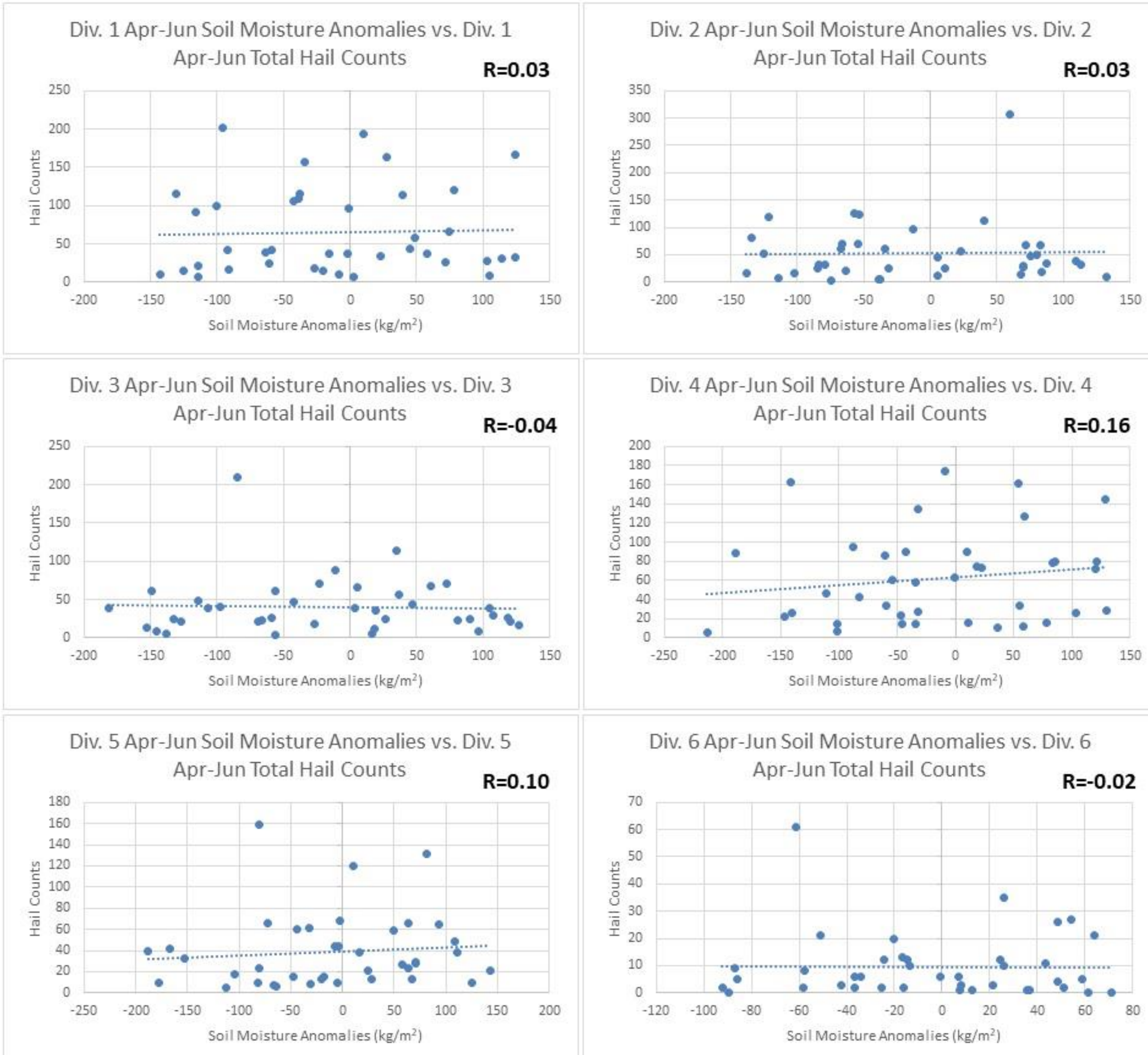


Fig. 29a. Top Left- Division 1 April-June soil moisture anomalies compared with division 1 April-June all hail reports. Fig. 29b. Top Right- Same as in 29a, but for division 2. Fig. 29c. Middle Left- Same as previous graphs, but for division 3. Fig. 29d. Middle Left. Same as in previous graphs, but for division 4. Fig. 29e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 29f. Bottom Right- Same as in previous graphs, but for division 6. None of the climate divisions saw statistical significance.

3.11 State In-Season Soil Moisture Compared with In-Season Wind Reports

The state in-season soil moisture anomalies compared with in-season all wind reports, wind reports < 60 kts, and wind reports ≥ 60 kts are shown below in Fig. 30. All categories saw a positive correlation, but none were statistically significant.

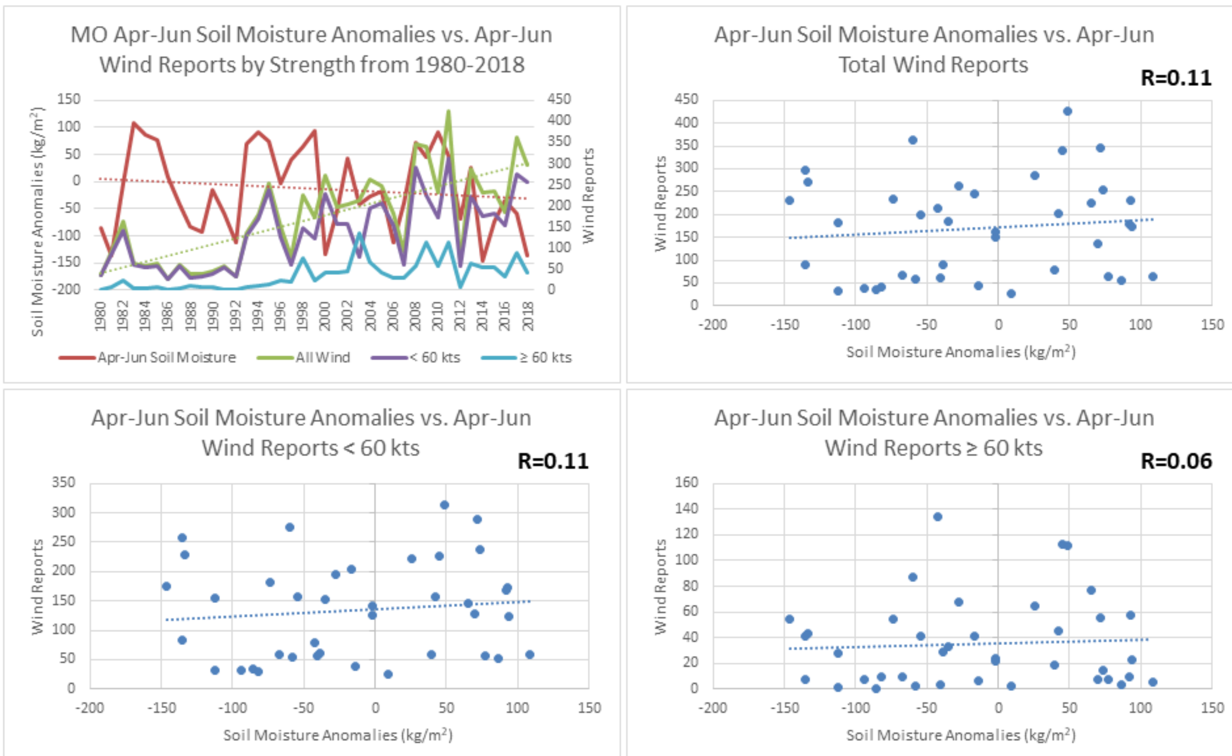
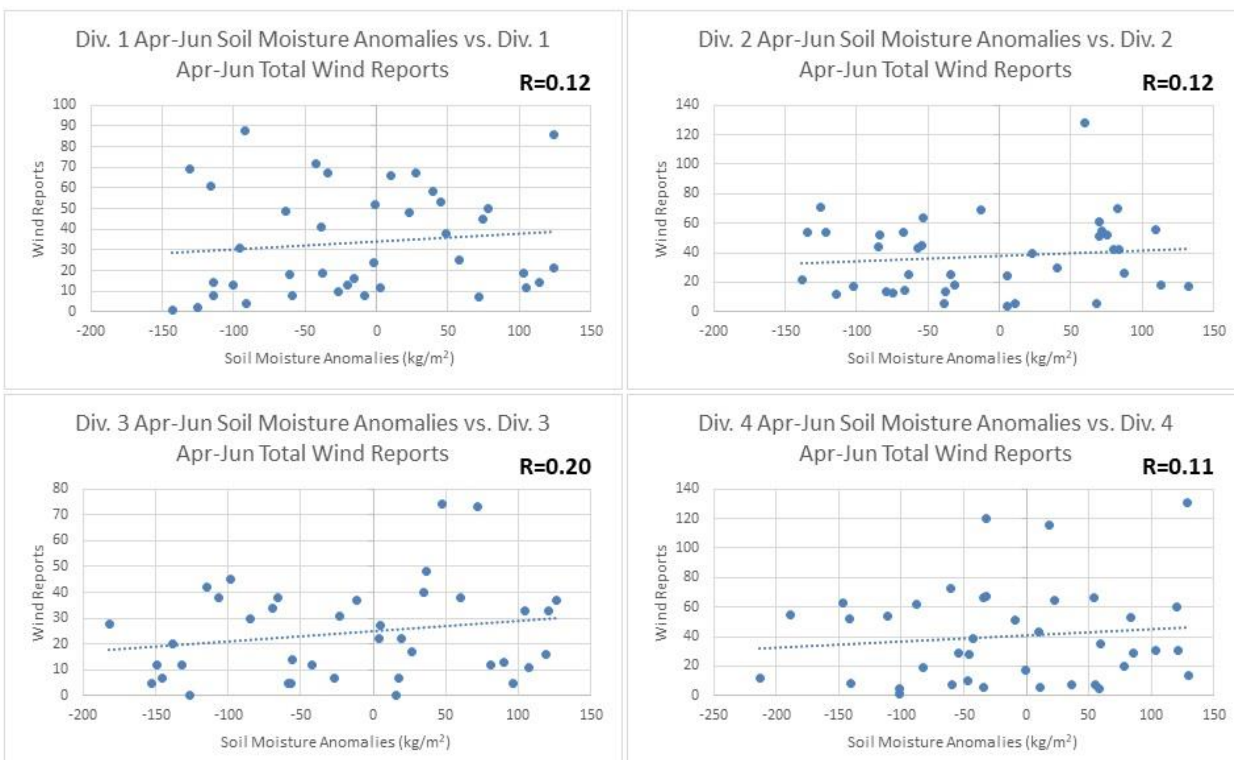
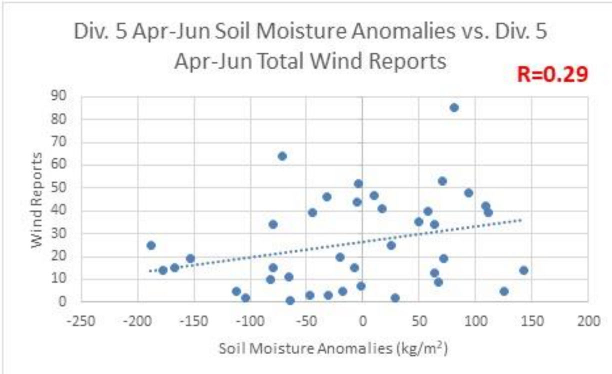


Fig. 30a. Top Left- April-June soil moisture anomalies (red line) compared with April-June all wind reports (green line), wind reports < 60 kts (purple line), and wind reports ≥ 60 kts (blue line). Fig. 30b. Top Right- April-June soil moisture anomalies versus April-June total wind reports. Fig. 30c. Bottom Left- Same as in 30b, but for wind reports < 60 kts. Fig. 30d. Bottom Right- Same as in previous graph, but for wind reports ≥ 60 kts. No statistical significance was seen.

3.12 Divisional In-Season Soil Moisture Compared with Divisional In-Season Wind Reports

The divisional in-season soil moisture anomalies are compared with the divisional in-season wind reports in Fig. 31. All divisions showed a positive correlation. Surprisingly, division 5 saw a significant positive correlation ($p \leq 0.05$). Division 3 was also close with a significant positive correlation at the 11% level ($p \leq 0.11$). This is interesting since the wind reports within the state were not statistically significant. This suggests that localized areas within the state may behave differently than the state as a whole.





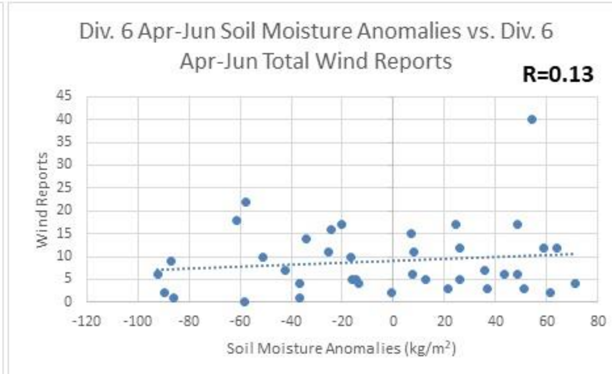


Fig. 31a. Top Left- Division 1 April-June soil moisture anomalies compared with division 1 April-June all wind reports. Fig. 31b. Top Right- Same as in 31a, but for division 2. Fig. 31c. Middle Left- Same as previous graphs, but for division 3. Fig. 31d. Middle Left. Same as in previous graphs, but for division 4. Fig. 31e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 31f. Bottom Right- Same as in previous graphs, but for division 6. All divisions showed a positive correlation with division 5 seeing a significant correlation ($p \leq 0.05$).

CHAPTER 4. SECOND EXPERIMENT RESULTS

4.1 State 3-Month Antecedent Soil Moisture Compared with In-Season Tornado Counts

The figure below (Fig. 32) shows the 3-month antecedent soil moisture anomalies compared to the in-season tornado counts > E(F0), tornado counts E(F0)-E(F1), and tornado counts E(F2)-E(F5). In contrast to the in-season soil moisture anomalies comparison (section 3.5, Fig. 24), tornado counts > E(F0) (Fig. 32b) and tornado counts E(F0)-E(F1) (Fig. 32c) showed a negative correlation, although non-significant. The 3-month antecedent tornado counts E(F2)-E(F5) showed a slight positive correlation. In-season tornado counts compared with in-season soil moisture anomalies (section 3.5) showed a significant correlation ($p \leq 0.10$) in Figs. 24b and 24d.

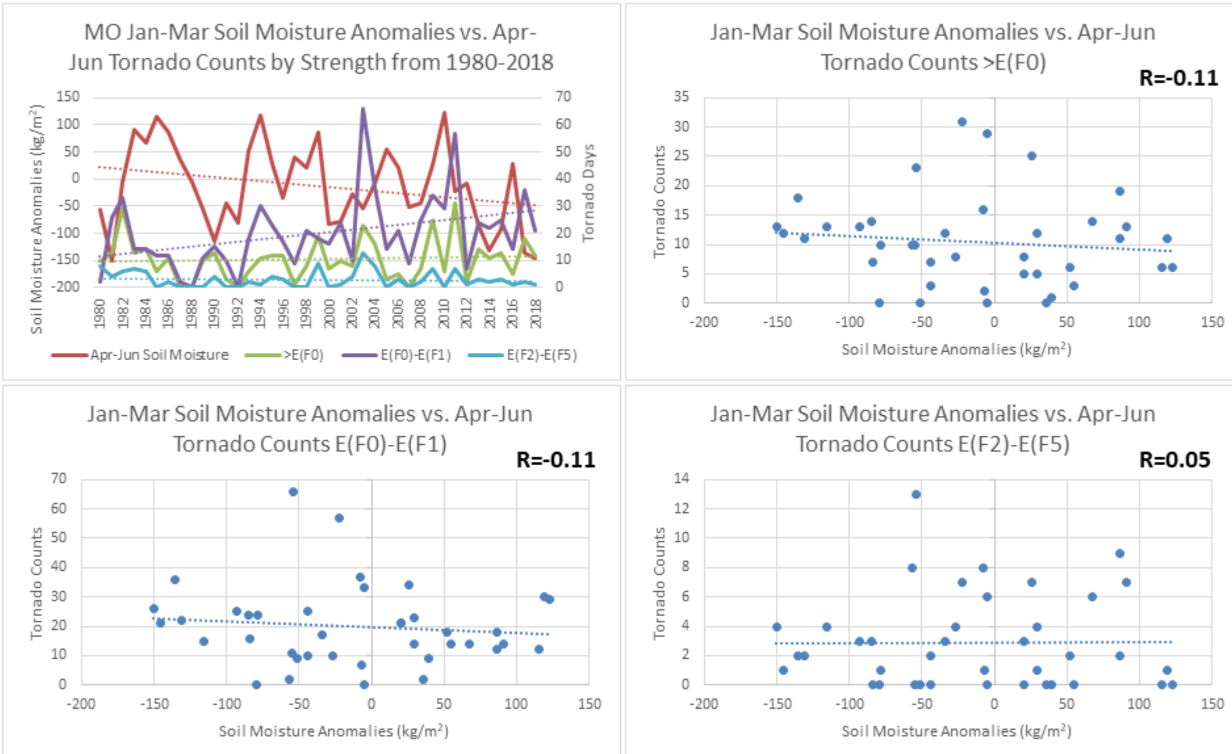


Fig. 32a. Top Left- January-March soil moisture anomalies (red line) compared with April-June tornado counts > E(F0) (green line), tornado counts E(F0)-E(F1) (purple line), and tornado counts E(F2)-E(F5) (blue line). Fig. 32b. Top Right- January-March soil moisture anomalies versus April-June tornado counts > E(F0). Fig. 32c. Bottom Left- Same as in 32b, but for tornado counts E(F0)-E(F1). Fig. 32d. Bottom Right- Same as previous graph, but for tornado counts E(F2)-E(F5). No significant correlations were found.

4.2 State 3-Month Antecedent Soil Moisture Compared with In-Season Tornado Days

The 3-month state soil moisture anomalies compared with in-season tornado days > E(F0), tornado days E(F0)-E(F1), and tornado days E(F2)-E(F5), are displayed below in Fig. 33. Much like section 4.1, these results differ from that of the in-season soil moisture anomalies (section 3.6, Fig. 25). The results below show a negative, but non-statistically significant correlation. In contrast, the results in section 3.6 all showed positive correlations, one of which was significant ($p \leq 0.10$) (Fig. 25c)

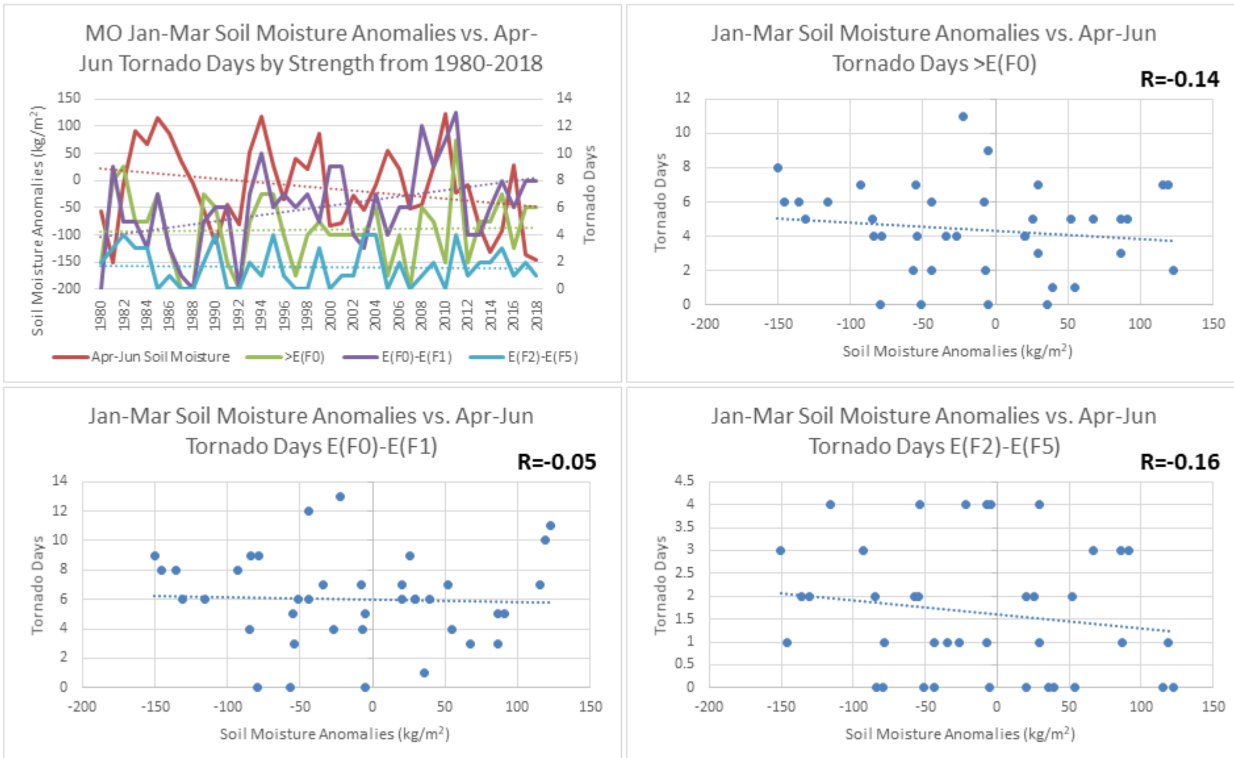


Fig. 33. As in Fig. 32, except for tornado days. No significant correlations were found.

4.3 Divisional 3-Month Antecedent Soil Moisture Compared with Divisional In-Season Tornado Counts

The divisional 3-month antecedent soil moisture anomalies were compared with the divisional in-season tornado counts below in Fig. 34. Division 2 was the only division which saw a positive correlation, and it was the only one that had a statistically significant correlation ($p \leq 0.10$). All others had negative correlations and saw no statistical significance. This division also saw a positive significant correlation ($p \leq 0.05$) with the in-season soil moisture comparison in section 3.7. Surprisingly, none of the 3-month antecedent tornado counts in any category within the state (section 4.1, Figs. 32b-d) were statistically significant. Because of the shallow gradients within the equations of some of the comparisons, predictions of future scenarios (dry/wet soils to severe weather outcome) are not likely to be made. Therefore, only the steeper gradients should be considered (those with higher absolute R-values).

Fig. 34a. Top Left- Division 1 January-March soil moisture anomalies compared with division 1 April-June all tornado counts. Fig. 34b. Top Right- Same as in 34a, but for division 2. Fig. 34c. Middle Left- Same as previous graphs, but for division 3. Fig. 34d. Middle Left. Same as in previous graphs, but for division 4. Fig. 34e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 34f. Bottom Right- Same as in previous graphs, but for division 6. All divisions showed a negative correlation, except for division 2 which saw a significant positive correlation (p ≤ 0.10).

4.4 Divisional 3-Month Antecedent Soil Moisture Compared with Divisional In-Season Tornado Days

The divisional 3-month soil moisture anomalies were compared with the divisional in-season tornado counts below in Fig. 35. Division 3 had a significant negative correlation ($p \leq 0.10$). Division 5 (within this section) also saw statistical significance; a negative correlation ($p \leq 0.05$) and was significant ($p \leq 0.10$) in section 3.8 with the in-season soil moisture comparison. Interestingly, the 3-month antecedent tornado days within the state (section 4.2, Fig. 33b) were not statistically significant at either level. Divisions 1 and 4 saw non-significant negative correlations, while divisions 2 and 6 had slight non-significant positive correlations.

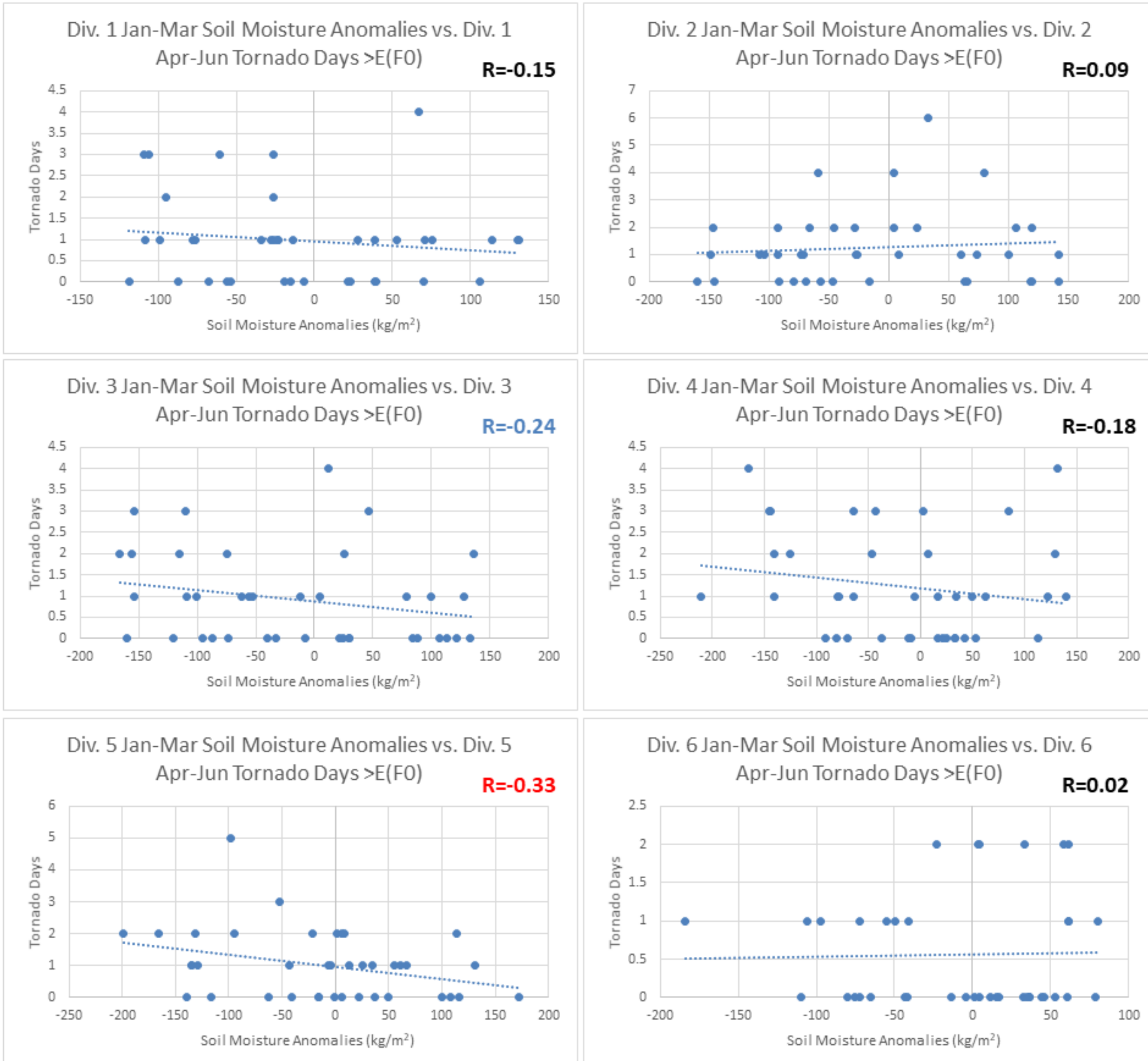


Fig. 35. As in Fig. 34, except for tornado days > E(F0). Divisions 3 and 5 had negative correlations that were statistically significant. Division 3 had a significant correlation at the 10% level ($p \le 0.10$), while division 5 was at the 5% level ($p \le 0.05$).

4.5 State 3-Month Antecedent Soil Moisture Compared with In-Season Hail Reports

The 3-month state soil moisture anomalies compared with in-season all hail reports, hail reports < 1.25 in., and hail reports ≥ 1.25 in. are displayed below in Fig. 36. All categories had a negative, but non-significant, correlation. This is in contrast with the in-season soil moisture comparison in section 3.9 (Figs. 28b-d), where all categories saw a positive, although non-significant correlations.

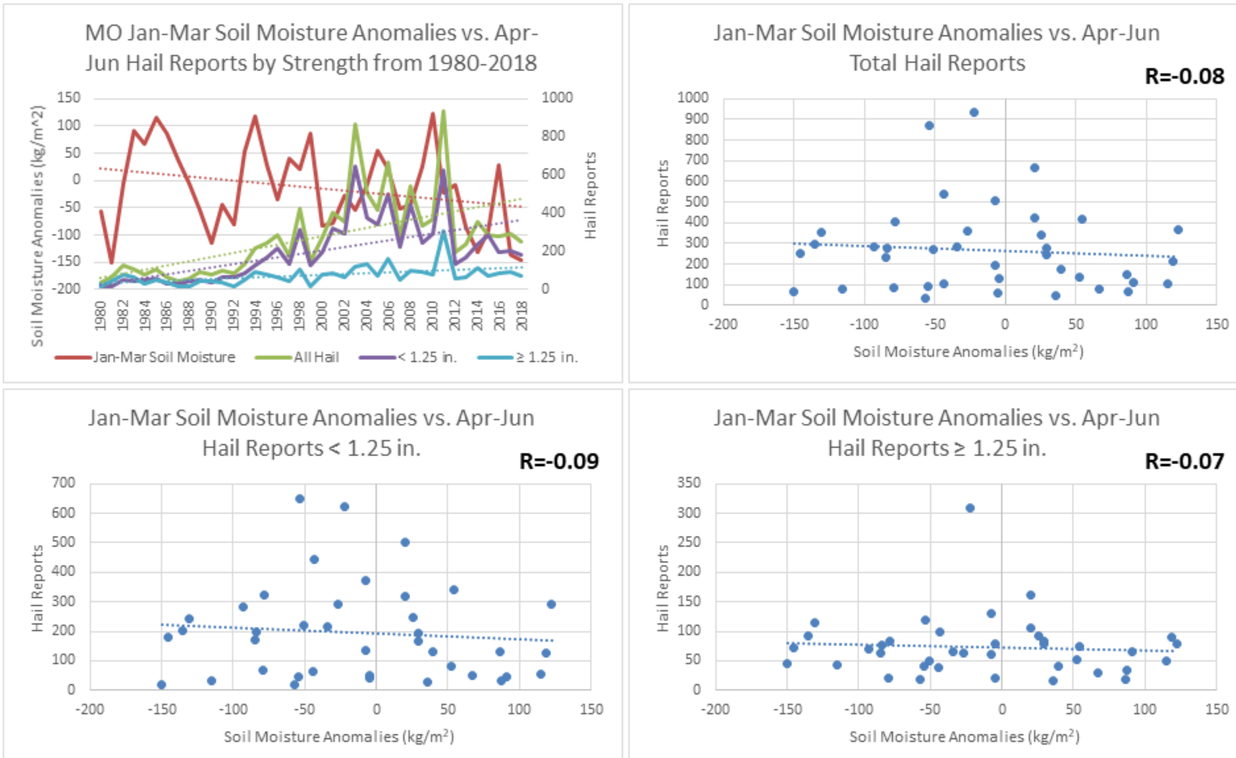


Fig. 36a. Top Left- January-March soil moisture anomalies (red line) compared with April-June all hail reports (green line), hail reports < 1.25 in. (purple line), and hail reports ≥ 1.25 in. (blue line). Fig. 36b. Top Right- January-March soil moisture anomalies versus April-June total hail reports. Fig. 36c. Bottom Left- Same as in 36b, but for hail reports < 1.25 in. Fig. 36d. Bottom Right- Same as in previoud graph, but for hail reports ≥ 1.25 in. No statistical signifance was found.

4.6 Divisional 3-Month Antecedent Soil Moisture Compared with Divisional In-Season Hail Reports

The divisional 3-month soil moisture anomalies were compared with the divisional in-season hail reports below in Fig. 37. All divisions saw a negative correlation except for division 6. All divisions were also statistically non-significant. The only division to have the same trendline within itself as the in-season soil moisture comparisons was division 3.

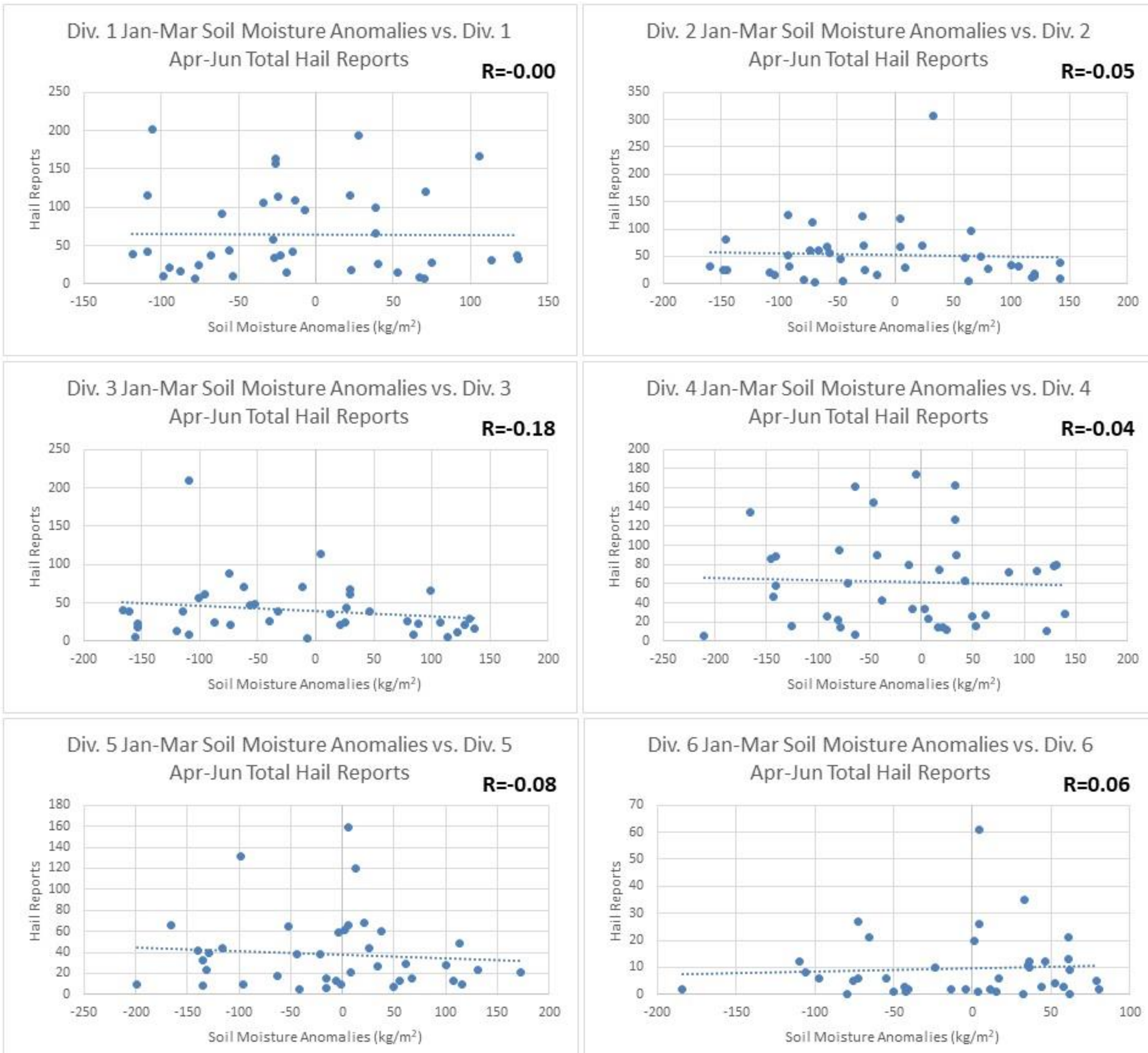


Fig. 37a. Top Left- Division 1 January-March soil moisture anomalies compared with division 1 April-June all hail reports. Fig. 37b. Top Right- Same as in 37a, but for division 2. Fig. 37c. Middle Left- Same as previous graphs, but for division 3. Fig. 37d. Middle Left. Same as in previous graphs, but for division 4. Fig. 37e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 37f. Bottom Right- Same as in previous graphs, but for division 6. No climate divisions saw statistical significance.

4.7 State 3-Month Antecedent Soil Moisture Compared with In-Season Wind Reports

The 3-month state soil moisture anomalies compared with in-season all wind reports, wind reports < 60 kts, and wind reports ≥ 60 kts are displayed below in Fig. 38. All categories had a negative correlation with wind reports ≥ 60 kts seeing a significant correlation ($p \leq 0.10$). This contrasts with the in-season soil moisture comparison in section 3.11 (Figs. 30b-d) where all categories saw a positive correlation, although non-significant.

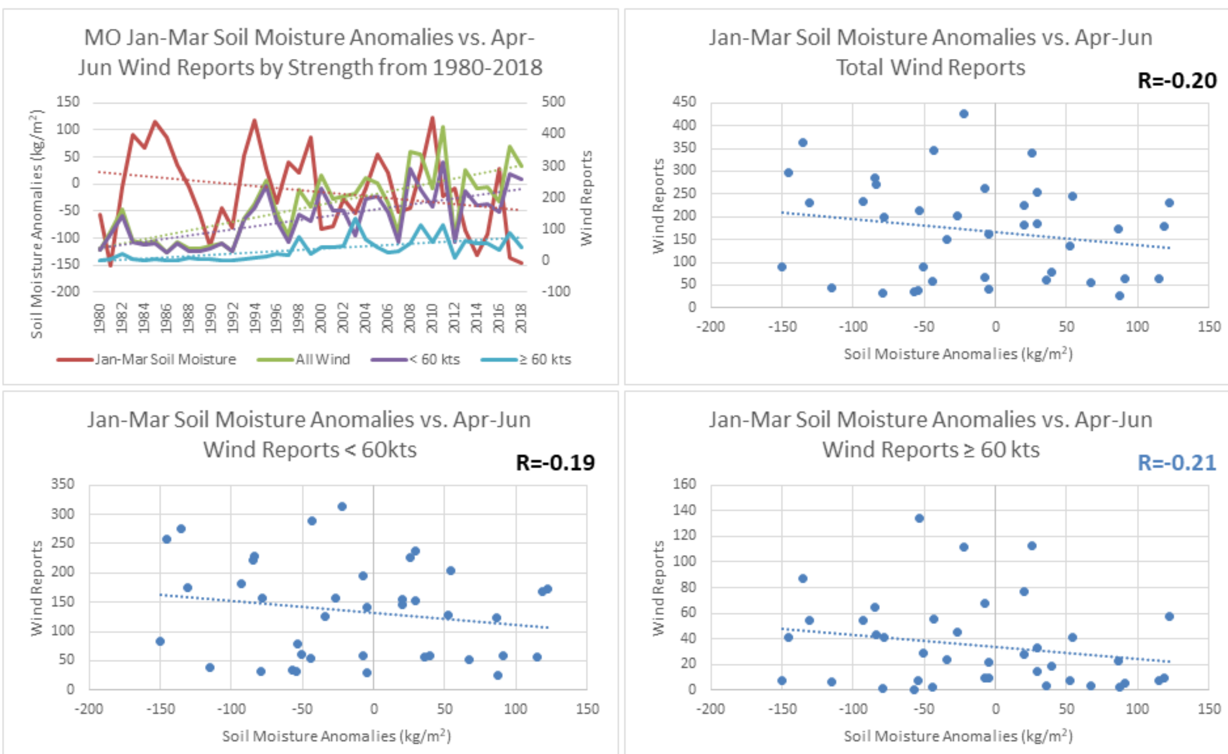
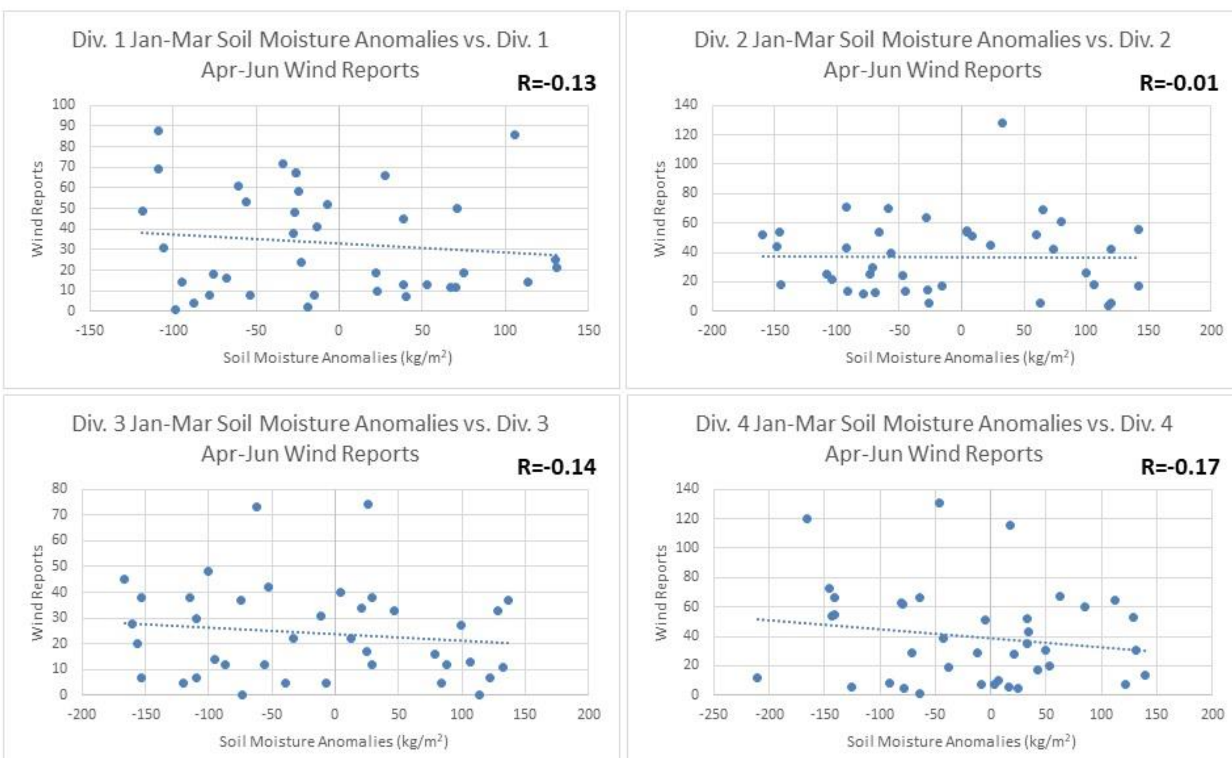
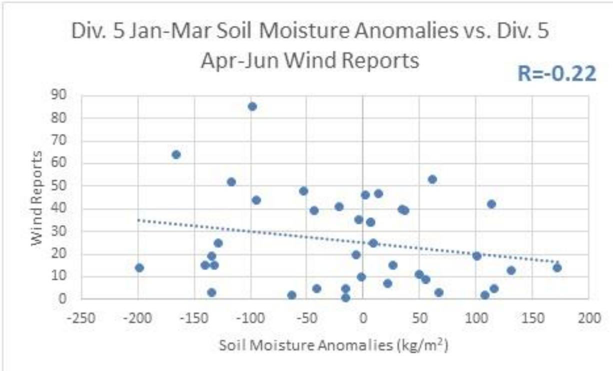


Fig. 38a. Top Left- January-March soil moisture anomalies (red line) compared with April-June all wind reports (green line), wind reports < 60 kts (purple line), and wind reports ≥ 60 kts (blue line). Fig. 38b. Top Right- January-March soil moisture anomalies versus April-June total wind reports. Fig. 38c. Bottom Left- Same as in 38b, but for wind reports < 60 kts. Fig. 38d. Bottom Right- Same as in previous graph, but for wind reports ≥ 60 kts. A significant correlation ($p \leq 0.10$) was seen with the wind reports ≥ 60 kts.

4.8 Divisional 3-Month Antecedent Soil Moisture Compared with Divisional In-Season Wind Reports

The divisional 3-month soil moisture anomalies were compared with the divisional in-season wind reports below in Fig. 39. All divisions saw negative correlations with division 5 having a significant correlation at the 10% level ($p \leq 0.10$). This contrasts with the in-season soil moisture comparison in section 3.12 where all divisions saw positive correlations. Much like division 5 in this section, division 5 in section 3.12 (Fig. 31e) was also significant, but at the 5% level ($p \leq 0.05$).





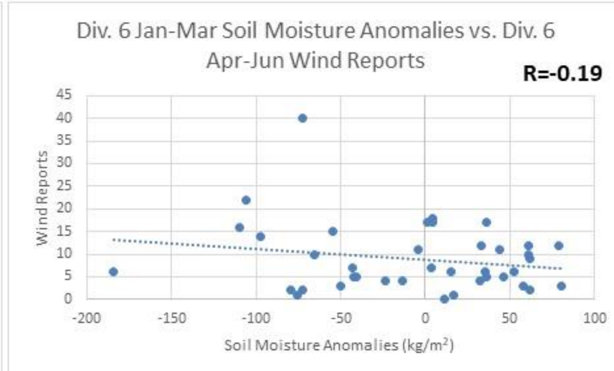


Fig. 39a. Top Left- Division 1 January-March soil moisture anomalies compared with division 1 April-June all wind reports. Fig. 39b. Top Right- Same as in 39a, but for division 2. Fig. 39c. Middle Left- Same as previous graphs, but for division 3. Fig. 39d. Middle Left. Same as in previous graphs, but for division 4. Fig. 39e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 39f. Bottom Right- Same as in previous graphs, but for division 6. Division 5 saw a significant negative correlation ($p \leq 0.10$).

CHAPTER 5. THIRD EXPERIMENT RESULTS

5.1 State 6-Month Antecedent Soil Moisture Compared with In-Season Tornado Counts

The first part of the third experiment compares the results for the 6-month antecedent state moisture anomalies with the in-season tornado counts and are shown below in Fig. 40. Much like the 3-month antecedent moisture in section 4.1, the state tornado counts were divided into three categories: tornado counts > E(F0), tornado counts E(F0)-E(F1), and tornado counts E(F2)-E(F5). All categories showed a slight positive correlation, although non-significant. This is in comparison to the 3-month soil moisture comparison (section 4.1, Figs. 32b-d) where all categories showed no statistical significance (two categories had negative correlations and one was positive). This also compares to the in-season soil moisture comparison (section 3.5, Figs. 24b-d) where all categories were positive. Within that comparison, two categories were significant at the 10% level ($p \leq 0.10$).

To see if the correlation is affected by larger outbreaks, like the Wakefield et al. (2015) paper, the year 2011 was omitted (not shown here). When removed, the correlation of tornado counts > E(F0) went from 0.03 to -0.07, which is still not statistically significant. This is closest to the southern Plains region from the Wakefield et al. (2015) study where the correlation was -0.06.

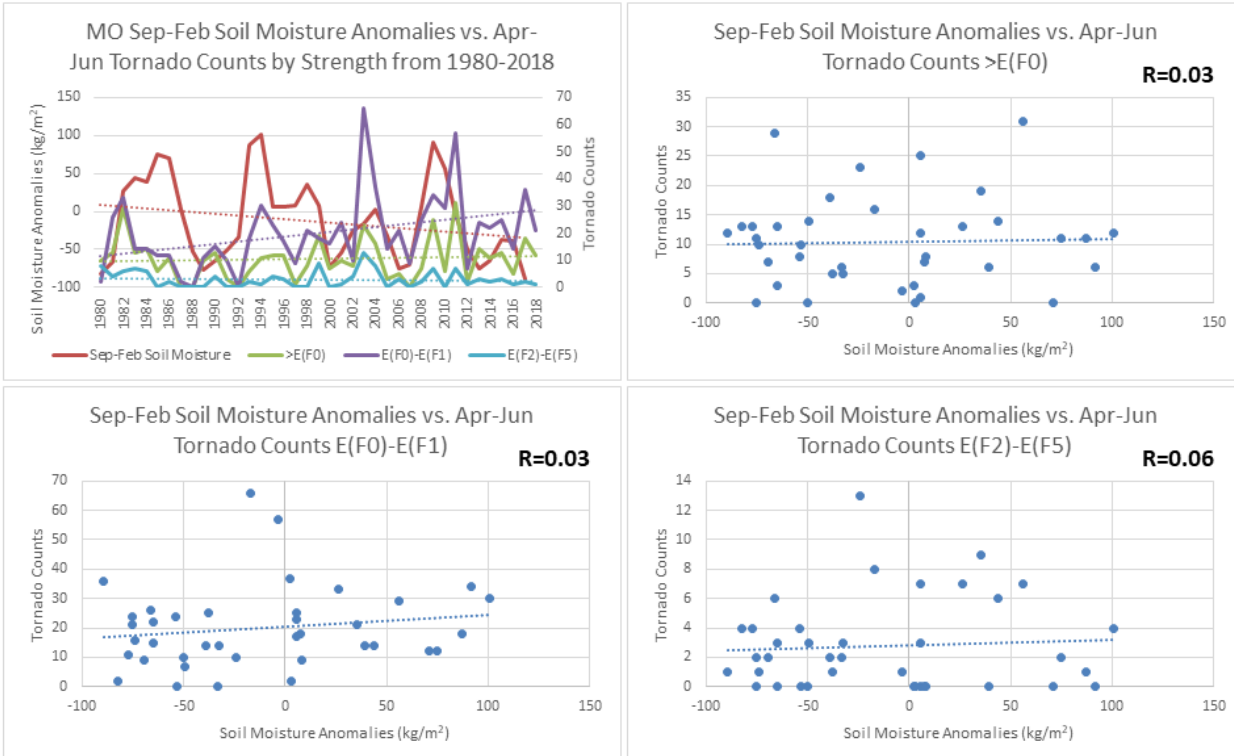


Fig. 40a. Top Left- September-February soil moisture anomalies (red line) compared with April-June tornado counts > E(F0) (green line), tornado counts E(F0)-E(F1) (purple line), and tornado counts E(F2)-E(F5) (blue line). Fig. 40b. Top Right- September-February soil moisture anomalies versus April-June tornado counts > E(F0). Fig. 40c. Bottom Left- Same as in 40b, but for tornado counts E(F0)-E(F1). Fig. 40d. Bottom Right- Same as previous graph, but for tornado counts E(F2)-E(F5). No statistical significance was found.

5.2 State 6-Month Antecedent Soil Moisture Compared with In-Season Tornado Days

The 6-month antecedent soil moisture anomalies for the state are compared with the in-season tornado days below in Fig. 41. The categories were the same as those used in section 5.1. All categories had a slight negative correlation, but no statistical significance was found. These were similar to the results within the 3-month soil moisture comparison (section 4.2, Figs. 33b-d) where all categories were also negative and non-significant. This contrasts with the in-season soil moisture comparison (section 3.6, Figs. 25b-d) where all the categories were positive with one being significant ($p \leq 0.10$) (Fig. 25c).

Like section 5.1, the year 2011 was omitted (not shown here). When removed, the correlation was increased from -0.05 to -0.15, although still not statistically significant. This is interesting since -0.15 is between the southern (0.15) and northern Plains (-0.34) region of the Wakefield et al. (2015) paper. This is reasonable because southern Missouri lies within the southern Plains and the northern half of the state is within the northern Plains regions (Fig. 18).

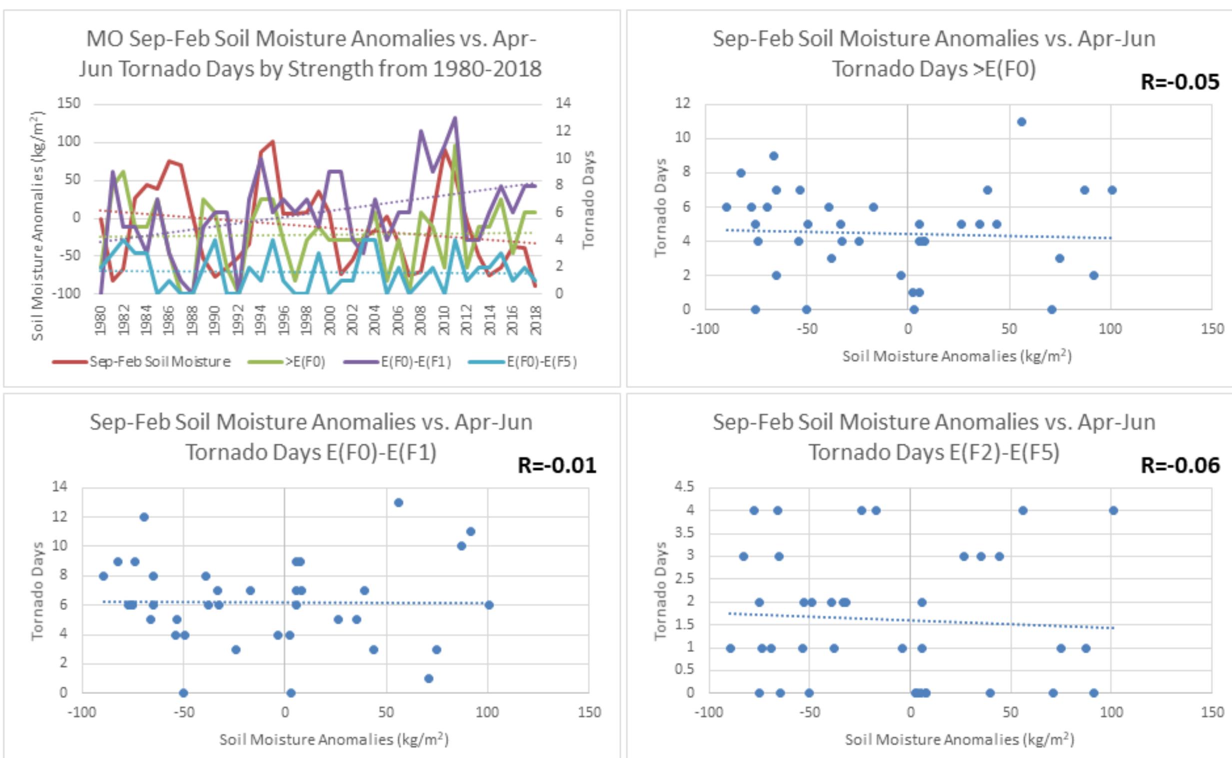
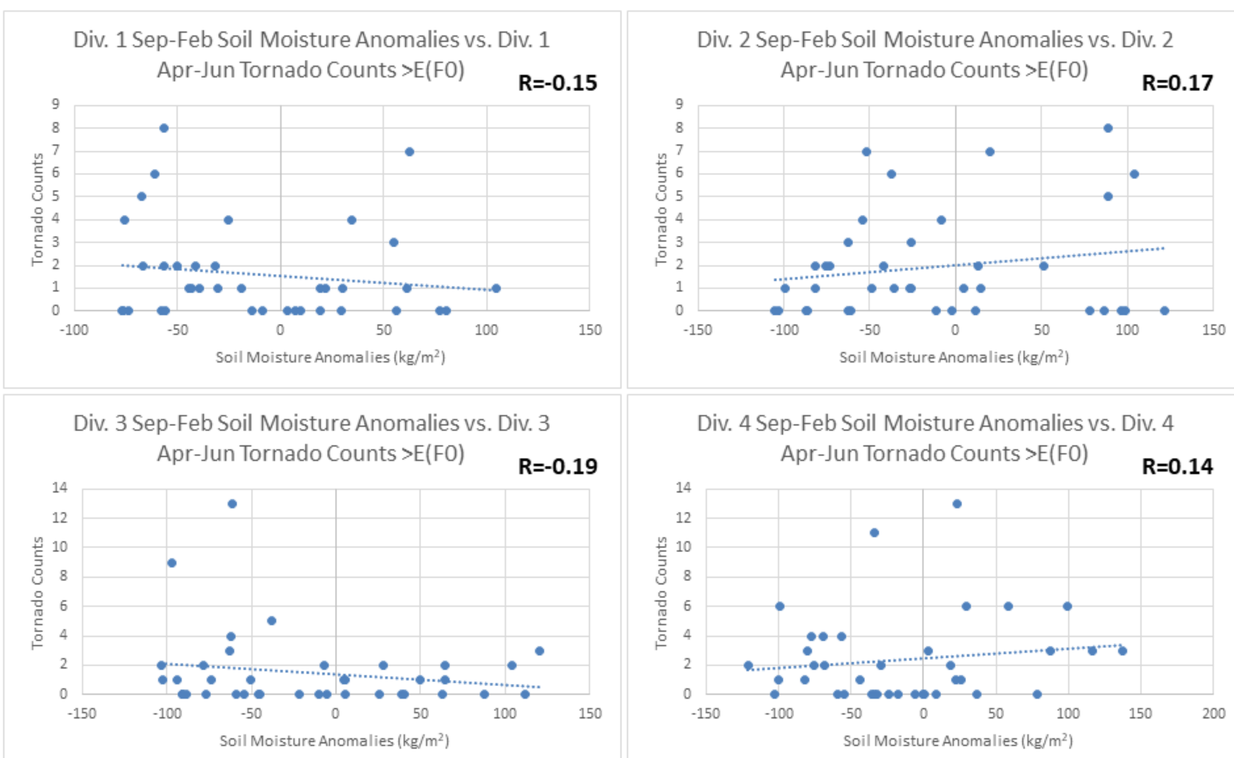


Fig. 41a. As in Fig. 40, except for tornado days. No statistical significance was found.

5.3 Divisional 6-Month Antecedent Soil Moisture Compared with Divisional In-Season Tornado Counts

Below in Fig. 42 are the divisional 6-month antecedent soil moisture anomalies compared with the divisional in-season tornado counts > E(F0). Four of the divisions (2, 4, 5, 6) had positive correlations and two divisions (1, 3) had negative correlations. None had any statistical significance. Similar to the 3-month antecedent soil moisture comparison (section 4.3, Figs. 34b-d), no statistical significance was found. These results contrast to those found in section 3.7 where two divisions (2, 5) saw significant correlations at the 5% level ($p \leq 0.05$) (Figs 26b, 26e).



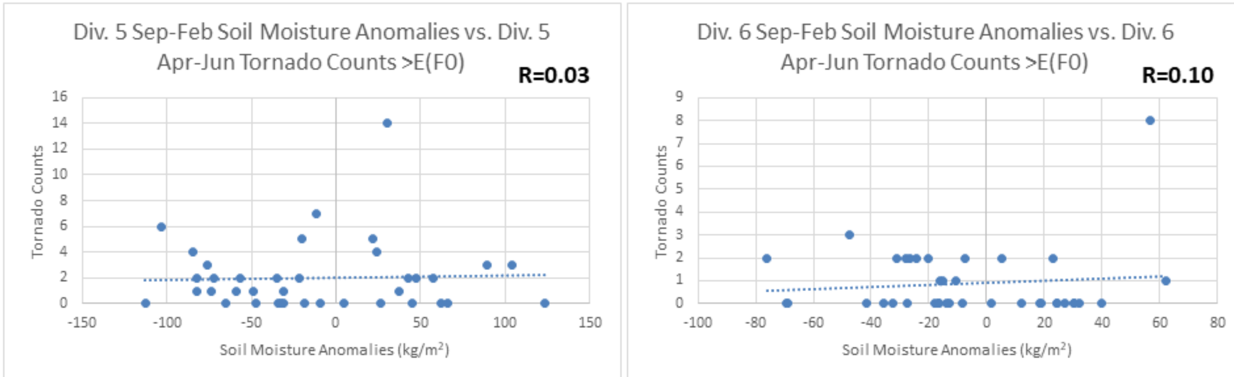


Fig. 42a. Top Left- Division 1 September-February soil moisture anomalies compared with division 1 April-June all tornado counts > E(F0). Fig. 42b. Top Right- Same as in 42a, but for division 2. Fig. 42c. Middle Left- Same as previous graphs, but for division 3. Fig. 42d. Middle Left. Same as in previous graphs, but for division 4. Fig. 42e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 42f. Bottom Right- Same as in previous graphs, but for division 6. No divisions saw statistical significance.

5.4 Divisional 6-Month Antecedent Soil Moisture Compared with Divisional In-Season Tornado Days

Below (Fig. 43) shows the divisional 6-month antecedent soil moisture anomalies compared with in-season tornado days > E(F0). Much like the tornado counts in the previous section (section 5.3), no statistical significance was found. Divisions 1, 3, and 5 saw slight negative correlations, while divisions 2, 4, and 6 had small positive correlations. This differs from the 3-month antecedent soil moisture comparison (section 4.4) where divisions 3 and 5 saw statistical significance (Figs. 35c, 35e). Both had negative correlations with division 3 having significance at the 10% level ($p \leq 0.10$) and division 5 having significance at the 5% level ($p \leq 0.05$). Also, the results in this section contrasts with the results in section 3.8 (in-season soil moisture comparison) where divisions 2, 4, and 5 saw positive correlations at the 10% level ($p \leq 0.10$) (Figs. 27b, 27d, 27e).

Like sections 5.1 and 5.2, some of the larger values of tornado day > E(F0) within the study period were omitted (not shown here). This was done by removing those whose numbers were greater/less than their average + standard deviation. From this, little difference was seen between the divisions. The higher tornado days do not seem to affect the overall outcome within the state and its climate divisions.

Fig. 43a. As in Fig. 42, except for tornado days > E(F0). No divisions saw statistical significance.

5.5 State 6-Month Antecedent Soil Moisture Compared with In-Season Hail Reports

The 6-month antecedent state soil moisture anomalies are compared with in-season hail reports below in Fig. 44. The categories used were total hail reports, hail reports < 1.25 in., and hail reports ≥ 1.25 in. Little increase or decrease was seen with the correlation coefficient for all three of the categories. Somewhat of interest, two of the categories had negative correlations, while one had a positive correlation. The categories of the hail reports within the in-season (section 3.9, Figs. 28b-d) had all positive correlations and the hail reports within the 3-month antecedent soil moisture comparison (section 4.5, Figs. 36b-d) had all negative correlations. While this information is interesting, it is likely non-significant since all categories (within each section) are below statistical significance.

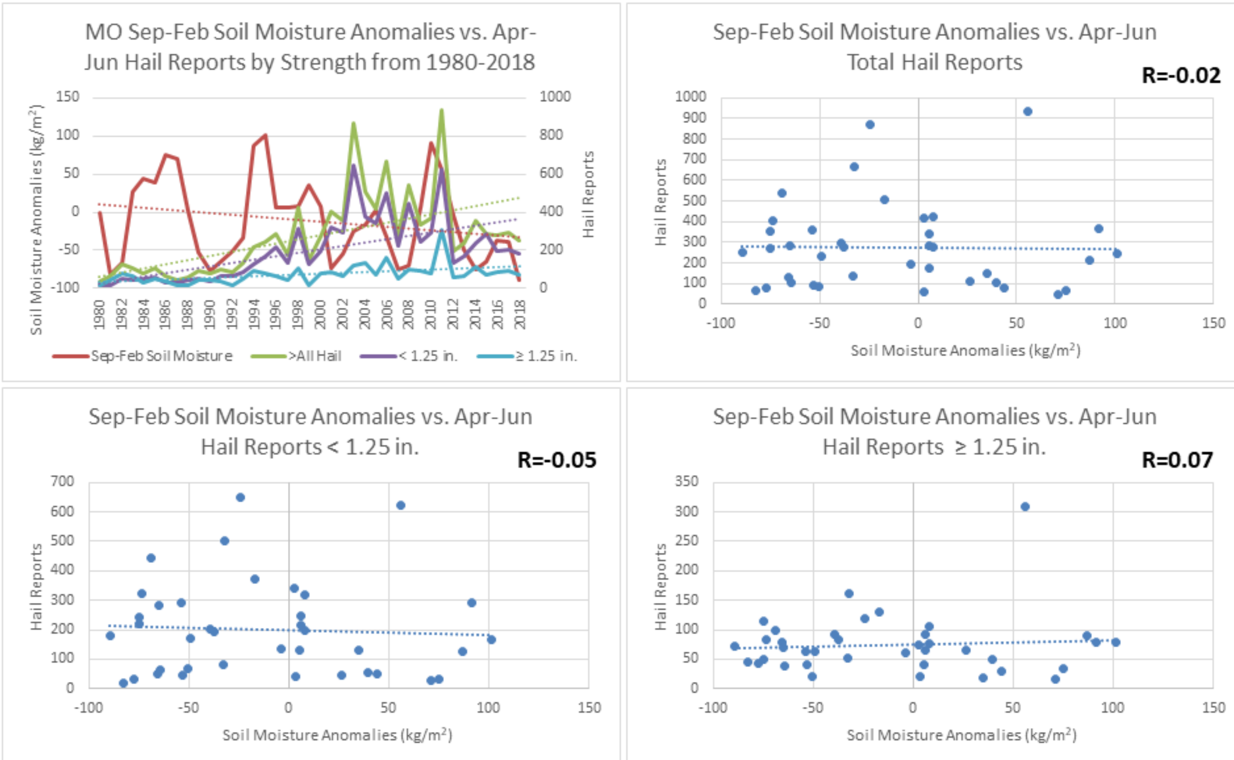


Fig. 44a. Top Left- September-February soil moisture anomalies (red line) compared with April-June all hail reports (green line), hail reports < 1.25 in. (purple line), and hail reports ≥ 1.25 in. (blue line). Fig. 44b. Top Right- January-March soil moisture anomalies versus April-June total hail reports. Fig. 44c. Bottom Left- Same as in 44b, but for hail reports < 1.25 in. Fig. 44d. Bottom Right- Same as in previoud graph, but for hail reports ≥ 1.25 in. No statistical significance was found.

5.6 Divisional 6-Month Antecedent Soil Moisture Compared with Divisional In-Season Hail Reports

The divisional 6-month antecedent state soil moisture anomalies are compared with the divisional in-season hail reports below in Fig. 45. No statistical significance was found within any of climate divisions. Interestingly, although most likely non-significant, divisions 3 and 5 had negative correlations for all three experiments (in-season, 3-month, 6-month).

Fig. 45a. Top Left- Division 1 September-February soil moisture anomalies compared with division 1 April-June all hail reports. Fig. 45b. Top Right- Same as in 45a, but for division 2. Fig. 45c. Middle Left- Same as previous graphs, but for division 3. Fig. 45d. Middle Left. Same as in previous graphs, but for division 4. Fig. 45e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 45f. Bottom Right- Same as in previous graphs, but for division 6. No statistical significance was found.

5.7 State 6-Month Antecedent Soil Moisture Compared with In-Season Wind Reports

The 6-month state antecedent soil moisture anomalies are compared with the in-season wind reports below in Fig. 46. As in the previous experiments, the three categories included all wind reports, wind reports < 60 kts, and wind reports ≥ 60 kts. Much like in section 4.7 (3-month antecedent soil moisture comparison, Figs. 38b-d), all categories showed negative correlations. However, the category of wind reports ≥ 60 kts in section 4.7 (Fig. 38d) had a significant correlation ($p \leq 0.10$) with the other two categories close behind. In contrast, the in-season soil moisture comparison (section 3.11, Figs. 30b-d) showed all positive correlations, although statistically non-significant.

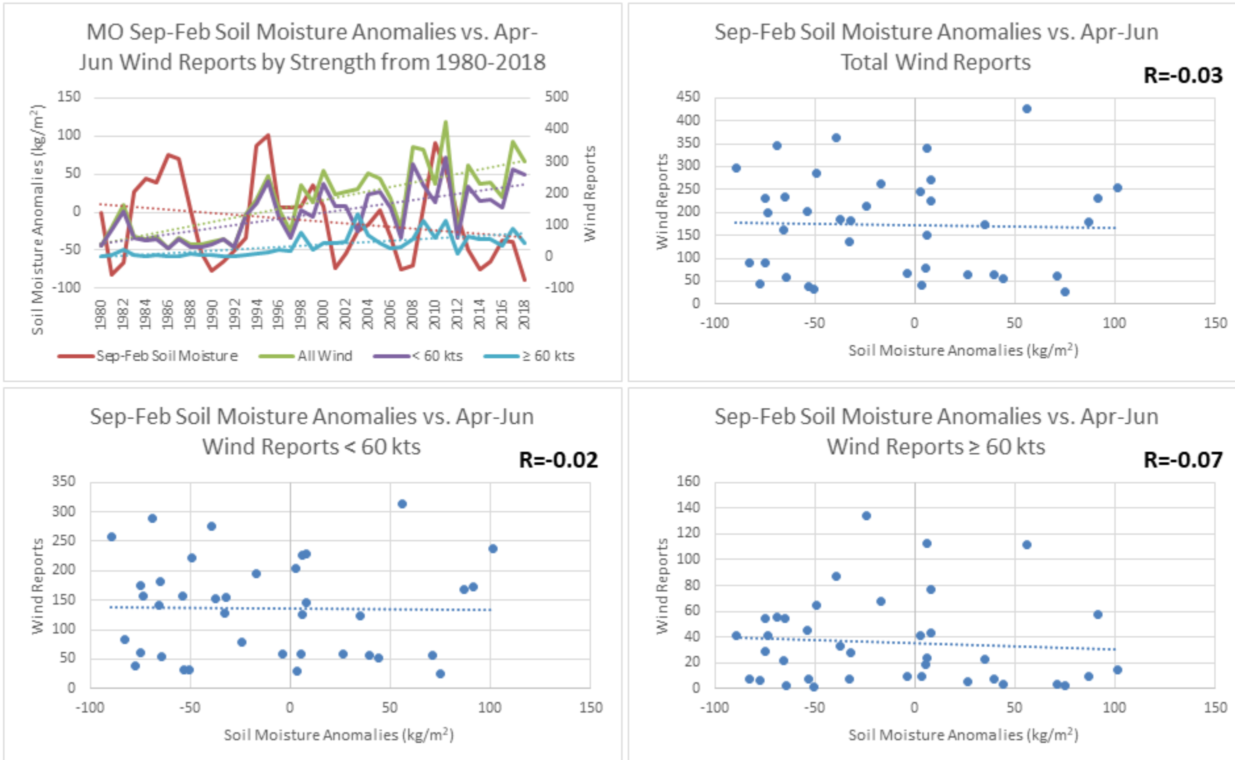


Fig. 46a. Top Left- September-February soil moisture anomalies (red line) compared with April-June all wind reports (green line), wind reports < 60 kts (purple line), and wind reports ≥ 60 kts (blue line). Fig. 46b. Top Right- September-February soil moisture anomalies versus April-June total wind reports. Fig. 46c. Bottom Left- Same as in 46b, but for wind reports < 60 kts. Fig. 46d. Bottom Right- Same as in previous graph, but for wind reports ≥ 60 kts. No statistical significance was found.

5.8 Divisional 6-Month Antecedent Soil Moisture Compared with Divisional Apr-Jun Wind Reports

The divisional 6-month antecedent state soil moisture anomalies are compared with the divisional in-season wind reports below in Fig. 47. No statistical significance was found within any of the climate divisions. Three of the divisions saw positive correlations (2, 4, 5) while three saw negative correlations (1, 3, 6). When looking back at the other two experiments, the in-season soil moisture comparison (section 3.12, Fig. 31) saw all positive correlations with division 5 being significant ($p \leq 0.05$) (Fig. 31e). The 3-month antecedent soil moisture comparison (section 4.8, Fig. 39) had all divisions having negative correlations with division 5 seeing significance ($p \leq 0.10$) (Fig. 39e).

Fig. 47a. Top Left- Division 1 January-March soil moisture anomalies compared with division 1 April-June all wind reports. Fig. 47b. Top Right- Same as in 47a, but for division 2. Fig. 47c. Middle Left- Same as previous graphs, but for division 3. Fig. 47d. Middle Left. Same as in previous graphs, but for division 4. Fig. 47e. Bottom Left- Same as in previous graphs, but for division 5. Fig. 47f. Bottom Right- Same as in previous graphs, but for division 6. No statistical significance was found.

CHAPTER 6. ADVECTION OF SOIL MOISTURE

Correlations between certain divisions were calculated to see if there might be a component of surface soil moisture advection. Divisions that were correlated were those which were oriented southwest to northeast and that were adjacent to one another. This was to account for southwesterly flow, which is the general flow regime during severe weather setups. Rabin et al. (1990) showed that convective activity will first occur downwind of a moist surface area. Only in-season months were calculated since it is unlikely that transported moisture from the surface would stay in the atmosphere of the same area for months.

Below (Fig. 48) are the correlations for three regions using tornado counts > E(F0). Soil moisture transport from division 1 into division 2 was used since division 1 is west of division 2. The same is true for division 3 into division 2 and for division 4 into division 5. The comparison of division 1 soil moisture to division 2 tornado counts > E(F0) (Fig. 48a) showed a significant positive correlation ($p \leq 0.05$). The comparison of division 4 soil moisture to division 5 tornado counts > E(F0) (Fig. 48c) also had a significant positive correlation ($p \leq 0.05$). Comparing division 3 soil moisture to division 2 tornado counts > E(F0), there was a significant positive correlation at the 10% level ($p \leq 0.10$).

It is important to note that this study was only to see if there is a connection between soil moisture from the surface into the atmosphere of the adjacent division that lies east/northeast of that division. This can be indicative of the advection of surface moisture to neighboring areas. However, just because there is a correlation does not necessarily mean that advection of soil moisture alone is causing increased severe weather. Other analysis is necessary such as upper level maps, low-level wind direction, certain indices, and radar data. Generalized areas would also need to be examined. Regardless, this is an interesting find that requires further investigating.

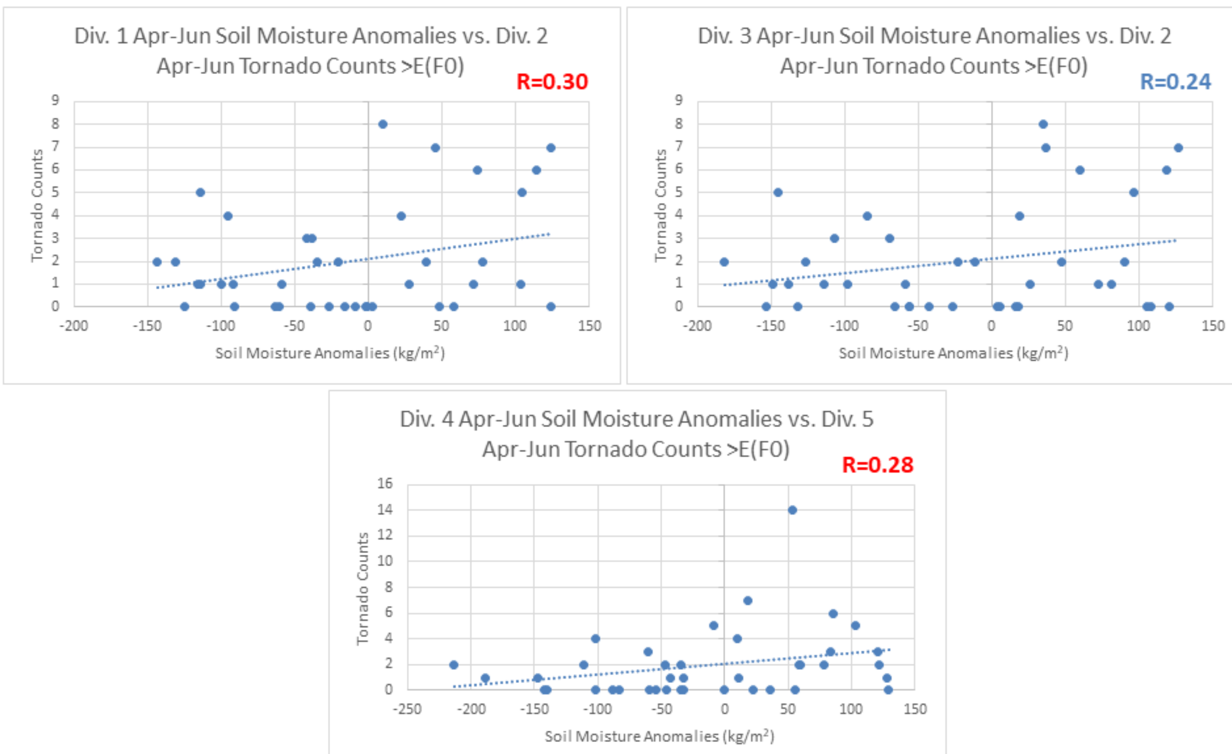


Fig. 48a. Top Left- Division 1 April-June soil moisture anomalies compared with division 2 April-June tornado counts > E(F0). Fig. 48b. Top Right- Same as Fig. 48a, but comparing division 3 soil moisture anomalies to division 2 tornado counts E(F0). Fig. 48c. Bottom- Same as previous figures, but comparing division 4 soil moisture anomalies to division 5 tornado counts > E(F0). Figs. 48a and 48b had significant positive correlations ($p \leq 0.05$). Fig. 48c. had a significant positive correlation at the 10% level ($p \leq 0.10$).

Fig. 49, below, shows the same correlations, but for tornado days > E(F0). Unlike the previous comparisons, the only region which saw statistical significance ($p \leq 0.10$) was the comparison of division 4 soil moisture to division 5 tornado days > E(F0) (Fig. 49c).

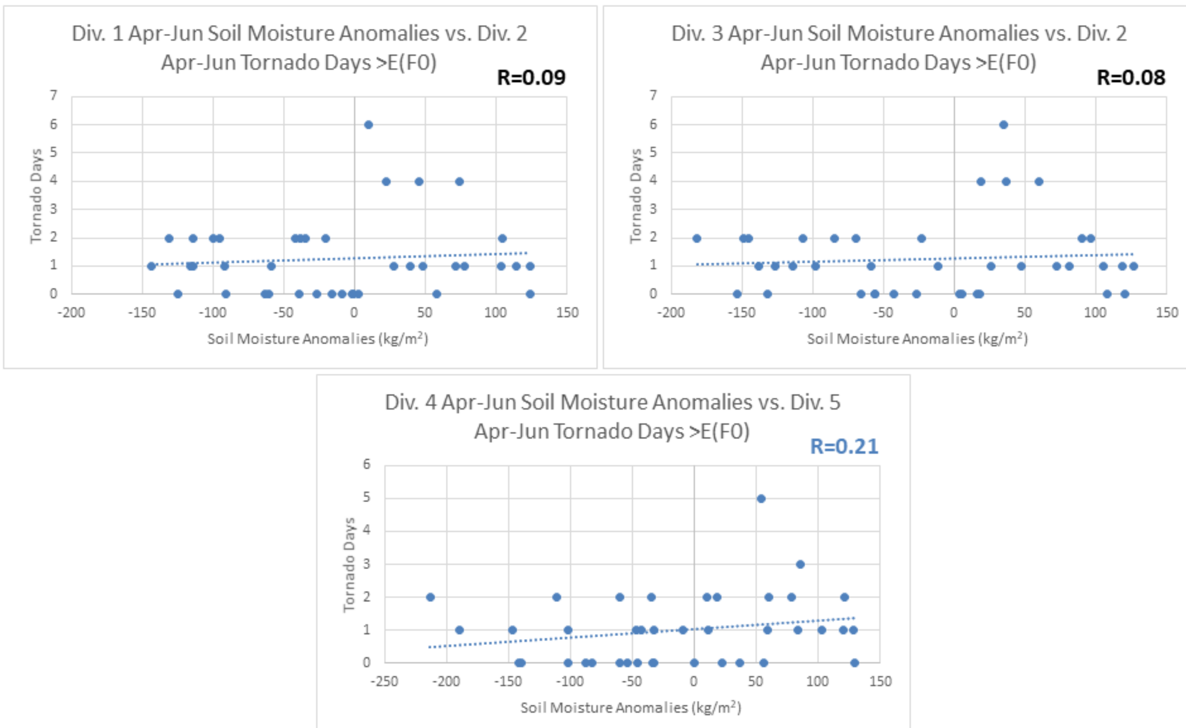


Fig. 49. As in Fig. 48, except for tornado days > E(F0). Fig. 49c had a significant positive correlation ($p \leq 0.10$).

CHAPTER 7. SOIL MOISTURE DISCUSSION

Soil moisture anomalies were compared to official storm reports (tornadoes, hail, wind) to find out if a correlation exists at the 10% level ($p \leq 0.10$). This was accomplished through several methods. The first experiment used in-season (April-June) soil moisture anomalies which were compared to in-season storm reports. This experiment included the state and its individual climate divisions. For the state, the storm reports were divided into categories. They are as follows: tornado days and counts (> E(F0), E(F0)-E(F1), E(F2)-E(F5)), hail reports (all hail, < 1.25 in., ≥ 1.25 in.), and wind reports (all wind, < 60 kts, ≥ 60 kts). The climate divisions included only tornado days and counts > E(F0), all hail reports, and all wind reports. Through this research, tornado counts had more categories with statistical significance (tornado counts > E(F0) at the 10% level ($p \leq 0.10$) and counts E(F2)-E(F5) also at the 10% level ($p \leq 0.10$)) than did tornado days (tornado days > E(F0) at the 10% level ($p \leq 0.10$)) within the state. All findings of significance were positive correlations for the state and climate divisions. Tornado counts > E(F0) within the climate divisions had two divisions that were significant ($p \leq 0.05$), while tornado days > E(F0) had three divisions that were significant ($p \leq 0.10$). Divisions 2 and 5 were significant for both tornado days and counts > E(F0). None of the hail reports, within the state or climate divisions, produced statistical significance. As far as wind reports, none of the state categories showed statistical significance, although division 5 did show significance ($p \leq 0.05$). Below in Fig. 50 summarizes where the positive and negative correlations for tornado days > E(F0) occurred within the state during the in-season experiment. The non-colored white areas indicate a negative correlation, while the colored areas are where there were positive correlations.

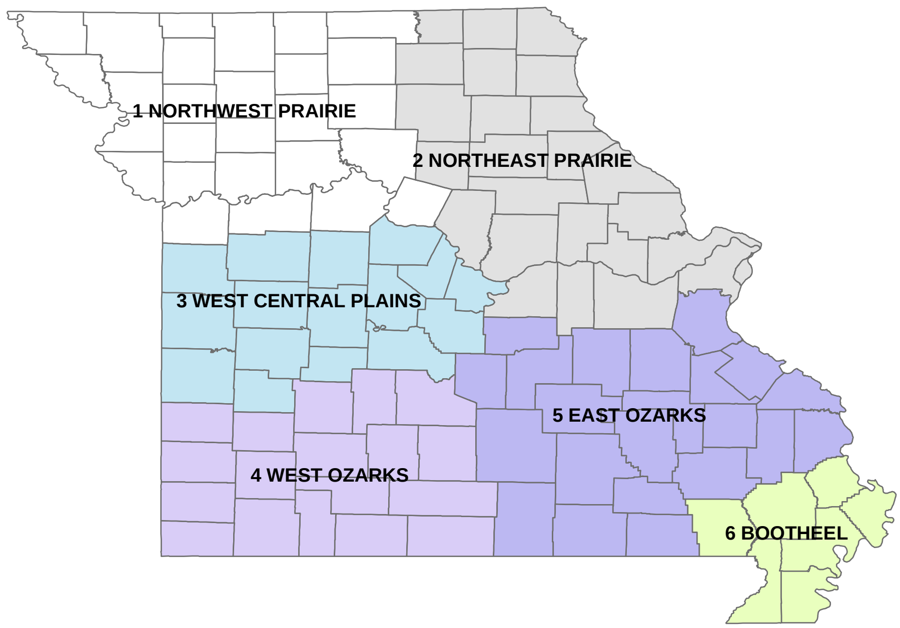


Fig. 50. Positive and negative correlations across the six Missouri climate divisions for the in-season soil moisture study. Noncolored (white) areas are negative correlations between soil moisture anomalies and tornado days > E(F0), while colored areas are positive correlations. All divisions saw positive correlations, except for division 1. Divisions 2, 4, and 5 saw statistical significance ($p \leq 0.10$). Produced through ArcMap 10.7.1.

For the second experiment, the same methods were applied as above, except for 3-month antecedent soil moisture anomalies (January-March). This was chosen to see if soil moisture before the primary tornado season (April-June) has any effect on the season's severe convective activity. None of the tornado categories within the state proved significant. For tornado counts > E(F0), division 2 had a positive significance ($p \leq 0.10$). For tornado days > E(F0), division 3 showed negative significance at the 10% level ($p \leq 0.10$) and division 5 negative at the 5% level ($p \leq 0.05$). None of the hail reports, within the state categories or climate divisions proved significant. Wind reports showed statistical negative significance within the state with the ≥ 60 kts category ($p \leq 0.10$). Division 5 was also found to have statistical negative significance at the 10% level ($p \leq 0.10$). Below in Fig. 51 summarizes where the positive and negative correlations for tornado days > E(F0) occurred within the state during the 3-month antecedent experiment.

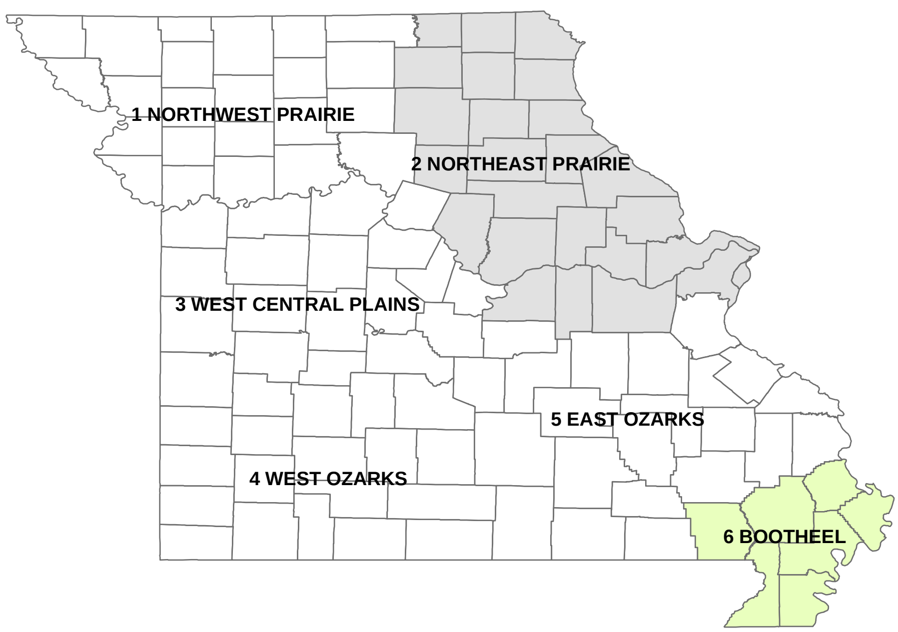


Fig. 51. Positive and negative correlations across the six Missouri climate divisions for the 3-month antecedent soil moisture study. Noncolored (white) areas are negative correlations between soil moisture anomalies and tornado days > E(F0), while colored areas are positive correlations. Divisions 2 and 5 saw positive correlation with elsewhere having negative correlations. Division 3 was statistical at the 10% level ($p \leq 0.10$) and division 5 at the 5% level ($p \leq 0.05$). Produced through ArcMap 10.7.1.

Much like the previous two experiments, the third experiment used the same methods, except for 6-month antecedent soil moisture anomalies. This was performed to compare to the results of the Wakefield et al. (2015) paper which had the state of Missouri split between the Southern Plains and the Northern Plains. Missouri is not only interesting because it lies close to all 4 major regions (Fig. 18) studied in that research, but it is also in the middle of the country, so the weather is influenced by many variables. None of the state categories or divisions for any of the storm reports produced significant correlations for this experiment. Even though no significant correlations can be made, it was still comparable to that of the research by Wakefield et al. (2015). It appears Missouri, as a whole, fits better into the Southern Plains region because of the low correlation values. Because each division within Missouri had differing correlation values and signs, no apparent relationship can be made. This is probably due to many factors such as the location of Missouri within the United States, the topography of the state (Fig. 2), and the low quantity of storm reports used within each division. Below, in Fig. 52 summarizes where the positive and negative correlations for tornado days > E(F0) occurred within the state during the 6-month antecedent experiment.

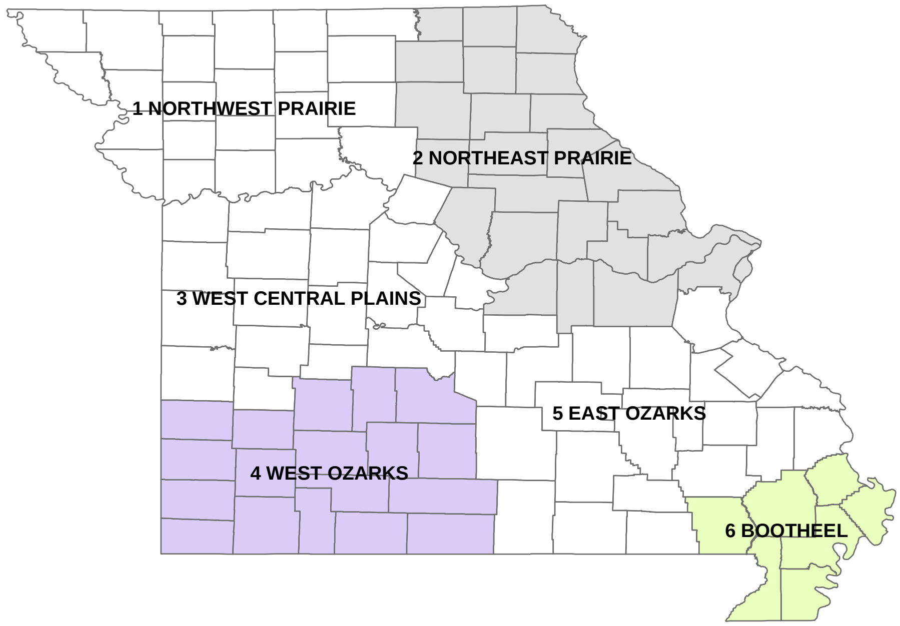


Fig. 52. Positive and negative correlations across the six Missouri climate divisions for the 6-month antecedent soil moisture study. Noncolored (white) areas are negative correlations between soil moisture anomalies and tornado days > E(F0), while colored areas are positive correlations. Divisions 1, 3, and 5 saw negative correlations with elsewhere having positive correlations. No divisions saw statistical significance. Produced through ArcMap 10.7.1.

Comparing all data, higher correlations are made the closer it gets to the in-season time frame. As mentioned above, no significant correlations were found with the 6-month antecedent soil moisture comparison. The 3-month antecedent data saw three statistical significance categories at the 10% level ($p \leq 0.10$) and at the 5% level ($p \leq 0.05$) between tornado days and counts. Division 2 had a positive correlation ($p \leq 0.10$) for tornado counts > E(F0). Divisions 3 ($p \leq 0.10$) and division 5 ($p \leq 0.05$) had statistical negative significance with tornado days > E(F0). For the in-season antecedent soil moisture comparison, there were five total categories that saw statistical significance (two for division 2, one for division 4, two for division 5) between tornado days and counts, two of which had statistical significance ($p \leq 0.05$) (divisions 2 and division 5 with tornado counts > E(F0)). Interestingly, Eastern Missouri (divisions 2, 5) had better correlations than the western half of the state with both divisions seeing statistical significance with tornado days and counts in both in-season and 3-month antecedent soil moisture comparisons. Divisions 3 and 4 each had only one significant correlation. Division 5 saw a significant positive correlation with the in-season and a significant negative correlation with the 3-month study. Further study is needed to determine why it is positive followed by negative a few months later. Also of interest, division 5 had statistical significance with wind reports for both the in-season ($p \leq 0.05$) and 3-month ($p \leq 0.10$) studies. Since divisions 2 and 5 are east/northeast of the Ozark plateau, the plateau might be contributing to these correlations, although, more research is needed to see if and how this is possible. Northwest Missouri (division 1) and the bootheel (division 6) saw no significant correlations.

It is important to note that just because in-season correlations are higher, this does not necessarily mean moisture increases the severe convection. It is hard to know if the increased soil moisture causes increased convection or vice versa. The increased soil moisture could be created by additional convection. Also, several other variables could cause this relationship. A favorable synoptic setup could further enhance severe storms, regardless of the amount of soil moisture present. Additional investigating would be needed using several methods to understand this phenomenon.

There appears to be some soil moisture advection contributing to the enhanced convection west/southwest to east/northeast. As shown in chapter 6, significant correlations are seen between regions with increased soil moisture to the west/southwest and tornado reports to the east/northeast of these regions. It is possible south/southwesterly flow is attributing to these values, bringing moisture into the overlying boundary layer and creating a more buoyant atmosphere. Therefore, contributing to a more unstable airmass. Further research is needed to conclude if this is indeed the case.

CHAPTER 8. ANALYSIS OF SYNOPTIC CHARTS AND ENSO

To find out if El Niño or La Niña produced more convection, composite maps were made by choosing two seasons, one for each. The time frame that was chosen was in correspondence to the spring severe convection. Therefore, the April-June months were used. The ENSO years are outlined in Fig. 53, as provided by Center for Ocean-Atmospheric Prediction studies (COAPS, found online at coaps.fsu.edu/jma). Only the years within this study are provided (1980-2018). As mentioned in section 1.4, the ENSO years are defined by the JMA definition of having a five-month continuous SST departure from the mean. These SST anomalies lie within the region of 4°N-4°S, 150°W-90°W in the tropical Pacific Ocean basin. To be considered an El Niño year, there must be six consecutive months where SST are ≥ 0.5°C. La Niña years are those where SST are < -0.5°C and neutral conditions are those between the two values. ENSO events must include the months of October, November, and December. The ENSO year is considered to run from October to the following September (Birk et al 2010). For example, the La Niña year of 2007 would run from October 2007 to September 2008. Therefore, the spring of 2008 would fall into a La Niña period even though 2008 is considered a neutral period. Each year (El Niño and La Niña, no neutral years were considered) were analyzed and determined which ones would be best suited for the analysis. To achieve this, all La Niña and El Niño years were compiled according to Fig. 53. These years were compared with the corresponding soil moisture anomalies and tornado days > E(F0). For example, the La Niña April-June of 2008 was compared with the soil moisture anomalies and tornado days > E(F0) of the same time frame with the corresponding year.

The average tornado days for all La Niña years during the period of April-June from 1980-2018 was 10.5 (6.5 > E(F0)) with an average soil moisture anomaly of -25 kg/m^2. The standard deviation was then calculated for each. The standard deviation of tornado days was 3.8 (2.4 > E(F0)) during the La Niña periods with the soil moisture anomaly standard deviation being 107 kg/m^2. Thus, any years outside the standard deviations were eliminated since they were not considered to be of "normal." The only year which fit into this criterion was 2008 (average of 13 tornado days (6 > E(F0)) and soil moisture anomaly of 71 kg/m^2). For the El Niño years, the average tornado days was 5.9 (5.5 > E(F0)) with an average soil moisture anomaly of -16 kg/m^2. The standard deviation for tornado days was 4 (2.5 > E(F0)) with a standard deviation of 77 for the soil moisture anomaly. The year 2003 was chosen because it was the closest El Niño year to these averages (tornado days of 8 (4 > E(F0)) with soil moisture anomaly having -42 kg/m^2).

La Niña	Neutral	El Niño
1988	1980-1981	1982
1998-1999	1983-1985	1986-1987
2007	1989-1990	1991
2010	1992-1996	1997
2017	2000-2001	2002
	2003-2005	2006
	2008	2009
	2011-2013	2014-2015
	2016	2018

Fig. 53. ENSO years according to Center for Ocean-Atmospheric Prediction studies (COAPS, found online at coaps.fsu.edu/jma).

8.1 Composite Maps

Composite maps and analysis were made for each of these years (2003, 2008) for the period of April-June. Parameters chosen for analysis were the following: 300-hPa vector wind and height, 500-hPa vector wind and height, 700-hPa heights, 700-hPa vector wind, 700-hPa omega, 700-hPa specific humidity, 850-hPa heights, 850-hPa vector wind, 850-hPa moisture availability, MSLP (mean sea level pressure), latent heat flux at the surface, relative humidity at the surface, sensible heat flux at the surface, 2-m temperature, 2-m dew point, lifted index, moisture availability, and surface based CAPE. These are displayed in Appendix E.

Going from the top of the atmosphere to the surface in conjunction with the mandatory levels, comparisons were made between the two seasons. At the 300-hPa level (Appendix E.1), the heights were slightly higher in 2003 (Fig. A.10a) and the vector winds were higher in 2008 (Fig. 10d). The southeastern part of the state was in the equatorward entrance region of the jet streak. This would allow divergence aloft and convergence at the surface in this region, giving way to more upward motion. In the year 2003 (Fig. 10c), southwest Missouri was in the equatorward exit. This would allow for downward motion since there would be convergence aloft and divergence at the surface.

8.1.1 500-hPa Composite Maps

For the 500-hPa level (Appendix E.2), the heights were roughly the same (Figs A.11a-b), while the vector winds were higher in 2008 (Fig. 11d). A strong jet streak was positioned right over the northern half of the state, putting the southern half of Missouri in the equatorward entrance region of the jet streak. In 2003, a weaker jet streak was located over Tennessee and Kentucky (Fig. A.11c). The strongest winds over Missouri were within the southern part of the state.

8.1.2 700-hPa Composite Maps

For the 700-hPa level (Appendix E.3), the heights were close to the same (Figs. A.12a-b). Much like the previous levels, the vector winds were much stronger in 2008 (7-8m/s in 2003 compared to > 10 m/s in 2008) (Fig. A.12d). The position of the jet streak (from eastern Kansas/Oklahoma into West Virginia) put the southern half of the state within the equatorward entrance region. In 2003, the jet streak extended off the Atlantic Coast, allowing for weaker flow at this level in the Missouri region (Fig. A.12c). Omega values were also lower in 2008 (Fig. A.13d), meaning stronger upward motion. Furthermore, was slightly higher in 2008 (Fig. A.13b).

8.1.3 850-hPa Composite Maps

For the 850-hPa level (Appendix E.4), heights were higher in 2008 (Fig. A.14b). The vector winds were also much higher in 2008 (3-4 m/s in 2003 compared to 5-8m/s in 2008) and were southwesterly, mainly over southern Missouri (Fig. A.14d). There was a strong jet streak during the 2008 time frame over southern Missouri, positioning the southern and central parts of the state in the poleward exit region. This would allow for convergence and upward motion at the surface to take effect. The strong jet streak also suggests a low-level jet present during this period which would allow moisture flow from the Gulf of Mexico and could contribute to severe weather such as Mesoscale Convective Systems (MCSs). These systems are known to produce hail, strong winds, and tornadoes (Kumjian et al. 2006). Specific humidity was slightly greater in 2008, as well (Fig. A.15b).

8.1.4 Surface Level Composite Maps

For the surface level (Appendices E.5-8), the mean sea level pressure (MSLP) was lower in 2008 (Fig. A.16b), indicating the potential for more unsettled weather during this time. 2-m temperatures for the 2003 and 2008 April-June time frame were comparatively the same (Figs. A.16c-d). The latent heat flux at the surface was lower in 2008 (Fig. A.17d), while the sensible heat flux at the surface was higher during this time (Fig. A.17b). This implies more latent heat consumption during the 2008 season. Relative humidity at 2m was slightly higher in 2008 (Fig. A.18b) and so was the dew point at this level (Fig. A.18d). Moisture availability was considerably higher in 2008 (Fig. A.19b). With moisture being higher and LH lower, it appears that moisture is being advected into the region, most likely from the Gulf of Mexico. This scenario would also suppress the local evaporation rate. Therefore, local effects of soil moisture do not seem important. Analyzing the instability, lifted index values were slightly lower in 2008 (Fig. 20b). Instability was much greater in 2008 with 500-800 J/kg (Fig. A.20d). 2003 had CAPE values under 600 J/kg for the entire state during the period (Fig. A.20c). The core of CAPE values in 2008 was in northeast Oklahoma where values over 1000 J/kg were seen. In contrast, this area saw 600-800 J/kg of CAPE in 2003.

8.1.5 Composite Maps Discussion

Even though soil moisture is greater in El Niño years, it seems that La Niña years produce more tornadoes in the Missouri Region. The drier surface may contribute to more sensible heating, thus more warming of the boundary layer. This, in turn, would create more instability that storms would require for strength and sustainability. The most favorable area was found to be over southern Missouri where greater convergence at the surface (divergence aloft), instability, and moisture were present. This suggests that the increase in tornadoes is more due to the synoptic setup than soil moisture. Along with composite maps, mesoscale analysis would be needed for further conclusions. Considering Missouri's location, relative to the Gulf of Mexico and east of the Rocky Mountains, this is an ideal location for severe weather setups.

8.2 Interannual Variability Analysis

Fourier transforms were generated for total tornado days and total tornado counts for the April-June, 1980-2018 period. The graphs are shown below in Figure 54. The red line indicates the tornado days/counts, the green dashed-line is the statistical significance at the 5% level ($p \leq 0.05$) assuming a red noise spectrum, while the blue dashed-line is the statistical significance at the 5% level ($p \leq 0.05$) assuming a white noise spectrum. Refer to section 2.2.2 for further descriptions of these spectrums. Within the total tornado days (Fig. 54a), there were significant peaks at approximately 13, 6.5, 4.3, and 3.5 years. This indicates ENSO variability (2-7-year period) in 3 of the cycles and one interdecadal variability. The 13-year cycle, which happens to be the greatest, falls in line with the interdecadal variability of 10-15 years (Henson et al 2016). Within total tornado counts (Fig. 54b), significant peaks occurred at approximately 9.8, 6, 4.3, 2.4, 2, and 1.7 years. Four of these cycles fall into the ENSO cyclical period with one cycle close to the interdecadal cycle.

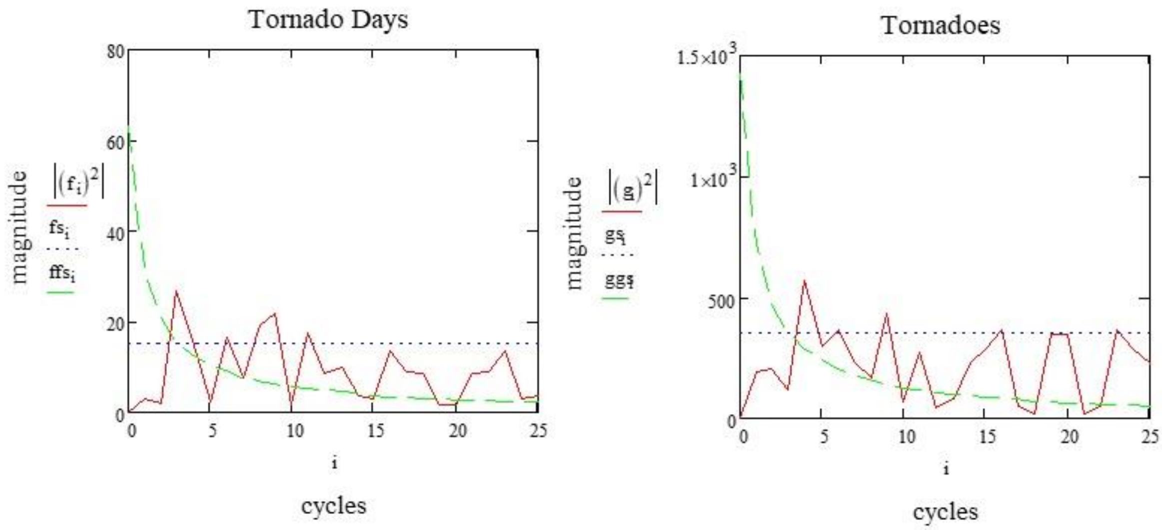


Fig. 54a. Left- Fourier transform for total tornado days for Missouri from April-June, 1980-2018. Fig. 54b. Right- Same as in 54a, but for total tornado counts. The red lines are the tornado numbers, the green dashed-lines are the statistical significance at the 5% level ($p \leq 0.05$) assuming a red noise spectrum, while the blue dashed-lines are the statistical significance at the 5% level ($p \leq 0.05$) assuming a white noise spectrum.

Significant peaks are also evident in the soil moisture anomalies Fourier transform below in Fig. 55a. These peaks include the approximate yearly cycles of 13, 6.5, 3, and 1.6. Two of the significant peaks fall into an ENSO period, while one (13-year period) falls into the interdecadal variation. When analyzing the coherence between total tornado days and soil moisture anomalies (Fig. 55b), significant peaks were found approximately in the years: 13, 7.8, 4.3, and 2. Four of these are consistent with the ENSO variability, while one (13-year period) falls in line with the interdecadal variability. For the coherence between total tornado counts and soil moisture anomalies, there were peaks that were considered significant. These included the approximate periods of 6.5, 4.3, 2.6, 2.1, and 1.7 years. Four of these fell into the ENSO variability, while one (1.7-year cycle) was just below a typical ENSO period.

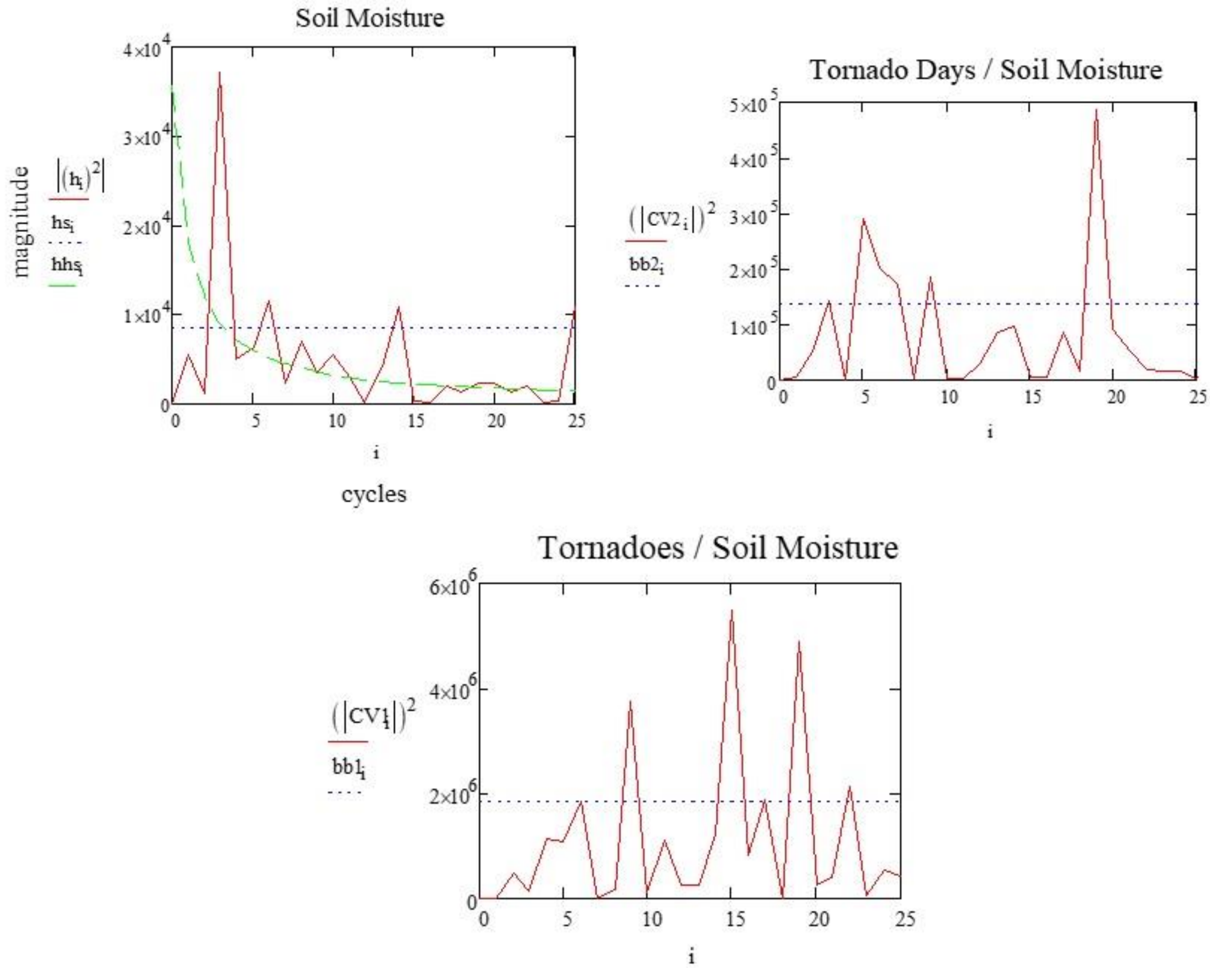


Fig. 55a. Top Left- Fourier transform for soil moisture anomalies for Missouri from April-June, 1980-2018. Fig. 55b. Top Right- Coherence between total tornado days and soil moisture anomalies for the same time period as in 55a. Fig. 55c. Bottom- Same as in 55b, but for total tornado counts. The red lines are the magnitudes, the green dashed-line is the statistical significance at the 5% level ($p \leq 0.05$) assuming a red noise spectrum, while the blue dashed-lines are the statistical significance at the 5% level ($p \leq 0.05$) assuming a white noise spectrum.

8.2.1 Interannual Variability Discussion

It appears that ENSO and interdecadal variability contributing to an increase in tornado activity and soil moisture during the months of April-June exists within the Missouri region. This is consistent with the work done by Bove (1998) and Browning (1998). In addition, Mayes et al (2007) showed an enhanced area of significant tornadoes within the

Missouri Ozarks during La Niña years. This lines up with this area being in the most suitable position for severe weather during this period (chapter 8.1). The coherence between soil moisture and tornadoes further suggests that there may be a correlation between soil moisture and tornadoes during some ENSO years. As mentioned in section 8.1.5, the overall synoptic setup may contribute more than soil moisture. Although, it is possible that soil moisture may still increase severe weather to a degree, especially the transport of soil moisture into the overlying atmosphere (chapter 6) More research would be needed to see how much.

CHAPTER 9. CONCLUSIONS

This research attempted to find a correlation between soil moisture and severe convection. Results showed significant positive correlations with some of the categories (two with tornado counts > E(F0) and one with tornado days > E(F0) for the state, two for tornado counts > E(F0) and three for tornado days > E(F0) within the divisions) with the in-season (April-June) tornado activity and the corresponding soil moisture months. It is unclear whether the correlations were from the convection causing more soil moisture or, vice versa, where the increased soil moisture may have caused an increase in convection. None of the hail reports showed statistical significance for this time period. Within the wind analysis, none of the state categories showed statistical significance, only division 5 ($p \leq 0.05$). Some significant correlations were also found within the 3-month (January-March) antecedent soil moisture comparison with in-season tornado activity, but only for the divisional analysis (one with tornado counts > E(F0) and two with tornado days > E(F0)). The higher wind reports within the state were found to have a statistical negative correlation at the 10% level ($p \leq 0.10$). Division 5 also saw a significant negative correlation ($p \leq 0.10$). Most of the significant correlations were negative (one was positive) with this experiment, whereas all significant positive correlations were observed with the in-season study. With the 6-month antecedent (September-February) storm reports to the following spring (April-June) severe convection experiment, no significant correlations were found. A mix of positive and negative correlations were found. Overall, most of the correlations were positive during the in-season and negative for the 3-month experiments. This is surprising and remarkably interesting. The eastern part of Missouri was found to have the most divisions with statistical correlations (both positive and negative) between tornado counts and days > E(F0). Division 5 also had statistical significance with the wind reports in both the in-season (positive significance at the 5% level ($p \leq 0.05$)) and 3-month (negative significance at the 10% level ($p \leq 0.10$)) studies. It appears that some divisions within the state may behave differently than that of the state as a whole. It needs to be understood that divisions are quite small, so advection of the environmental air becomes an issue. Additional information would be needed to understand how this advection affects neighboring divisions. The Ozark plateau may also contribute to the significant correlations found in eastern Missouri because of its location. It was further shown that this area is in a prime position for severe weather during La Niña years.

Moisture advection from southwest to northeast also seems to attribute to higher tornado activity areas to the northeast. Out of the three regions analyzed with tornado counts > E(F0), all showed statistical positive significance, two at the 5% level ($p \leq 0.05$) and one at the 10% level ($p \leq 0.10$). One showed statistical positive significance ($p \leq 0.10$) with tornado days > E(F0). Much like the in-season experiment, it is unclear whether the correlation is because of precipitation that the storms already produced. One must be cautious since this study only compares soil moisture to tornadic events. However, it does try to account for southwesterly flow, but other analysis is necessary such as upper level maps, low-level wind direction, certain indices, and radar data. Generalized areas would also need to be examined. Nevertheless, there is a strong correlation, especially with tornado days.

A strong correlation was shown to exist with some ESNO years between the interannual cycle and tornado activity within the Missouri region, with La Niña years having the highest tornado activity. There also appears to be an interdecadal cycle. Southern Missouri may have the highest activity because of its location regarding the synoptic setup during La Niña years. Coherence between tornado activity and soil moisture further showed peak activity during ENSO years. This indicates that soil moisture along with tornadic events is more related to the synoptic setup than just the relationship between the two.

Overall, there appears to be some correlation between soil moisture and tornadic, and in some instances, wind events. Although there is a correlation within some of the findings, soil moisture seems to play a minute role in severe convection within the large scale. The added moisture is likely being advected from the Gulf of Mexico into the region causing extra buoyancy needed for convection, with the synoptic setup being the main factor in producing severe convection. Additional studies are needed to see if there is a relationship on a much smaller time scale or within the microscale.

CHAPTER 10. FUTURE WORK

Ultimately, it would be beneficial to pursue additional research regarding the analysis of severe convection. Specifically, this study was limited to data collected from 1980-2018. Each division was also limited to few data, especially with tornado days. To get a better understanding of the correlation between soil moisture and severe convection, more years could be executed. This would allow for more data and therefore, a more accurate analysis. It would also be of use to analyze each individual climate division with respect to ENSO to realize how each division is affected. It would also be helpful to examine all ENSO years, not just 2003 and 2008.

Future research into the in-season analysis is needed to see whether the strong correlations found are because of soil moisture already present or because of the precipitation being produced by storms. Radar analysis, synoptic maps, and nowcasting products could be used to determine which is the case. This would, however, be an exhaustive and time-consuming undertaking. Also, an analysis is needed to understand the why 3-month study has mainly negative correlations, while in-season are positive.

Since there are some indications that the Ozark Plateau may influence convection, to a degree, it would be interesting to see if there is indeed a correlation. This could be accomplished by analyzing radar data and trends as storms propagate eastward/northeastward over the plateau. Once again, this would be a challenging project.

APPENDIX A. SOIL MOISTURE WITHIN EACH CLIMATE DIVISION

A.1 Sep-Feb Soil Moisture Within Each Climate Division

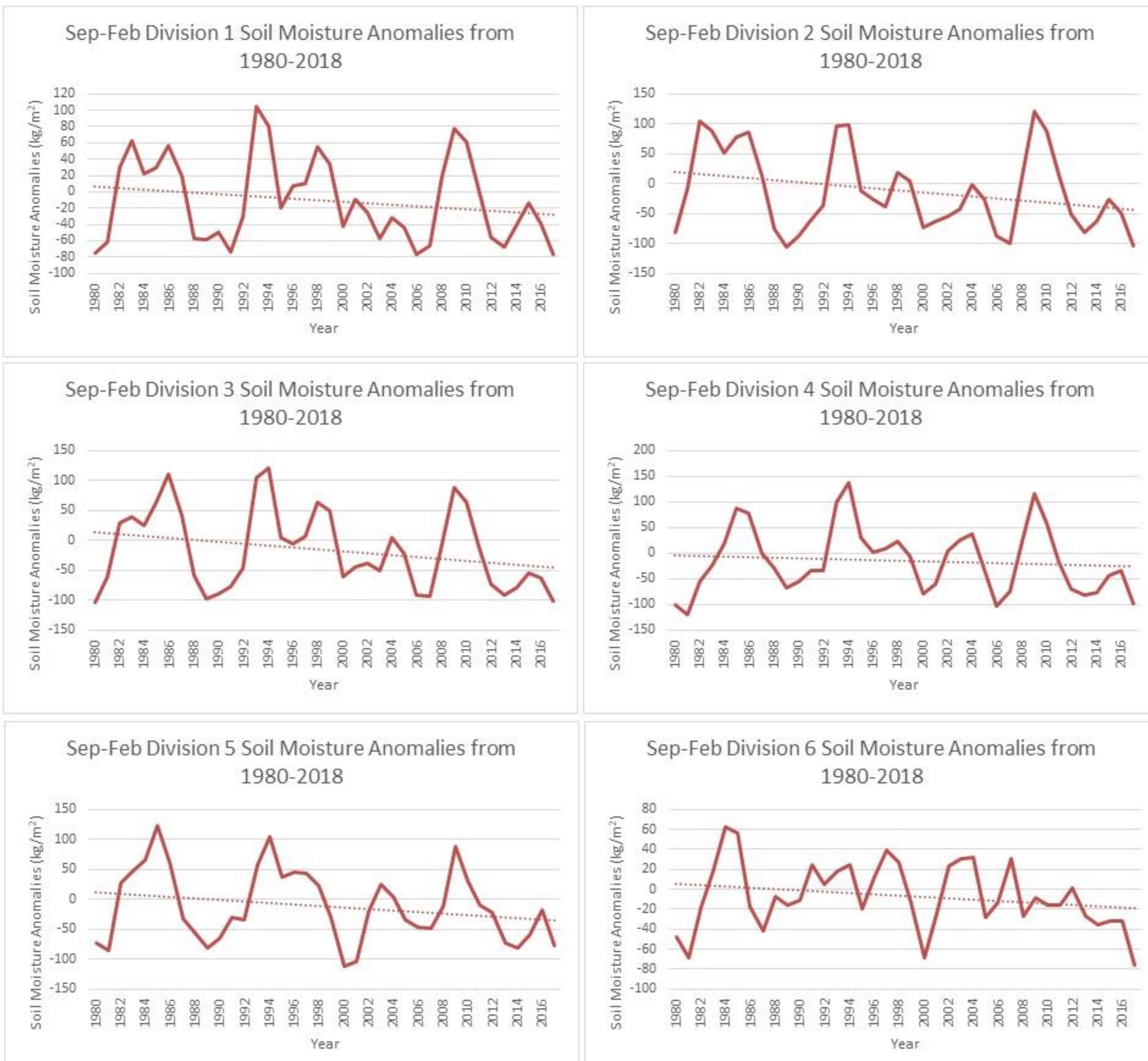


Fig. A.1. Soil moisture anomalies for each of the six climate divisions within Missouri for the September-February period from 1980-2018.

A.2 Jan-Mar Soil Moisture Within Each Climate Division

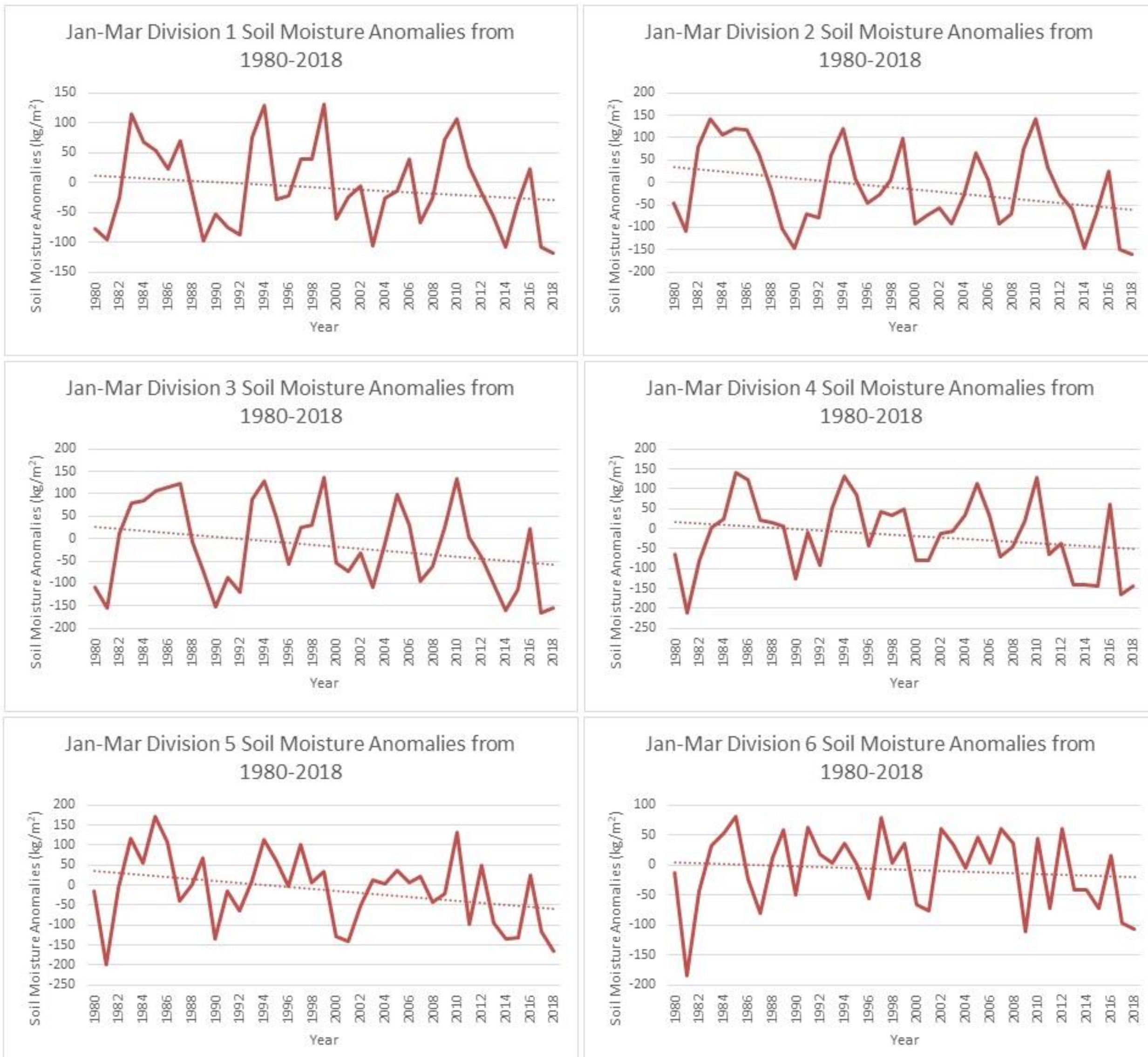


Fig. A.2. Soil moisture anomalies for each of the six climate divisions within Missouri for the January-March period from 1980-2018.

A.3 Apr-Jun Soil Moisture Within Each Climate Division

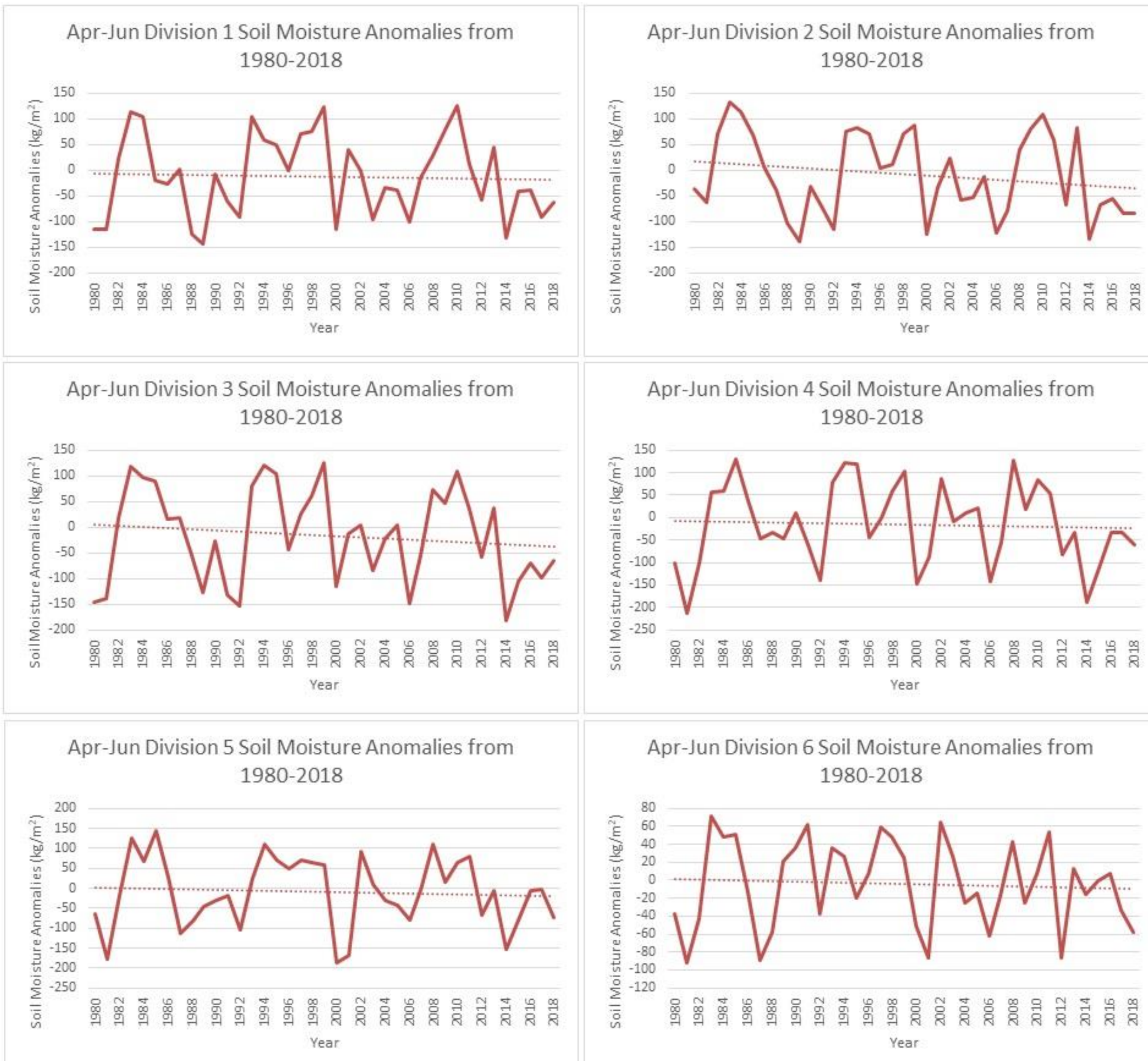


Fig. A.3. Soil moisture anomalies for each of the six climate divisions within Missouri for the April-June period from 1980-2018.

APPENDIX B. TORNADO REPORT WITHIN EACH CLIMATE DIVISION

B.1 Tornado Counts within Each Climate Division

B.1.1 Total Tornado Counts

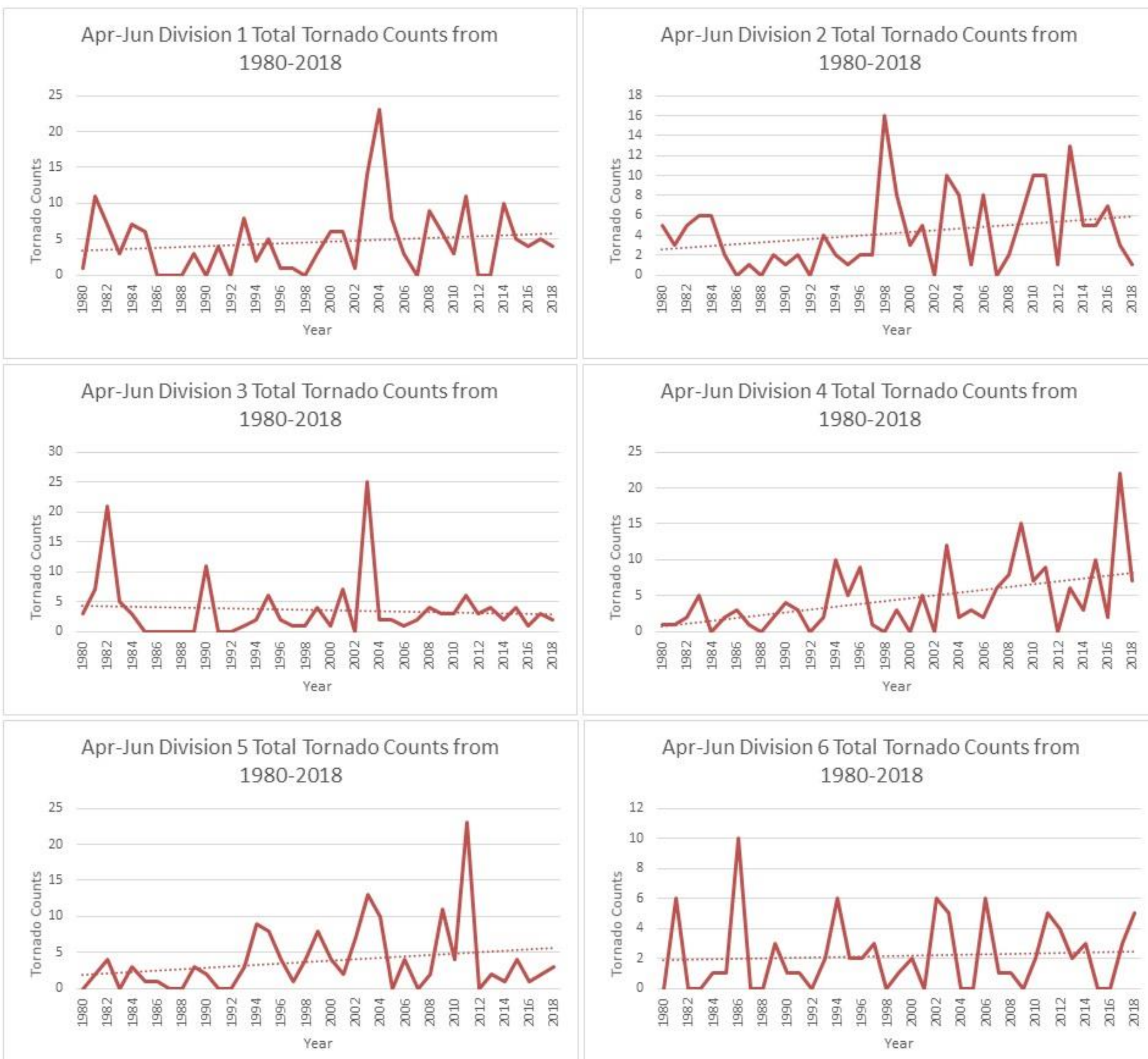


Fig. A.4 Total tornado counts for each of the six climate divisions within Missouri for the April-June period from 1980-2018.

B.1.2 Tornado Counts > E(F0)

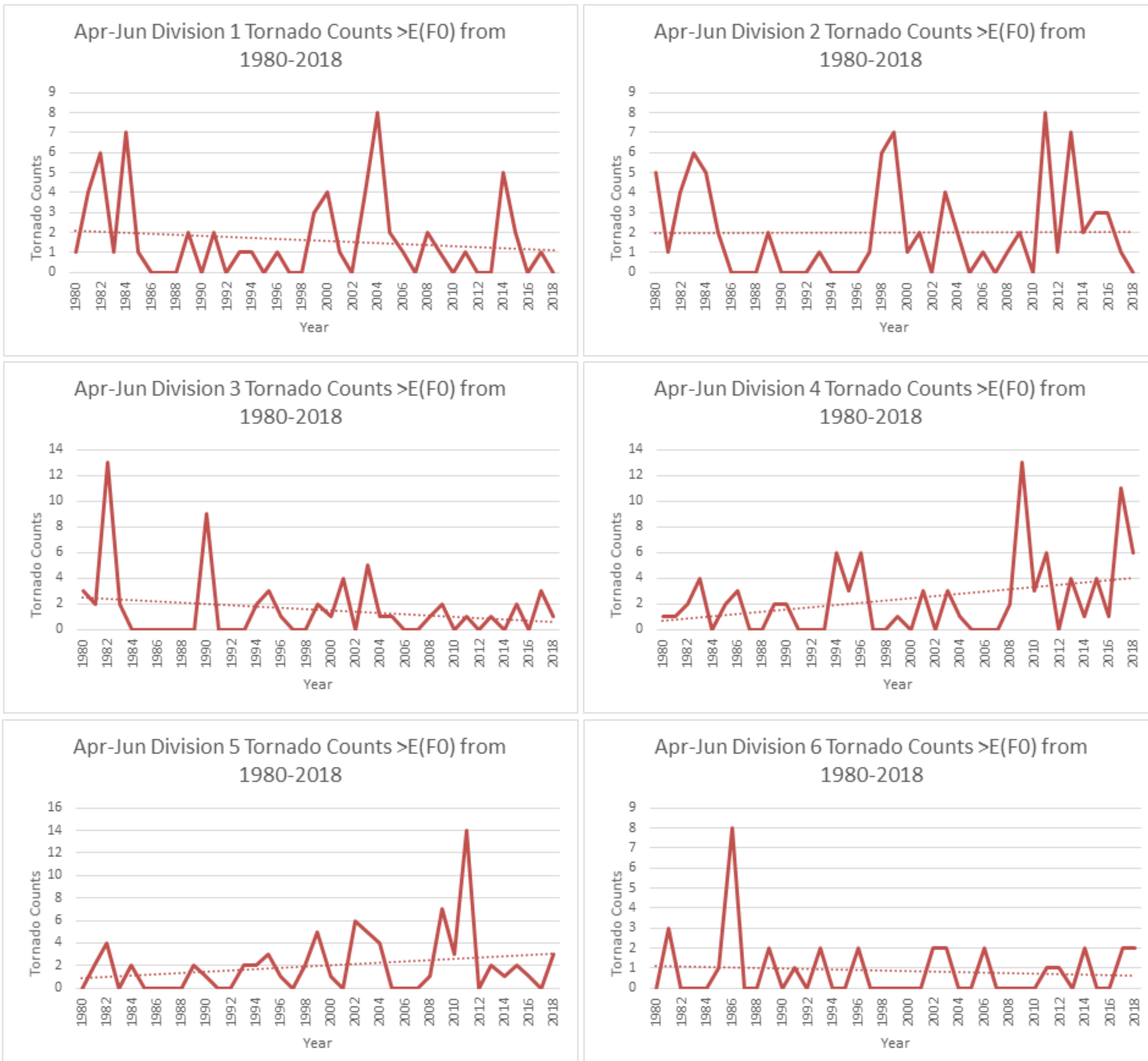


Fig. A.5 Total tornado counts > E(F0) for each of the six climate divisions within Missouri for the April-June period from 1980-2018.

B.2 Tornado Days within Each Climate Division

B.2.1 Total Tornado Days

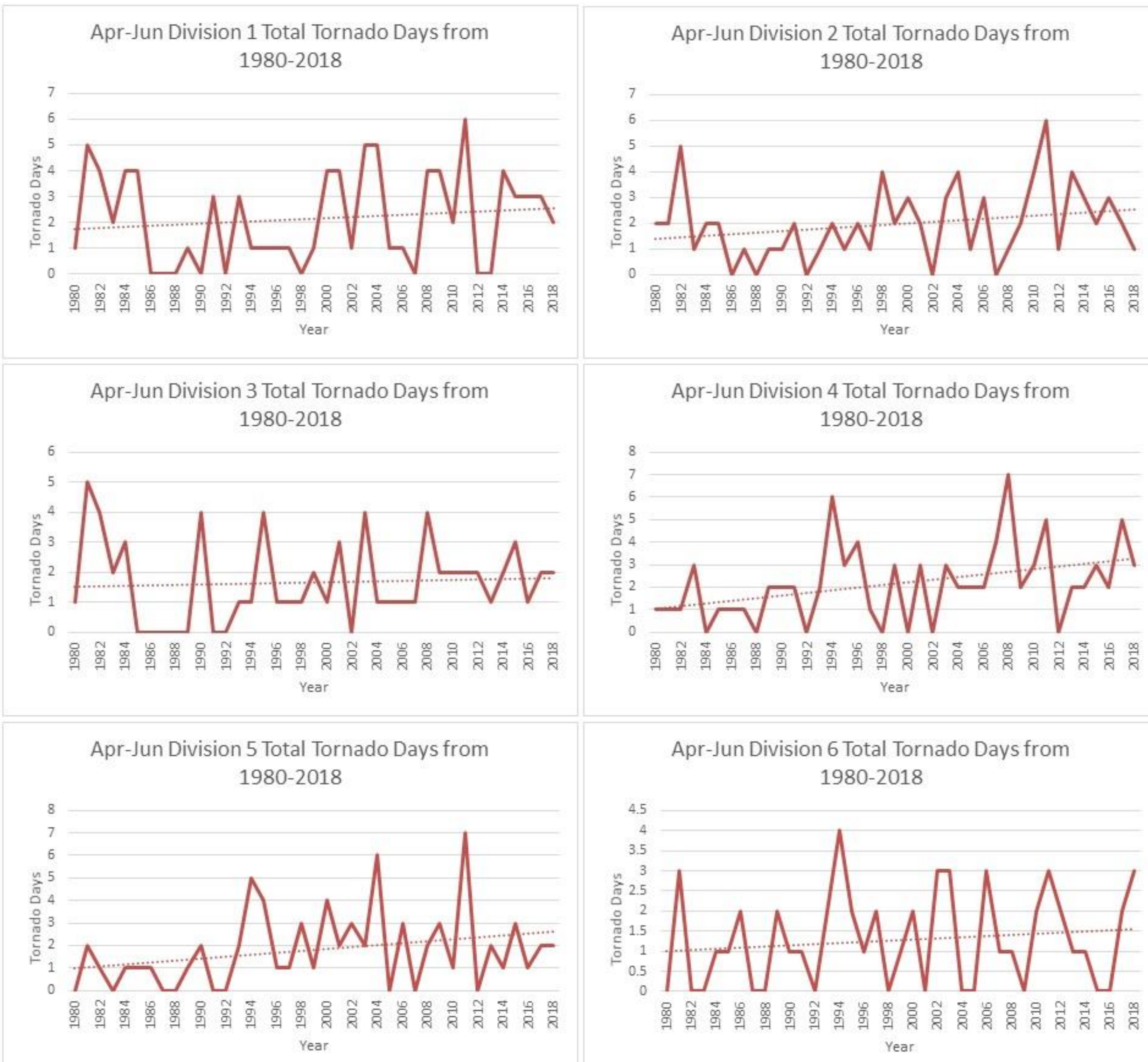


Fig. A.6. Total tornado days for each of the six climate divisions within Missouri for the April-June period from 1980-2018.

B.2.2 Tornado Days > E(F0) within Each Climate Division

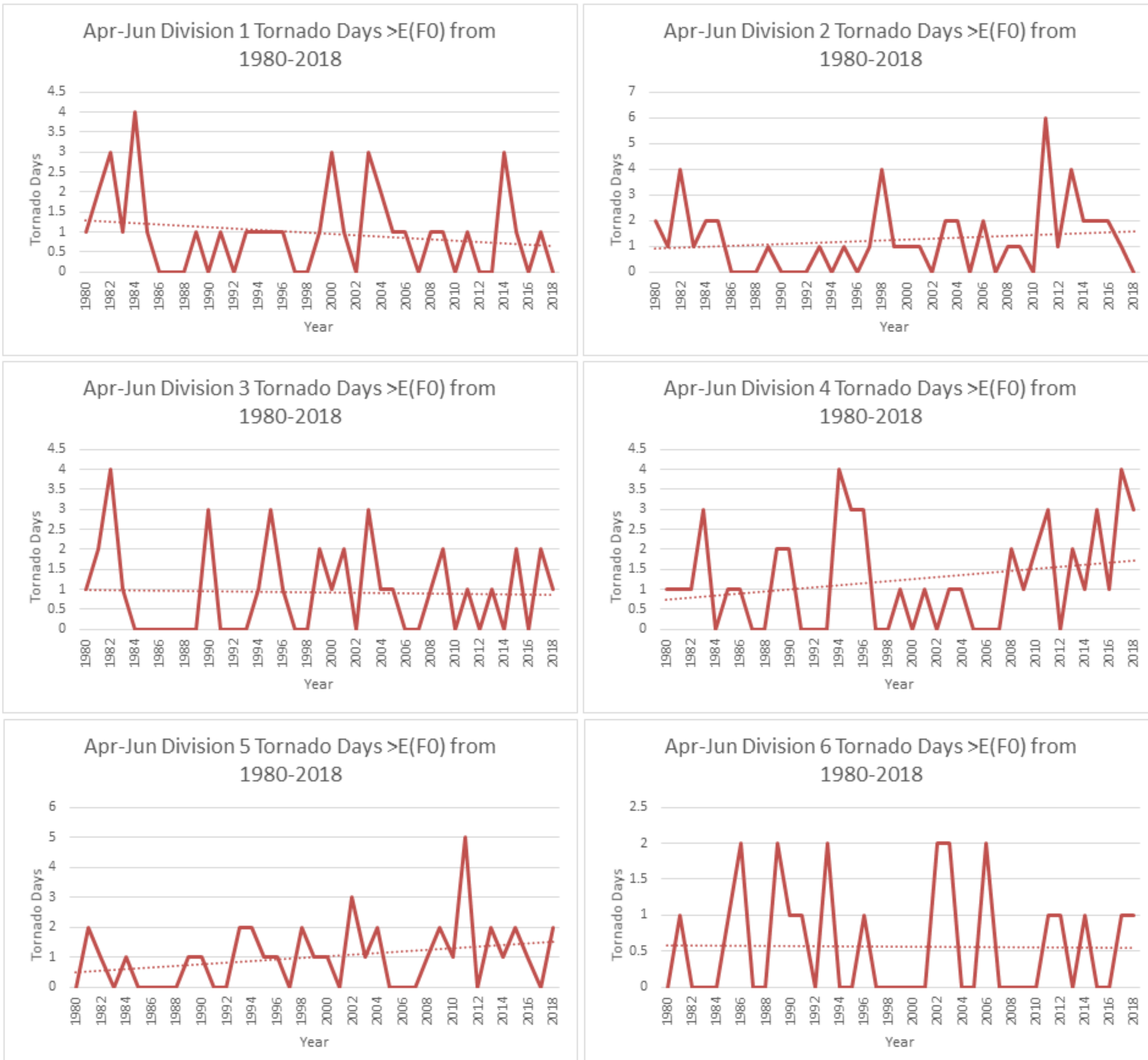


Fig. A.7. Total tornado days > E(F0) for each of the six climate divisions within Missouri for the April-June period from 1980-2018.

APPENDIX C. HAIL REPORTS WITHIN EACH CLIMATE DIVISION

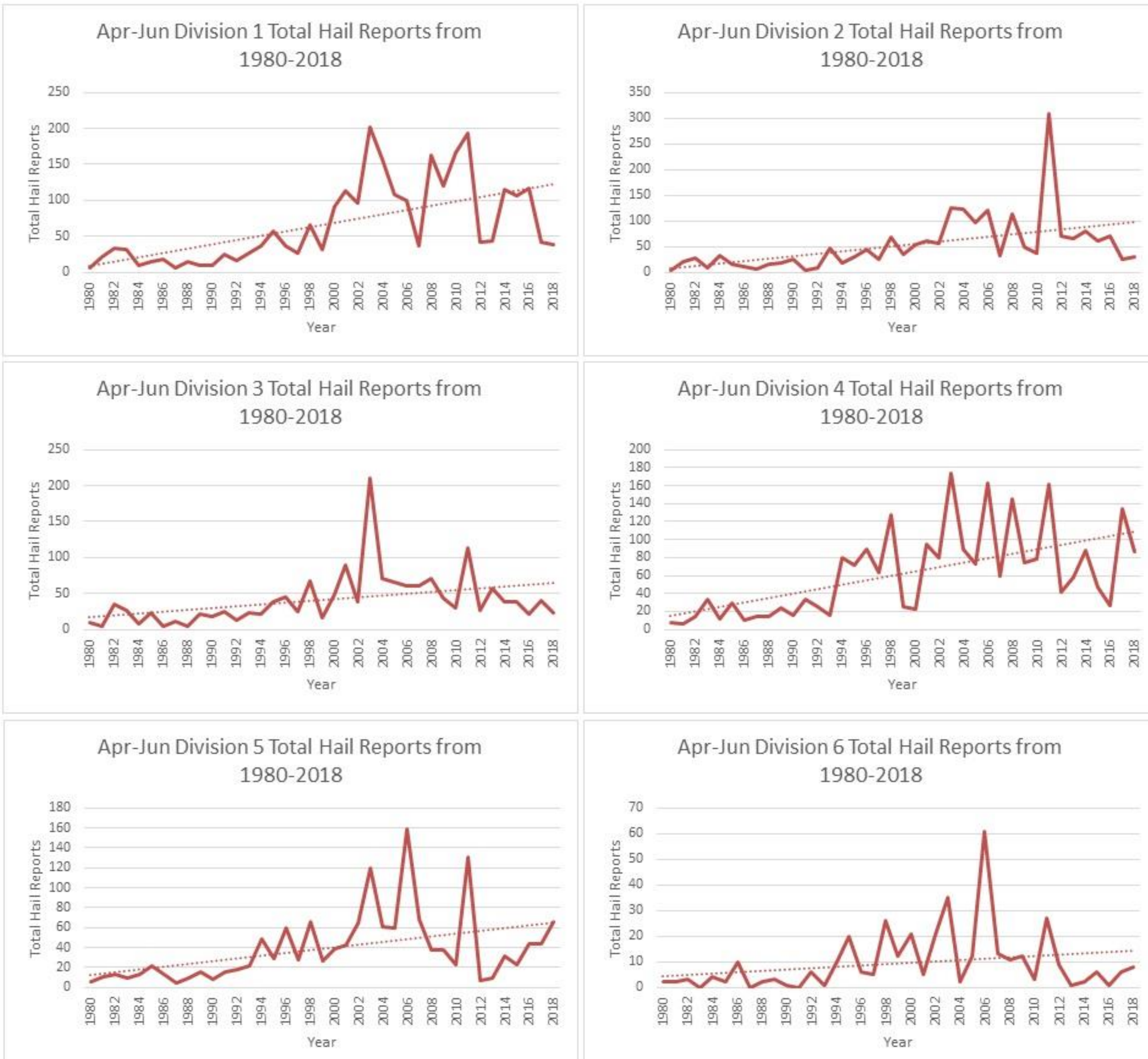


Fig. A.8. Total hail reports for each of the six climate divisions within Missouri for the April-June period from 1980-2018.

APPENDIX D. WIND REPORTS WITHIN EACH CLIMATE DIVISION

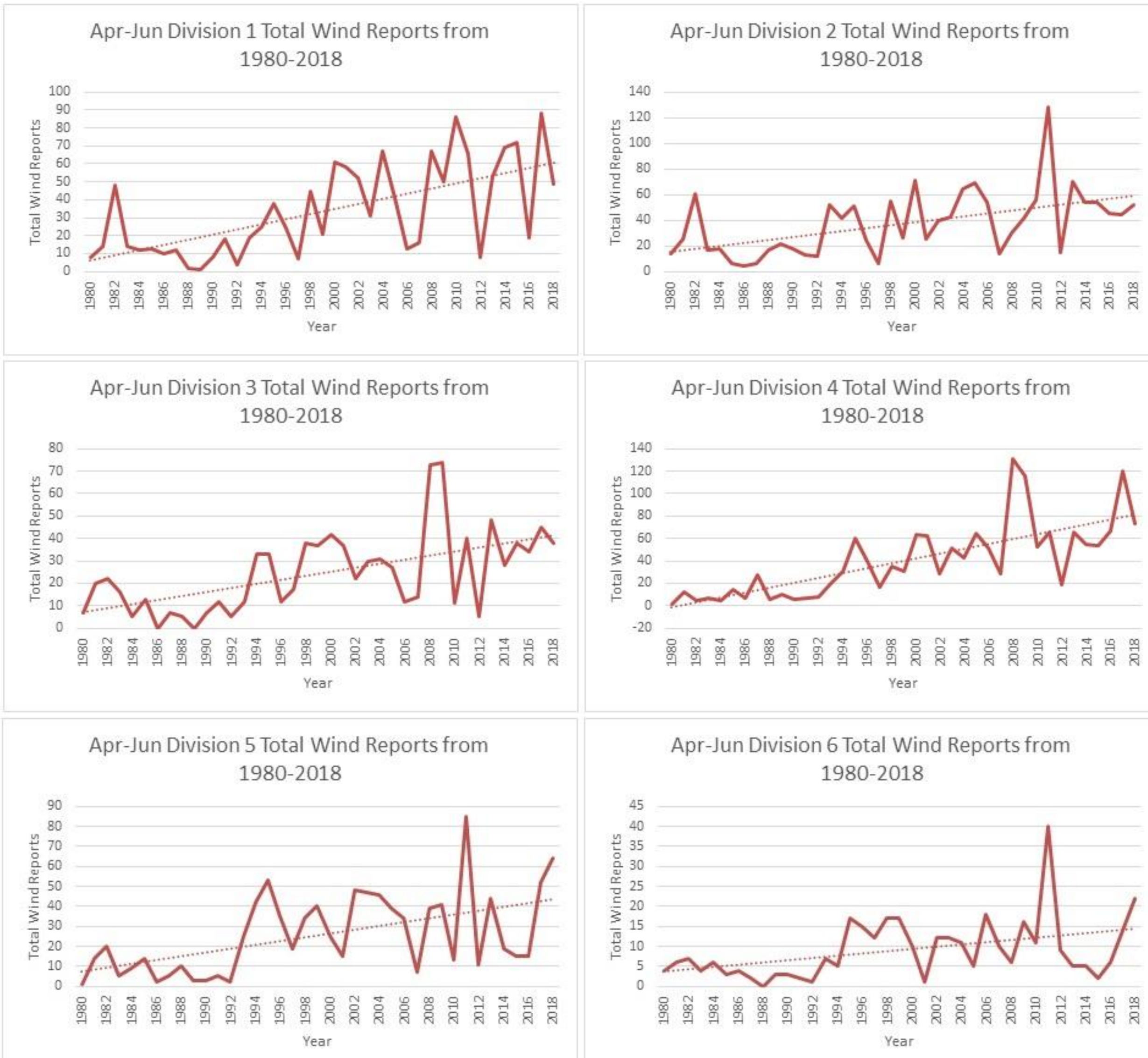


Fig. A.9. Total wind reports for each of the six climate divisions within Missouri for the April-June period from 1980-2018.

APPENDIX E. COMPOSITE MAPS

E.1 300-hPa Composite Maps

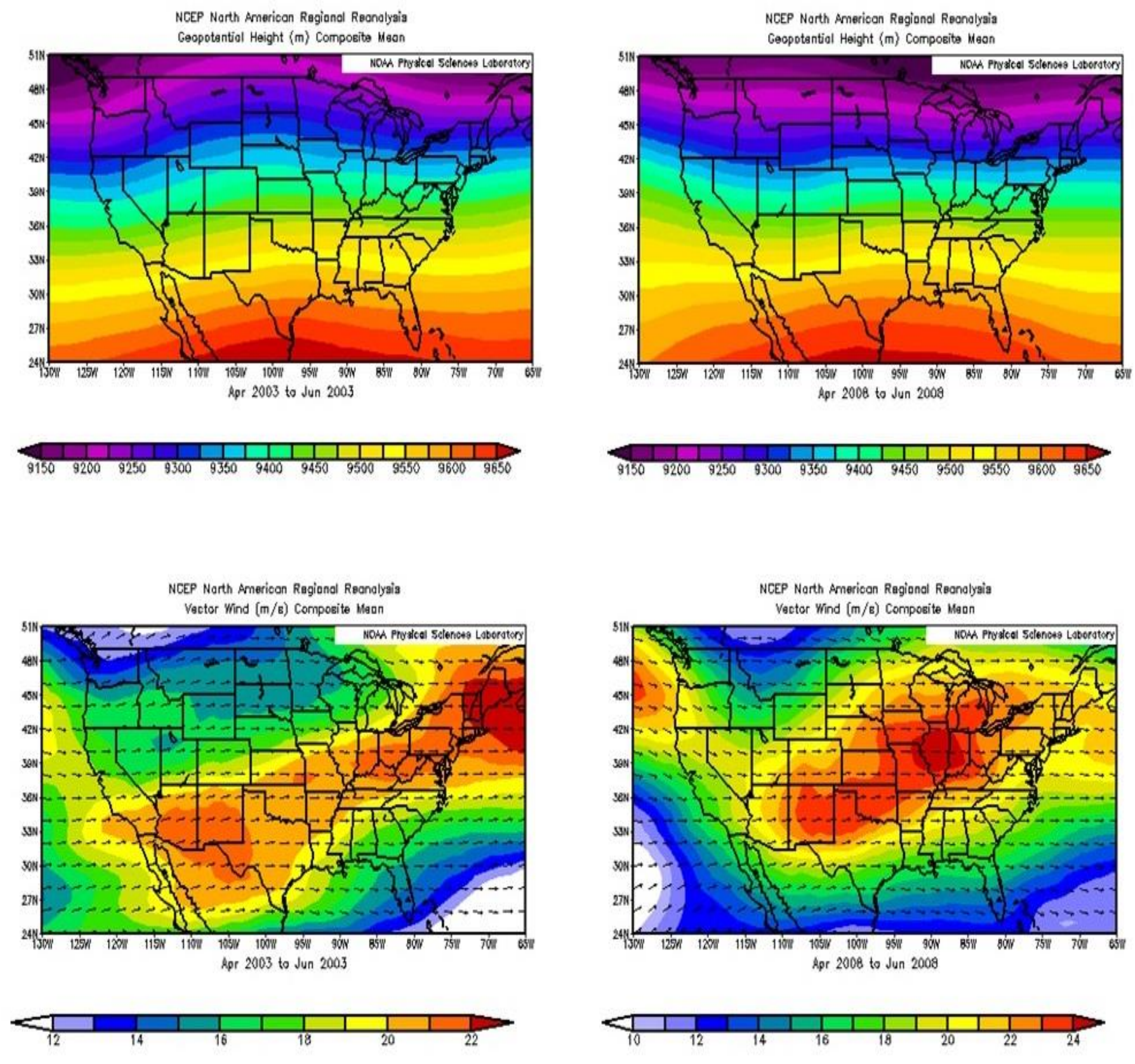


Fig. A.10a. Top Left- April-June, 2003 300-hPa mean geopotential height (m) composite map .Fig. A.10b Top Right- Same as in A.10a, but for 2008.Fig. A.10c Bottom Left- April-June, 2003 300-hPa mean vector wind (m/s) composite map. Fig.A.10d. Bottom Right- Same as in A.10c, but for 2008.

E.2 500-hPa Composite Maps

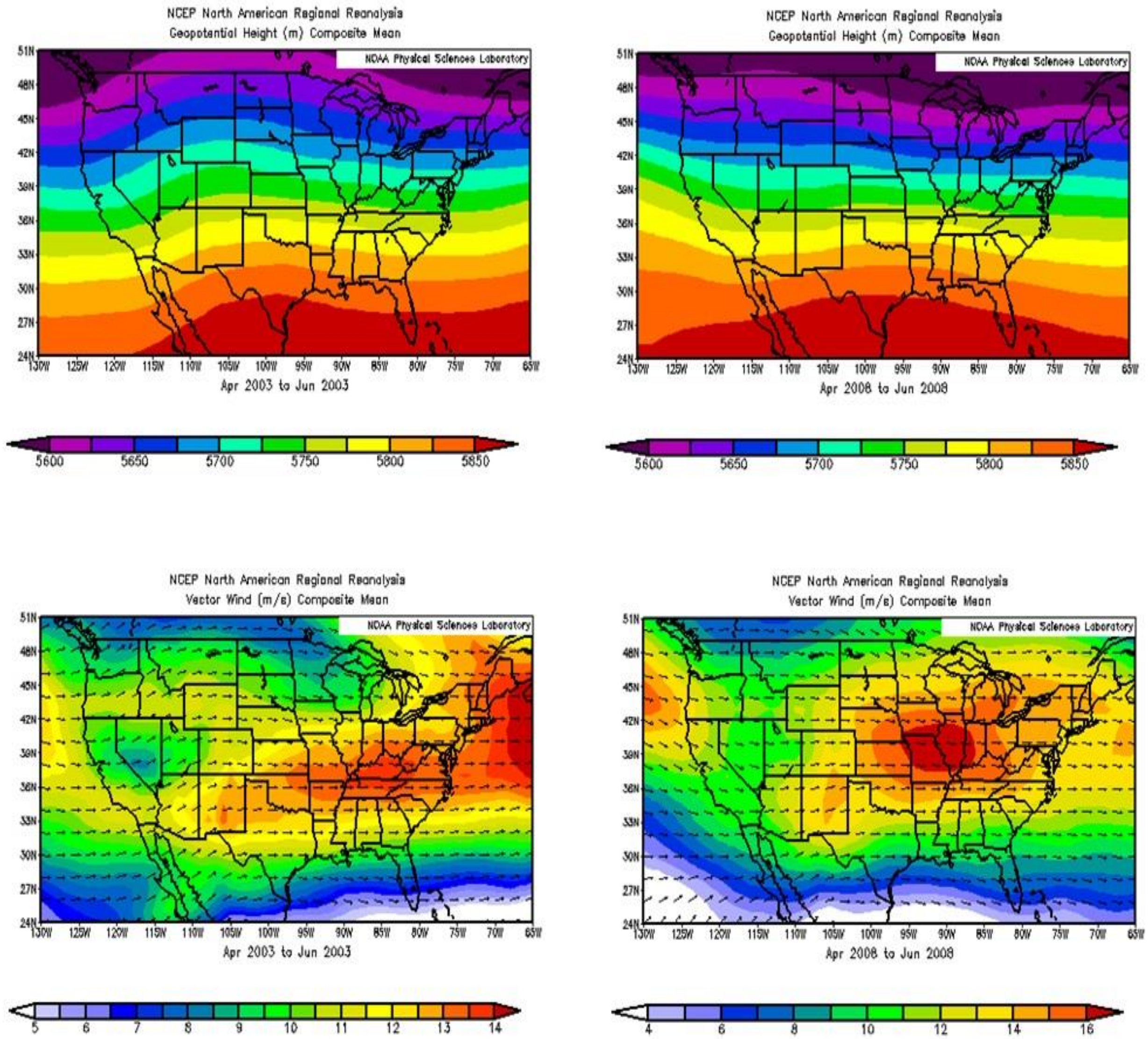


Fig. A.11a. Top Left- April-June, 2003 500-hPa mean geopotential height (m) composite map. Fig. A.11b. Top Right- Same as in A.11a, but for 2008. Fig. A.11c. Bottom Left- April-June, 2003 500-hPa mean vector wind (m/s) composite map. Fig. A.11d. Bottom Right- Same as in A.11c, but for 2008.

E.3 700-hPa Composite Maps

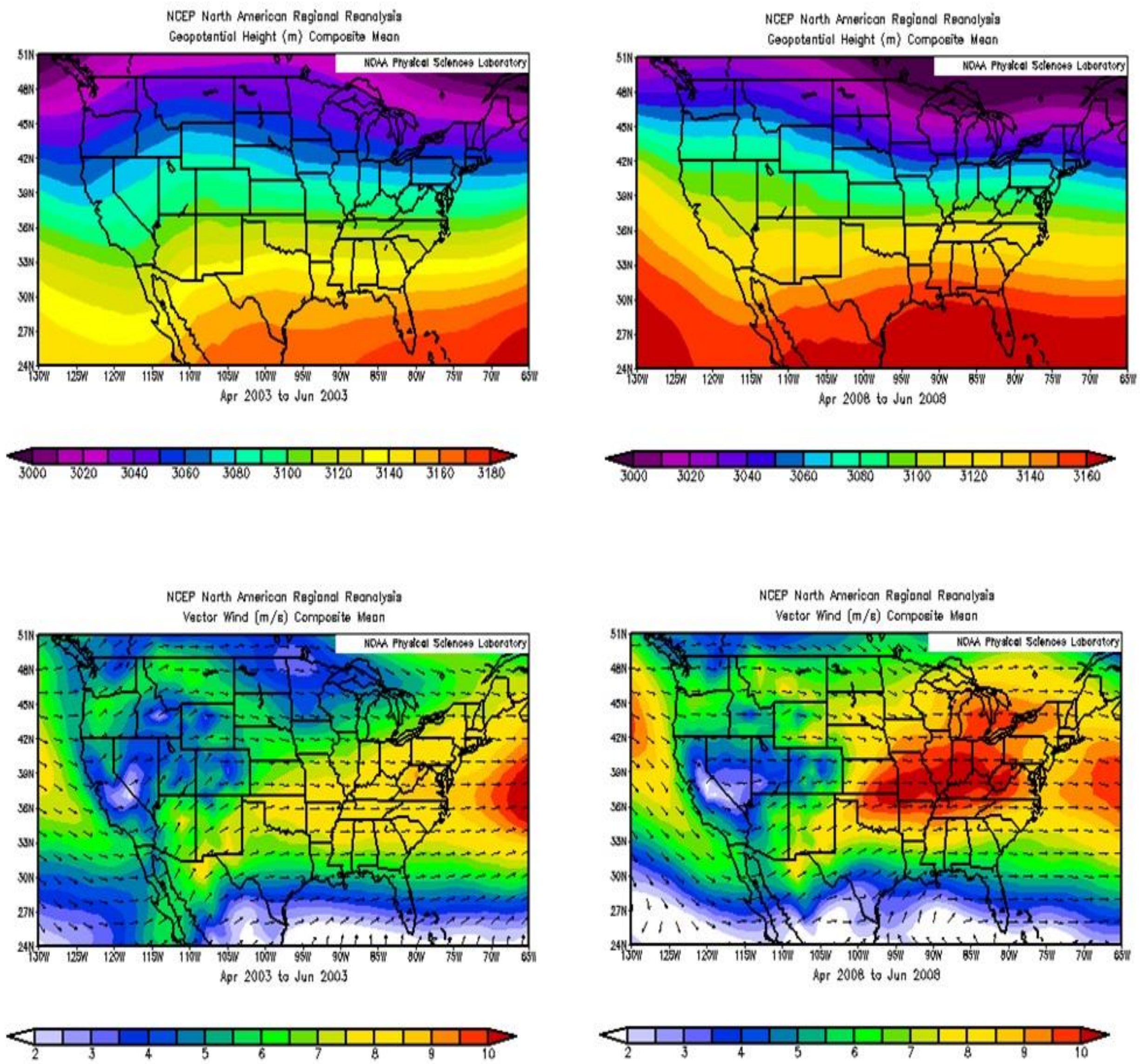


Fig. A.12a. Top Left- April-June, 2003 700-hPa mean geopotential height (m) composite map. Fig. A.12b. Top Right- Same as in A.12a, but for 2008. Fig. A.12c Bottom Left- April-June, 2003 700-hPa mean vector wind (m/s) composite map. Fig. A.12d. Bottom Right- Same as in A.12c, but for 2008.

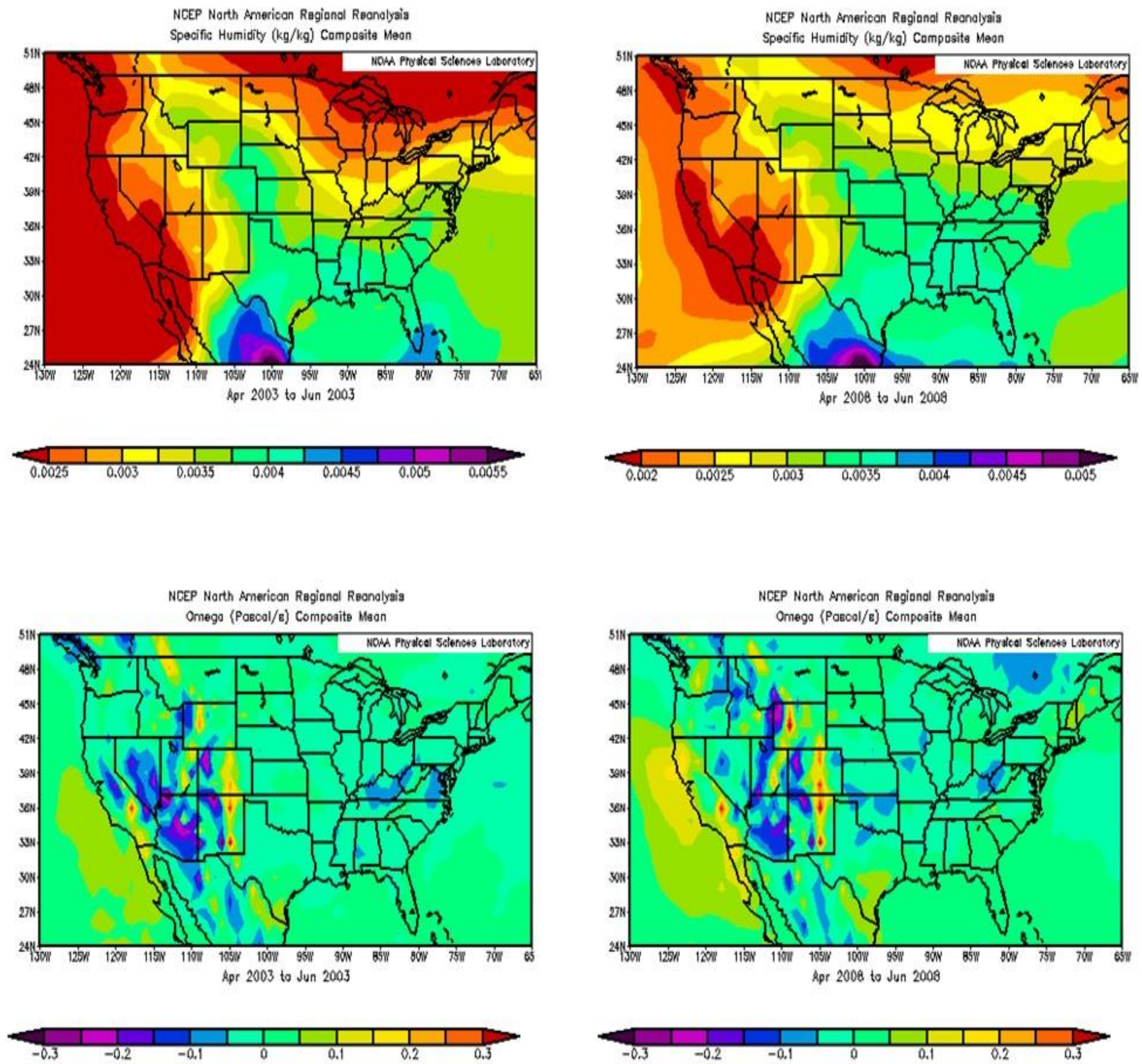


Fig. A.13a. Top Left- April-June, 2003 700-hPa mean specific humidity (kg/kg) composite map. Fig. A.13b. Top Right- Same as in A.13a, but for 2008. Fig. A.13c. Bottom Left- April-June, 2003 700-hPa mean omega (Pascal/s) composite map. Fig. A.13d. Bottom Right- Same as in A.13c, but for 2008.

E.4 850-hPa Composite Maps

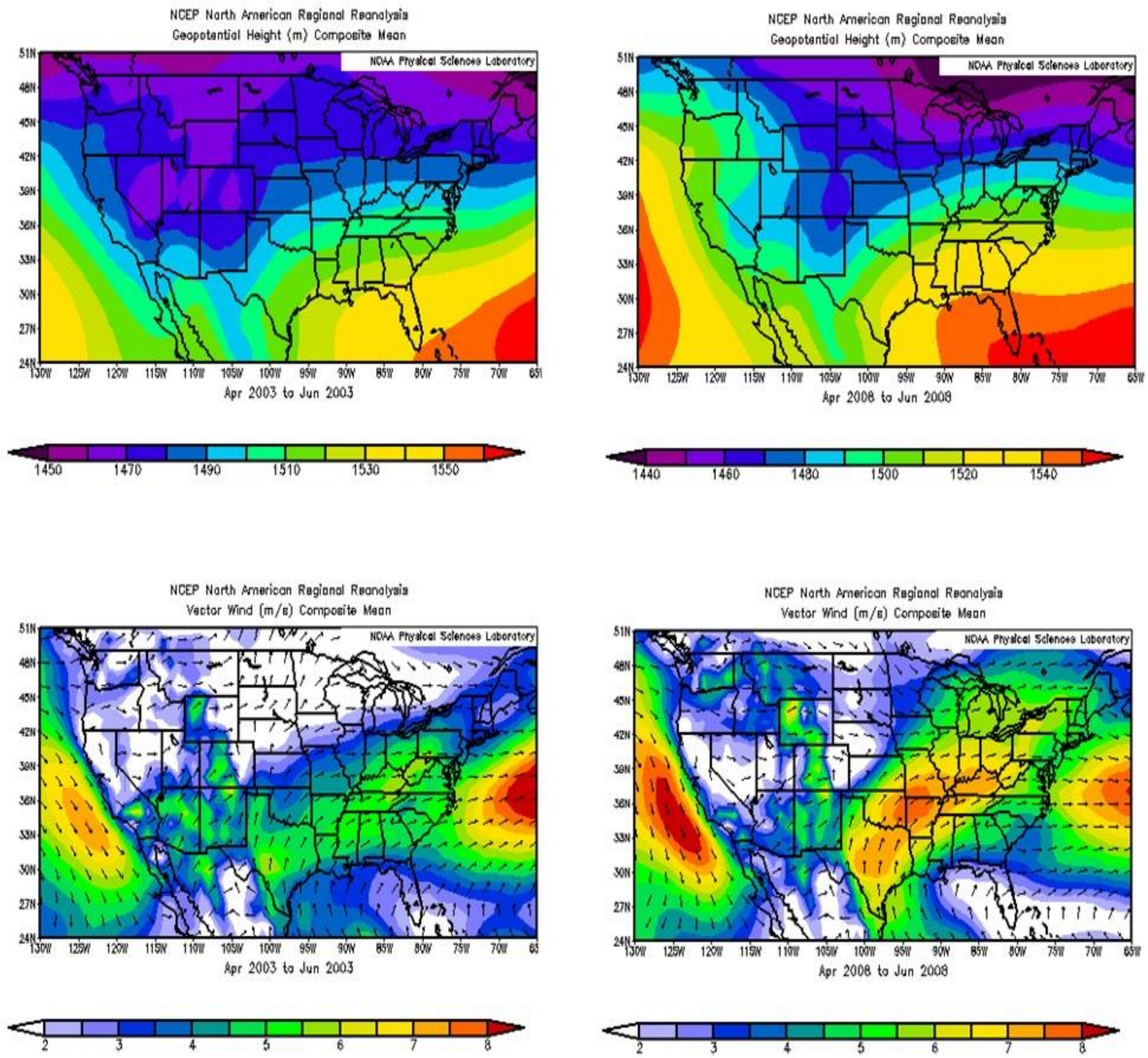


Fig. A.14a. Top Left- April-June, 2003 850-hPa mean geopotential height (m) composite map. Fig. A.14b. Top Right- Same as in A.14a, but for 2008. Fig. A.14c. Bottom Left- April-June, 2003 850-hPa mean vector wind (m/s) composite map. Fig. A.14d. Bottom Right- Same as in A.14c, but for 2008.

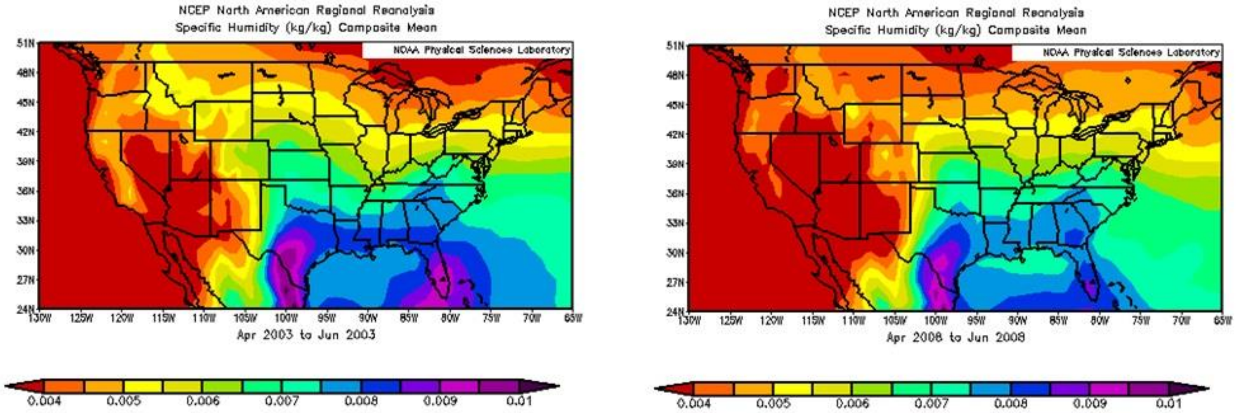


Fig. A.15a. Left- April-June, 2003 850-hPa mean specific humidity (kg/kg) composite map. Fig. A.15b. Right- Same as in A.15a, but for 2008.

E.5. Surface Pressure and Temperature Composite Maps

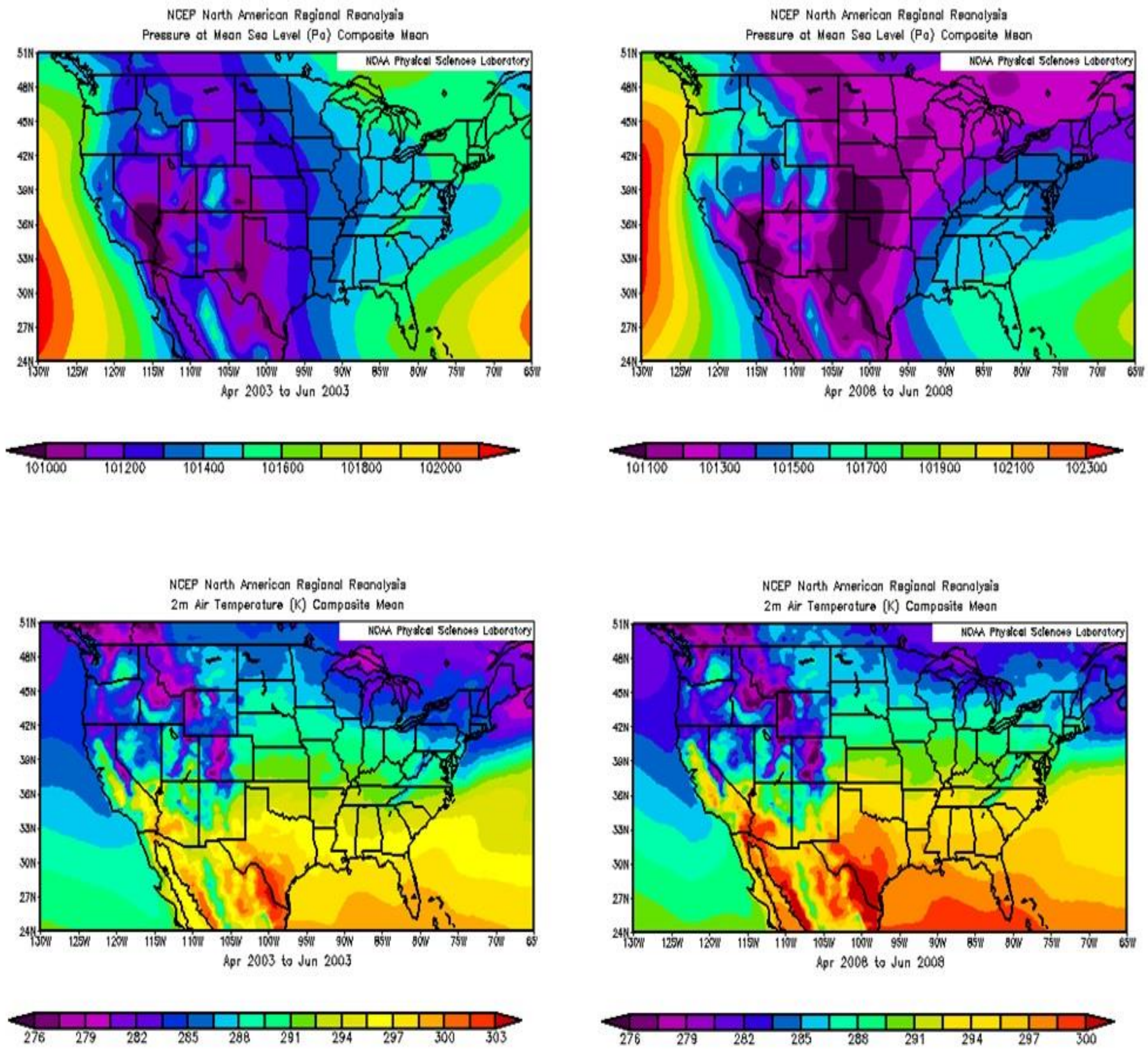


Fig. A.16a. Top Left- April-June, 2003 mean MSLP (Pa) composite map. Fig. A.16b. Top Right- Same as in A.16a, but for 2008. Fig. A.16c. Bottom Left- April-June, 2003 mean 2-m temperature (K) composite map. Fig. A.16d. Bottom Right- Same as in A.16c, but for 2008.

E.6. Surface Heat Flux Composite Maps

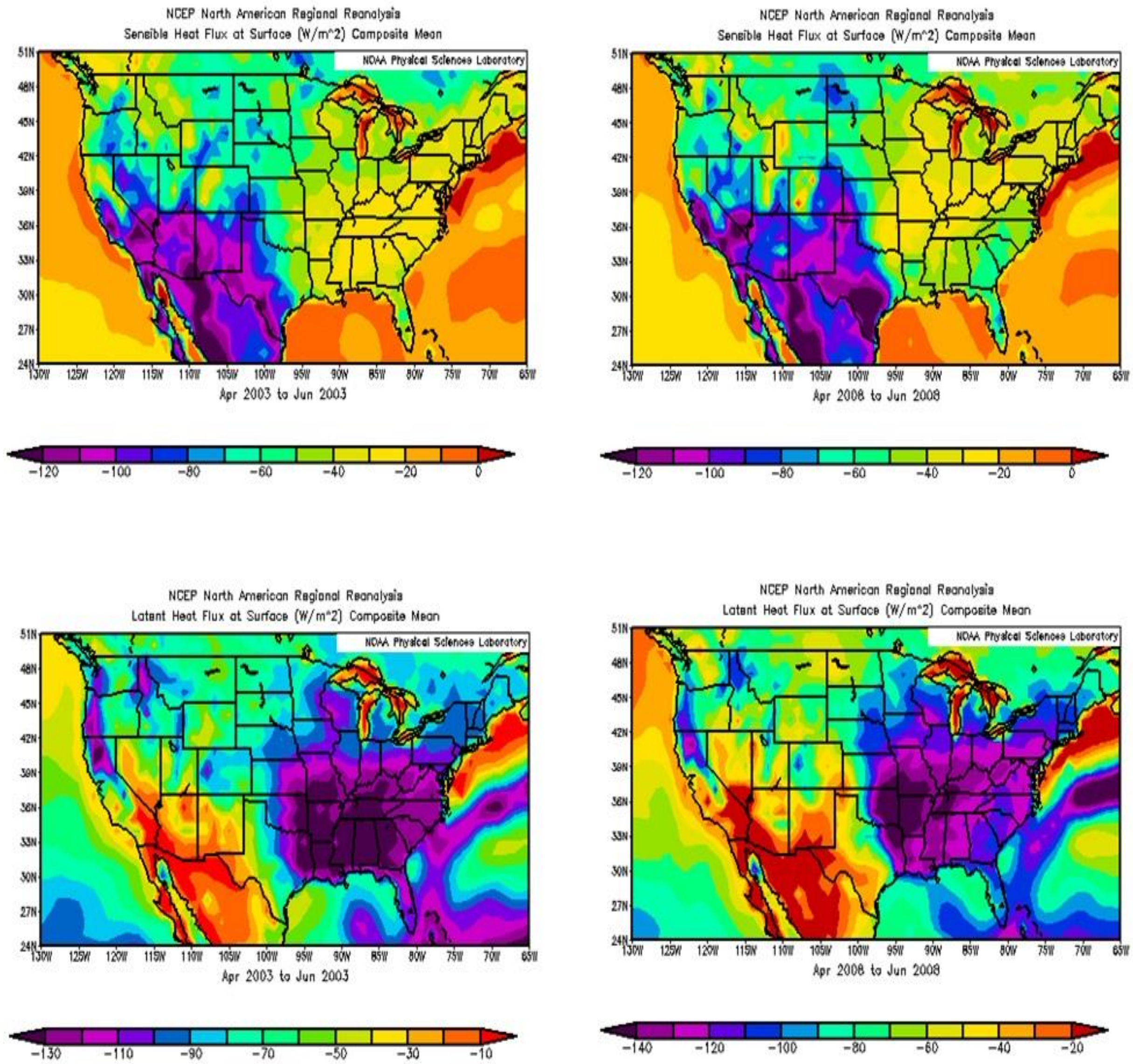


Fig. A.17a. Top Left- April-June, 2003 mean sensible heat flux at the surface (W/m^2) composite map. Fig. A.17b. Top Right- Same as in A.17a, but for 2008. Fig. A.17c. Bottom Left- April-June, 2003 mean latent heat flux at the surface (W/m^2) composite map. Fig. A.17d. Bottom Right- Same as in A.17c, but for 2008.

E.7. Surface Humidity Composite Maps

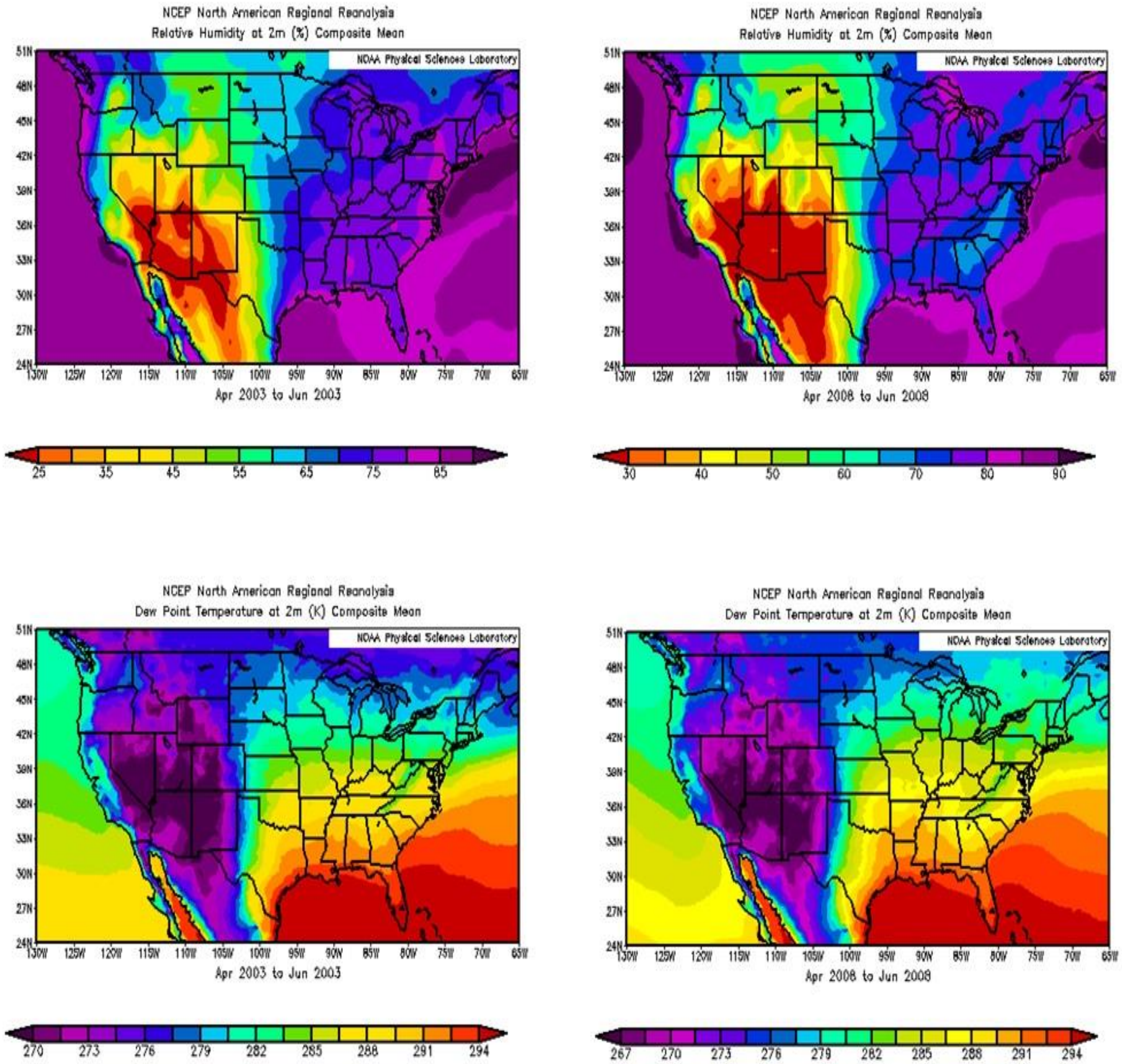


Fig. A.18a. Top Left- April-June, 2003 mean 2-m relative humidity (%) composite map. Fig. A.18b. Top Right- Same as in A.18a, but for 2008. Fig. A.18c. Bottom Left- April-June, 2003 mean 2-m dew point temperature (K) composite map. Fig. A.18d. Bottom Right- Same as in A.18c, but for 2008.

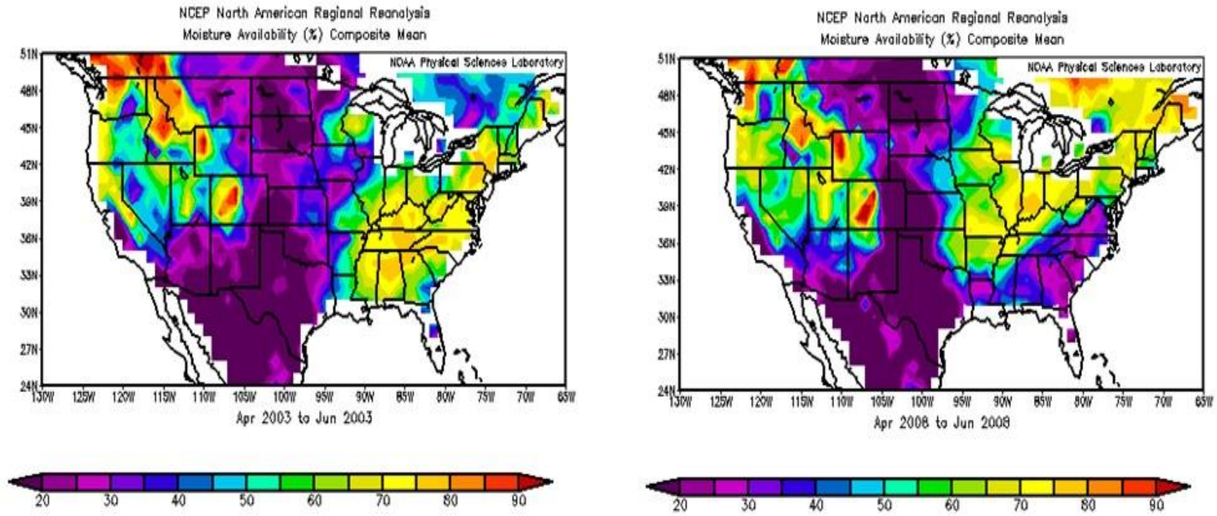


Fig. A.19a. Left- April-June, 2003 mean 2-m moisture availability (%) composite map. Fig. A.19b. Right- Same as in A.19a, but for 2008.

E.8. Instability Composite Maps

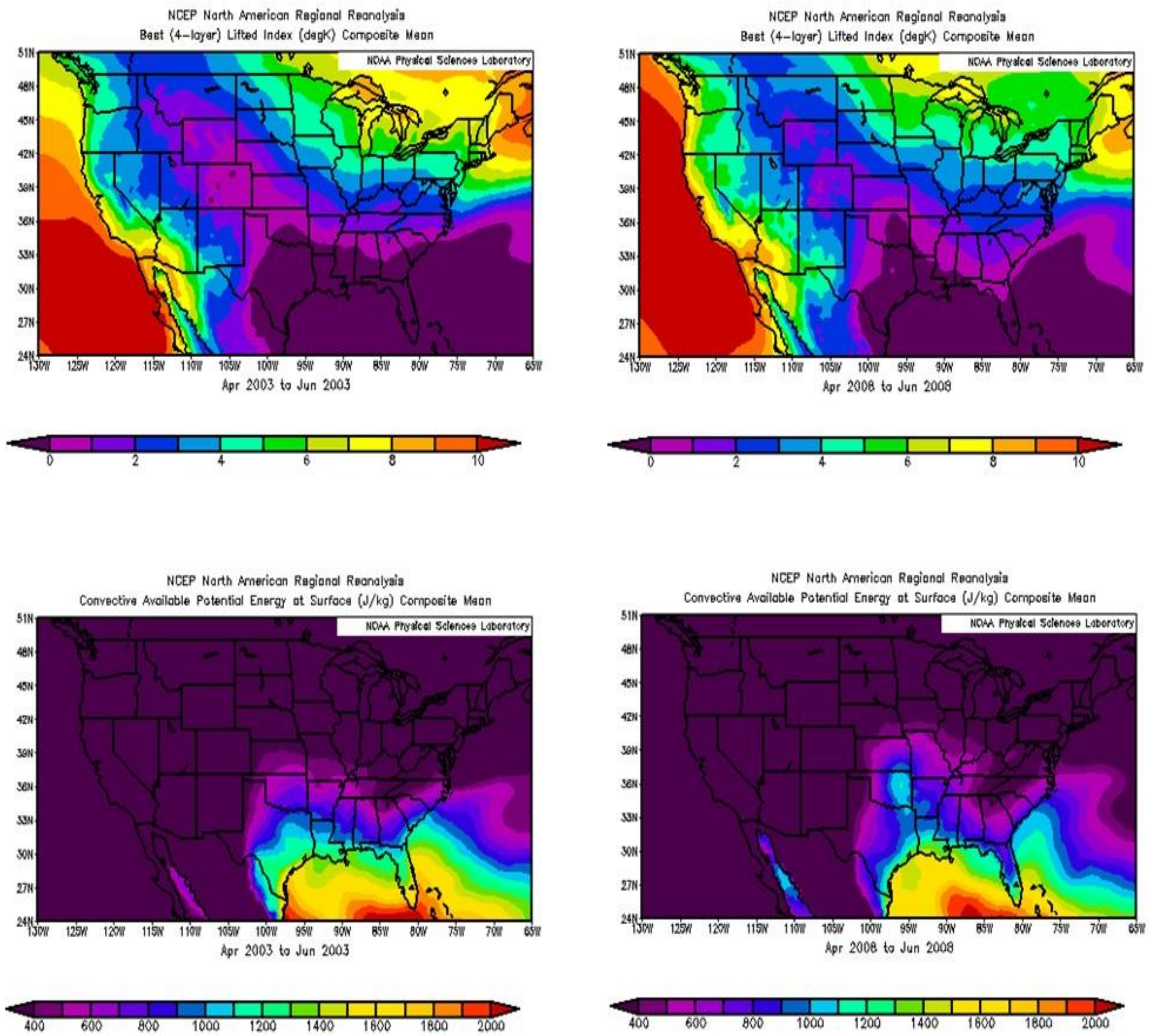


Fig. A.20a. Top Left- April-June, 2003 mean best (4-layer) lifted index (deg/K) composite map. Fig. A.20b. Top Right- Same as in A.20a, but for 2008. Fig. A.20c. Bottom Left- April-June, 2003 mean surface based CAPE (J/kg) composite map. Fig. A.20d. Bottom Right- Same as in A.20c, but for 2008.

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