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RESEARCH

Using soil moisture and variability with respect to ENSO as a predictor for spring convective events within the State of Missouri, USA

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Abstract

Previous studies demonstrated that increased soil moisture can affect the water vapor in the overlaying atmospheric boundary layer (ABL). This can increase the surface buoyancy which can be more conducive for the occurrence of severe weather. This research will demonstrate that soil moisture can be an indicator for increased tornado, large hail, and severe wind activity within the state of Missouri for the period from 1980–2018. Then, using data obtained from the Storm Prediction Center in Norman, OK, the April–June soil moisture anomalies were used to determine if there is a correlation to severe weather occurrence during those months. The correlation of soil moisture anomalies for the months of January–March and September through February before the April–June severe weather season was examined next. These experiments will use the Pearson correlation coefficient and a Poisson regression to test for significance. Only significant results from the Pearson correlation method will be shown for brevity. Then, synoptic maps, in conjunction with the ENSO phenomena, were examined to understand what other mechanisms were contributing to the increase/decrease in storm reports within the state. A spectral analysis using Fourier transforms was conducted to examine the interannual variability of severe weather occurrence with respect to soil moisture. Results showed a significant positive relationship between April–June soil moisture with April–June tornado and severe wind activity. Fewer significant positive and negative relationships were found relating the January–March soil moisture with April–June severe weather reports. However, no statistical significance was found between September–February soil moisture and the ensuing April–June severe weather reports. Most of the statistically significant correlations were noted in south central Missouri. 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 a greater number of tornadic systems, while El Niño produces more potent systems.

Keywords Soil moisture · ENSO · Climate variability · Severe weather · Tornadoes

1 Introduction

There are many known mechanisms which contribute to convection (e.g., Newton 1963, Brooks and Craven 2002, Kim et al. 2003, Sherburn and Parker 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 besides temperature, as this enables a parcel to accelerate through the atmosphere (e.g., Rasmussen and Blanchard 1998). Therefore, it is reasonable to assume moisture within soil can, at least partly, contribute to the overlying moisture content within the atmosphere above (e.g., Ek and Holtslag 2004, Siqueira et al. 2009, Wakefield et al. 2016). 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 advection. Thus, an investigation on whether antecedent soil moisture, or lack of it, correlates with the occurrence of severe weather has been examined following Wakefield et al. (2016).

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Since the state of Missouri lies within the middle of the USA, it is influenced by weather systems from several areas, for example, storm systems moving over the Rocky Mountains to the west, cool and northerly flow from Canada, and warm moist southerly flow from the Gulf of Mexico (e.g., Berger et al. 2003; Andresen et al. 2012). The unique position of Missouri also could place the western half of the state in a narrow transition zone, meaning both dry soils and wet soils can lead to convection. The eastern half of the state has been shown to have more of a positive feedback effect for precipitation with soil moisture (e.g., Findell and Eltahir 2003). Furthermore, within the state, there is the Ozark Plateau. There has been anecdotal and published evidence (e.g., Bongard et al. 2020) that this terrain can affect weather in and around the region. The plateau, along with the position of Missouri in the transition zone, makes the state an interesting area for the study of convective storms, the severe weather they generate, and how the presence of soil moisture can lead to enhanced or decreased severe potential.

It is known that the El Niño-Southern Oscillation (ENSO) influences the weather in the Midwest (e.g., Lupo et al. 2012a). El Niño is known to bring above-average temperatures to the central USA during the winter and spring, while most winter months are wet and most spring months dry (e.g., Lupo et al. 2007, Birk et al. 2010). During La Niña years we find the opposite (e.g., McPhaden 2002, Birk et al. 2010). Both of these studies used a Fourier or wavelet analysis and showed significant variability at 3, 6, and 20 years when looking at mean monthly temperature and precipitation for the central USA. These results also confirm earlier studies (e.g., Hu et al. 1998) which were similar across the Midwest region. The former periods were attributed to the ENSO cycle, while the 20-year period was attributed to variability associated with the Pacific decadal oscillation (PDO). Outside the central USA, El Niño brings wet weather to the southeast and western California during the spring months (e.g., Kahya and Dracup 1993).

Several studies have demonstrated that the occurrence of severe weather varies with ENSO across the Midwest (e.g., Akyuz et al. 2004 and references therein). 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. Akyuz et al. (2004) also proved an increase in tornadic events within the central Plains during La Niña years, including Missouri from 1948–1999. Their study focused on those greater than E(F1). Marzban and Schaefer (2001) demonstrated a small but significant correlation between SST anomalies in the Pacific Ocean and the spatial distribution on the occurrence of tornadoes in the USA. Their results revealed 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. This was confirmed later by Cook and Shaefer (2008), with the exception that ENSO-neutral years favor more tornado occurrences. Monfredo (1999), Moore et al. (2018), and Renken et al. (2022) find that the La Niña phase favored higher tornado numbers in the continental USA (CONUS) during the severe weather season as defined by each respective work. Their results emphasize the importance of how the severe weather season is defined (see also Moore 2019), the area examined, and what constitutes a severe weather day.

Allen et al. (2015) and Renken et al. (2022) demonstrated that La Niña years favored the frequency of occurrence of hail events as well across the USA east of the Rockies, and the latter study also include days with a large number of severe wind events (greater than or equal to 25.9 m s^{-1}). Cook et al. (2017) found that the southeastern USA (e.g., Dixon et al. 2011) was more active (from 1950–2016) during La Niña years, while the southern and central plains region of the USA was more active during El Niño years. Lepore et al. (2017) demonstrate that the winter season ENSO phase can be used to anticipate spring season severe weather (tornado and hail) activity. Their work implied that La Niña years showed more success, especially for hail events.

This study proposes to investigate whether there is a link between the occurrence of severe weather and soil moisture and if it can be identified within the state of Missouri. This study will examine in-season and antecedent soil moisture in a manner similar to Wakefield et al. (2016), and this work will divide up Missouri into six climate divisions. These divisions group counties together which have similar climate, as dictated by NOAA. This research will also attempt to identify which type of statistical analysis for establishing this connection is appropriate. This will be done by comparing a Pearson correlation coefficient method and a quasi-Poisson regression method. These two were chosen as they seem the most appropriate for this type of analysis due to the linearity of the data. Furthermore, the relationship of ENSO teleconnections and the overall synoptic setup during ENSO will be explored. In addition, this work will extend the climatology of Akyuz et al. (2004) to include the early part of the twenty-first century. Section 2 describes the data and methods used, while Section 3 will present the results. Section 4 will summarize the work and present what was learned in this work.

2 Data and methods

2.1 Data

2.1.1 Soil moisture and composite map 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. The 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. Seasonal composites including the time frames of April–June (called "in season"—see definition for severe weather season), January–March (immediately pre-severe weather season), and September–February (long-term preseason) were chosen for this study. The long-term preseason period was chosen to match the meteorological fall and winter seasons, and this was consistent with Wakefield et al. (2016).

Using the NCEP/NCAR Reanalysis (e.g., Kalnay et al. 1996) database, several other composite maps were also constructed using different parameters for 1980–2018. Composites that were made for this research include 300-hPa vector winds (m s^{-1}) and heights (m); 500-hPa vector winds (m s^{-1}) and heights (m); 700-hPa vertical motion (mb s^{-1}), specific humidity (kg kg^{-1}), heights (m), and vector winds (m s^{-1}); 850-hPa vector winds (m s^{-1}), heights (m), and specific humidity (kg kg^{-1}); and mean sea-level pressure (MSLP, hPa), latent and sensible heat flux (W m^{-2}), 2-m relative humidity, 2-m temperature (°C), lifted index, 2-m dew point, moisture availability, and surface convective available potential energy (CAPE (J kg^{-1})). These parameters were chosen to determine if there is also a correlation between the synoptic conditions and soil moisture. This will be analyzed below.

2.1.2 El Niño and Southern Oscillation

The definition for ENSO used in this study is described in Birk et al. (2010) and references therein, and a brief description is given here. The Japanese Meteorological Agency (JMA) ENSO index is available via the Center for Ocean and Atmospheric Prediction Studies (COAPS) from 1868 to the present (http://www.coaps.fsu.edu). The JMA classifies ENSO phases by using SST within the bounded region of 4° S to 4° N, 150° W to 90° W and defines the start of an ENSO year as the 1st of October and its conclusion on the 30th of September of the following year. This index is used in many other published works (see Birk et al. (2010) and references therein), and a list of years is provided (Table 1). This index is useful since it acknowledges the longevity of ENSO events, but it may produce different classifications for years versus other definitions. For example, Hanley et al. (2003) found that, while the JMA index is more sensitive to La Niña events than other definitions, it is less sensitive than other indices to El Niño events.

2.1.3 Storm data

The storm data, which contains tornado, hail, and wind, was collected through the Storm Prediction Center's (SPC—http://www.spc.noaa.gov) database. This data includes all tornado counts and tornado days within the state of Missouri for 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 long enough to determine whether there is a correlation between soil moisture and severe weather associated with spring convection. The monthly time frame was decided upon for a couple of reasons. First, it matches those used in a study conducted at the University of Oklahoma (Wakefield et al. 2016), which is the basis for this research. Second, spring is the season when the most severe weather occurs. Long and Stoy (2014) suggests peak tornado season in Tornado Alley occurs on the 19th of May, while Renken et al. (2022) suggest this peak is close to the 15th of May approximately for severe weather in the whole USA. The latter also showed that the standard deviation is about 1.4 months for tornado occurrences; thus, April–June is a reasonable choice here. Additionally, in the USA and across MO, these months observe more than 50% of the annual number of reports and days (e.g., Renken et al. 2022).

The tornadoes identified here 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 these events within Missouri. In-depth radar analysis would be needed to distinguish between convective activity that produces severe weather and that which does not (https://www2.mmm.ucar.edu/imagearchive/). This would also be needed to determine more precisely the origins of severe weather, which because of time constraints for this research, was not able to be performed. The same issue was reported for the individual climate divisions within the state.

Table 1 List of ENSO years used here. The years below are taken from Birk et al. (2010) and the COAPS website

El Niño (EN)	Neutral (NEU)	La Niña (LN)
1982	1977–1981	1988
1986–1987	1983–1985	1998–1999
1991	1989–1990	2007
1997	1992–1996	2010
2002	2000–2001	2017
2006	2003–2005	
2009	2008	
2014–2015	2011–2013	
2018	2016	
	2019	

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. Additionally, 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 to be in 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 these were found. Ultimately, we concluded that there were far too many observed reports for duplicates to make a significant difference.

Tornado data was categorized with all tornado counts, tornado counts greater than or equal to E(F0), all tornado days, and weak and strong tornadoes. Weak tornadoes were considered those with E(F0) and E(F1) strength. Strong tornadoes were those with strengths between E(F2) and 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. We noticed many wind reports of unknown intensity within the SPC database. Since it was difficult to establish the strength of the wind, these reports were recorded as "null" 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 in CSV format, it was imported into the ArcMap program. It is also useful to physically see the differences when portrayed geographically. 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. 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 (see Fig. 1), the function "extract by mask" 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). 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 spatial join function was used to find the number of storm reports for each of the six climate divisions.

2.2.2 Fourier transforms

To find a correlation between ENSO and the occurrence of severe weather and 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 using the Mathcad software. Fourier transforms converts Cartesian coordinates to wave space which is useful for the identification of cyclical periods. In this case, the identification of interannual and interdecadal variability was analyzed to determine whether there were congruent cycles found in severe weather occurrence and soil moisture amounts. The observed wave spectrum can then be compared against white and red noise spectra to determine statistical significance (e.g., 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 (e.g., Wilks 2006). Significant periods were found by dividing peak waves by the number of years.

The power spectra for the time series 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. The resulting power spectra were analyzed on their own and then used to perform a cross-spectral analysis (e.g., Lupo et al. 2012b, Henson et al. 2017). This analysis involves the convolution of power spectra to create a combined power spectrum used for the examination of periodicities. The resulting covariance spectra were analyzed for dominant periods, which represent the periodicities shared by the two individual time series. The peaks found in the resulting spectra were tested for significance against a white noise continuum, assuming no particular frequency to be dominant (e.g., Wilks 2006).

2.2.3 Statistical methods

The April to June 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, two methods were chosen: the Pearson correlation coefficient and a Poisson regression. For the Pearson correlation coefficient, the following equation was used (e.g., Asuero et al. 2006), where x and y are the comparison values and $\bar{x}$ and $\bar{y}$ are their corresponding mean values. This was done in Excel where the CORREL function was used.

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

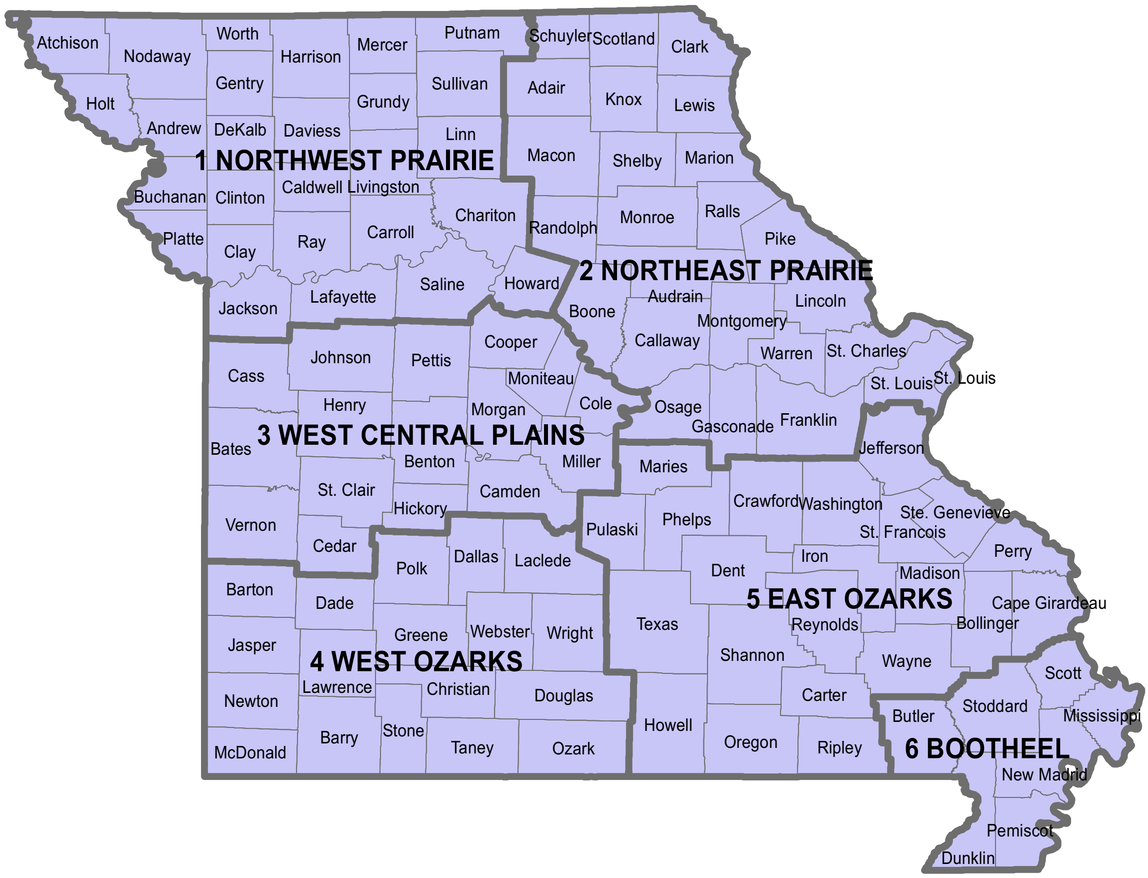

Fig. 1 A map of the six climate divisions within Missouri, as identified by the National Oceanic and Atmospheric Administration (NOAA) (produced through ArcMap 10.7.1)

To test the significance of the Pearson correlation, the following *t*-test equation was used (e.g., Illowski 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). 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. (2016). Additionally, weaker tornadoes have been shown to not accurately represent the number of tornadoes, due to these being overestimated, especially within large population centers. 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 Section 3, a p-value of 0.10–0.05 is denoted in blue (R value which denotes the Pearson correlation coefficient), and those with a p-value ≤ 0.05 are denoted in red (R value). From here on, any correlations with a p-value of 0.10–0.05 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 kts and those with a magnitude of ≥ 60 kts were used. For hail events, all reports, those with a magnitude < 1.25 in. and 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 in Fig. 1.

3 Statistical results

3.1 State soil moisture compared with tornado counts and days

When comparing in-season soil moisture anomalies to in-season tornado counts for Missouri and using the Pearson correlation method, there was a statistically significant correlation observed. Soil moisture versus tornado counts > E(F0) and soil moisture versus tornado counts E(F2)-E(F5) showed significant positive correlations ($p \leq 0.10$). In the same comparison using in-season soil moisture anomalies with in-season tornado days within the state, only the tornado days E(F0)-E(F1) had a significant correlation ($p \leq 0.10$) (Fig. 2). In this research, we noted that there was an increase in strong tornadoes E(F2)-E(F5). It is important to note that there may be several factors contributing to the increase in tornadic events (e.g., Akyuz et al. 2004). One could be the population growth and better reporting. Other factors may include interannual and interdecadal variability. This will be discussed below.

The quasi-Poisson method was used to construct a residual vs. fitted plot and is displayed in Fig. 3 with the residuals on the *y*-axis and the predicted values on the *x*-axis. The residuals are the distance between a data point and the predicted value. The red line is the smoothing of the data to fit the model. Linearity holds true if the red line is close to zero. No statistical significance was observed with any of the plots. It is important to note that it can be difficult to make assumptions by looking at a residuals vs. fitted plot. Therefore, one needs to be cautious. Within the following residuals vs. fitted plots throughout the rest of this paper, all seem to hold linearity, indicating that a quasi-Poisson model is a good choice (e.g., Ver Hoef and Boveng, 2007).

Figures 2 and 3 are shown as examples and will not be displayed in further sections. Instead, tables will be displayed with the same information, in order to summarize the information more concisely. An example of this is in Table 2. For the Pearson correlation method, blue text (*R* value) indicates a value of $p \leq 0.10$, while red text (*R* value)

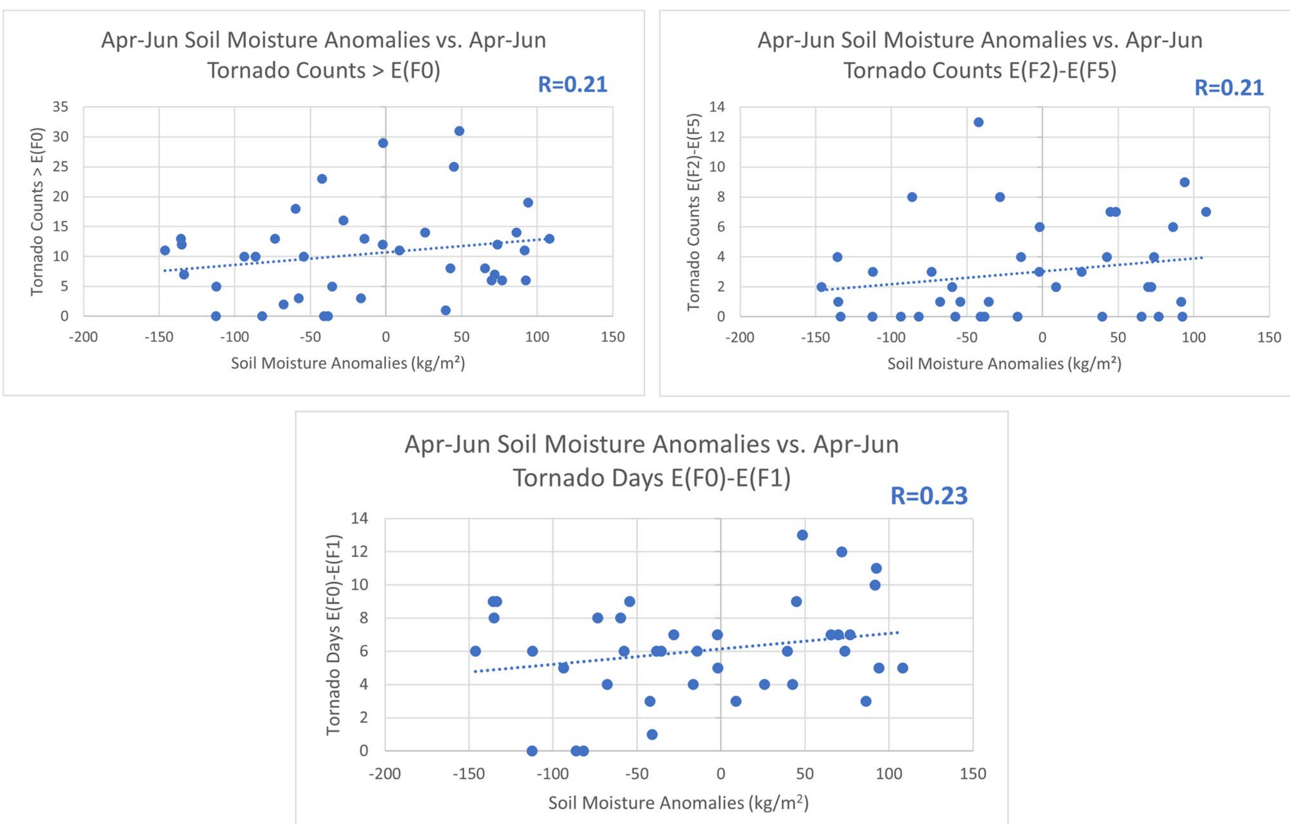

Fig. 2 Pearson's correlation—April to June soil moisture anomalies (kg m^{-2}) compared to April to June tornado counts and days for **a** Top Left- tornado counts > E(F0), **b** Top Right- tornado counts E(F2)-E(F5), and **c** Bottom - tornado days E(F0)-E(F1). Significant positive correlations ($p \leq 0.10$) are noted in all figures

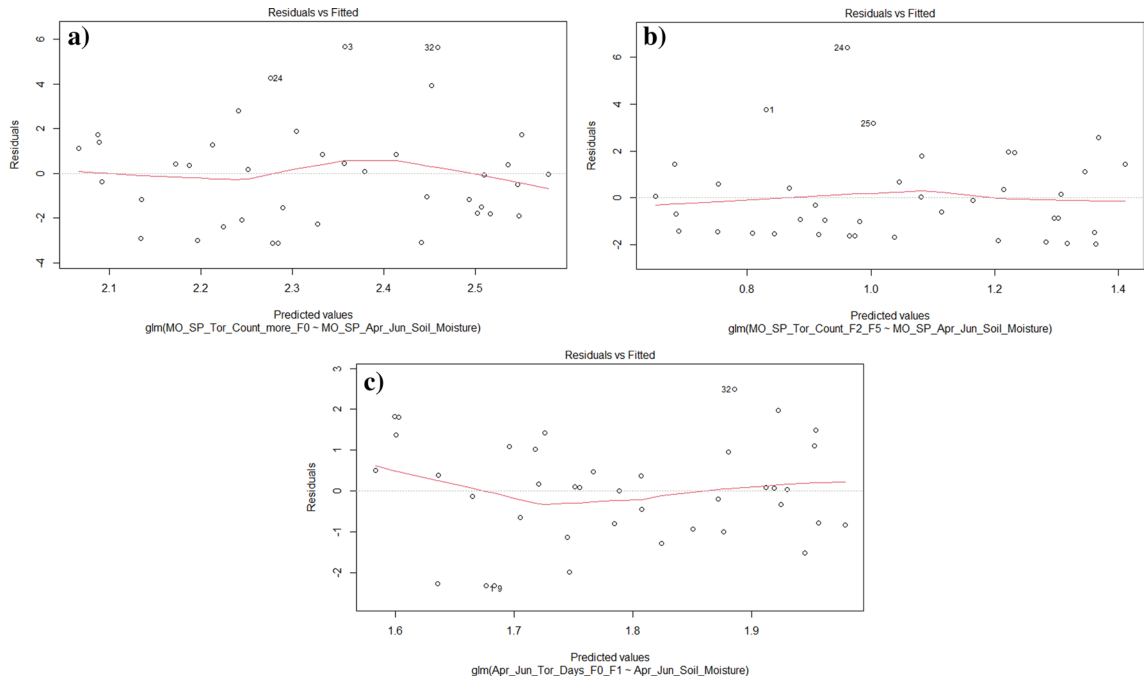

Fig. 3 Quasi-Poisson regression—residuals (ordinate) vs. predicted values (abscissa)/fitted plots for in-season (Apr–June) soil moisture anomalies versus April to June tornado counts for **a** tornado counts > E(F0), **b** tornado counts E(F2)-E(F5), and **c** tornado days E(F0)-E(F1). The red line is a fitted curve to the data using the quasi-Poisson model. No statistical significance was found

indicates a value of $p \leq 0.05$. In addition, negative values show a negative correlation with positive indicating a positive correlation. For the quasi-Poisson regression analysis, *R* values are not given within the raw data, only *p*-values. Therefore, NS refers to a non-significant result, while S is significant (the blue and red text remains the same for the significance).

In contrast to the in-season soil moisture anomaly comparison, the 3-month antecedent soil moisture versus the state tornado counts > E(F0) and tornado counts E(F0)-E(F1) showed a negative correlation, although non-significant. The same comparison for tornado counts of E(F2)-E(F5) showed a slight positive correlation but which was not statistically significant. The 3-month antecedent soil moisture anomalies compared with in-season tornado days > E(F0), tornado days E(F0)-E(F1), and tornado days E(F2)-E(F5) also differ from that of the in-season soil moisture anomalies. The results showed a negative but non-statistically significant correlation. This is in contrast to the in-season study where it all showed positive correlations, one of which was significant ($p \leq 0.10$).

3.2 Climate divisions soil moisture versus tornado counts and days

The divisional in-season soil moisture anomalies are compared with the divisional in-season tornado counts in Table 3. Within the six climate divisions for the Pearson correlation method, divisions 2 and 5 showed significant positive correlations ($p \leq 0.05$). The quasi-Poisson method also showed divisions 2 and 5 as having significant correlations ($p \leq 0.05$ and $p \leq 0.10$, respectively). The divisional in-season soil moisture anomalies compared with the divisional in-season tornado days (Table 4) showed significant positive correlations ($p \leq 0.10$) for divisions 2, 4, and 5 with the Pearson correlation method. None of the divisions exhibited significance with the quasi-Poisson method.

Table 2 State tornadoes with their corresponding *R* values

State Tornadoes						
	Pearson (Sep-Feb)	Pearson (Jan-Mar)	Pearson (Apr-Jun)	Quasi-Poisson (Apr-Jun)	Quasi-Poisson (Jan-Mar)	Quasi-Poisson (Sep-Feb)
>EF0 Counts	0.03	0.11	0.21	NS	NS	NS
EF0-EF1 Counts	0.03	-0.11	0.16	NS	NS	NS
EF2-EF5 Counts	0.06	0.05	0.21	NS	NS	NS
>EF0 Days	-0.05	-0.14	0.19	NS	NS	NS
EF0-EF1 Days	-0.01	-0.05	0.23	NS	NS	NS
EF2-EF5 Days	-0.06	-0.16	0.11	NS	NS	NS

The divisional 3-month antecedent soil moisture anomalies for the Pearson correlation method are also compared with the divisional in-season tornado counts and days > E(F0) in Table 3. For tornado counts > E(F0), division 2 was the only division that had a statistically significant correlation ($p \leq 0.10$). This division also saw a positive significant correlation ($p \leq 0.05$) with the in-season soil moisture comparison. Surprisingly, none of the 3-month antecedent tornado counts in any category within the state were statistically significant for the other divisions. For tornado days > E(F0) (Table 4), division 3 had a significant negative correlation ($p \leq 0.10$). Furthermore, division 5 saw statistical significance—a negative correlation ($p \leq 0.05$)—and was significant ($p \leq 0.10$) with the in-season soil moisture comparison. Interestingly, the 3-month antecedent tornado days within the state were not statistically significant at either level. When compared, the quasi-Poisson method demonstrates less significance. Only one category (division 5) showed significance ($p \leq 0.05$).

3.3 Soil moisture compared with wind reports

The divisional in-season soil moisture anomalies are compared with the divisional in-season wind reports in Table 5. Division 5 saw a statistically significant positive correlation ($p \leq 0.05$), while division 3 observed a correlation at the 11% level ($p \leq 0.11$) for the Pearson correlation method. This is interesting since none of the other wind reports within the state were statistically significant. This suggests that localized areas within the state may behave differently than the state as a whole. For the quasi-Poisson approach, division 5 also showed significance but not as strong ($p \leq 0.10$). None of the others exhibited any significance within the state or divisions.

The 3-month antecedent soil moisture within the state and divisions for the Pearson correlation method is displayed (Table 5). All state categories had a negative correlation with wind reports ≥ 60 kts observing a significant correlation ($p \leq 0.10$). This contrasts with the in-season soil moisture comparison where all categories saw a positive correlation, although non-significant. All divisions saw

Table 3 Divisional tornado counts with their corresponding *R* values and statistical results

Tornado Divisions (Counts)						
	Pearson (Sep-Feb)	Pearson (Jan-Mar)	Pearson (Apr-Jun)	Quasi-Poisson (Apr-Jun)	Quasi-Poisson (Jan-Mar)	Quasi-Poisson (Sep-Feb)
Div 1	-0.15	-0.14	-0.11	NS	NS	NS
Div 2	0.17	0.23	0.42	S	NS	NS
Div 3	-0.19	-0.20	0.04	NS	NS	NS
Div 4	0.14	-0.16	0.15	NS	NS	NS
Div 5	0.03	-0.16	0.29	S	NS	NS
Div 6	0.10	-0.18	-0.07	NS	NS	NS

Table 4 Divisional tornado days with their corresponding *R* values and statistical results

Tornado Divisions (Days)						
	Pearson (Sep-Feb)	Pearson (Jan-Mar)	Pearson (Apr-Jun)	Quasi-Poisson (Apr-Jun)	Quasi-Poisson (Jan-Mar)	Quasi-Poisson (Sep-Feb)
Div 1	-0.02	-0.15	-0.12	NS	NS	NS
Div 2	0.07	0.09	0.25	NS	NS	NS
Div 3	-0.11	-0.24	0.08	NS	NS	NS
Div 4	0.14	-0.18	0.23	NS	NS	NS
Div 5	-0.10	-0.33	0.21	NS	S	NS
Div 6	0.00	0.02	0.12	NS	NS	NS

Table 5 State and divisional wind reports with their corresponding statistical analysis approach

Wind Reports						
	Pearson (Sep-Feb)	Pearson (Jan-Mar)	Pearson (Apr-Jun)	Quasi-Poisson (Apr-Jun)	Quasi-Poisson (Jan-Mar)	Quasi-Poisson (Sep-Feb)
Total Wind Reports	-0.03	-0.20	0.11	NS	NS	NS
Wind Reports <60	-0.02	-0.19	0.11	NS	NS	NS
Wind Reports ≥60	-0.07	-0.21	0.06	NS	NS	NS
Div 1	-0.05	-0.13	0.12	NS	NS	NS
Div 2	0.06	-0.01	0.12	NS	NS	NS
Div 3	-0.13	-0.14	0.20	NS	NS	NS
Div 4	0.03	-0.17	0.11	NS	NS	NS
Div 5	0.07	-0.22	0.29	S	NS	NS
Div 6	-0.06	-0.19	0.13	NS	NS	NS

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 where all divisions saw positive correlations. Much like division 5 in this section, division 5 with the in-season experiment was also significant but at the 5% level ($p \leq 0.05$). No significant results were seen with the quasi-Poisson regression method, and only one category observed a positive correlation (all wind reports within the state).

3.4 Soil moisture compared with hail reports

For the in-season soil moisture anomalies versus hail reports, the correlations were positive but not statistically significant. This is shown in Table 6.

All state categories for the 3-month analysis had a negative but non-significant correlation. This is in contrast with the in-season soil moisture comparison, where all categories saw positive although non-significant correlations. All climate divisions observed 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.

3.5 Comparing the 6-month antecedent soil moisture versus April–June severe weather reports with previous studies

The third experiment used the same methods as the previous two experiments, except using September–February soil moisture as a predictor for the following April–June convection. None of the results within the state or divisions proved statistically significant within any of the methods (tornado, wind, hail). The results had a mix of positive and negative correlations. When compared with the Wakefield et al. (2016) paper, these results were comparable to their results. Correlations of the 6-month antecedent soil moisture to tornado counts > E(F0) had a value of $r = -0.07$ when the 2011 season outlier was removed, which is closest to the southern Plains region of Wakefield et al. (2016). In their study, the correlation had an R value of −0.06. Furthermore, when comparing the 6-month antecedent soil moisture to the in-season tornado days > E(F0), the results were also similar to that of Wakefield et al. (2016). When the 2011 outlier was removed, the correlation increased from −0.05 to −0.15, although still not statistically significant. The value (−0.15) from this study is between the results of Wakefield et al. (2016) for the Southern (0.15) and Northern Plains (−0.34) regions. This is reasonable because southern Missouri lies within the Southern Plains and the northern half of the state is within the Northern Plains regions.

3.6 Advection of soil moisture

Correlations between certain divisions were calculated to see if there might be a component of surface soil moisture advection that is soil moisture in one division correlating to severe weather downwind. Divisions correlated versus each other were oriented southwest to northeast and 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.

The first part of this study (Table 7) looked at the correlations for three regions using tornado counts > E(F0) and used the Pearson correlation method. 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

Table 6 State and divisional hail reports with their corresponding statistical analysis approach

Hail reports	Pearson (Sep–Feb)	Pearson (Jan–Mar)	Pearson (Apr–Jun)	Quasi-Poisson (Apr–Jun)	Quasi-Poisson (Jan–Mar)	Quasi-Poisson (Sep–Feb)
Total hail reports	−0.02	−0.08	0.04	NS	NS	NS
Hail reports < 1.25	−0.05	−0.09	0.03	NS	NS	NS
Hail reports ≥ 1.25	0.07	−0.07	0.06	NS	NS	NS
Div 1	0.00	0.00	0.03	NS	NS	NS
Div 2	0.01	−0.05	0.03	NS	NS	NS
Div 3	0.11	−0.18	−0.04	NS	NS	NS
Div 4	−0.10	−0.04	0.16	NS	NS	NS
Div 5	−0.04	−0.08	0.10	NS	NS	NS
Div 6	0.10	0.06	−0.02	NS	NS	NS

Table 7 Downwind soil moisture advection with their corresponding statistical analysis approach and values

Advection of Soil Moisture				
	Pearson (Counts)	Quasi-Poisson (Counts)	Pearson (Days)	Quasi-Poisson (Days)
Div 1 to Div 2	0.30	S	0.09	NS
Div 3 to Div 2	0.24	NS	0.08	NS
Div 4 to Div 5	0.28	S	0.21	NS

division 1 soil moisture to division 2 tornado counts > E(F0) (Fig. 7a) showed a significant positive correlation ($p \leq 0.05$). The comparison of division 4 soil moisture to division 5 tornado counts > E(F0) (Fig. 7c) also had a significant positive correlation ($p \leq 0.05$). Comparing division 3 soil moisture to division 2 tornado counts > E(F0) (Fig. 7b), there was a statistically significant positive correlation at the 10% level ($p \leq 0.10$).

It is important to note that this study was done 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 the 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 investigation.

The same comparisons are made (Table 7) using a quasi-Poisson regression. All showed positive correlations with two of the areas observing statistical significance. The comparisons of division 1 soil moisture to division 2 tornado counts > E(F0) and division 4 soil moisture to division 5 tornado counts > E(F0) saw significance at the 10% level ($p \leq 0.10$).

Table 7 also shows the same correlations for the Pearson correlation method 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) (Table 7). The same comparisons are made using a quasi-Poisson regression. Once again, all showed positive correlations, except none of the areas exhibited significance.

4 Analysis of synoptic charts and ENSO

In order to determine whether El Niño or La Niña produced more severe weather events, 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 (April–June). Only the years within this study are provided (1980–2018). The ENSO year is considered to begin on 1st of October to the following 30th of September (e.g., Birk et al 2010). For example, the La Niña year of 2007 would persist from October 2007 to September 2008. Therefore, the spring of 2008 would be classified as a La Niña year. Each year (El Niño and La Niña, no neutral years were considered) was analyzed and determined which ones would be best suited for the analysis. 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 (tornado days were chosen instead of tornado counts because tornado days give a better accurate depiction of tornado activity (Raddatz and Cummine 2003)) 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. The year chosen to be representative of La Niña conditions was 2008 (13 tornado days (6 > E(F0)) and soil moisture anomaly of 72 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). It is important to analyze each of the two El Niño (2003) and La Niña (2008) years that were chosen. As a whole, El Niño years seem to produce greater soil moisture content than La Niña (−16 kg/m^2 compared to −25 kg/m^2, respectively). This difference is very negligible as it equates to approximately 0.35 in. of liquid content. Therefore, it can be assumed that El Niño and La Niña years produce relatively the same amount of soil moisture during the months of April–June when averaged over the state of Missouri. Since the El Niño year chosen was considerably drier (roughly

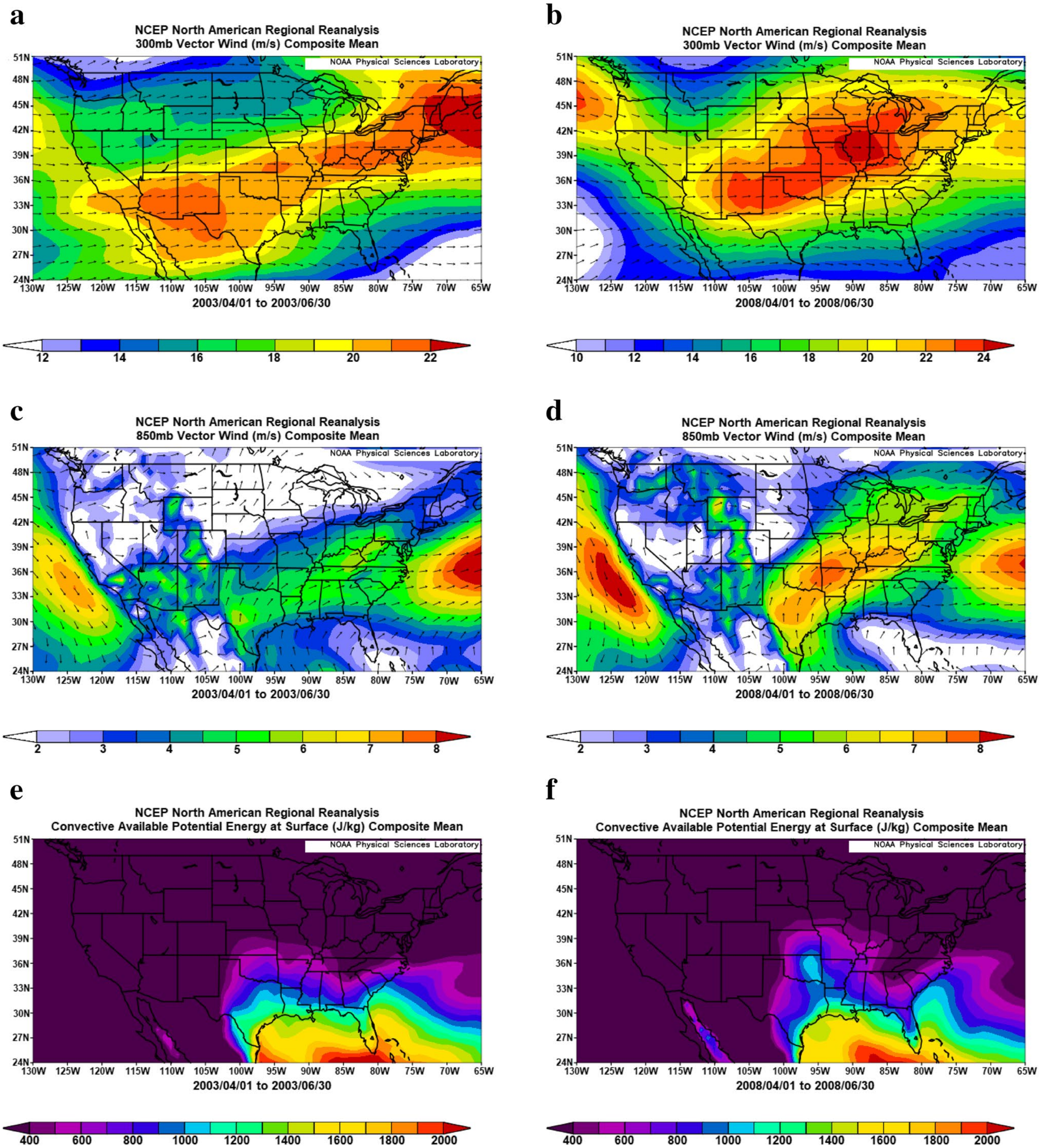

Fig. 4 The April–June composites for the **a** 2003 and **b** 2008 300-hPa mean vector wind (m s^{-1}), **c** 2003 and **d** 2008 850-hPa mean vector wind (m s^{-1}), and **e** 2003 and **f** mean surface-based CAPE (J kg^{-1})

4.5 in. of soil moisture less) than that of the chosen La Niña year, the following composite maps will be more of a "dry" period versus a "wet" period. The two years chosen are also what will be considered typical ENSO events as they both fall into the "normal" category.

4.1 Composite maps

Composite maps and analyses were made for each of these years (2003, 2008) for the period of April–June (Figs. 4, 5, 6, and 7). During the 2008 La Niña year, the synoptic

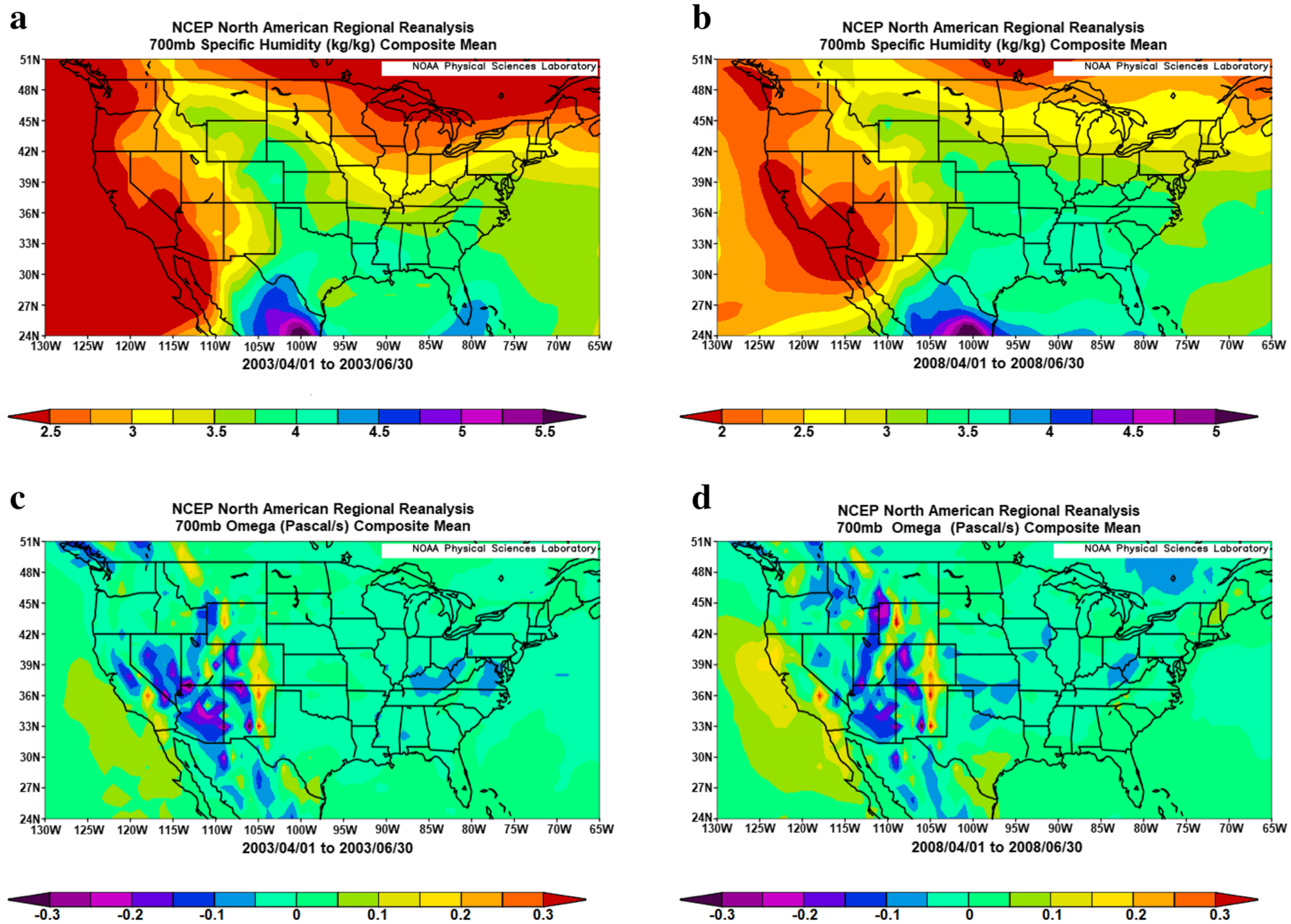

Fig. 5 The mean April–June composite maps of 700-hPa specific humidity (kg kg^{-1}) for **a** 2003 and **b** 2008 and **c** 2003 and **d** 2008 700-hPa mean omega (Pa s^{-1}) composite map

observations showed that Missouri was in a much better position for the occurrence of severe weather, as compared to 2003. Interestingly, 2003 did produce a greater number of tornadoes, but the number of tornado days was less than 2008. Since tornado days gives a more accurate depiction of tornado activity (e.g., Raddatz and Cummine 2003), the synoptic character of 2008 may produce more tornadic systems or outbreaks as shown in the composite figures. This is consistent with the results of Cook et al. (2017) and references therein.

In Fig. 4, there is more CAPE (Fig. 4e, f) and stronger upper-level winds noticeable in 2008 (Fig. a, b). Also noticeable in the latter maps, the 2008 configuration of the upper-level winds resembles those of Cook et al. (2017) for La Niña years and Kastman et al. (2017) for enhanced divergence aloft. A low-level jet (Fig. 4f) is also observed in 2008 with southern Missouri north of the nose, meaning more surface convergence in this area. The higher specific humidity (Fig. 5b) provides for more moisture advection into the Missouri region. Additionally, the background vertical motion shows stronger upward motions for 2008 (Fig. 5d). In Fig. 6, the surface latent heat flux anomalies were similar, while the surface sensible heat flux anomalies were less negative in 2008 during these months. This implies more evaporation from the surface during the 2008 season. Furthermore (not shown), the surface (2 m) temperature, relative humidity, and dewpoint were higher in 2008.

Even though the mean soil moisture is slightly greater in El Niño years, it seems that La Niña years produce more tornado days in the Missouri region. With regards to soil moisture differences, a wetter soil can enhance moisture within the boundary layer. The added moisture can contribute to more instability, as the surface parcel is more buoyant and is able to accelerate through the atmosphere at a faster rate. These variables allow for a more convective environment.

When analyzing individual La Niña (2008) and El Niño (2003) years, a typical La Niña year (Fig. 7b) produces more soil moisture and more tornado days within the state of Missouri. The most favorable area was found to be over southern Missouri where greater convergence at the surface (divergence

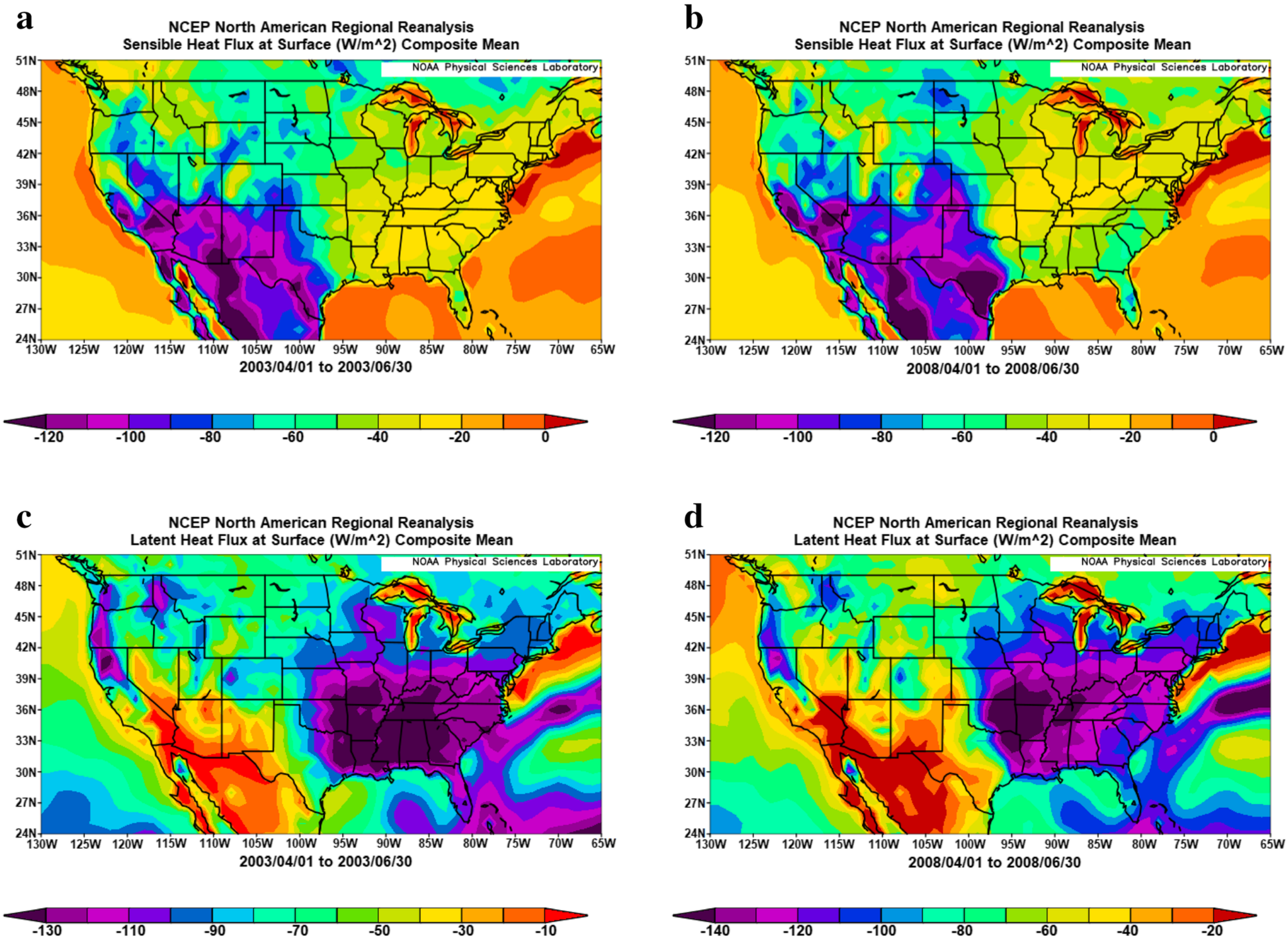

Fig. 6 As in Fig. 5, except for **a** and **b** surface sensible heat flux anomalies (W m^{-2}) and **c** and **d** surface latent heat flux anomalies (W m^{-2})

aloft), instability, and moisture were present. This suggests that soil moisture, along with the synoptic setup, can be a useful tool in analyzing severe weather events. In addition to composite maps, mesoscale analysis would be needed to understand the full relationship that soil moisture plays in developing convective activity. It is reasonable to assume that the effects of soil moisture would be more on a mesoscale level.

Drier soils may contribute to more potent systems (outbreaks) as there is more sensible heating and warming of the boundary layer for an atmosphere already primed for severe weather, whereas moist soils may bring an overall greater number of tornadic systems into the area. Moist soils, in this case, would allow for more buoyancy and thus instability. Both sceneries allow for an increase in instability, so it is thought-provoking to see which one is best suited for convective activity. In general, the synoptic setup seems to be a main player, with soil moisture playing only a small part. Missouri also has various types of soils throughout the state which was not accounted for here. Soil types could affect the soil moisture quantity within a given area.

4.2 Interannual variability analysis

Fourier transforms were generated for the time series of total tornado days and total tornado counts for the April–June 1980–2018 period. The graphs are shown in Fig. 8. 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. Within the total tornado days (Fig. 8a), there were significant peaks at approximately 13, 6.5, 4.3, and 3.5 years. This indicates both long- and short-term ENSO variability (2–7-year period) as well as interdecadal variability. This interdecadal variability is consistent with Akyuz et al. (2004) and Henson et al. (2017). Within total tornado counts (Fig. 8b), significant peaks occurred at approximately 10, 6, 4, and 2 years, which is similar to that for Fig. 8a.

A comparison of the numbers found here with those of Akyuz et al. (2004) demonstrates that during 1977–1998

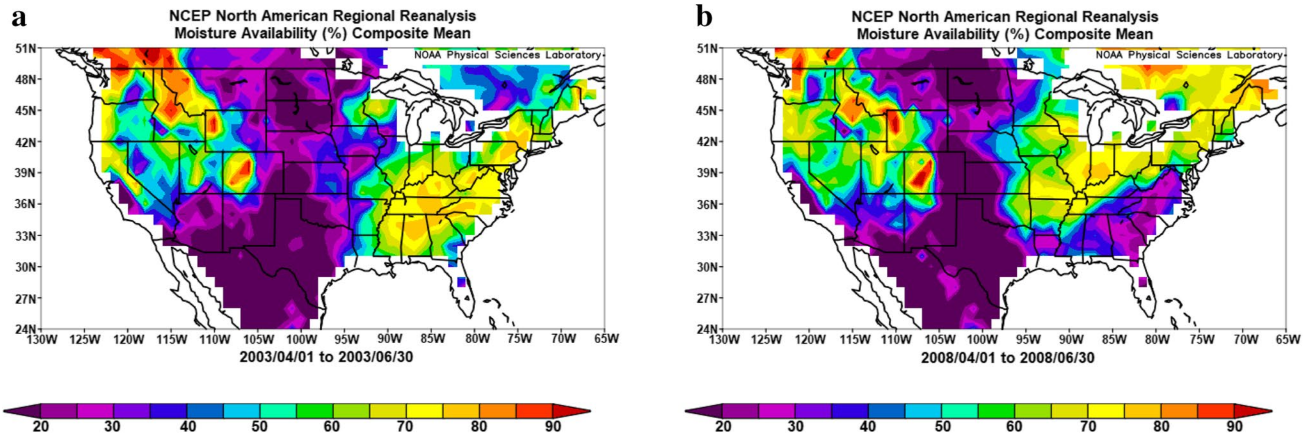

Fig. 7 The mean April–June 2-m moisture availability (%) for **a** 2003 and **b** 2008

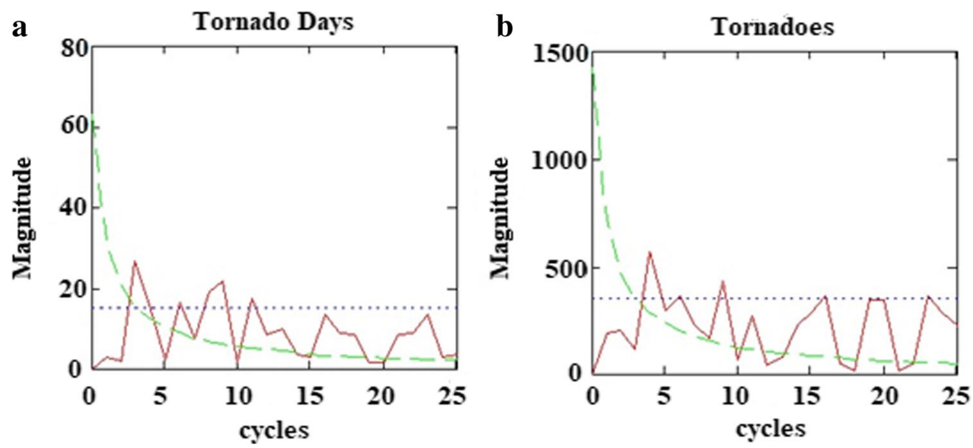

Fig. 8 The Fourier power spectra derived from a time series (1980–2018) of April–June Missouri tornadoes for **a** days and **b** counts (red lines). The green (blue) dashed (dotted) lines are the statistical significance at the 5% level ($p \leq 0.05$) assuming a red (white) noise spectrum

(PDO phase 1), the mean number of significant tornadoes, E(F2)-E(F5), was 4.5. Using the number significant tornadoes from 1999–2018 found here was 10.1 (PDO phase 2), and this is consistent with the raw count of significant tornadoes from 1950–1976 found in Akyuz et al. (2004) which was 9.5. La Niña years did observe more significant tornadoes (10.7) in the latest period, but this was not significantly more than El Niño years (8.0). However, this is consistent with the results above and studies by Cook et al. (2017) and Renken et al. (2022).

Additional Fourier transforms for soil moisture and tornadic activity are displayed (Fig. 9). Significant peaks are evident in the power spectra for the soil moisture anomaly time series (Fig. 9a). These peaks include the approximate yearly cycles of 13, 7, 3, and 2 years. These are consistent with long- and short-term ENSO variability, while the 13-year period indicates interdecadal variability. When analyzing the coherence between total tornado days and soil moisture anomalies (Fig. 9b), significant peaks were found approximately in the years 13, 8, 4, and 2. For total tornado counts and soil moisture anomalies (Fig. 9c), periods 7, 4, 3, and 2 years were statistically significant. Thus, ENSO variability is confirmed for these datasets.

Thus, the ENSO and interdecadal variability in the occurrence of severe weather (tornado counts) is consistent with past studies for this region (e.g., Bove 1998; Akyuz e al. 2004; Cook et al. 2017, and Renken et al. 2022). In addition, Mayes et al. (2007) showed an enhanced area of significant tornadoes within the Missouri Ozarks during the La Niña years. This work, like previous work, demonstrates that the background synoptic environment is more favorable during the La Niña years. Additionally, this work demonstrated consistent interannual and interdecadal variability for the in-season soil moisture. The blended power spectra showed coherence between soil moisture and tornadoes further suggesting that there may be a correlation between soil moisture and tornadoes during some ENSO years. As previously mentioned, the overall synoptic background likely contributes to a greater degree than soil moisture, although it is possible that soil moisture may be a contributing factor to severe weather occurrence, especially the transport of soil moisture into the overlying atmosphere.

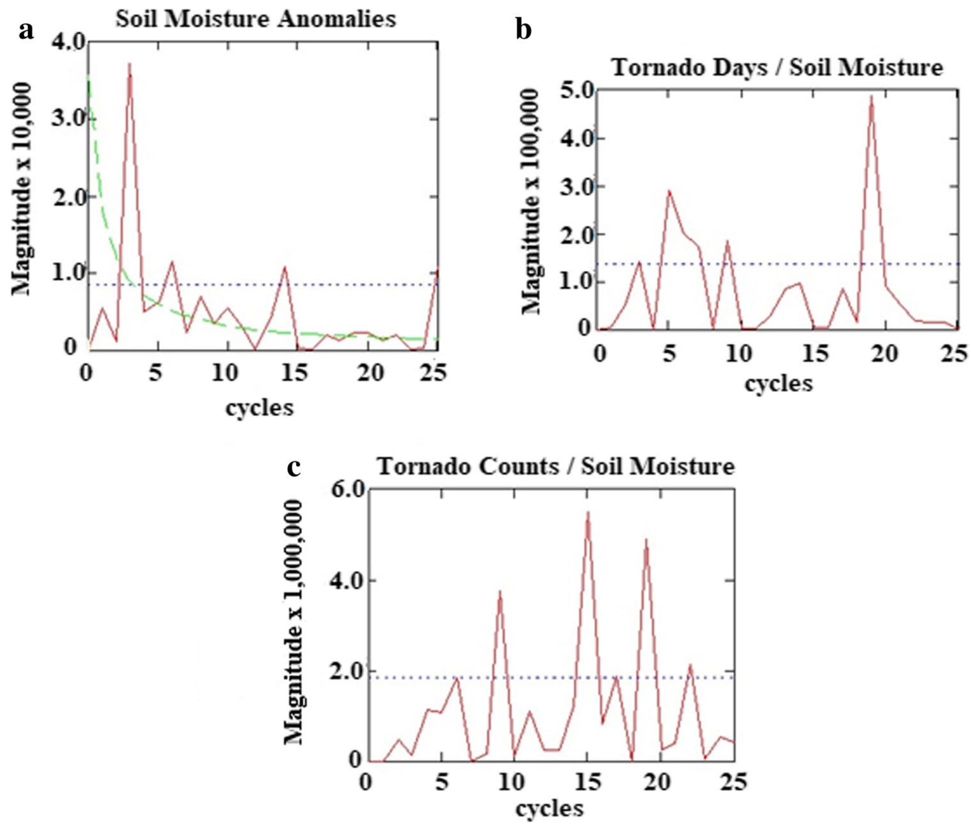

Fig. 9 The power spectrum for **a** the time series of soil moisture anomalies for Missouri from April–June 1980–2018 (red). The blended spectra (red) for **b** tornado days and **c** tornado counts with soil moisture are displayed here. The green (blue) dashed (dotted) line has the same meaning as in Fig. 8

5 Summary and conclusions

This research attempted to find a correlation between soil moisture and severe convection. Two statistical methods were used: a Pearson correlation coefficient and a quasi-Poisson regression. Results showed significant positive correlations with some of the severe weather categories with the in-season (April–June) activity, especially for tornadoes, and the corresponding soil moisture months. The higher correlations were associated with the Pearson correlation method. Using the quasi-Poisson method, some statistical significance was still found, although not as strong.

It is unclear whether the significant correlations were the result of convection and precipitation causing more soil moisture or, vice versa, where the increased soil moisture correlated to severe weather occurrence using composite data. The study of the synoptic maps suggested that wetter conditions and more days with convection went hand-in-hand with a favorable large-scale weather pattern as in 2008. However, a drier surface may provide additional heating for an atmosphere already primed to produce severe weather as well. This could enhance an individual outbreak. None of the April–June hail report data showed statistical significance for in-season soil moisture anomalies. For the wind analysis, none of the Missouri or divisional categories showed statistical significance, with the exception of division 5. This was observed for both statistical methods but higher for the Pearson correlation coefficient.

Some statistically 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. Once again, higher and more significance was seen with the Pearson correlation method. The higher wind reports within the state were found to have statistically significant negative correlations but only with the Pearson correlation approach. Division 5 also observed a significant negative correlation with this method. Most of the significant correlations were negative with this experiment, as opposed to the finding of significant positive correlations observed for the in-season study.

With the 6-month study, very few significant correlations were found. Overall, 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 some statistical significance with the wind reports in both the in-season and 3-month studies. Thus, 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 the advection of the environmental air could be 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. Much like the in-season experiment, it is unclear whether the correlation is because of the precipitation that storms already produced. As in the previous experiments, the Pearson correlation method showed more significance than the quasi-Poisson method. One must be cautious since this study only compares soil moisture to tornadic events. However, it does try to account for southwesterly flow which was implied by the composites, 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.

Significant interannual variability associated with ENSO was shown to exist in the tornado activity within the Missouri region, with La Niña years having the highest tornado activity (tornado days and significant tornadoes). There is also interdecadal variability consistent with previous studies of this region, and this may account for the recent increase in Missouri tornado activity during the latest two decades. Also, coherence between tornado activity and in-season soil moisture further showed significant ENSO-related variability. This indicates that soil moisture and tornado-producing events are related through the background large-scale and synoptic setup than just the relationship between the two. Similar conclusions were demonstrated from previous studies for events such as snowfall occurrence in the region. Although there is a correlation between severe weather and soil moisture anomalies, it is felt that these soil moisture anomalies play a smaller role than the atmospheric conditions. The added moisture is likely being advected from the Gulf of Mexico and deposited into the region. This may cause enhanced buoyancy needed for severe weather-producing convection. Additional studies are needed to see if there is a relationship on a much smaller time scale or within the mesoscale/microscale.

This study shows that the strength of the results is a function of the statistical analysis used. A linear model using a Pearson correlation coefficient is most commonly used in the field of meteorology, but as shown, it may not always be the most accurate or appropriate. Due to overdispersion and other factors, additional methods should be employed to test the strength of these relationships. If the type of data being used is count, a Poisson method is preferred when compared to a Pearson correlation method, as shown in this research and previous literature.

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Data availability The analyzed data can be found on the computers within the Global Climate Change Laboratory at the University of Missouri.

Declarations

Institutional review board statement Not applicable.

Informed consent statement(s) Not applicable.

Conflicts of interest The authors declare no competing interests.

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