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Winter-Spring Tornadoes and Drought over the Southern Mississippi River Valley

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WINTER-SPRING TORNADOES AND DROUGHT OVER THE SOUTHERN MISSISSIPPI RIVER VALLEY

by

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Abstract

Recent research has shown tornado activity over portions of the U.S. is impacted by internal ocean-atmospheric forcing. Impacts of seasonal and annual precipitation on tornado activity have also been assessed in previous studies, but no published research has included a full assessment of the soil moisture balance despite the known influences of soil moisture on thunderstorm activity. Therefore, this research explores the influence of soil moisture balance on tornado activity over Arkansas, Louisiana, Mississippi, and the western portion of Tennessee. Two measures of the soil moisture balance were used, the Palmer Drought Severity Index (PDSI) and the Palmer Z-Index. Tornado day counts were computed from tornado path data and transformed into percent of normal values for comparison with the two drought variables and various ocean-atmospheric teleconnections (e.g., El Niño-Southern Oscillation). Results suggest the impact of soil moisture balance on tornado counts over the Southern Mississippi River Valley is mostly during the warmer months from late winter into the spring. Forward and backward stepwise regression modeling identified the Z-Index and the winter (December-January-February) Oceanic Niño Index as the most important variables influencing tornado day variability over the Southern Mississippi River Valley during the spring season (March-April-May).

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1. Introduction

The relationships between tornado activity and various modes of internal climate variability have been of significant interest in the literature due to the potential to predict active weeks and seasons in advance (Allen et al. 2015; Molina et al. 2016; Gensini et al. 2019; Nouri et al. 2021). Soil moisture balance is another potential variable that could be useful in predicting seasonal activity given the known influences of soil moisture on thunderstorm activity (e.g., Findell and Eltahir 2003; Koster et al. 2004; Williams 2019; Liu et al. 2022). Galway (1979) suggested a possible, weak relationship between seasonal and annual total precipitation and tornado activity over three regions (Georgia-Alabama, Kansas-Oklahoma, and Illinois-Indiana) although there is the caveat that this is an older publication that also uses a portion of the tornado database subject to quality issues (Doswell and Burgess 1988; Grazulis 1993; Verbout et al. 2006). Shepherd et al. (2009) found weak correlations between fall-winter precipitation and tornado activity during the following spring over northern Georgia.

However, temperature is a key component of the overall soil moisture balance, and little published research exists examining the relationship between the tornado activity and two widely used drought indicators: the Palmer Z-Index and the Palmer Drought Severity Index (PDSI). Both indicators of soil moisture balance are derived from a combination of moisture supply (precipitation) and demand (evapotranspiration which is typically a function of temperature). The computed values are in the form of indices, where negative values indicate a deficit of soil moisture and positive values indicate a surplus (Palmer 1965; Vose et al. 2014). However, the Z-Index is a better indicator of short-term changes is soil moisture balance (monthly), while the PDSI is a better indicator for long-term (annually) changes. Their utility in identifying relationships between drought and tornado forecasting has not been thoroughly assessed but a

M.S. thesis by Andersen (2010) did utilize the Palmer Z-Index and discovered drought periods in northern Alabama and northern Georgia were "…strongly associated with equal to or below normal tornado days". These findings highlight the need for an examination of the relationship between tornadoes and drought over other regions with high tornado frequency.

Problem Statement/Hypothesis

The Mid-South region is known for its frequency of fatal tornadoes relative to other areas of the U.S. (Ashley 2007). Therefore, this thesis explores the possible influence of drought conditions on tornado activity across this region. The area of research is focused on the states of Arkansas, Louisiana, Mississippi, and the western portion of Tennessee. This area is hereafter referred to as the "Southern Mississippi River Valley," and was constructed based on the geographic layout of the climate divisions outlined by NOAA's National Centers for Environmental Information (NCEI) (Figure 1). This thesis concentrates on answering the following research questions:

- Is there a relationship between drought and spring (March-May) tornado activity over the Southern Mississippi River Valley?
- Is the relationship stronger during a particular month in the spring?
- Can fall (September-November) and/or winter (December-February) soil moisture conditions be used as a predictor for an above or below normal tornado season?
- Could other teleconnections (e.g., La Niña conditions or above normal Gulf of Mexico sea surface temperature; Allen et al. 2015; Molina et al. 2016) play a role in overriding or offsetting an above or below average tornado season?

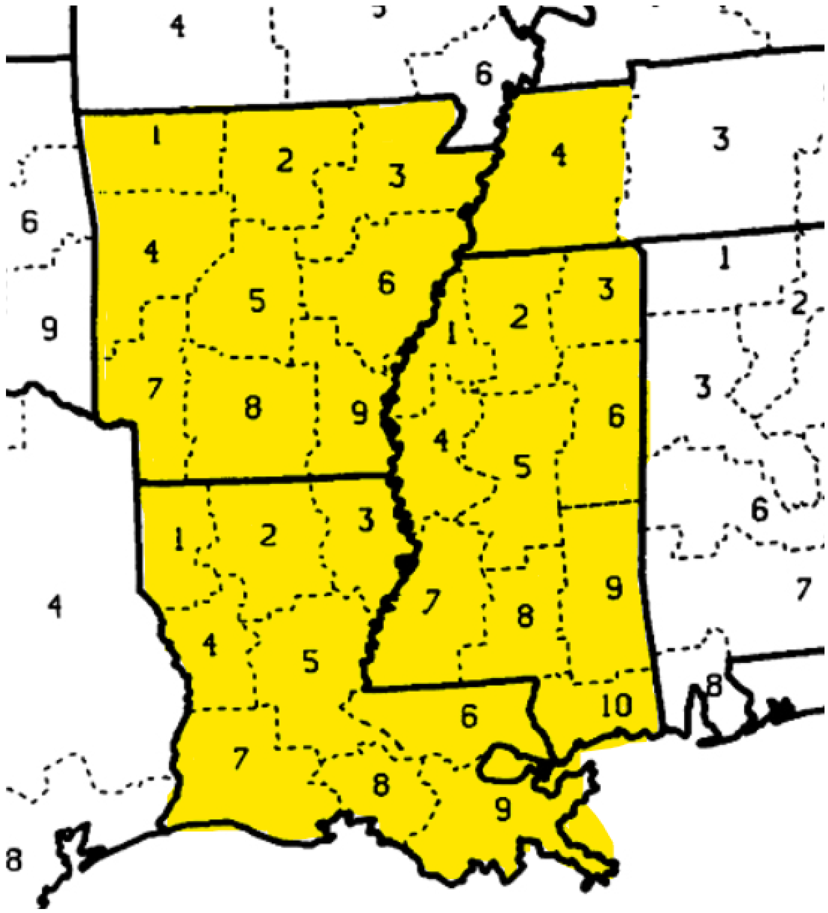

Figure 1. The “Southern Mississippi River Valley” (highlighted in yellow) will serve as the study area for this thesis. The climate divisions in each state are represented by the dashed outlines.

I hypothesize a significant, positive relationship will exist between percent of normal tornado days and drought over the Southern Mississippi River Valley. Given the number of high shear/low CAPE events in the Southeast U.S. (Anderson-Frey et al. 2019), the relationship between drought and tornado activity is expected to be stronger during the warmer months, when thunderstorms are more thermodynamically driven and low-level moisture is more important. Drought is just one variable that can influence tornado variability across the Southern Mississippi River Valley though. I also expect to find ocean-atmospheric variability to potentially weaken or override the relationship with soil moisture conditions (e.g., La Niña conditions in the Pacific could result in an above normal number of tornado days regardless of drought).

2. Data and Methods

This thesis restricts the assessment of drought and tornado activity to the 41-year period running from 1980 to 2020 to avoid increased quality issues in the tornado database prior to 1980 (Doswell and Burgess 1988; Grazulis 1993; Verbout et al. 2006). Data on soil moisture balance for each climate division was gathered from the U.S. Climate Divisional Database (nClimDiv) (Vose et al. 2014), which included monthly values of PDSI and the Palmer Z-Index back to 1895. These data have been screened and corrected to maximize homogeneity (i.e., impacts from station moves, changes in observation methods, etc. have been minimized; Vose et al. 2014). PDSI and Palmer Z-Index data from each climate division were downloaded and an average for the entire Southern Mississippi River Valley region was then computed monthly and seasonally.

Tornado path data for the Southern Mississippi River Valley were obtained from NOAA's Storm Prediction Center (Figure 2; NOAA 2022a). This thesis focuses on tornado day counts where a tornado day is defined as a day when any full or partial tornado path occurs within the Southern Mississippi River Valley region (Figure 1). Computing tornado day counts in this way minimizes the impact of outbreaks and the subjectivity associated with other thresholds that require a specific number of tornadoes to represent one tornado day (Verbout et al. 2006). Total tornado days per month from March through May and per spring season were computed and transformed into a percent of normal, where normal is defined as the mean number of tornado days per month and per spring season from 1980 to 2020. If the average number of tornado days in a given month or three-month period was less than one, percent of normal calculations were not performed.

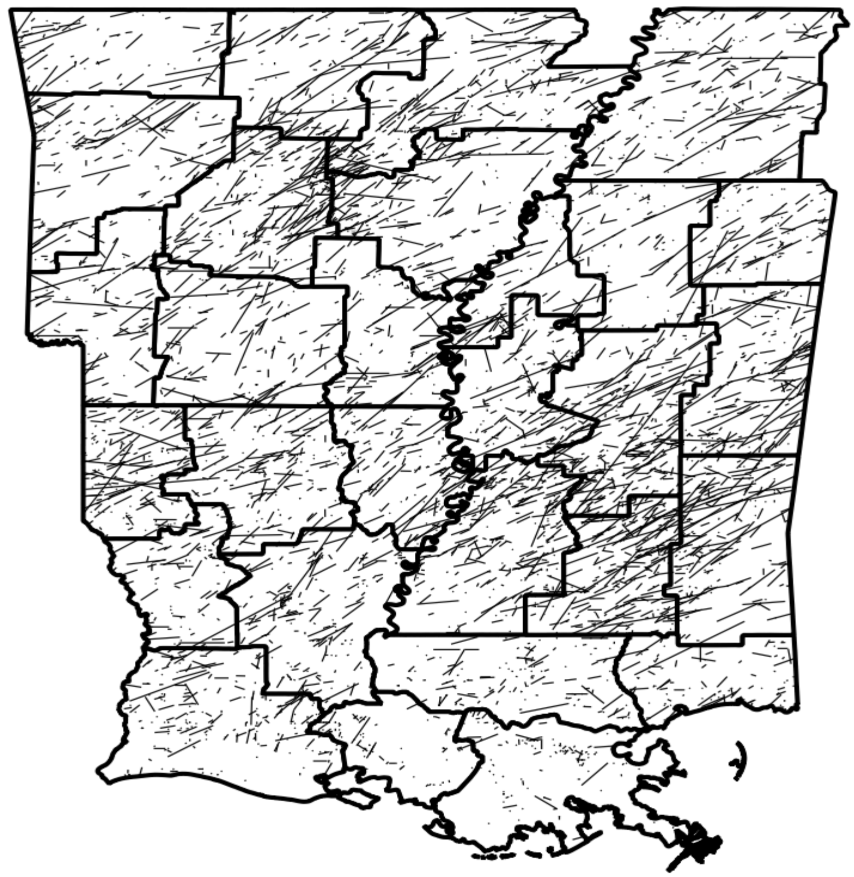

Figure 2. Tornado paths within the Southern Mississippi River Valley from 1980-2020. This study filtered out tornadic activity before 1980 due to quality issues associated with the early portion of the tornado record. Tornado path data was provided by the Storm Prediction Center Severe Weather GIS database which contains records since 1950 (SVRGIS; NOAA 2022a).

Spearman correlation analysis was used to explore the relationship between the PDSI, Palmer Z-Index, and percent of normal tornado days on a monthly and seasonal basis. Monthly antecedent and seasonal antecedent conditions were also studied, where antecedent refers to leading the Palmer Z-Index by one to six months and by one to two seasons to determine if soil moisture conditions in the months or seasons prior to the winter and spring tornado activity had an impact on tornado occurrence. Significance testing was conducted assuming a null hypothesis of no correlation between these drought indices and tornado activity in the region.

The study area was also divided into two halves at the Mississippi River. This was done to examine the potential for differences between the western half and the eastern half of the region given larger regions can tend to mask more localized signals. The climate divisions of Arkansas and Louisiana constituted the area west of the Mississippi River and the climate divisions of Mississippi and western Tennessee denote the area east of the Mississippi River. These two areas are denoted as “Arkansas-Louisiana” and “Mississippi-West Tennessee” (Figure 3). Monthly and seasonal PDSI and Z-Index averages and tornado days were computed for each half using the aforementioned drought datasets and tornado paths. In a case where any tornado path crossed from Arkansas-Louisiana into Mississippi-West Tennessee, it would be counted twice: once for Arkansas-Louisiana’s tornado day count and once for Mississippi-Tennessee’s tornado day count. Relationships between monthly and seasonal percent of normal tornado days and drought were then examined using Spearman correlation methods and significance testing.

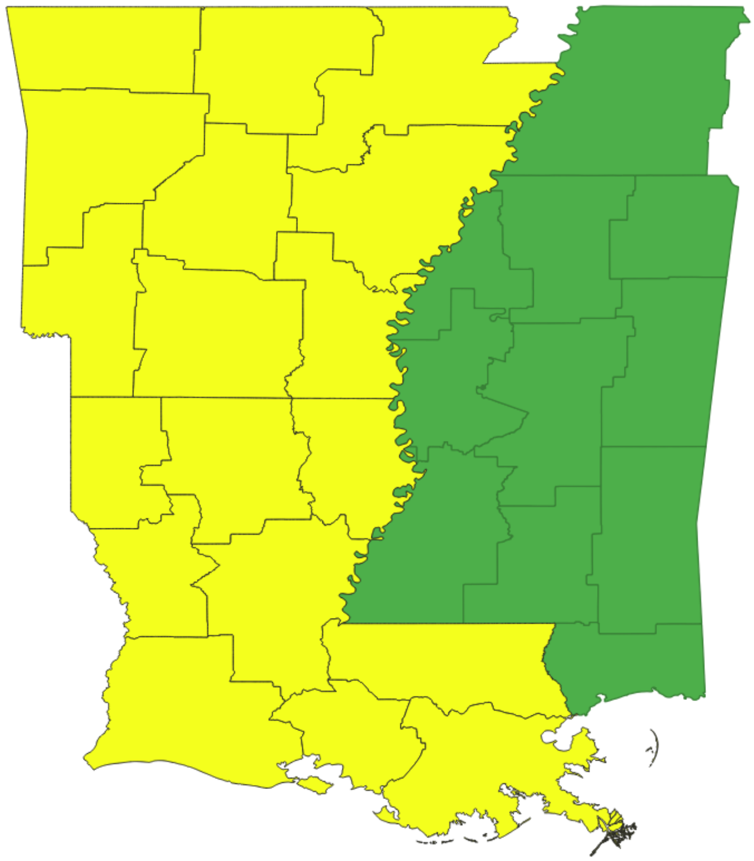

Figure 3. The areas within the Southern Mississippi River Valley denoted as "Arkansas-Louisiana" (left in yellow) and "Mississippi-West Tennessee (right in green).

While this thesis research concentrates on the assessment of tornado activity and soil moisture balance, previous literature has shown monthly and seasonal tornado activity can also be explained, in part, by the various atmospheric teleconnections (Allen et al. 2015; Molina et al. 2016; Gensini et al. 2019; Nouri et al. 2021). Thus, it is important to put the new drought results into context with the teleconnections. The teleconnections that were explored included Gulf of Mexico sea surface temperature, El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation, the Pacific/North American Pattern, the Trans-Niño Index, the North Atlantic Oscillation, and the Arctic Oscillation. Gulf of Mexico sea surface temperature data were obtained from the HadISST dataset, which contains monthly sea surface temperature data for the globe on a one-degree by one-degree latitude/longitude grid back to 1870 (Rayner et al. 2003). All sea surface temperature grid points from 18.5°N to 30.5°N and 96.5°W to 82.5°W were averaged into one continuous time series. These values were then detrended via simple linear regression and transformed into anomalies relative to the 1980-2020 mean. Detrending is necessary to mitigate the anthropogenic warming trends that can cluster warm sea surface temperature anomalies to the last decade. These steps are similar to methods used by Molina et al. (2016) to extract a suitable time series for the full Gulf of Mexico in their analysis of the Gulf of Mexico's influence on severe thunderstorm activity over the U.S. Data on all other teleconnections from 1980-2020 were obtained from NOAA (2022b). Spearman correlation analysis was used to explore the relationship between teleconnections and percent of normal tornado days over the study area.

3. Results

Palmer Drought Severity Index (PDSI) Correlations

Spearman correlations analysis found evidence of a relationship between the PDSI and percent of normal tornado days in the Southern Mississippi River Valley. These results are summarized in Tables 1 and 2. Note the significant and moderately positive correlation during the three-month period of April, May and June (AMJ). Due to the very low count of tornado days for the months of July and August in Mississippi-West Tennessee from 1980 to 2020, Spearman correlation analysis was not performed for those months or the May-June-July (MJJ) and June-July-August (JJA) periods in that area. These are displayed as "NA" in Tables 1 and 2.

Table 1. Spearman correlation analysis results showing monthly PDSI correlations with the percent of normal tornado days for January through August, from 1980-2020. Values in bold are statistically significant ($p<0.05$).

PDSI Correlations

Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.5783	0.8965	**0.0343**
r	-0.0894	0.021	**-0.3314**
February			
p	0.1735	0.6412	0.2135
r	0.2167	0.075	0.1985
March			
p	0.9138	0.8177	0.8856
r	0.0174	0.0371	0.0232
April			
p	0.1418	0.2122	0.1051
r	0.2334	0.199	0.2568
May			
p	**0.023**	**0.031**	**0.016**
r	**0.3543**	**0.3373**	**0.3739**
June			
p	0.0555	0.1854	**0.0038**
r	0.3014	0.211	**0.4423**
July			
p	0.3435	0.9032	NA
r	0.1518	0.0196	NA
August			
p	0.2702	0.157	NA
r	0.1763	0.2251	NA

Table 2. Spearman correlation analysis results displaying seasonal PDSI correlations with the percent of normal tornado days from 1980-2020. Values in bold are statistically significant ($p<0.05$).

Season			
JFM	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.7198	0.6123	0.549
r	-0.0578	-0.0815	-0.0963
FMA			
p	0.7569	0.8503	0.556
r	0.0499	0.0304	0.0947
MAM			
p	0.1496	0.1023	0.0792
r	0.2291	0.2588	0.2773
AMJ			
p	**0.0074**	**0.0241**	**0.0047**
r	**0.4125**	**0.3518**	**0.4329**
MJJ			
p	**0.0166**	**0.0399**	NA
r	**0.3722**	**0.3223**	NA
JJA			
p	0.1777	0.3393	NA
r	0.2147	0.1531	NA

The significant and moderately positive AMJ correlation was examined further in Figure 4. The positive correlation suggests drought periods (low PDSI) tend to be associated with a below average number of tornado days over the Southern Mississippi River Valley. The relationship is sustained for pluvials with above average rainfall being associated with above average tornado days. May is the most statistically significant month during the AMJ period ($r = 0.3543$, $p = 0.023$; Table 1).

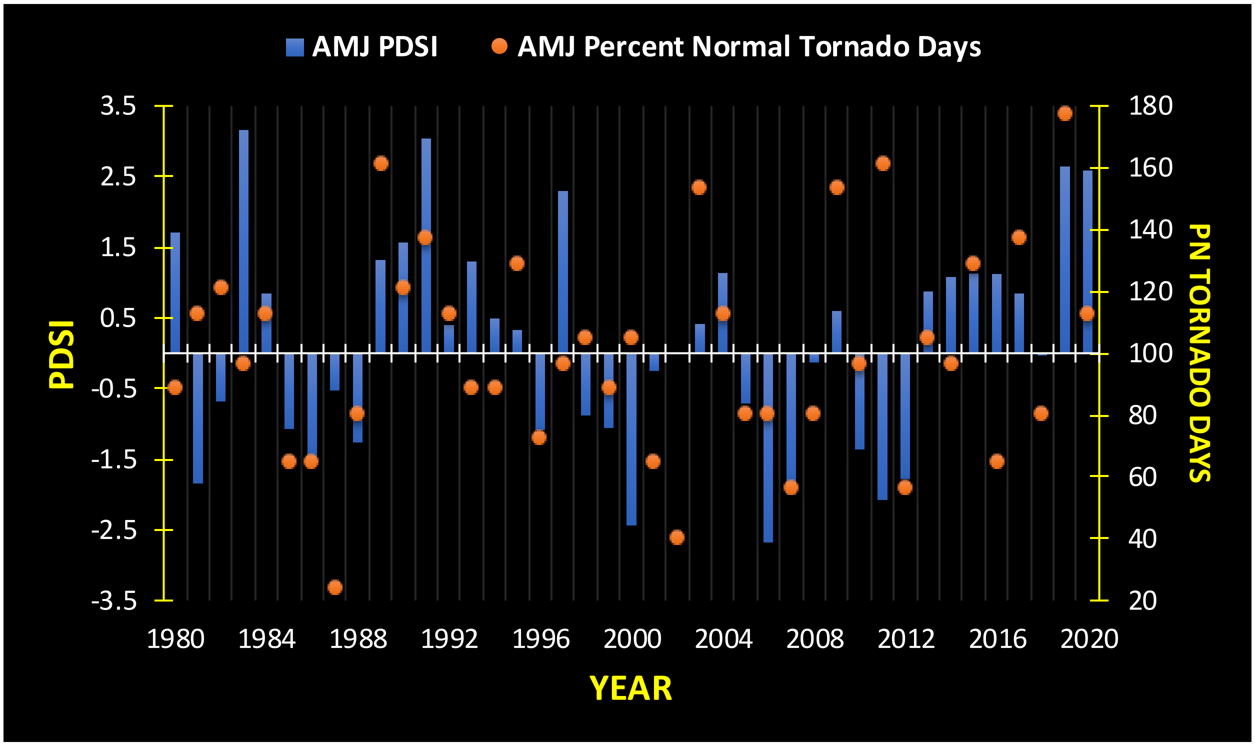

Figure 4. The April-May-June (AMJ) PDSI correlation with the percent of normal (PN) of tornado days for 1980-2020 ($r = 0.4125$, $p = 0.0074$) over the Southern Mississippi River Valley. During the majority of this period, negative PDSI numbers (indicating drought) are associated with equal to below average PN tornado days; positive PDSI values (indicating pluvials) are associated with above average PN tornado days.

Further differences were noted when the Southern Mississippi River Valley is split into western and eastern halves. For instance, June appears as a statistically significant month with a strong, positive correlation in Mississippi-West Tennessee. In contrast, Arkansas-Louisiana shows a negligible signal (Table 1). The month of May remains consistent as there is a moderately positive correlation in both regions. During the AMJ season, Mississippi-West Tennessee has a stronger correlation between PDSI and percent of normal tornado days although there is evidence that this relationship exists across the entire study area (Table 2 and Figure 4).

Palmer Z-Index Correlations

Based on correlation analysis findings for the Palmer Z-Index, there is evidence of a significant relationship between this drought variable and the percent of normal tornado days over the study area. Tables 3 and 4 summarize these results. Statistically significant positive correlations were found during two three-month intervals—March, April, and May (MAM) and April, May, and June (AMJ). Mississippi-West Tennessee have no correlation results for July and August or MJJ and JJA due to the region's low tornado day count during this period. These are displayed as "NA" in Tables 3 and 4.

Table 3. Monthly Palmer Z-Index correlations with the monthly percent of normal tornado days for the study area from 1980-2020. Values in bold are statistically significant ($p<0.05$).

Z-Index Correlations

Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	**0.008**	**0.0107**	0.2971
r	**0.4085**	**0.3947**	0.1669
February			
p	0.197	0.5608	**0.0351**
r	0.2057	0.0935	**0.3301**
March			
p	0.1128	0.0709	0.4109
r	0.2514	0.285	0.1319
April			
p	**0.00001**	**0.0002**	**0.0003**
r	**0.6359**	**0.5544**	**0.5394**
May			
p	**0.0002**	**0.0002**	**0.0001**
r	**0.5547**	**0.556**	**0.5836**
June			
p	0.0703	0.2477	**0.0177**
r	0.2856	0.1847	**0.3687**
July			
p	**0.0121**	0.0592	NA
r	**0.3885**	0.2972	NA
August			
p	**0.0328**	0.0909	NA
r	**0.334**	0.2675	NA

Table 4. Seasonal Z-Index correlations with the percent of normal tornado days for the study area from 1980-2020. Values in bold are statistically significant ($p<0.05$).

Season			
JFM	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.4971	0.6893	0.5743
r	0.1091	0.0644	0.0903
FMA			
p	0.334	0.4111	0.1209
r	0.1547	0.1319	0.2461
MAM			
p	**0.0044**	**0.0049**	**0.0115**
r	**0.4362**	**0.4313**	**0.391**
AMJ			
p	**0.00005**	**0.001**	**0.0001**
r	**0.5904**	**0.4962**	**0.5616**
MJJ			
p	**0.0015**	**0.004**	NA
r	**0.4806**	**0.4395**	NA
JJA			
p	0.0668	0.4347	NA
r	0.2891	0.1254	NA

A positive correlation was found for MAM (r = 0.4362, p = 0.0044; Figure 5) and AMJ (r = 0.5904, p = 0.00005; Figure 6). Thus, drier than average conditions tend to result in below average tornado days, while wetter conditions tend to correlate with above average activity (Figures 5 and 6).

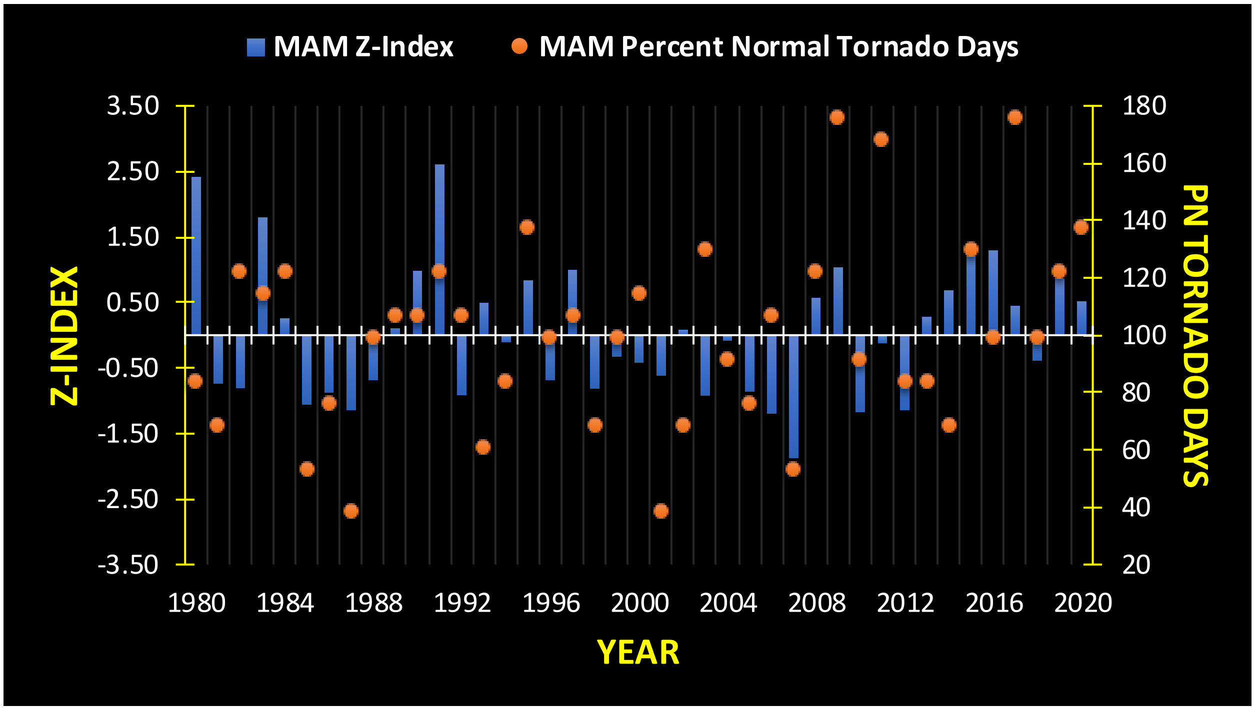

Figure 5. Spring Palmer Z-Index correlation with percent of normal tornado days for the Southern Mississippi River Valley from 1980-2020 ($r = 0.4362$, $p = 0.0044$). A moderately positive relationship is noted with less tornado days on average during droughts and above average numbers during wetter seasons.

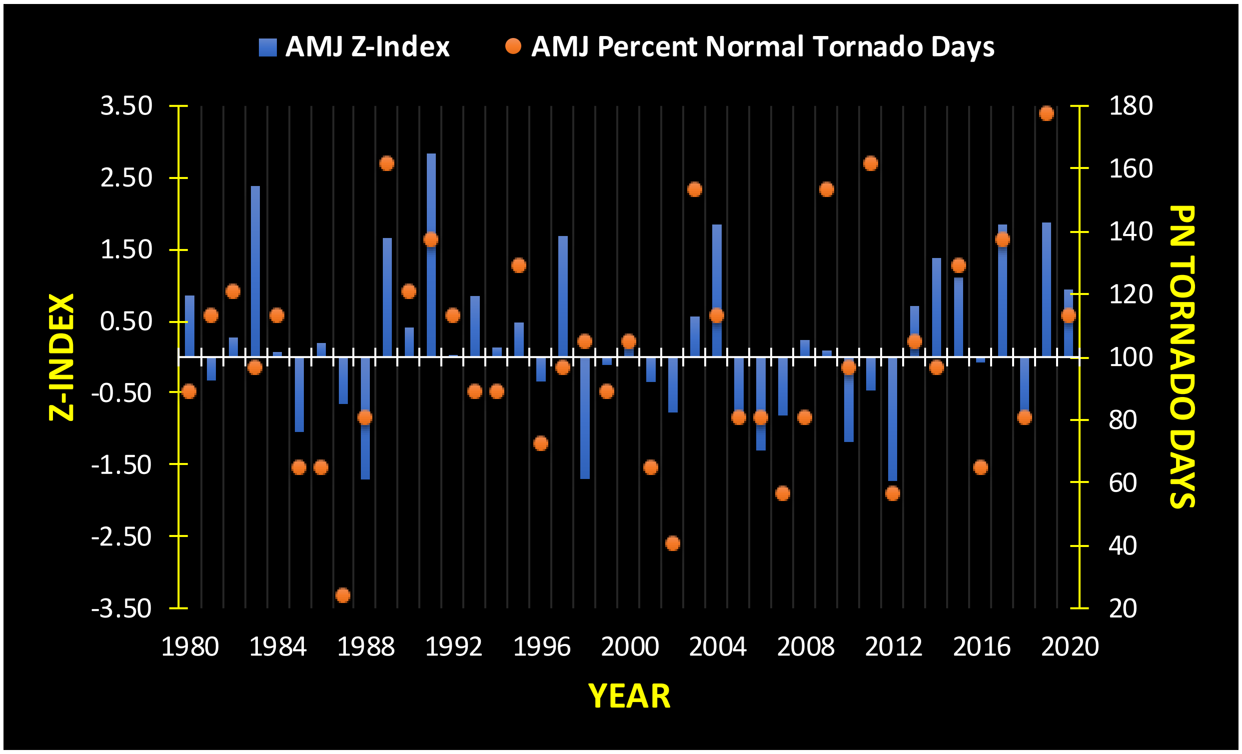

Figure 6. The April-May-June (AMJ) Z-Index correlation with percent of normal tornado days for the Southern Mississippi River Valley from 1980-2020 (r = 0.5904, p = 0.00005). The same trend is observed most years; droughts are associated with below average tornado activity while pluvials are associated with above average activity.

For the Southern Mississippi River Valley, the relationship between Z-indices and percent of normal tornado days is the strongest during the months of April and May (Table 3). In fact, the two strongest positive correlations in this study were found in both April and May. Significant correlations also exist for March, but not for June (Table 3). There is some evidence that suggests a relationship between the Z-Index and tornado activity during the summer months. The correlation is relatively weaker as Spearman coefficient values are lower compared to other times of the year. Despite this, the months of July and August meet the threshold for statistical significance. During the month of June, Mississippi-West Tennessee does show a significant signal while Arkansas-Louisiana has a weaker response (Table 3).

Z-Index correlations are stronger in Arkansas-Louisiana during the spring season (MAM). Nonetheless, Mississippi-West Tennessee is still statistically significant for this relationship. During the AMJ period, the Mississippi-West Tennessee region has a stronger response to drought and tornado activity compared to Arkansas-Louisiana (Table 4). This is due to the stronger correlation that appears in the month of June which is also observed in the region's PDSI correlation analyses (Table 1).

Antecedent Z-Index Correlations

Monthly antecedent relationships between the Z-Index and tornado activity were also studied using the same Spearman correlation analysis methods. Z-Indices from prior months were used alongside percent of normal tornado days in the months that followed. This was done to identify antecedent relationships between soil moisture and tornado activity within specific months of the year. Monthly percent of normal tornado days were compared with Z-Indices from one to six months prior. Tables 5 through 10 summarize these results. The aforementioned low tornado day count during July and August in Mississippi-West Tennessee led to a lack of correlation results during those months and the periods of MJJ and JJA. These are represented as "NA" in Tables 5 through 10.

Although most monthly antecedent analysis results show weak signals for the entire region, there is evidence of a significant and moderately negative correlation between the November Z-Index and January tornado activity in the Southern Mississippi Valley ($r = -0.4005$, $p = 0.0095$; Table 6). This relationship is consistent across the entire area. A significant negative relationship is observed between the October Z-Index and February tornado days in Arkansas-Louisiana ($r = -0.3773$, $p = 0.015$; Table 8). The same signal exists with the November Z-Index and April and May tornado days in this area (Tables 9 and 10). Therefore, negative Z-Indices during these fall months are associated with more tornado activity in the following spring months.

Table 5. Monthly antecedent correlations between the one-month prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., March = correlation between February Z-Indices and March percent of normal tornado days).

One-Month Antecedent

Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.8576	0.7859	0.3988
r	-0.0289	-0.0438	0.1354
February			
p	0.7463	0.8707	0.2796
r	0.0521	0.0262	0.1729
March			
p	0.2022	0.0676	0.608
r	-0.2034	-0.2882	-0.0825
April			
p	0.2791	0.1136	0.6644
r	-0.1731	-0.2509	-0.0698
May			
p	0.1334	0.1208	0.9854
r	0.2384	0.2462	0.0029
June			
p	0.2854	0.5002	0.1668
r	0.1709	0.1083	0.2201
July			
p	0.8623	0.8528	NA
r	0.0279	-0.0299	NA
August			
p	0.3628	0.6208	NA
r	-0.1459	-0.0796	NA

Table 6. Monthly antecedent correlations between the two-month prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., January = correlation between November Z-Indices and January percent of normal tornado days).

Two-Month Antecedent

Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	**0.0095**	**0.0315**	**0.002**
r	**-0.4005**	**-0.3364**	**-0.4691**
February			
p	0.5488	0.176	0.8514
r	0.0964	0.2155	-0.0302
March			
p	0.4622	0.3748	0.6332
r	-0.1181	-0.1423	0.0768
April			
p	0.3273	0.5062	0.7259
r	-0.1569	-0.1068	-0.0565
May			
p	0.8414	0.5397	0.4311
r	-0.0322	-0.0986	0.1264
June			
p	0.8008	0.451	0.9654
r	-0.0406	-0.121	0.007
July			
p	0.3982	0.5055	NA
r	0.1355	0.107	NA
August			
p	0.3423	0.4171	NA
r	0.1522	0.1302	NA

Table 7. Monthly antecedent correlations between the three-month prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., March = correlation between December Z-Indices and March percent of normal tornado days).

Three-Month Antecedent

Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.4852	0.268	0.4824
r	-0.1121	-0.1771	-0.1128
February			
p	0.7486	0.3423	0.7027
r	-0.0516	-0.1522	0.0615
March			
p	0.4413	0.1823	0.5562
r	0.1236	0.2125	0.0946
April			
p	0.9699	0.8314	0.6777
r	0.0061	-0.0343	0.0669
May			
p	0.4946	0.4432	0.5588
r	0.1097	0.1231	0.094
June			
p	0.5585	0.6335	0.9558
r	-0.0941	-0.0767	0.0089
July			
p	0.7149	0.5102	NA
r	-0.0588	-0.1058	NA
August			
p	0.2461	0.5302	NA
r	-0.1853	0.1009	NA

Table 8. Monthly antecedent correlations between the four-month prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., February = correlation between October Z-Indices and February percent of normal tornado days). Values in bold are statistically significant ($p<0.05$).

Four-Month Antecedent			
Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.7622	0.3935	0.9922
r	-0.0487	-0.1369	0.0016
February			
p	0.0815	**0.015**	0.5663
r	-0.2753	**-0.3773**	0.0922
March			
p	0.255	0.3202	0.6217
r	-0.1819	-0.1592	-0.0794
April			
p	0.5565	0.5981	0.8431
r	-0.0945	-0.0848	0.0319
May			
p	0.7639	0.3491	0.6621
r	-0.0484	-0.1501	-0.0703
June			
p	0.237	0.2721	0.0229
r	0.1889	0.1756	0.3547
July			
p	0.8197	0.6914	NA
r	-0.0367	-0.0639	NA
August			
p	0.8535	0.4007	NA
r	-0.0297	0.1348	NA

Table 9. Monthly antecedent correlations between the five-month prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., April = correlation between November Z-Indices and April percent of normal tornado days). Values in bold are statistically significant ($p<0.05$).

Five-Month Antecedent

Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.8811	0.8077	0.9982
r	0.0241	-0.0392	-0.0004
February			
p	0.9286	0.638	0.9637
r	0.0144	-0.0757	0.0073
March			
p	0.3044	0.0954	0.7897
r	-0.1644	-0.2639	-0.043
April			
p	0.0656	**0.0237**	0.1831
r	-0.2903	**-0.3526**	-0.2121
May			
p	0.923	0.2928	0.8039
r	-0.0156	-0.1683	0.04
June			
p	0.0617	0.084	0.1462
r	0.2944	0.2731	0.231
July			
p	0.3811	0.4655	NA
r	-0.1405	-0.1172	NA
August			
p	0.3223	0.1473	NA
r	0.1585	0.2304	NA

Table 10. Monthly antecedent correlations between the six-month prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., May = correlation between November Z-Indices and May percent of normal tornado days). Values in bold are statistically significant ($p<0.05$).

Six-Month Antecedent

Month			
January	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.2495	0.4899	0.5109
r	0.184	0.1109	0.1057
February			
p	0.799	0.3426	0.7497
r	0.041	-0.1521	0.0514
March			
p	0.0987	0.0961	0.4865
r	-0.2615	-0.2634	-0.1118
April			
p	0.3829	0.3455	0.7325
r	-0.1399	-0.1512	-0.055
May			
p	0.0977	**0.0461**	0.7184
r	-0.2622	**-0.3132**	0.0581
June			
p	0.6645	0.2471	0.481
r	0.0698	0.1849	-0.1132
July			
p	0.6531	0.4112	NA
r	0.0723	0.1319	NA
August			
p	0.9561	0.9944	NA
r	0.0089	-0.0011	NA

Z-Index values from prior three-month "seasons" were also utilized to assess relationships between antecedent soil moisture conditions and tornado activity (e.g., leading the percent of normal tornado days in MAM with the DJF and SON Z-Indices). Similar to prior analysis, no results are shown in Mississippi-Tennessee during MJJ and JJA due to low tornado day counts. A significant relationship with a moderately negative correlation is found between MAM tornado activity and the SON Z-Index in the Southern Mississippi Valley (r = -0.3477, p = 0.0259; Table 11).

Table 11. Seasonal antecedent correlations between the two-season prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., MAM = correlation between SON Z-Index and MAM percent of normal tornado days). Values in bold are statistically significant (p<0.05).

Two-Season Antecedent

Season			
JFM	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	0.8335	0.8793	0.9433
r	0.0339	-0.0245	0.0115
FMA			
p	0.1757	0.4017	0.8041
r	-0.2156	-0.1345	-0.04
MAM			
p	**0.0259**	**0.0069**	0.749
r	**-0.3477**	**-0.4156**	-0.0515
AMJ			
p	0.146	0.0734	0.6226
r	-0.2311	-0.2826	0.0792
MJJ			
p	0.2323	0.6139	NA
r	0.1932	0.0822	NA
JJA			
p	0.1274	0.0965	NA
r	0.2451	0.2665	NA

The signal for dry fall soil moisture conditions impacting tornado activity over the entire Southern Mississippi River Valley is murky due to the stark differences between the regions of Arkansas-Louisiana and Mississippi-West Tennessee. When comparing the two areas, the negative correlation is only significant in Arkansas-Louisiana (Table 11). The weak signal from Mississippi-West Tennessee offsets the significant signal detected from the west. Although the study area as a whole is statistically significant, it does not give an accurate depiction of the correlation itself as the signal is exclusively in Arkansas-Louisiana (Table 11). Thus, Figure 7, which illustrates the SON Z-Index and MAM percent of normal tornado days relationship, is restricted to Arkansas and Louisiana only.

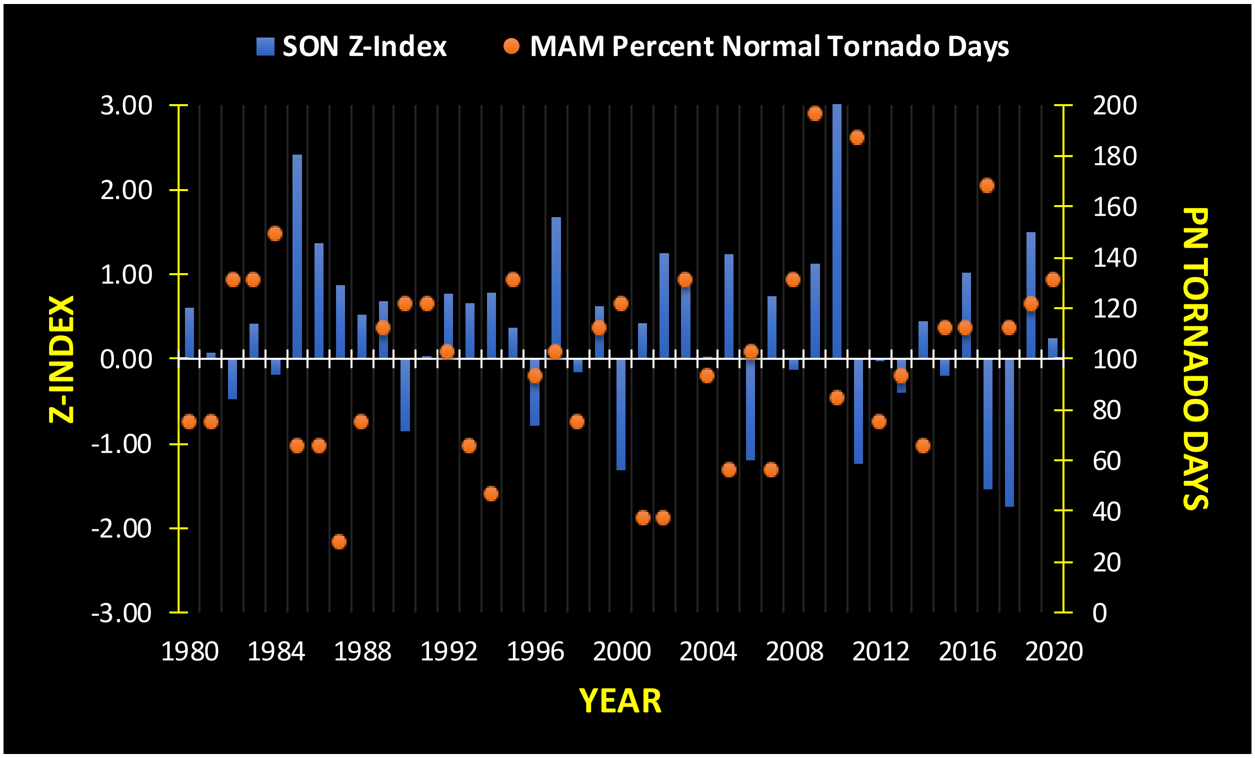

Figure 7. Antecedent fall Z-Index correlations (September-October-November) with the percent of normal tornado days from the following spring in Arkansas-Louisiana. Antecedent fall Z-Index values are plotted alongside spring percent of normal tornado day values from the following year. For example, the 2000 MAM percent of normal tornado days are plotted together with the 1999 fall Z-Index average.

A secondary antecedent relationship is found between October, November, and December (OND) Z-Indices and January, February, and March (JFM) tornado activity over the

Southern Mississippi River Valley (Table 12). Like the relationship noted in the first case above, the significant correlations are confined to the Arkansas-Louisiana area with no significant signal over the Mississippi-West Tennessee area. This correlation is also negative which indicates negative OND Z-Indices are associated with above average tornado activity during JFM. Figure 8 shows the negative correlation that exists in Arkansas-Louisiana. This region is shown specifically instead of the entire study area to visualize the relationship more clearly and to avoid interference from the weak signals in Mississippi-West Tennessee.

Table 12. Seasonal antecedent correlations between the one-season prior Z-Index and percent of normal tornado days from 1980-2020 (e.g., JFM = correlation between OND Z-Index and JFM percent of normal tornado days). Values in bold are statistically significant ($p<0.05$).

One-Season Antecedent

Season			
JFM	Southern MS Valley	Arkansas-Louisiana	Mississippi-West Tennessee
p	**0.0381**	**0.0347**	0.3444
r	**-0.325**	**-0.3308**	-0.1515
FMA			
p	0.5187	0.1576	0.5227
r	0.1051	0.2277	-0.1041
MAM			
p	0.1273	0.1039	0.5841
r	0.2452	0.2609	0.0892
AMJ			
p	0.8309	0.6174	0.6742
r	-0.0344	-0.0804	0.0677
MJJ			
p	0.7734	0.8904	NA
r	0.0464	0.0222	NA
JJA			
p	0.8542	0.7306	NA
r	-0.0296	0.0554	NA

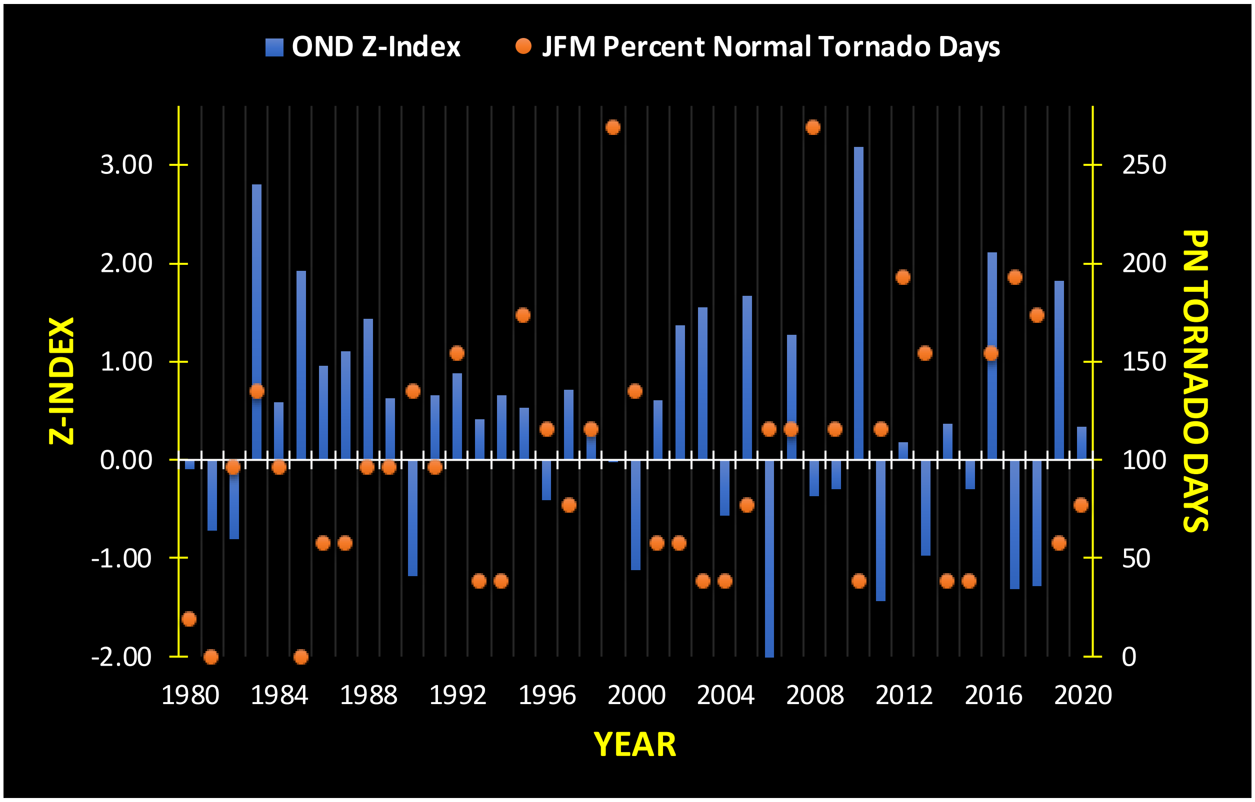

Figure 8. Antecedent October-November-December (OND) Z-Index correlations with the following January-February-March (JFM) percent of normal tornado days for Arkansas-Louisiana from 1980-2020 (r = -0.3308; p = 0.0347). Antecedent OND Z-Indices are plotted alongside JFM percent of normal tornado days from the following year. For example, 2000 JFM PN tornado days are plotted with the 1999 OND Z-Index.

4. Discussion

The positive correlations identified between the PDSI and percent of normal tornado days over the Southern Mississippi Valley, notably during the spring, indicate that long-term drought patterns can influence the frequency of tornado activity. Progressive, sustained droughts can enhance negative anomalies in the soil moisture balance and decrease tornado activity in the mid to late spring. This is a period when thunderstorms become more thermodynamically driven due to the typical weakening of the jet stream and the need for warmer temperatures and increased moisture from the Gulf of Mexico.

Positive Z-Index correlations with percent of normal tornado days on a monthly and seasonal basis indicate a stronger response to rapid-onset drought conditions on a monthly timescale. Short-term droughts are mainly driven by weather patterns that stabilize the atmosphere and limit the development of thunderstorms. Even though this relationship is consistent during the spring, the correlations flip when observing antecedent conditions. The negative correlation between fall Z-Indices and spring percent of normal tornado days suggests that short-term drought in the fall season leads to an active spring season with enhanced tornado activity. This could be due to short-term teleconnections influencing weather patterns, where a less active weather pattern in the fall yields a better chance for a more active pattern the following spring.

Prior research has shown teleconnections such as the El Niño Southern Oscillation (ENSO) and Gulf of Mexico sea surface temperatures have an influence on tornadic activity over the Southern Mississippi Valley (Allen et al. 2015; Molina et al. 2016; Gensini et al. 2019; Nouri et al. 2021), so it important to analyze these variables and assess them relative to the soil moisture balance. Spearman correlation analysis was conducted to study these and several additional teleconnections including the Pacific Decadal Oscillation (PDO), the Pacific/North American Pattern (PNA), the Trans-Niño Index (TNI), the North Atlantic Oscillation (NAO), and the Arctic Oscillation (AO) to assess the importance of these indices on percent of normal tornado days over the study area. Combined Pacific-Atlantic forcings (ONI-NAO and ONI+NAO; Seager et al. 2010; Stahle et al. 2012) were also assessed by renormalizing the ONI and NAO relative to the 1980-2020 period and then subtracting (ONI-NAO) or adding (ONI+NAO) the two indices. Tables 13 through 21 outline the correlation results for the entire study area.

The most consistent signals from all these teleconnections are found during the three-month period of January-February-March (JFM). Significant negative correlations are noted with the PDO and ONI-NAO (Tables 15 and 20) while significant positive correlations are noted with the TNI and AO (Tables 17 and 19). Nouri et al. (2021) note similar negative relationships with the PDO and with a combined ONI and NAO term. Positive relationships identified between the TNI and AO have also been found in previous literature (Lee et al. 2016; Childs et al. 2018; Nouri et al 2021). There is also a significant correlation between the winter NAO and the spring tornado season and the winter AO and the spring tornado season (Tables 18 and 19), which has not been documented before in the literature. A significant and moderately positive relationship exists between Gulf of Mexico SSTs and tornado activity during the spring season (MAM) (Table 13). This finding coincides with research results from Molina et al. (2016) which highlighted the connection between warmer sea surface temperatures and more tornado events. Weak, non-significant signals are found with the other teleconnections both on a seasonal and monthly basis. Like the drought correlations, this analysis was not performed in Mississippi-West Tennessee for the months of July and August and the three-month periods of MJJ and JJA due to the low count of tornado days during this period.

Table 13. Spearman correlation analysis results of Gulf of Mexico sea surface temperatures with percent of normal tornado days on a monthly and seasonal basis. Note DJF-MAM is a correlation between DJF Gulf of Mexico sea surface temperatures and MAM percent of normal tornado days. Values in bold are statistically significant (p<0.05).

Gulf of Mexico SSTs

Month			
January	Southern MS Valley	AR-LA	MS-TN
p	0.8254	0.5899	0.0949
r	-0.0355	0.0867	-0.2644
February			
p	0.0356	0.1158	0.0268
r	0.3292	0.2494	0.3457
March			
p	0.0521	0.1793	0.0883
r	0.3055	0.2139	0.2696
April			
p	0.4283	0.8434	0.2924
r	0.1271	0.0318	0.1685
May			
p	0.2598	0.2527	0.9019
r	0.1801	0.1828	0.0199
June			
p	0.2654	0.5311	0.1484
r	0.178	0.1007	0.2298
July			
p	0.4871	0.651	NA
r	0.1116	0.0728	NA
August			
p	0.114	0.185	
r	-0.2506	-0.2112	

Season			
JFM	Southern MS Valley	AR-LA	MS-TN
p	0.0799	0.1947	0.0851
r	0.2767	0.2067	0.2722
FMA			
p	0.0977	0.3419	0.0724
r	0.2622	0.1523	0.2835
MAM			
p	**0.0301**	0.0903	0.2173
r	**0.3391**	0.268	0.1969
AMJ			
p	0.1776	0.3166	0.368
r	0.2147	0.1603	0.1443
MJJ			
p	0.0503	0.0692	NA
r	0.3077	0.2867	NA
JJA			
p	0.514	0.5976	NA
r	0.1049	0.0849	NA
DJF_MAM			
p	0.7984	0.73	0.3596
r	-0.0412	-0.0556	-0.1468

Table 14. Spearman correlation analysis results of the Oceanic Niño Index (ONI) with percent of normal tornado days on a monthly and seasonal basis. Note DJF-MAM is a correlation between DJF ONI and MAM percent of normal tornado days.

Oceanic Niño Index

Month

January	Southern MS Valley	AR-LA	MS-TN
p	0.475	0.7744	0.1092
r	-0.1147	-0.0462	-0.2539
February			
p	0.2875	0.2658	0.462
r	-0.1702	-0.1779	-0.1181
March			
p	0.2259	0.203	0.8116
r	-0.1933	-0.203	-0.0384
April			
p	0.5181	0.9669	0.4022
r	0.1039	-0.0067	0.1344
May			
p	0.781	0.7561	0.8123
r	-0.0448	-0.05	-0.0383
June			
p	0.657	0.9246	0.527
r	0.0715	-0.0152	0.1017
July			
p	0.6488	0.9852	NA
r	-0.0733	-0.003	NA
August			
p	0.517	0.2021	NA
r	-0.1041	-0.2034	NA

Season

JFM	Southern MS Valley	AR-LA	MS-TN
p	0.1351	0.2014	0.1784
r	-0.2374	-0.2037	-0.2143
FMA			
p	0.3682	0.2972	0.8718
r	-0.1443	-0.1668	0.026
MAM			
p	0.8239	0.4766	0.5569
r	-0.0359	-0.1143	0.0945
AMJ			
p	0.4057	0.8266	0.6251
r	0.1334	0.0353	0.0786
MJJ			
p	0.8967	0.883	NA
r	-0.0209	-0.0237	NA
JJA			
p	0.4515	0.3181	NA
r	-0.1209	-0.1599	NA
DJF_MAM			
p	0.9429	0.6034	0.5621
r	0.0115	-0.0836	0.0932

Table 15. Spearman correlations between the Pacific Decadal Oscillation (PDO) and percent of normal tornado days on a monthly and seasonal basis. Note DJF-MAM is a correlation between DJF PDO and MAM percent of normal tornado days. Values in bold are statistically significant ($p<0.05$).

Pacific Decadal Oscillation

Month

January	Southern MS Valley	AR-LA	MS-TN
p	**0.0424**	0.1191	0.0621
r	**-0.3185**	-0.2472	-0.294
February			
p	**0.0241**	0.0557	0.2354
r	**-0.3519**	-0.3011	-0.1895
March			
p	**0.0309**	0.1251	0.1922
r	**-0.3375**	-0.2435	-0.2079
April			
p	0.8203	0.4795	0.8148
r	-0.0366	-0.1136	0.0377
May			
p	0.3529	0.1975	0.8595
r	-0.1489	-0.2054	-0.0285
June			
p	0.9244	0.878	0.5868
r	-0.0153	-0.0247	-0.0874
July			
p	0.7545	0.3973	NA
r	-0.0504	-0.1358	NA
August			
p	0.9405	0.7579	NA
r	0.012	0.0497	NA

Season

JFM	Southern MS Valley	AR-LA	MS-TN
p	**0.0005**	**0.0053**	**0.0049**
r	**-0.5209**	**-0.4273**	**-0.4312**
FMA			
p	**0.0194**	**0.0409**	0.1514
r	**-0.3636**	**-0.3207**	-0.2281
MAM			
p	0.1242	0.0889	0.5102
r	-0.244	-0.2691	-0.1058
AMJ			
p	0.6322	0.4357	0.4731
r	-0.077	-0.1251	-0.1152
MJJ			
p	0.763	0.5419	NA
r	-0.0486	-0.0981	NA
JJA			
p	0.9963	0.8469	NA
r	0.0007	0.0311	NA
DJF_MAM			
p	0.1788	0.1456	0.3396
r	-0.2141	-0.2313	-0.153

Table 16. Spearman correlations between the Pacific/North American Pattern (PNA) and percent of normal tornado days on a monthly and seasonal time frame. Note DJF-MAM is a correlation between DJF PNA and MAM percent of normal tornado days. Values in bold are statistically significant ($p<0.05$).

Pacific/North American Pattern

Month

January	Southern MS Valley	AR-LA	MS-TN
p	0.0522	0.0597	0.0607
r	-0.3053	-0.2965	-0.2954
February			
p	0.8449	0.7554	0.2358
r	-0.0315	0.0502	-0.1893
March			
p	0.2289	0.7313	0.1777
r	-0.1921	-0.0553	-0.2147
April			
p	0.6333	0.6679	0.4063
r	-0.0768	-0.0691	-0.1332
May			
p	0.6617	0.9911	0.3044
r	0.0704	0.0018	0.1644
June			
p	0.5514	0.7512	0.4034
r	-0.0958	-0.0511	-0.1341
July			
p	0.9911	0.5498	NA
r	-0.0018	-0.0962	NA
August			
p	0.1049	0.1297	NA
r	-0.2569	-0.2406	NA

Season

JFM	Southern MS Valley	AR-LA	MS-TN
p	0.107	0.5442	**0.0392**
r	-0.2554	-0.0975	**-0.3233**
FMA			
p	0.2303	0.7407	**0.0358**
r	-0.1915	-0.0533	**-0.3288**
MAM			
p	0.0952	0.1245	0.3178
r	-0.2641	-0.2438	-0.16
AMJ			
p	0.7882	0.8247	0.5739
r	-0.0433	-0.0357	-0.0904
MJJ			
p	0.8488	0.694	NA
r	0.0307	0.0633	NA
JJA			
p	0.8459	0.2257	NA
r	0.0313	0.1934	NA
DJF_MAM			
p	0.2236	0.1517	0.2956
r	-0.1942	-0.228	-0.1674

Table 17. Spearman correlations between the Trans-Niño Index (TNI) and percent of normal tornado days on a monthly and seasonal basis. Note DJF-MAM is a correlation between DJF TNI and MAM percent of normal tornado days. Values in bold are statistically significant ($p<0.05$).

Trans-Niño Index

Month

January	Southern MS Valley	AR-LA	MS-TN
p	0.41	0.4306	0.6475
r	0.1322	0.1265	0.0736
February			
p	**0.0101**	**0.0017**	0.2245
r	**0.3972**	**0.474**	0.1939
March			
p	0.0984	0.0779	0.6475
r	0.2617	0.2784	0.0736
April			
p	0.1132	0.2848	0.0509
r	-0.2512	-0.1711	-0.307
May			
p	0.4983	0.2255	0.7091
r	0.1088	0.1935	0.0601
June			
p	0.4225	0.9842	0.1948
r	-0.1287	0.0032	-0.2067
July			
p	0.3404	0.5536	NA
r	-0.1528	-0.0953	NA
August			
p	0.7822	0.797	NA
r	-0.0445	0.0414	NA

Season

JFM	Southern MS Valley	AR-LA	MS-TN
p	**0.0417**	**0.0138**	0.2662
r	**0.3195**	**0.3817**	0.1778
FMA			
p	0.1686	0.1	0.5808
r	0.2192	0.2605	-0.0888
MAM			
p	0.9013	0.441	0.3962
r	0.02	0.1237	-0.1361
AMJ			
p	0.8769	0.6575	0.3673
r	-0.025	0.0714	-0.1445
MJJ			
p	0.8259	0.3512	NA
r	0.0354	0.1494	NA
JJA			
p	0.3121	0.556	NA
r	-0.1618	-0.0947	NA
DJF_MAM			
p	0.7567	0.2124	0.3633
r	0.0499	0.1989	-0.1457

Table 18. Spearman correlations between the North Atlantic Oscillation (NAO) and percent of normal tornado days on a monthly and seasonal time frame. Note DJF-MAM is a correlation between DJF NAO and MAM percent of normal tornado days. Values in bold are statistically significant (p<0.05).

North Atlantic Oscillation

Month

January	Southern MS Valley	AR-LA	MS-TN
p	0.7905	0.6165	0.9961
r	0.0428	0.0806	-0.0008
February			
p	0.5927	0.7009	0.5448
r	0.086	0.0618	0.0974
March			
p	0.6334	0.585	0.9856
r	0.0767	0.0878	-0.0029
April			
p	0.6868	0.4273	0.6952
r	-0.0649	-0.1274	0.0631
May			
p	0.8382	0.832	0.9781
r	0.0329	0.0342	-0.0044
June			
p	0.4016	0.3226	0.4947
r	-0.1346	-0.1584	-0.1097
July			
p	0.9003	0.6643	NA
r	-0.0202	0.0699	NA
August			
p	0.8423	0.423	NA
r	0.0321	0.1286	NA

Season

JFM	Southern MS Valley	AR-LA	MS-TN
p	0.0748	0.1345	0.3588
r	0.2813	0.2377	0.1471
FMA			
p	0.1942	0.4205	0.1058
r	0.2069	0.1293	0.2563
MAM			
p	0.7161	0.8001	0.5681
r	0.0586	0.0408	-0.0918
AMJ			
p	0.9918	0.9699	0.3557
r	-0.0017	0.0061	-0.148
MJJ			
p	0.9725	0.9718	NA
r	0.0056	0.0057	NA
JJA			
p	0.6344	0.1555	NA
r	0.0765	0.2259	NA
DJF_MAM			
p	**0.0438**	0.0677	0.9738
r	**0.3165**	0.2882	-0.0053

Table 19. Spearman correlations between the Arctic Oscillation (AO) and percent of normal tornado days on a monthly and seasonal basis. Note DJF-MAM is a correlation between DJF AO and MAM percent of normal tornado days. Values in bold are statistically significant ($p<0.05$).

Arctic Oscillation

Month

January	Southern MS Valley	AR-LA	MS-TN
p	0.962	0.7186	0.578
r	0.0077	-0.058	0.0895
February			
p	0.2008	0.5082	0.2231
r	0.204	0.1063	0.1944
March			
p	0.5166	0.6674	0.7322
r	0.1042	0.0692	0.0551
April			
p	0.9298	0.6396	0.7681
r	-0.0142	-0.0754	-0.0475
May			
p	0.6953	0.3814	0.3067
r	0.0631	0.1404	-0.1636
June			
p	0.1166	0.0311	0.6667
r	-0.2489	-0.3371	-0.0693
July			
p	0.5105	0.395	NA
r	0.1057	0.1364	NA
August			
p	0.1434	0.0825	NA
r	0.2326	0.2744	NA

Season

JFM	Southern MS Valley	AR-LA	MS-TN
p	**0.0401**	0.1742	0.1295
r	**0.322**	0.2164	0.2407
FMA			
p	0.1275	0.4086	0.0644
r	0.2419	0.1326	0.2916
MAM			
p	0.2369	0.4372	0.9507
r	0.1889	0.1247	-0.01
AMJ			
p	0.7116	0.7088	0.6281
r	0.0595	0.0601	-0.078
MJJ			
p	0.8985	0.876	NA
r	-0.0206	-0.0252	NA
JJA			
p	0.5217	0.5325	NA
r	0.103	0.1003	NA
DJF_MAM			
p	**0.0045**	**0.0101**	0.5769
r	**0.4343**	**0.3974**	0.0897

Table 20. Spearman correlations between a combined Oceanic Niño Index (ONI) and North Atlantic Oscillation (NAO) and percent of normal tornado days on a monthly and seasonal basis, where the combined ONI and NAO index value becomes larger if the ONI and NAO are out of phase. Note DJF-MAM is a correlation between DJF ONI-NAO and MAM percent of normal tornado days. Values in bold are statistically significant ($p<0.05$).

ONI - NAO

Month	Southern MS Valley	AR-LA	MS-TN
January			
p	0.4148	0.5682	0.1748
r	-0.1309	-0.0918	-0.2161
February			
p	0.3398	0.342	0.4098
r	-0.1529	-0.1522	-0.1323
March			
p	0.1968	0.1214	0.9786
r	-0.2058	-0.2458	0.0043
April			
p	0.1962	0.1905	0.6756
r	0.2061	0.2086	0.0674
May			
p	0.9295	0.8372	0.9153
r	-0.0142	-0.0331	0.0171
June			
p	0.2907	0.2964	0.5095
r	0.1691	0.1671	0.106
July			
p	0.5727	0.2976	NA
r	-0.0907	-0.1667	NA
August			
p	0.719	0.2614	NA
r	-0.0579	-0.1795	NA

Season	Southern MS Valley	AR-LA	MS-TN
JFM			
p	**0.0257**	0.0688	0.0983
r	**-0.3481**	-0.287	-0.2617
FMA			
p	0.1627	0.278	0.5556
r	-0.2222	-0.1735	-0.0948
MAM			
p	0.9942	0.773	0.3216
r	0.0012	-0.0465	0.1587
AMJ			
p	0.6065	0.9343	0.2851
r	0.0829	-0.0133	0.171
MJJ			
p	0.8289	0.8479	NA
r	-0.0348	-0.0309	NA
JJA			
p	0.2591	0.0507	NA
r	-0.1804	-0.3072	NA
DJF_MAM			
p	0.3448	0.285	0.6167
r	-0.1514	-0.171	0.0805

Table 21. Spearman correlations between a combined Oceanic Niño Index (ONI) and North Atlantic Oscillation (NAO) and percent of normal tornado days on a monthly and seasonal basis, where the combined ONI and NAO index value becomes larger if the ONI and NAO are in phase. Note DJF-MAM is a correlation between DJF ONI+NAO and MAM percent of normal tornado days.

ONI + NAO

Month			
January	Southern MS Valley	AR-LA	MS-TN
p	0.7273	0.8589	0.1811
r	-0.0561	0.0287	-0.213
February			
p	0.9459	0.7943	0.9352
r	-0.0109	-0.042	0.0131
March			
p	0.7783	0.7658	0.8338
r	0.0453	0.048	0.0338
April			
p	0.7354	0.725	0.3495
r	0.0544	-0.0567	0.1499
May			
p	0.8852	0.8146	0.9541
r	0.0233	0.0378	0.0093
June			
p	0.4769	0.2289	0.7194
r	-0.1143	-0.1921	-0.0578
July			
p	0.7543	0.7703	NA
r	-0.0504	0.047	NA
August			
p	0.8611	0.9869	NA
r	-0.0282	0.0027	NA

Season			
JFM	Southern MS Valley	AR-LA	MS-TN
p	0.9407	0.9852	0.4744
r	-0.012	0.003	-0.1149
FMA			
p	0.692	0.9588	0.2412
r	0.0638	-0.0083	0.1872
MAM			
p	0.8087	0.9985	0.8312
r	0.039	-0.0003	-0.0343
AMJ			
p	0.6659	0.8523	0.9349
r	0.0695	0.03	-0.0132
MJJ			
p	0.9411	0.9548	NA
r	0.0119	0.0091	NA
JJA			
p	0.6025	0.9571	NA
r	-0.0838	-0.0087	NA
DJF_MAM			
p	0.4815	0.8832	0.7888
r	0.1131	0.0237	0.0431

Simple linear regression models were derived between the percent of normal tornado day and the Z-Index on a three-month seasonal basis over the Southern Mississippi River Valley to assess 1) how much variance could be explained through Z-Index alone and 2) how much improvement would be gained by considering the other teleconnections. Table 22 shows the R^2 values for January-February-March (JFM), February-March-April (FMA), and March-April-May (MAM) that slowly increase with time. This is similar to the correlation results and suggests the most significant impact of Z-Index on percent of normal tornado days is during the warmer months of the late-winter and spring season.

Table 22. R^2 values for JFM, FMA, and MAM over the Southern Mississippi River Valley to determine the explained variance through the Palmer Z-Index.

Season	R^2
JFM	0.00773
FMA	0.02304
MAM	0.1557

Forward and backward stepwise regression was used to further explore the relationship between the three-month percent of normal tornado days, teleconnections, and Z-Index. Teleconnections were first selected as candidate predictors for regression modeling if the correlations were statistically significant. For January-February-March, these teleconnections included the PDO, TNI, AO, and ONI-NAO. Only the PDO was statistically significant across the entire region for February-March-April. Finally, Gulf of Mexico sea surface temperatures, December-January-February (DJF) NAO, and DJF AO were selected for March-April-May (MAM). Given the documented response of ENSO in the literature (Allen et al. 2015), MAM ONI and DJF ONI were also added to into the variable selection process for MAM. Z-Index was also included as a candidate predictor in each three-month period. The best model for each three-month period was then selected based on the Akaike information criterion (Akaike 1974). The results are reported in Tables 23-25.

Table 23. Variables selected from stepwise regression modeling for January-February-March (JFM) over the Southern Mississippi Valley and their significance values. (Adjusted $R^2 = 0.2817$).

Variable	P-Value
PDO	0.03522
TNI	0.00667

Table 24. Variables selected from stepwise regression modeling for February-March-April (FMA) over the Southern Mississippi Valley and their significance values. (Adjusted $R^2 = 0.09284$).

Variable	P-Value
PDO	0.0297

Table 25. Variables selected from stepwise regression modeling for March-April-May (MAM) over the Southern Mississippi Valley and their significance values (Adjusted $R^2 = 0.1983$).

Variable	P-Value
DJF ONI	0.04937
Z-Index	0.00275

The Z-Index was not selected as a predictor in either JFM or FMA (Tables 23 and 24), but it was selected in MAM (Table 25). PDO and TNI tend to be better predictors during the cooler months at the start of the year (Tables 23 and 24). Z-Index was selected as a predictor in MAM, but so was DJF ONI. This seems to indicate that the winter mode of ENSO could enhance or offset the impact of soil moisture balance on tornado days over the Southern Mississippi River Valley.

Conclusions

The relationships between tornado activity and several types of climate variability are a topic of great interest in the literature. Drought is one of those variables which can play a role in the development of tornadoes. Although studies have been conducted assessing the relationship between seasonal and annual precipitation and tornado activity in the United States (Galway 1979; Shepherd et al. 2009), assessments of the soil moisture balance are more limited. This research explored the role of soil moisture balance on tornado activity over the Southern Mississippi River Valley, including the states of Arkansas, Louisiana, Mississippi, and west Tennessee. The Palmer Drought Severity Index (PDSI) and the Palmer Z-Index, two indices which measure soil moisture balance both long-term (PDSI) and short-term (Z-Index), were used alongside tornado path data. Tornado day counts were calculated from the tornado path record and then transformed into a percent of normal to observe trends over time. Monthly and seasonal averages of the PDSI and Z-Index were obtained. Spearman correlation methods were utilized to identify relationships between these drought indices and tornado activity. Analysis did find significant positive correlations as well as significant antecedent negative correlations with the PDSI and especially the Z-Index. Monthly and seasonal analyses also suggest the impact of soil moisture balance on tornado counts over the Southern Mississippi River Valley is during the warmer months from late winter into the spring.

Previous research also studied the impacts of teleconnections on seasonal tornado activity (Allen et al. 2015; Molina et al. 2016; Gensini et al. 2019; Nouri et al. 2021). Therefore, Spearman correlation analysis and regression modeling were used to explore these teleconnections (e.g., Gulf of Mexico sea surface temperatures, ENSO, etc.) to determine if they could be used with soil moisture balance as potential predictors. Spearman correlations revealed Gulf of Mexico sea surface temperatures, PDO, TNI, NAO, AO, and a combined ONI-NAO all had a significant relationship with percent of normal tornado days from the late-winter into the spring, consistent with previous literature. Moreover, a significant relationship between March-April-May tornado days and winter (December-January-February) NAO and AO was detected, which has not been shown before in the literature. Stepwise regression modeling suggested the PDO and TNI both were better predictors than the Z-Index for tornado activity in January-February-March. Only the PDO was selected as an important variable in February-March-April. Finally, in March-April-May, both a winter (December-January-February) ONI and the Z-Index were selected by the stepwise regression modeling. It is noteworthy that the winter ONI did not have a significant correlation with tornado days yet was selected during the stepwise regression modeling phase. It suggests a signal is in the data, which would be consistent with previous literature (Allen et al. 2015). This result also suggests that ENSO could enhance or offset the impact of soil moisture balance on tornado days over the Southern Mississippi River Valley.

Limitations with this study include the use of tornado days instead of tornado counts though counts of tornadoes have issues with inhomogeneities due to increases in spotters, population density, technology, etc. (Verbout et al. 2006). Nonetheless, previous research has used tornado counts combined with reanalysis products to assess variability and change through time (e.g., Allen et al. 2015). This study concentrated on an empirical analysis of drought and teleconnections on tornado activity, but more advanced statistical methods such as machine learning approaches would likely allow for a more rigorous assessment of the interactions between numerous independent variables and tornado activity. Additionally, expanding this study to include reanalysis datasets may allow the derivation of more independent variables that are difficult to quantify using real-time datasets (e.g., moisture advection) that can yield further clues in predicting active tornado periods in months or seasons in advance. Given differences were detected by the western and eastern portions of the Southern Mississippi River Valley, a gridded analysis may also improve the assessment of soil moisture balance on tornado activity, especially with the aid of reanalysis products which are gridded datasets. The addition of PDSI and Z-Index as potential predictors to the various teleconnections shows some promise in improving seasonal and sub-seasonal tornado forecasts over the United States.

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