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THE RELATION OF EL NINO SOUTHERN OSCILLATION (ENSO) TO WINTER TORNADO OUTBREAKS

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1. INTRODUCTION

The impact of El Niño-Southern Oscillation (ENSO) on United States tornadoes has been a controversial topic in the last 15 years. Widely varied and contradicting conclusions exist regarding the topic, especially when attempting to correlate shifts in location of tornadoes to ENSO phase. For instance, Hagemeyer (1998) noted a tendency toward stronger, more frequent tornadoes in Florida during El Niño years. Meanwhile, Schaefer and Tatum (1998) could find no statistical basis for correlation between Florida tornadoes and ENSO phase, and Bove (1998) suggested that Florida experiences fewer tornadoes in both El Niño and La Niña phases. Research by Schaefer and Tatom (1998) and Marzban and Schaefer (2000) found some change in tornado frequency for La Niña years in the Mid-eastern and Northeastern United States, respectively. Browning (1998) also saw some change in frequency of tornadoes across northwestern Missouri as a function of ENSO phase. However, Agee and Zurn-Birkhimer (1998) noted ENSO related shifts in tornadic activity throughout the entire two-thirds of the United States.

Some controversy also exists in discerning the role of ENSO phase in the strength of tornadoes. Some research (Knowles and Pielke 1993, Bove 1998) suggests that stronger tornadoes occur in La Niña patterns, while others (Agee and Zurn-Birkhimer 1998, Schaefer and Tatom 1998) suggest phase does not have a role in the development of stronger or longer track tornadoes in any phase.

In addition, researchers do not agree on the seasonal and monthly variations of tornado activity as a function of ENSO phase. Schaefer and Tatom (1998) address monthly variations in tornado activity as a function of ENSO phase and suggest very little correlation between tornado occurrences and phase throughout the entire United States east of the Rockies. Sankovitch et al. (2004) investigated winter ENSO phase associated with southeast United States tornado patterns and could not identify shifts in tornadic activity due to ENSO phase, although they did find shifts in thermodynamic and kinematic upper air profiles which were associated with ENSO phase. Agee and Zurn-Birkhimer (1998) found shifts in tornado maxima across the Central and Southern Plains and Gulf Coast in strong El Niño years, shifting to the Ohio and Tennessee Valleys and mid-Atlantic region during La Niña years. These results contradict those of Schaefer and Tatom (1998) and Schaefer and Marzban (2000), which show very little indication of seasonal and monthly variations of tornado activity as a function of ENSO phase.

The present paper discusses shifts in historic winter tornadic activity across the United States according to ENSO phase. The strength and length of tornadoes occurring in individual outbreaks, along with the frequency of tornado outbreaks, will also be discussed. Shifts in occurrence of tornado outbreaks will then be related with shifts in jet stream patterns prescribed by the Climate Prediction Center (CPC). This paper will conclude with a brief discussion on severe weather in relation to ENSO.

2. METHODOLOGY

A tornado day is defined as 24 hour period (06 UTC-06 UTC) during which 6 or more tornadoes occurred within the contiguous United States (CONUS). Tornado days during the winters (January, February, and March) of 1950 through 2003 were identified. Violent tornado days are defined as days containing 5 or more tornadoes rated F2 or greater within a 24 hour period between 06 UTC and 06 UTC. These criteria were chosen in an attempt to be compatible with the Galway (1975) definition of a tornado outbreak. Tornado days are used in order to identify tornado activity that has synoptic scale organization because the global effects of the teleconnections associated with ENSO are more likely to be observed on large scales in time and space (i.e. synoptic) rather than in smaller scales (i.e. mesoscale).

Using tornado outbreak days helps to focus this investigation on synoptically forced tornadoes while eliminating localized and more isolated incidences of tornadoes in which mesoscale processes are primarily responsible (i.e. seabreeze convection, landspouts). The criteria for identifying violent tornado days helps to distinguish between high-impact, significant tornado outbreaks (i.e. March 13, 1990, January 21, 1999) and less extensive, less intense outbreaks.

Monthly sea surface temperature anomalies in the Niño 3.4 region (5°N to 5°S and from 170°W to 120°W) compiled by the Climate Prediction Center (CPC) were used to determine 3 month (January, February, and March) averages of sea surface temperature and a resultant ENSO phase for the winter. Three month average SST anomalies greater than 0.5°C define El Niño (EN) conditions. Average anomalies between 0.5°C and -0.5°C indicate neutral conditions, and average anomalies lower than -0.5°C are La Niña (LN) conditions. The years in each ENSO phase are given in Table 1. Of the 54 winter seasons studied, 12 (22%) are classified as EN, 17 (31%) are classified as LN, and 25 (46%) are classified as neutral. Having established the ENSO phase for each of the winters between 1950 and 2003, tornado days and violent tornado days were stratified into EN, neutral, and LN phases. Of the 162 tornado days identified, 37 (23%) occurred during an EN winter, 51 (31%) occurred during a LN winter, and 74 (46%) occurred during a neutral winter. Of the 86 violent tornado days identified, 14 (16%) occurred during an EN winter, 28 (33%) occurred during a LN winter, and 44 (51%) occurred during a neutral winter.

Phase (Winter months only)					
El Niño		La Niña		Neutral	
1958	1987	1950	1974	1952	1979
1966	1988	1951	1975	1953	1980
1969	1992	1955	1976	1954	1981
1973	1995	1956	1985	1957	1982
1977	1998	1962	1989	1959	1984
1983	2003	1965	1996	1960	1986
		1968	1999	1961	1990
		1971	2000	1963	1991
			2001	1964	1993
				1967	1994
				1970	1997
				1972	2002
				1978	

Table 1: Winter ENSO phase. (Climate Prediction Center 2006)

3. METEOROLOGICAL CONSIDERATIONS

To determine shifts in spatial patterns possibly related to ENSO Phase, data from identified tornado days were analyzed using Severe Plot (Hart and Janish 1999). The resulting charts show reported tornadoes in all winter tornado outbreak days (i.e., organized winter tornado activity) for each of the three ENSO phases.

In general, spatial characteristics of the distribution of winter tornadoes indicate distinct shifts in tornadic activity that appear to be related to ENSO phase. During the neutral phase (Figure 3a), organized winter tornado activity is not uncommon over the all but the northern portions (south of about 43^{o}N) of the eastern half of the United States (east of about 98^{o}W). The most frequent activity lies in a 700 km wide east-west band that runs from central Oklahoma through North Carolina. It should be noted that very few of these tornadoes occur along the Gulf Coast from east of Houston, TX through Florida. When only tornadoes that occur on strong and violent tornado days are considered (Figure 3b), the pattern is similar. The west to east orientation of the activity stands out prominently.

The pattern of organized tornado activity during the winter EN phase seems to be markedly different (Figure 1a). Although there are some exceptions, tornadoes on tornado days generally occur within 500km of the Gulf Coast in a band from extreme eastern Texas through Louisiana, Mississippi, Alabama and Florida. The lack of organized EN tornado activity in Georgia could simply be a result of the small sample size there (only 36 tornado days in 12 winters). The pattern of tornadoes on winter EN violent tornado days (Figure 1b) is similar to the pattern observed in tornado days. The long-tracked, strong tornadoes that have occurred with EN winters in central Mississippi and Florida are very apparent. It must be noted that occasional tornado outbreaks, some of them significant, occur outside of this general geographic pattern.

A markedly different pattern of tornado activity is seen during the winter LN phase (Figure 2a). The area of most frequent tornadic activity lies in a southwest to northeast zone that stretches from southwest Louisiana to Michigan. The zone is quite wide along the Gulf Coast extending from eastern Texas to central Alabama and becomes narrower with increasing latitude. Tornado

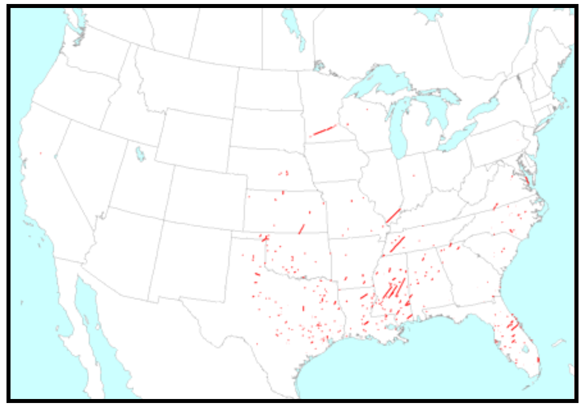

Figure 1a: Tornadoes occurring on "tornado days" during the winter EN phase

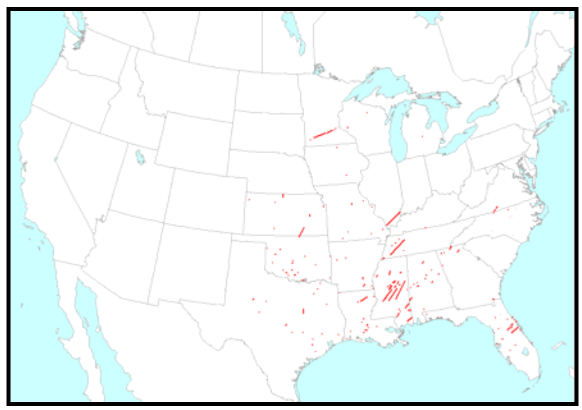

Figure 1b: Tornadoes occurring on "violent tornado days" during the winter EN phase.

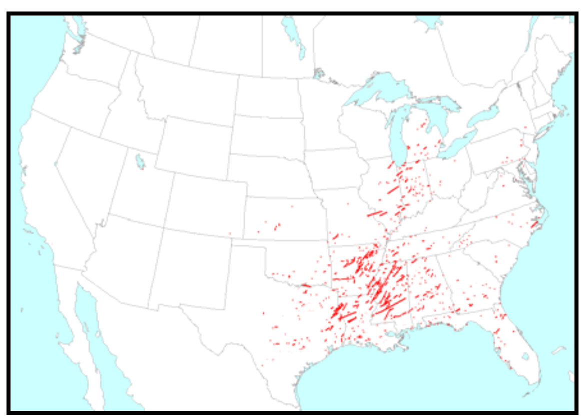

Figure 2a: Tornadoes occurring on "tornado days" during the winter LN phase.

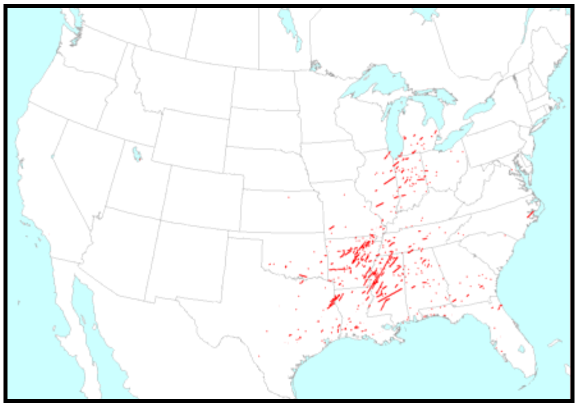

Figure 2b: Tornadoes occurring on "violent tornado days" during the winter LN phase.

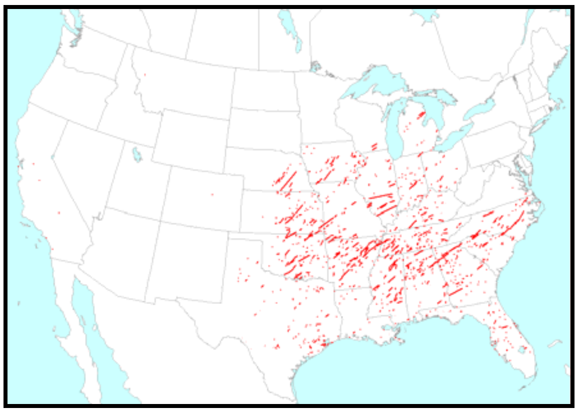

Figure 3a: Tornadoes occurring on "tornado days" during the winter neutral phase.

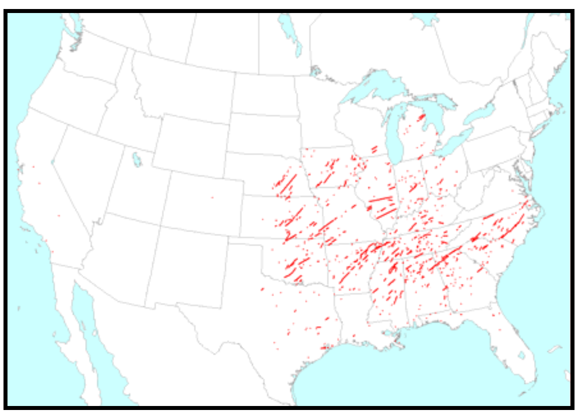

Figure 3b: Tornadoes occurring on “violent tornado days” during the winter neutral phase.

activity on strong and violent winter LN tornado days is most pronounced in the Mississippi Delta region (extreme east Texas, Louisiana, Arkansas, and Mississippi).

This apparent shift in tornado activity is qualitatively similar to the ENSO phase related shift in typical jet stream pattern across the CONUS (Figure 4 - Climate Prediction Center 2005). During EN, warm sea surface temperatures in the equatorial Pacific Ocean cause troughiness aloft. The result is a southwardly displaced jet stream, entering the United States in southern California and passing over the southern portion of the Rocky Mountains. In the eastern part of the U.S., the typical jet in EN conditions roughly parallels the Gulf Coast. The Florida and central Mississippi strong/violent tornadoes reflect that the Gulf Coast region has an immediately available source of low-level moisture and lies to the immediate right of the typical EN winter storm track (Hagemeyer and Almeida, 2003).

In contrast, a ridge develops in the eastern Pacific during LN conditions. This forces the jet to typically enter North America through the northwestern United States or southwestern Canada. A trough is forced east of the Rockies with an accompanying ridge near the East Coast. This typically gives southwest to northeast mid and upper-level flow over the Mississippi Valley.

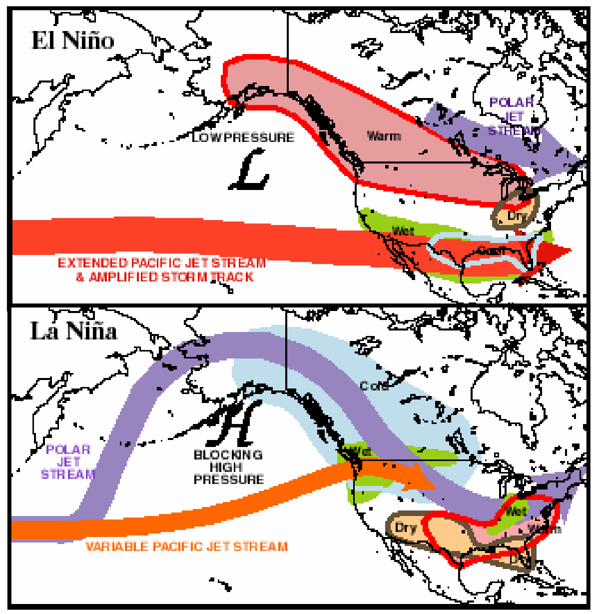

Figure 4: Typical weather anomalies and jet stream position in moderate to strong El Niño and La Niña winters (Climate Prediction Center 2005)

A traditional “rule of thumb” for forecasting is that the severest thunderstorm activity occurs under and to the south of the jet stream (Lee and Galway, 1956: Miller, 1972: Doswell and Schaefer, 1976). Thus, it would not be surprising to find synoptically organized tornado activity is displaced to the south in EN conditions, while LN conditions favor the occurrence of tornadoes in a southwest to northeast band in the midsections of the country.

4. STATISTICAL VALIDATION

In addition to the apparent shifts in the spatial distribution of organized tornado activity during the three ENSO phases, several trends can be identified in seasonally averaged tornado frequency and intensity comparisons (Table 2). It appears that there are differences in the number of winter tornado days and winter violent tornado days as a function of ENSO phase. Nearly half of all winter tornado days included in the data set occurred during the neutral phase, while significantly lesser percentages (23% and 31%) were experienced in EN and LN phases, respectively.

To see if this heuristic observation is statistically supported, a χ^2 distribution (Hoel, 1962) is used to test to see if it is possible to say that the distribution of tornado days varies (i.e., is not homogeneous) with ENSO phase. The χ^2 statistic for both tornado days and violent tornado days (Table 2) is well below even the 90% critical level of 4.605. Thus the hypothesis that the distribution of both tornado days and violent tornado days is unaffected by the ENSO phase cannot be discounted!

A 5-level box and whiskers plot (Poly Software International, 1999) shows that the median number of winter tornado days is virtually independent of ENSO phase (Figure 5). The major difference between the frequency distribution of winter tornado days between the three ENSO phases is in the spread of the upper 10% of the data for each distribution (i.e., the number of tornado days observed in the 10% of the years in that phase which had the most tornado days).

The data also appears to indicate that winter-time tornadoes occurring on tornado days during neutral phases are stronger and longer-lived than tornadoes occurring in either EN or LN phases (Table 3). Thompson and Vescio (1998) developed the Destruction Potential Index (DPI) to measure the potential for damage posed by tornado outbreaks. The DPI considers the number of tornadoes, their F-scale, and the area affected by each tornado. Thus the DPI is weighted towards long track, violent tornadoes. A cursory examination of this index shows an increase in strength and duration of tornadic activity with ENSO phase.

A χ^2 test was to test the DPI data to determine is this observation has statistical significance. The test showed that one can reject with 99% certainty the hypothesis that winter DPI for both tornado days and violent tornado days is independent of ENSO phase. The box and whiskers plot of the DPI data (Figure 6) shows considerable differentiation between the three DPI distributions. The 90th percentile value of the EN DPI is less than the median value of the neutral DPI, and less than the 75th percentile value of the LN DPI.

The data clearly show a tendency for stronger, longer-track tornadoes to occur during LN and neutral winters compared to EN winters. However, because “zero values” for DPI have been observed in each of the three ENSO phases in the past, the ENSO phase by itself is not a tornado forecast tool, or even a historical proxy to gage a past winter’s tornado activity.

This empirical observation of ENSO phase related differences in geographic location of organized tornado activity can also be statistically evaluated. A state-by-state tabulation of the number of tornadoes occurring on winter tornado days in each ENSO phase and the χ^2 statistic is given in Table 4. The χ^2 statistic for all of the applicable fields are well above the 2 degree of freedom 99.9% critical value of 9.210, so one put extreme confidence in the hypothesis that the number of tornadoes in a state on a winter tornado day when sorted by ENSO phase is homogeneous (it is indeed dependent on ENSO phase).

Table 4 also gives the expected number of winter tornado day tornadoes that would occur in each state if there were absolutely no ENSO effect (in parentheses). The shaded cells in the table show when the observed value is different from the expected value by more than 25%. During EN winters, only 2 states (Florida and North Carolina) experience substantially more (>125%) organized tornadoes than would be expected from an ENSO independent distribution (dark shading). In contrast, during EN winters most of the states in the Central Plains and Great Lakes regions that

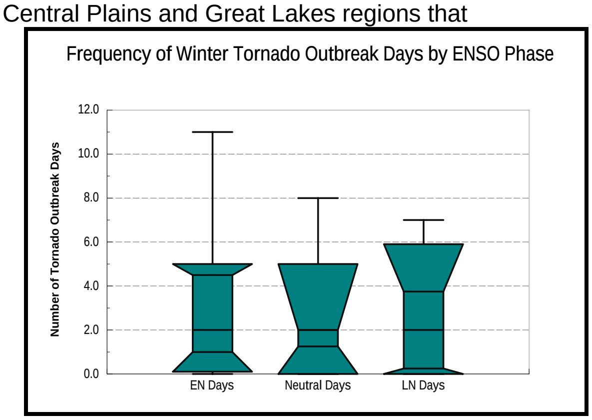

Figure 5: Winter Tornado Outbreak Days per year, stratified into ENSO phase. The top and bottom horizontal lines of each icon indicates the observed maximum and minimum values in the appropriate category, the 10% and 90% values of the distribution are at the top and bottom of the colored portion of the icon, the 25% and 75% values are the top and bottom of the thin portion of the icon, and the median (50%) value is the line inside the thin portion of the icon.

	El Niño	La Niña	Neutral	χ^2 stat.
Total number of "tornado days"	37 (23%)	51 (31%)	74 (46%)	0.04
Average number of "tornado days" per winter	3	3	2.96	0.003
Number of “violent tornado days”	14 (16%)	28 (33%)	44 (51%)	1.84
Average number of "violent tornado days" per winter	1.167	1.647	1.76	n/a
Number of winters in each phase	12 (22%)	17 (31%)	25 (46%)	---

Table 2: Frequency of tornado days and violent tornado days according to ENSO phase. In the χ^2 statistic column, a “n/a” indicates that at lease one of the categories contained 5 or less events and that the χ^2 test could not be applied (Wilks, 1995).

	El Niño	La Niña	Neutral	χ^2 statistic
Total DPI for all "tornado days"	519.7	2604.5	6248.7	2029.11
Average DPI for all "tornado days"	14.44	51.07	84.44	14.27
Tornadoes rated F2+ on "tornado days" (%)	32%	38%	49%	2.54
DPI for all "violent tornado days"	415	2330.6	5782.5	2054.90
Average DPI for all " violent tornado days"	29.64	83.24	131.42	14.67
Tornadoes rated F2+ on "violent tornado days" (%)	52%	47%	55%	---

Table 3: Average strength and duration of tornadoes as indicated by DPI and percent of tornadoes rated F2 or stronger.

have experienced organized winter tornado activity, had substantially less (>75%) storms than would be expected from a ENSO independent distribution. This gives credence to the heuristic postulate that during EN winters organized tornado activity in the CONUS is generally restricted to the area immediately adjacent to the Gulf of Mexico.

During LN conditions, the states with substantially enhanced activity all lie within the southwest to northeast band from Louisiana to Michigan. The states on either side of this zone generally have markedly reduced activity. While neither Tennessee nor Kentucky have substantially increased activity, the geographic layout of these states with their long eastward extension may well mask an active zone in their western portions.

The statistics also lend credibility to the observation that during neutral winters, organized tornado activity is most prevalent in an east-west zone across the mid-section of the country. Oklahoma, Kansas, Tennessee, and Georgia (with its elongated north-south dimension) all have substantially more activity than would be expected. The intervening states (Arkansas, Missouri, Nebraska, Kentucky, and the Carolinas) mostly had large counts, but one of the categories had too few events for the χ^2 test to be valid. States to the south (Louisiana and Mississippi) had markedly fewer organized tornadoes.

As a further test of the concept of ENSO driven changes in the geographic distribution of organized winter tornado activity, the destruction potential index (DPI) data that attempts to account for both the intensity and strength of tornadoes was examined by state. The DPI data indicates that during EN winters, the only state with markedly long-strong tornadoes is Florida. All other states had DPI totals lower than would be produced by an ENSO independent distribution (all but Texas had less than 75% of the independent value).

During the LN and the neutral phases, the belt of high DPI lies in the same general area as the zone of the

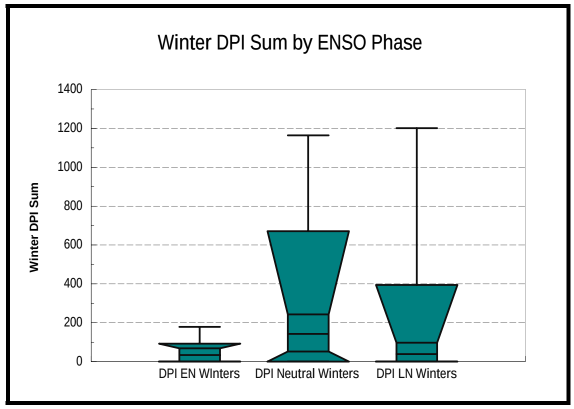

Figure 6: Winter DPI Sum by ENSO phase.

greatest tornado activity (From the Mississippi Delta to the Great Lakes during LN and from Oklahoma/Kansas through the Carolinas during neutral ENSO events).

Thus two different measures of tornado activity, the actual tornado count and the DPI, give indications as to how the zone of increased tornado activity during the winter months is affected by the ENSO phase.

5. DISCUSSION & CONCLUSIONS

By playing a large role in positioning the jet stream as it crosses the CONUS, the ENSO phase is a major factor in seasonal weather conditions in the CONUS. EN episodes are associated with cool and wet winters in the Gulf Coast states, wet winters in southern California, and wet summers in the northern Rockies. In contrast, LN is associated with warm, dry winters from the southwestern states across the Gulf Coast states, and cool wet winters in the northwest (Halpert and Ropelewski 1987, 1992; Ropelewski and Halpert 1989).

The mean position of the jet along the Atlantic seaboard during EN conditions induce increased troposphere vertical wind shear and a flow that is less anticyclonic than during the other two ENSO phases (Gray, 1984). Consequently, the typical EN environment is less favorable for the development and maintenance of tropical cyclones, resulting in suppressed hurricane activity in the western Atlantic during EN conditions (Bove et al., 1998).

However, as the scale of the meteorological phenomenon becomes smaller, the influence of synoptic scale features decrease. The ingredients necessary for thunderstorm development (McNulty, 1985) are only a small subset of those required for tornadogenesis (Johns and Doswell, 1992). In a study of the occurrence of tornadoes during drought years, Galway (1979) found no validity to the hypotheses that tornado activity would be at a minimum during dry weather regimes.

Tornado development requires not only the horizontal and vertical juxtapositioning of the moisture, temperature, and wind fields so that a moist, conditionally and convectively unstable, high helicity environment exists, but also the presence of horizontal discontinuities in one or more of these fields so that localized updrafts can be generated.

	Number of Tornadoes on Winter Tornado Days				DPI of Tornadoes on Winter Tornado Days			
State	El Niño	La Niña	Neutral	χ^2 statistic	El Niño	La Niña	Neutral	χ^2 statistic
TX	97 (84.9)	136 (120.3)	149 (176.9)	176.85	90.7 (112.6)	260.9 (159.6)	155.3 (234.7)	95.45
OK	25 (28.0)	23 (39.7)	78 (58.3)	58.33	38.3 (85.8)	60.6 (121.6)	287.2 (178.8)	122.66
AR	5 (51.1)	128 (72.4)	97 (106.5)	106.48	17.0 (337.1)	389.3 (477.6)	1110.7 (702.3)	557.75
LA	30 (26.2)	69 (37.1)	19 (54.6)	54.63	18.9 (60.8)	245 (86.1)	9.7 (126.7)	429.9
MS	53 (49.6)	110 (70.2)	60 (103.2)	103.24	122.9 (305.5)	962 (432.8)	289.7 (636.5)	945.8
TN	9 (28.0)	32 (39.7)	85 (58.3)	58.33	10.8 (89.1)	81.2 (126.3)	309.1 (185.7)	166.94
AL	16 (35.6)	74 (50.4)	70 (74.1)	74.07	18.7 (104.3)	86.0 (147.8)	364.7 (217.3)	196.05
GA	11 (24.2)	23 (34.3)	75 (50.5)	50.46	5.3 (259.3)	24.1 (367.4)	1137.6 (540.3)	1230
FL	64 (38.9)	35 (55.1)	76 (81.0)	81.02	20.6 (10.3)	11.3 (14.6)	14.5 (21.5)	13.28
SC	7 (9.1)	3 (12.9)	31 (19.0)	n/a	0.4 (135.7)	0.3 (192.2)	609.0 (282.7)	n/a
NC	31 (17.8)	9 (25.2)	40 (37.0)	37.037	7.1 (102.7)	9.9 (145.5)	445.3 (214.0)	465.34
KS	6 (19.6)	10 (27.7)	71 (40.7)	40.74	10.9 (135.6)	1.0 (192.0)	598.1 (282.4)	n/a
MO	5 (16.9)	26 (23.9)	45 (35.2)	35.19	2.0 (67.1)	114.3 (95.1)	185.7 (139.8)	n/a
NE	6 (4.7)	0 (6.6)	15 (9.7)	n/a	0.0 (46.8)	0.0 (66.3)	210.7 (97.5)	n/a
IA	2 (10.9)	0 (15.4)	47 (22.7)	n/a	0.0 (38.9)	0.0 (55.1)	175.1 (81.1)	n/a
IL	0 (10.7)	23 (15.1)	25 (22.2)	n/a	0.0 (65.0)	242.0 (92.1)	50.4 (135.4)	n/a
IN	1 (17.3)	40 (24.6)	27 (36.1)	n/a	0.0 (34.8)	77.3 (49.3)	79.4 (72.5)	n/a
KY	0 (10.4)	4 (14.8)	43 (21.8)	n/a	0.0 (29.5)	0.2 (41.7)	132.4 (61.4)	n/a
MI	1 (7.3)	17 (10.4)	15 (15.3)	n/a	0.3 (9.5)	19.6 (13.5)	23 (19.9)	n/a

Table 4: First 5 columns give the number of tornadoes occurring on a winter tornado day sorted by state according to ENSO phase. Numbers in parentheses indicate the theoretical value of tornadoes expected if tornadoes were independent of ENSO phase. The next 4 columns give the DPI of tornadoes occurring on a winter tornado day sorted by state and ENSO phase. Numbers in parentheses indicate the theoretical DPI independent of ENSO. States with less than 10 such tornadoes are omitted. States with less than 10 such tornadoes in all three phases omitted. Black cells indicated that the observed values are less than 75% of the expected value. Grey cells indicate that observed value is greater than 125% of the expected value. Clear cells indicate that the observed value is within 25% of the expected value. In the χ^2 statistic column, a "n/a" indicates that at lease one of the categories for the state contained 5 or less events and that the χ^2 test could not be applied.

The study of upper air observations from the southeastern United States by Sankovitch and Schaefer (2004), showed that the ENSO phase which gives the most favorable thermodynamic environment for severe thunderstorms is often the phase which results in the most unfavorable kinematics for storm development. Large scale conditions by themselves do not set the stage even for organized tornado activity.

Even though statistically significant differences in the frequency of tornadoes are not seen in examinations of simple tornado counts (Marzban and Schaefer, 2001), differences become evident when the frequency organized winter tornado activity, as indicated by the number of tornadoes occurring on winter tornado days, is examined. A statistically significant trend for stronger, longer-track tornadoes to occur during LN and neutral winters compared to EN winters is seen.

An examination of the tracks of organized winter tornado activity shows that a statistically significant ENSO phase related shift in the geographic region most favored by organized winter tornadoes occurs. During EN winters, long-tracked strong and violent tornadoes are most likely to occur along the coast of the Gulf of Mexico, and in Florida. During the LN phase organized tornado activity occurs in a southwest to northeast belt that stretches from the Mississippi Delta to the Central Great Lakes region. In neutral phase years, the zone of organized tornadoes is most likely to occur in a wide belt that stretches from the Oklahoma/Kansas area eastward through Tennessee towards the Mid-Atlantic.

It must be emphasized that these ENSO induced preferred patterns for organized tornado activity, like other climate related weather patterns, only set the background stage for tornado activity. In any particular situation, meteorological forces may interact in such a way as to cause organized tornadoes to occur in atypical places. One example is the local tornado outbreak that occurred in southern Minnesota on March 29, 1998, an EN year when the climatically preferred area for tornado activity was along the Gulf Coast.

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