The Relation of El Niño–Southern Oscillation (ENSO) to Winter Tornado Outbreaks

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ABSTRACT

Winter tornado activity (January–March) between 1950 and 2003 was analyzed to determine the possible effect of seasonally averaged sea surface temperatures in the equatorial Pacific Ocean, the ENSO phase, on the location and strength of tornado outbreaks in the United States. Tornado activity was gauged through analyses of tornadoes occurring on tornado days (a calendar day featuring six or more tornadoes within the contiguous United States) and strong and violent tornado days (a calendar day featuring five or more tornadoes rated F2 and greater within the contiguous United States). The tornado days were then stratified according to warm (37 tornado days, 14 violent days), cold (51 tornado days, 28 violent days), and neutral (74 tornado days, 44 violent days) winter ENSO phase. It is seen that during winter periods of neutral tropical Pacific sea surface temperatures, there is a tendency for U.S. tornado outbreaks to be stronger and more frequent than they are during winter periods of anomalously warm tropical Pacific sea surface temperatures (El Niño). During winter periods with anomalously cool Pacific sea surface temperatures (La Niña), the frequency and strength of U.S. tornado activity lies between that of the neutral and El Niño phase. ENSO-related shifts in the preferred location of tornado activity are also observed. Historically, during the neutral phase, tornado outbreaks typically occurred from central Oklahoma and Kansas eastward through the Carolinas. During cold phases, tornado outbreaks have typically occurred in a zone stretching from southeastern Texas northeastward into Illinois, Indiana, and Michigan. During anomalously warm phases activity was mainly limited to the Gulf Coast states, including central Florida. The data are statistically and synoptically analyzed to show that they are not only statistically significant, but also meteorologically reasonable.

1. Introduction

Several authors (Nunn and DeGaetano 2004; Smith et al. 1998; Ropelewski and Halpert 1989) have observed a shift in mean jet stream patterns over the contiguous United States (CONUS) related to the phase of El Niño–Southern Oscillation (ENSO). The impact of this ENSO-related shift of the mean jet stream position on U.S. tornadoes has been a controversial topic in the last 15 yr. 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, 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 (2001) found some change in tornado frequency for La Niña years in the mideastern and northeastern United States, respectively. Browning (1998) also saw some change in the frequency of tornadoes across northwestern Missouri as a function of ENSO phase. However, Agee and Zurn-Birkhimer (1998) noted ENSO-related shifts in tornado activity throughout the eastern two-thirds of the United States.

Some controversy also exists in discerning the role of ENSO phase on the strength of tornadoes. Some researchers (Knowles and Pielke 2005; Bove 1998) suggest 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 whether sea-

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sonal and monthly variations of tornado activity are a function of ENSO phase. Schaefer and Tatom (1998) suggest very little correlation between tornado occurrences and ENSO phase throughout the entire United States east of the Rockies. Sankovich et al. (2004) investigated winter ENSO phase associated with southeast U.S. tornado patterns and could not identify shifts in tornado 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. This contradicts Schaefer and Tatom (1998) and Schaefer and Marzban (2000), who show very little indication of seasonal and monthly variations of tornado activity as a function of ENSO phase.

The present paper discusses shifts in organized winter tornado activity across the United States according to ENSO phase. The strength and pathlength of tornadoes occurring in individual outbreaks, along with the frequency of tornado outbreaks, are also discussed. Shifts in occurrence of tornado outbreaks are then related to shifts in jet stream patterns. This paper concludes with a discussion on cold season tornadoes in relation to ENSO phase.

2. Methodology

We define a tornado day as a 24-h period (0600–0600 UTC) during which six or more tornadoes occurred within CONUS. Violent tornado days are defined as days containing five or more tornadoes rated F2 or greater within a 24 h period between 0600 and 0600 UTC. These criteria were chosen in an attempt to be compatible with the Galway (1975) definition of a tornado outbreak (minimum of six tornadoes). The study began with identification of tornado days and violent tornado days during the winters (January–March) of 1950 through 2003. Tornado data were compiled using the Storm Prediction Center (SPC) Severe Weather Reports Database (Schaefer et al. 1980; Schaefer and Edwards 1999) and analyzed through the extensive use of Severe Plot software, version 2.0 (Hart and Janish 1999).

Tornado days are used 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). This helps to focus the investigation on synoptically forced tornadoes while eliminating localized and more isolated incidences of tornadoes in which mesoscale processes are primarily responsible (i.e., sea-breeze convection, landspouts). In addition, violent tornado days help to distinguish between high-impact, significant tornado outbreaks (i.e., 13 March 1990, 21 January 1999) and less extensive, less intense outbreaks.

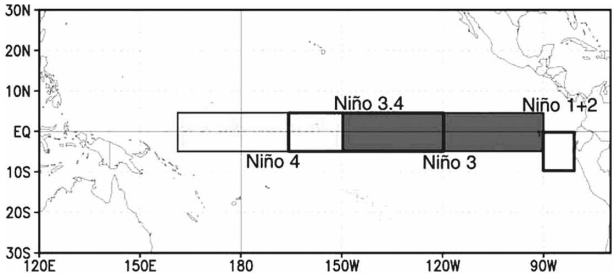

FIG. 1. Niño-3.4 regions outlined by the CPC (available online at http://www.cpc.ncep.noaa.gov).

For the definition of ENSO phase, we use the database of the Climate Prediction Center (CPC; data are available online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml), which is based on the three-month (January–March) extended reconstruction SST analysis, version 2 (ERSST.v2) average sea surface temperatures anomalies in the Niño-3.4 region (5°N–5°S, 170°–120°W; Fig. 1). Trenberth and Hoar (1996) identified the Niño-3.4 region as a key area in which the sea level pressure anomalies and sea surface temperature anomalies in the equatorial Pacific are very well correlated. Following CPC, three-month-average SST anomalies greater than 0.5°C define El Niño (EN) conditions, average anomalies between −0.5° and 0.5°C indicate neutral (N) 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.

a. Observations

Of the 54 winter seasons studied, 12 (22%) are classified as EN, 17 (31%) are classified as LN, and 25 (46%) are classified as N. Having established the ENSO phase for each of the winters between 1950 and 2003, tornado days and violent tornado days were stratified into EN, N, and LN categories (Table 2). Of the 162 tornado days identified, 37 (23%) occurred during an EN winter, 51 (31%) occurred during an LN winter, and 74 (46%) occurred during an N winter. Of the 86 violent tornado days identified, 14 (16%) occurred during an EN winter, 28 (33%) occurred during

TABLE 1. Winter ENSO phase (available online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

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

an LN winter, and 44 (51%) occurred during an N winter. Given the fact that the percentage of tornado days occurring during EN, LN, and N winters (23%, 31%, and 46%, respectively) are quite similar to the percentages of winters classified as EN, LN, or N (22%, 31%, and 46%), and that roughly three tornado days occur per winter regardless of ENSO phase (Table 2), it is safe to say that the ENSO phase has little effect on the frequency of organized tornado activity across the contiguous United States as a whole.

Shifts in intensity and total square area affected by tornadoes as a function of ENSO phase were quantified via the destruction potential index (DPI) developed by Thompson and Vescio (1998). The DPI considers the number of tornadoes, their F scale, and the area affected by each tornado, and is weighted toward stronger, longer-track tornadoes.

The average DPI of tornadoes occurring on tornado days during the N phase is 84.44. During the LN phase, DPI drops to 51.07, and during the EN phase, it drops to only 14.44 (Table 3). On strong tornado days, average DPI is 131.42 for the N phase, 83.24 for LN, and 29.64 for EN. This cursory examination of the DPI index indicates that there may be a dependence on tornado strength and duration with ENSO phase with stronger and longer-tracked tornadoes occurring during the N phase relative to the EN phase.

b. *Statistical evaluation on the national scale*

To determine if these heuristic observations have statistical support, an χ^2 distribution (Hoel 1962) is used to examine whether it is possible to say that the distribution of these parameters (tornado days, average DPI) varies (i.e., is not homogeneous) with ENSO phase. If the χ^2 statistic is larger than the prescribed critical value, the hypothesis that the distributions are independent of the ENSO phase can be rejected. However, as seen in Table 2, the χ^2 statistic for both tornado days (0.04) and violent tornado days (1.84) is well below even the 90% critical level of 4.605. *Thus one cannot discount the hypothesis that the frequency of tornado days and violent tornado days over the contiguous United States is unaffected by the ENSO phase.* This confirms the findings of Marzban and Schaefer (2001).

A 5-level box-and-whiskers plot (Poly Software International 1999) shows that the median number of tornado days in a winter is virtually independent of ENSO phase (Fig. 2). The major difference in the frequency distribution of winter tornado days between the three ENSO phases is 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 largest number of winter tornado outbreak days in a given year oc-

TABLE 2. Frequency of tornado days and violent tornado days according to ENSO phase. In the χ^2 statistic column, n/a indicates that at least one of the categories contained five or fewer events and that the χ^2 test could not be applied (Wilks 1995).

	El Niño	La Niña	Neutral	χ^2 statistic
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
Total 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 according to ENSO phase	12 (22%)	17 (31%)	25 (46%)	—

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

	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
Percent of tornadoes rated F2 or greater on "tornado days"	32	38	49	2.54
Total DPI for all "strong/violent tornado days"	415	2330.6	5782.5	2054.90
Average DPI for all "strong/violent tornado days"	29.64	83.24	131.42	14.67
Percent of tornadoes rated F2 or greater on "strong/violent tornado days"	52	47	55	—

curred during 1998, during an EN phase. The 10th percentile mark on the box-and-whiskers plot shows only a slightly higher frequency of tornado days in the LN phase than in the other ENSO phases.

The χ^2 test can also be used to determine whether the DPI observations have statistical significance (Table 3). The χ^2 statistic for ENSO-related differences in the average DPI for winter tornado days (14.27) is well above even the 99.9% confidence level (9.210). Therefore, one can have confidence in *rejecting the hypothesis that average DPI on winter tornado days is independent of ENSO phase.* Similarly, the average DPI strong/violent winter tornado days is 14.67, well above the 99.9% confidence level, and the null hypothesis for strong/violent tornado day DPI can also be rejected with high confidence.

A box-and-whiskers plot of the DPI (Fig. 3) shows considerable differentiation between the three average DPI distributions. Despite the fact that over 90% of the N DPI values are less than the median value of the N DPI distribution, there is a significant relationship between DPI values and ENSO phase. DPI tends to be highest during the N phase and lowest during the EN phase, indicating that long-track, strong tornadoes tend to occur more frequently during LN and N winters compared to EN winters. However, it is important to ensure that these are not "nonsense correlations" relating two variables (location and strength, in this case) that arise simply because they are correlated to a third variable (ENSO phase) yet do not imply a causal relationship (James and James 1959). In the next section, ENSO-related meteorological factors are identified to demonstrate sound meteorological reasons for shifts in location and strength of organized cool-season U.S. tornado activity.

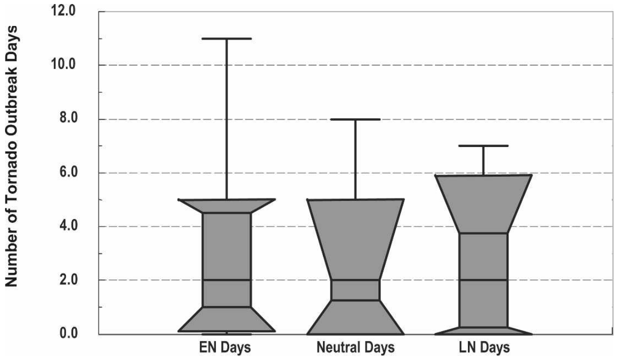

FIG. 2. Winter tornado outbreak days per year, stratified into ENSO phase. The top and bottom horizontal lines of each icon indicates the observed maximum and minimum values in the appropriate category, the 10% and 90% values of the distribution are at the top and bottom of the colored portion of the 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.

3. Meteorological considerations

a. ENSO teleconnections

During EN conditions, or warm ENSO phases, negative anomalies of sea level pressure develop over the eastern tropical Pacific, and positive anomalies develop over northern Australia and Indonesia. These anomalies are essentially reversed during LN, the cool phase of ENSO (Rasmusson and Carpenter 1982; Peixoto and Oort 1992). Rainfall patterns over the tropical Pacific exhibit a variation opposite in sign from that of pressure oscillation. During EN (LN), abnormally dry (wet) conditions occur over northern Australia, Indonesia, and the Philippines, with wetter (drier) conditions prevailing over the west coasts of tropical North and South America.

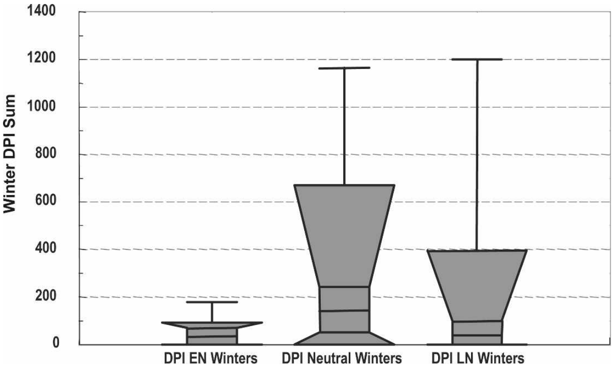

FIG. 3. Winter DPI sum by ENSO phase.

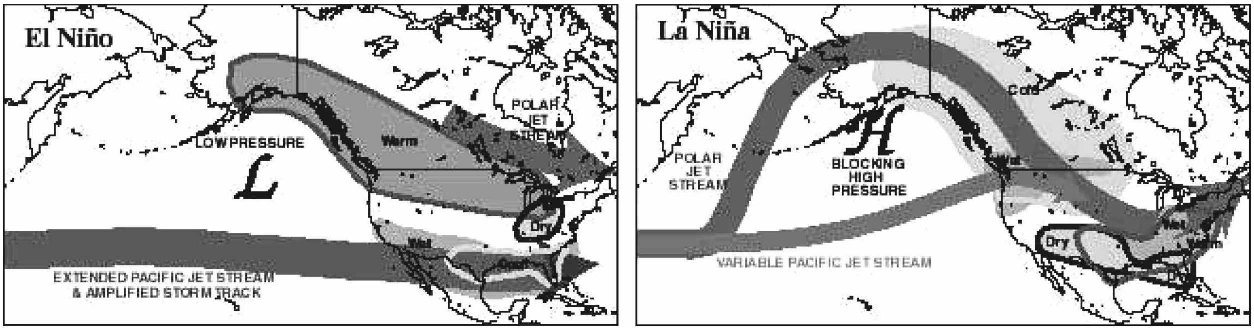

FIG. 4. Typical weather anomalies and jet stream position in moderate-to-strong El Niño and La Niña winters (available online at http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/nawinter.shtml).

These changes in the tropics (particularly shifts in convection over the tropical Pacific and resultant latent heat release) lead to shifts in the position of atmospheric circulation features. These shifts result in an abnormally intense subtropical jet stream extending eastward over the southern United States and northern Mexico during the winter months. As a result, the winter EN pattern over the contiguous United States features cooler, wetter winters across the Gulf Coast states and in Southern California and warmer conditions over the northern United States (Rasmusson and Mo 1993; additional information is available online at http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/nawinter.shtml).

In contrast, LN phases of ENSO feature cooler-than-average sea surface temperatures over the eastern Pacific. The subtropical jet is weaker compared to the EN phase. As a result, the southern half of the United States experiences drier and warmer conditions than are normally expected, while wetter-than-normal conditions can be expected further to the north along the polar jet. Figure 4 is a schematic of the EN and LN jet stream and weather patterns across the North Pacific and the contiguous United States prepared by the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center (additional information is available online at http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/nawinter.shtml).

This schematic is consistent with the upper-air patterns observed during the winters of the years in this study. Mean winter 0000 UTC 250-hPa charts were constructed using the gridded National Centers for Environmental Prediction (NCEP) reanalysis data (Mesinger et al. 2004) from 1979 through 2003. Because the LN phase occurred only six times during this period, only data from the six warmest EN winters and the six N winters with the smallest magnitude deviation from the climatological average were considered in the creation of these composites. At each grid point, the wind speeds from each of the approximately 90 winter days (January–March) in each of the six winters considered for each ENSO phase were averaged together.

Even with the smoothing implicit in the averaging together of this many cases, the shifts in jet stream patterns during each ENSO phase are quite distinct. During the EN phases considered, a mean trough is noted over the western United States as evidenced by cyclonically curved mean jet stream from northern Mexico to the eastern United States and weaker flow (lower U and V) over the intermountain states. Faster flow over south Texas and northern Mexico eastward across the southeastern United States indicates a strengthened subtropical jet across those areas. In contrast, the strongest of the flow in winter LN and N phase events are displaced farther to the north across the east-central United States (Fig. 5). A southwest–northeast tilt of the 250-hPa jet stream over the central United States is apparent in the composites of the individual winter months (Fig. 6).

b. ENSO-related patterns in historic tornado data

To determine if spatial shifts in winter tornado occurrence related to ENSO phase are present, tornado data from identified tornado days were analyzed using Severe Plot software, version 2.0 (Hart and Janish 1999). Figures 7–9 show tornadoes reported on 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 regions of preferred tornado activity that appear to be tied to ENSO-related shifts of the jet stream. During the N phase (Fig. 7a), organized winter tornado activity is not uncommon over all but the northern portions (south of about 43°N) of the eastern half of the United States (east of about 98°W). The most frequent activity lies in a 700-km-wide west–east band that runs from central

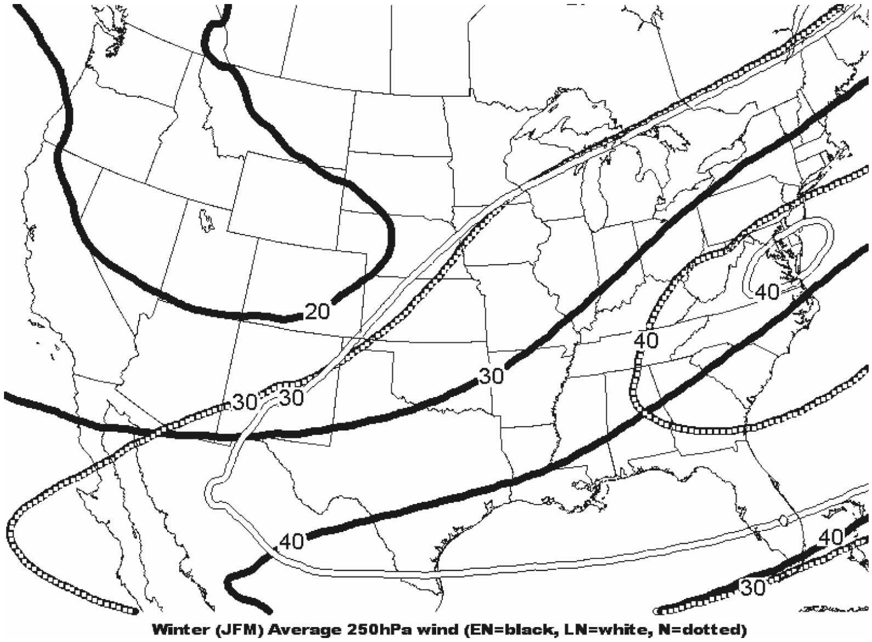

FIG. 5. Average wind speeds (m s^{-1}) in winter (averaged cumulatively) from 1979 through 2003, separated into ENSO phase. Averages computed using gridded NCEP reanalysis data (Mesinger et al. 2004). Notice the southwardly displaced mean jet stream evident in El Niño months (especially March) relative to La Niña and neutral phase.

Oklahoma through North Carolina. It should be noted that relatively few of these tornadoes occur along the Gulf Coast from east of Houston, Texas, through Florida. When only tornadoes that occur on strong and violent tornado days are considered (Fig. 7b), the pattern is similar. The west–east orientation of the activity stands out prominently.

The pattern of organized tornado activity during the winter EN phase is noticeably different (Fig. 8a). Although there are some exceptions, winter EN phase tornadoes on tornado days generally occur within 500 km 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 is likely 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 (Fig. 8b) is similar to the pattern observed in winter EN 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 (Fig. 9a). The area of most frequent tornado activity lies in a southwest–northeast zone that stretches from southwest Louisiana to Michigan. This zone is quite wide along the Gulf Coast, extending from eastern Texas to central Alabama and becoming narrower with increasing latitude. Tornado activity on strong and violent winter LN tornado days (Fig. 9b) is most pronounced in the lower Mississippi Valley region (extreme east Texas, Louisiana, Arkansas, and Mississippi).

c. *Implications on U.S. tornado outbreaks*

A traditional "rule of thumb" for forecasting is that the most severe thunderstorm activity occurs under and to the south of the jet stream (Lee and Galway 1956; Miller 1972; Doswell and Schaefer 1976). Thus, it is not surprising to find the apparent shift in winter tornado activity to be qualitatively similar to the ENSO phase–related shift in typical jet stream pattern across the eastern part of the United States.

The southward displacement of tornado activity in EN and the presence of strong/violent tornadoes in central Mississippi and Florida are indicative of a couple of contributing factors: 1) the availability of low-level moisture to those regions due to their proximity to the Gulf of Mexico and 2) the southward shift of the EN winter storm track [also implied in the analysis by Hagemeyer and Almeida (2002)]. In contrast, LN and N phases occur at much higher latitudes across the

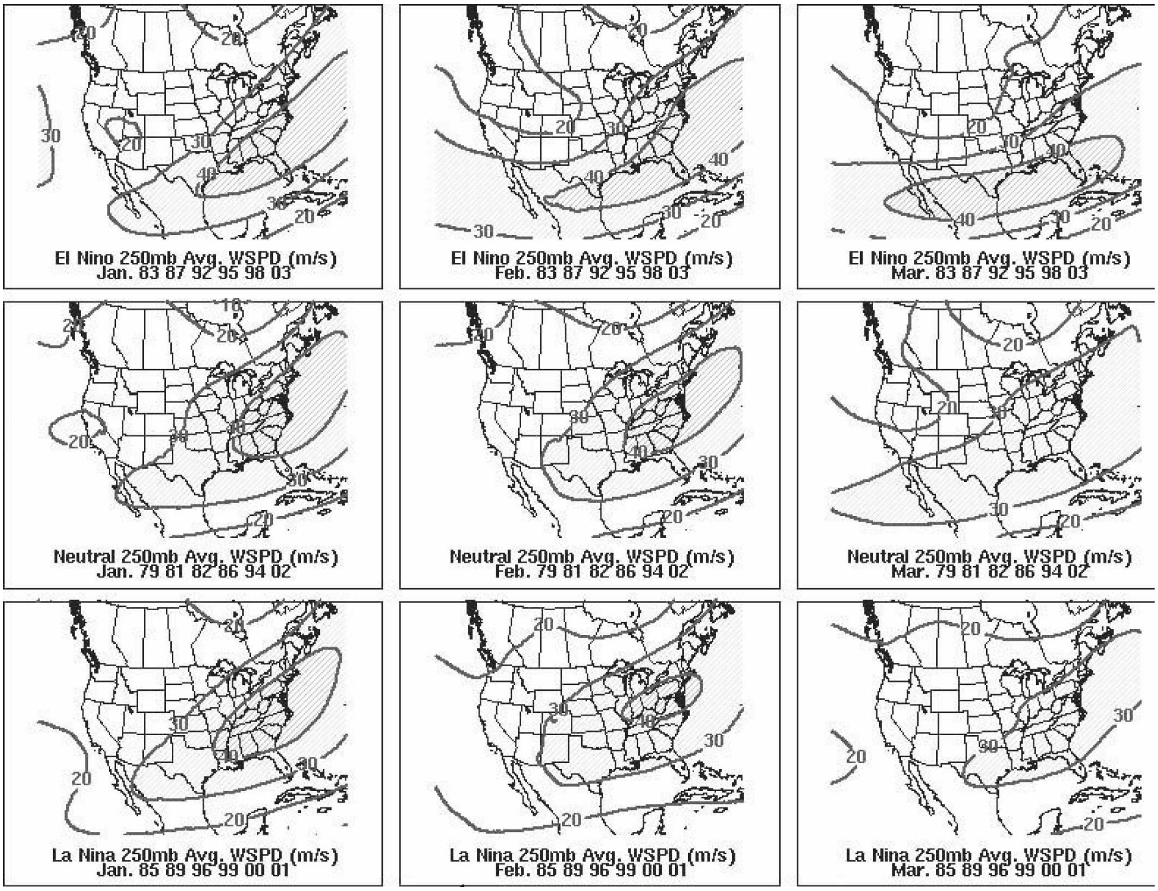

FIG. 6. Average wind speeds (m s^{-1}) in winter from 1979 through 2003, separated into ENSO phase with each month analyzed individually. Averages were computed using gridded NCEP reanalysis data (Mesinger et al. 2004). Notice the southwardly displaced and enhanced mean jet stream evident in El Niño months (especially March) relative to La Niña and neutral phase.

CONUS and appear to be related to the northward placement of maximum 250-hPa mean jet stream.

The ENSO-related winter tornado patterns are very similar to the tornado patterns found by Galway and Pearson (1981) in their study of synoptic systems that not only produced outbreaks of 10 or more tornadoes but also produced heavy snow or ice storms on the cold side of their surface low pressure system. They found two preferred storm tracks. The most common was a "Great Plains track" in which a surface low pressure area develops in west Texas, moves eastward through central Oklahoma, and then curves northeastward into western Michigan. The tornado activity with this track generally occurred from eastern Oklahoma and northern Louisiana northeastward into southern Illinois, very similar to the pattern of organized tornado activity during LN winters (Figs. 9a,b). This pattern is consistent with that found by Eichler and Higgins (2006), who discovered that surface cyclone storm tracks similar to the "Great Plains track" are prevalent during LN winters.

Galway and Pearson also identified a relatively rare "southeast track" in which the surface low forms in the Oklahoma–Texas Panhandle region and tracks east-southeastward across Arkansas, Mississippi, Alabama, and Georgia. This track is associated with tornadoes along the Gulf Coast, quite similar to the pattern of organized tornado activity during EN winters (Figs. 8a,b) and also consistent with Eichler and Higgins (2006), who found a southwardly displaced surface cyclone track during EN winter.

The relationship between ENSO phase and tornado activity is more complex than a simple relationship with jet stream position, however. Smith et al. (1998) found a connection between low-level wind fields and ENSO phase that potentially affects LN winter tornado activity. They noted that during the LN (cold) phase, an easterly displacement of the Bermuda anticyclone gives an anomalously convergent onshore flow at 850 hPa that concentrates low-level moisture across the lower Mississippi Valley. Although Smith et al. indicate higher variability in the LN (cold) phase low-level wind

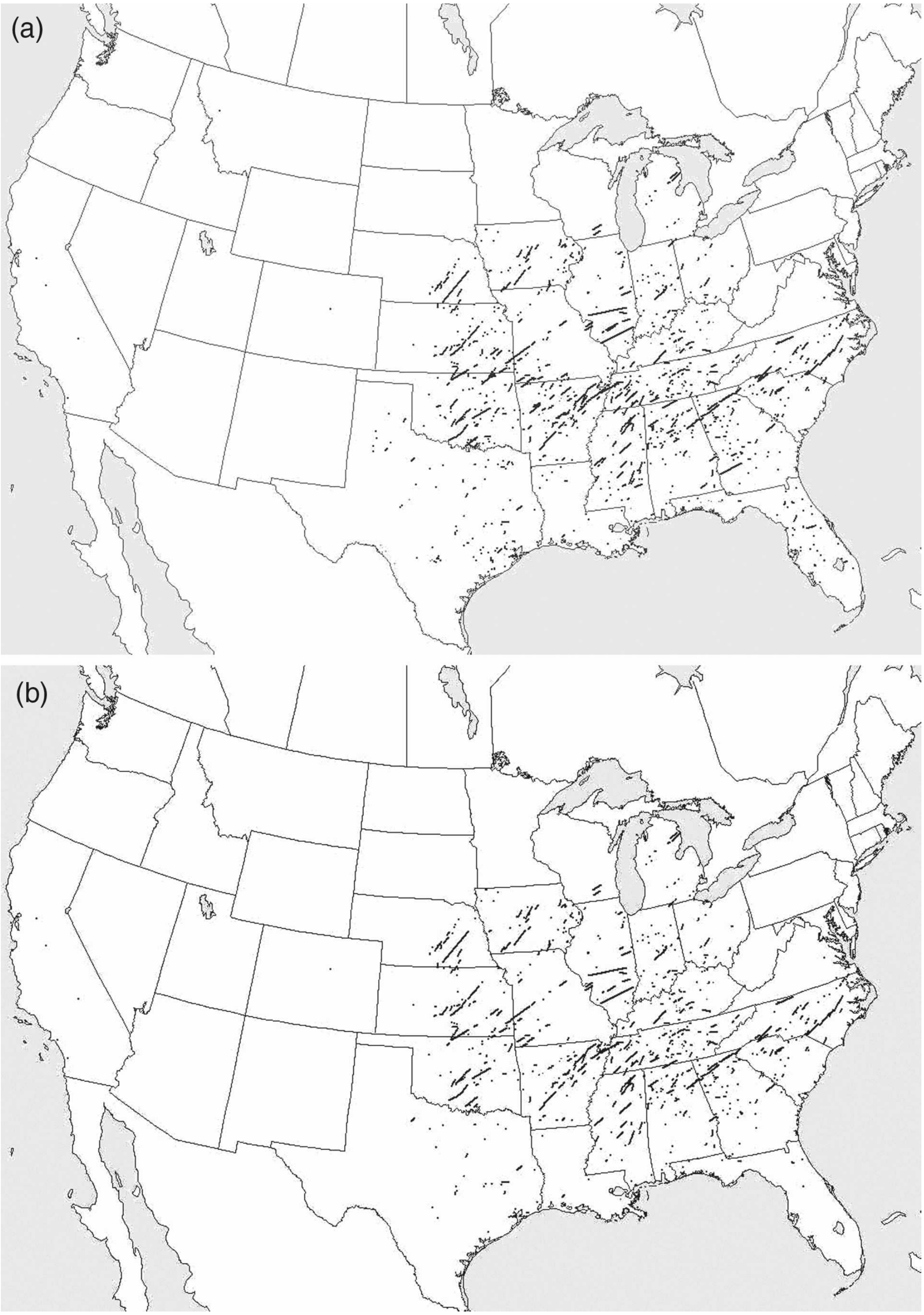

FIG. 7. (a) Tornadoes occurring on "tornado days" during the winter N phase. (b) Tornadoes occurring on "strong and violent tornado days" during the winter N phase.

FIG. 8. As in Fig. 7, but for the winter EN phase.

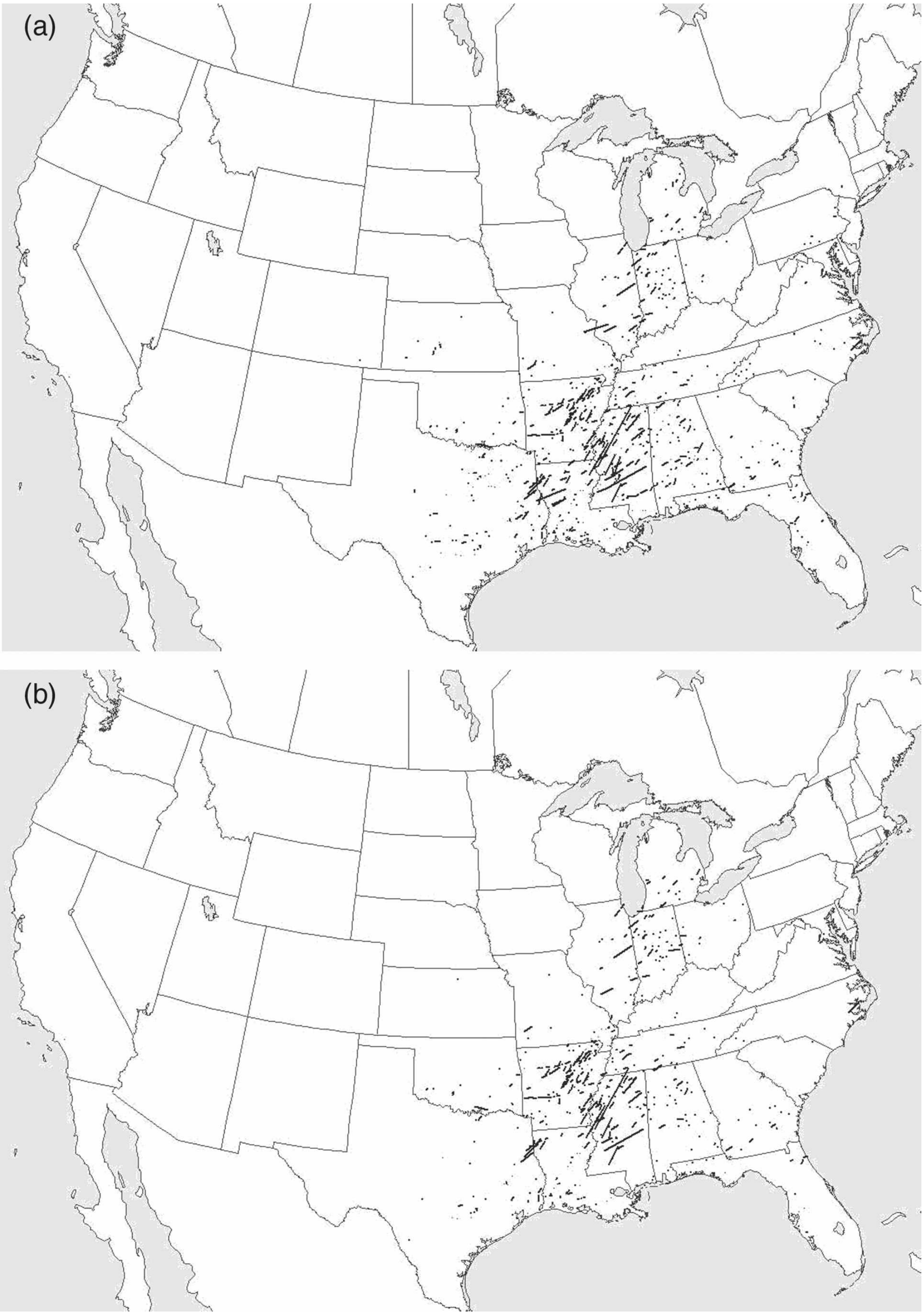

FIG. 9. As in Fig. 7, but for the winter LN phase.

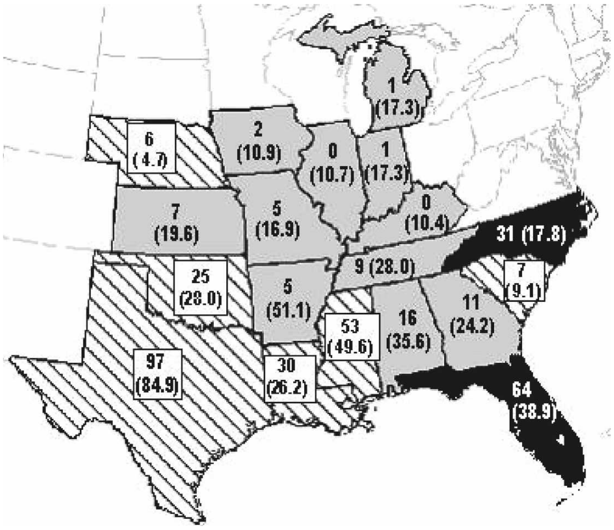

FIG. 10. Tornadoes occurring during EN winters by state. Numbers in parentheses are the expected values (independent of ENSO). Classifications of ENSO phase are made using the CPC ENSO phase classifications. States outlined in black experience greater than 125% of the expected number of tornadoes, while states outlined in gray experienced less than 75% of their expected value. States outlined in the stripes experience within 25% of the expected value of tornadoes.

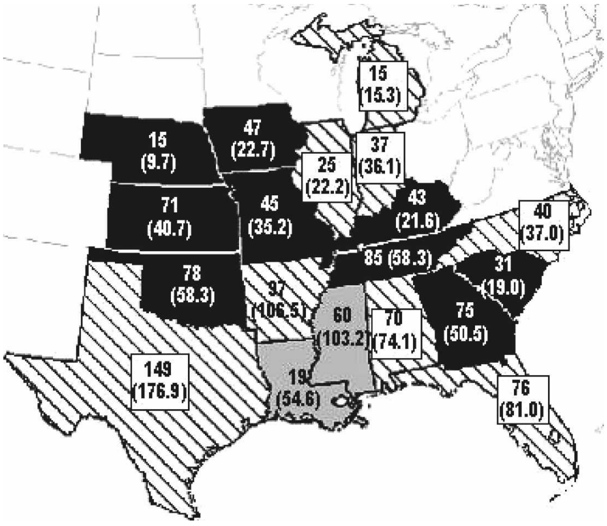

FIG. 11. Tornadoes occurring during N winters by state, as in Fig. 10.

fields relative to the EN (warm) phase, it seems that this phenomenon would tend to focus LN tornado activity into a narrow corridor across the lower Mississippi Valley northeastward into Michigan.

4. State-by-state statistical validation

To further investigate ENSO-related, regionally significant shifts in organized tornado activity, tornado counts for each individual state were tested to determine whether or not it can reasonably be assumed that the proportion of tornadoes occurring in each phase are equal (i.e., accept a null hypothesis). Figures 10–12 show state-by-state cumulative counts of tornadoes for each ENSO phase along with the "expected" number of tornadoes if there were no ENSO effects. This "expected number" is calculated by simply multiplying the cumulative number of tornadoes occurring in each state during the appropriate phase by the ratio of total number of seasons in that phase to the total number of seasons considered. [For example, Arkansas experienced 230 tornadoes on tornado days during the 54 yr in our study. Since there were 12 EN winter seasons, 17 LN winter seasons, and 25 N winter seasons, the "expected" or theoretical number of tornadoes is 51.1 (230 × 12/54) for EN, 72.4 for LN, and 106.5 for N.]

The various shadings for each state in Figs. 10–12 indicate if the observed value is different from the expected value by more than 25%. For example, Fig. 10 indicates that during EN winters, only two states (Florida and North Carolina) are dark, indicating that they experience substantially more (>125%) organized tornadoes than would be expected from an ENSO independent distribution (light shading). In contrast, during EN winters most of the states in the central plains and Great Lakes regions are shaded in gray, indicating that have had substantially less (<75%) storms than would be expected from an ENSO independent distribution.

Enhanced EN winter tornado activity in Florida

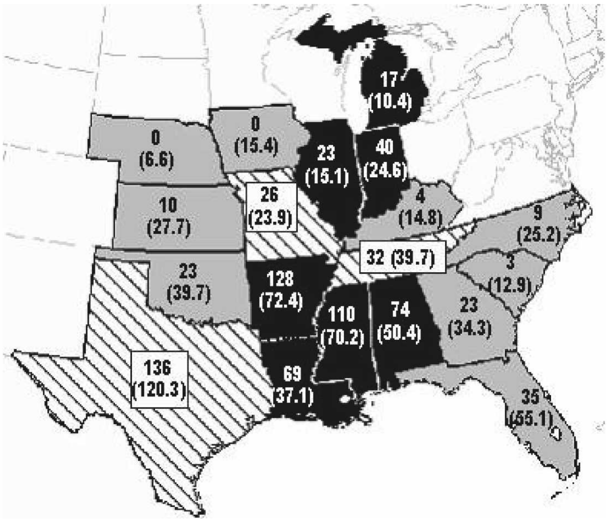

FIG. 12. Tornadoes occurring during LN winters by state, as in Fig. 10.

TABLE 4. DPI of tornadoes occurring on a winter tornado day sorted by state of initial touchdown and ENSO phase. Numbers in parentheses indicate the expected DPI independent of ENSO phase. States with fewer than 10 such tornadoes are omitted. States with fewer than 10 such tornadoes in all three phases are omitted. Boldface cells indicate that the observed values are less than 75% of the expected value. Italic cells indicate that observed value is greater than 125% of the expected value. Roman cells indicate that the observed value is within 25% of the expected value. In the χ^2 statistic column, n/a indicates that at least one of the categories for the state contained five or fewer events and that the χ^2 test could not be applied.

State	El Niño	La Niña	Neutral	χ^2 statistic
Texas	**90.7 (112.6)**	*260.9 (159.6)*	**155.3 (234.7)**	95.45
Oklahoma	**38.3 (85.8)**	**60.6 (121.6)**	*287.2 (178.8)*	122.66
Arkansas	**17.0 (337.1)**	389.3 (477.6)	*1110.7 (702.3)*	557.75
Louisiana	**18.9 (60.8)**	*245 (86.1)*	**9.7 (126.7)**	429.9
Mississippi	**122.9 (305.5)**	*962 (432.8)*	**289.7 (636.5)**	945.8
Tennessee	**10.8 (89.1)**	**81.2 (126.3)**	*309.1 (185.7)*	166.94
Alabama	**18.7 (104.3)**	**86.0 (147.8)**	*364.7 (217.3)*	196.05
Georgia	**5.3 (259.3)**	**24.1 (367.4)**	*1137.6 (540.3)*	1230
Florida	*20.6 (10.3)*	11.3 (14.6)	**14.5 (21.5)**	13.28
South Carolina	**0.4 (135.7)**	**0.3 (192.2)**	*609.0 (282.7)*	n/a
North Carolina	**7.1 (102.7)**	**9.9 (145.5)**	*445.3 (214.0)*	465.34
Kansas	**10.9 (135.6)**	**1.0 (192.0)**	*598.1 (282.4)*	n/a
Missouri	**2.0 (67.1)**	114.3 (95.1)	*185.7 (139.8)*	n/a
Nebraska	**0.0 (46.8)**	**0.0 (66.3)**	*210.7 (97.5)*	n/a
Iowa	**0.0 (38.9)**	**0.0 (55.1)**	*175.1 (81.1)*	n/a
Illinois	**0.0 (65.0)**	*242.0 (92.1)*	**50.4 (135.4)**	n/a
Indiana	**0.0 (34.8)**	*77.3 (49.3)*	79.4 (72.5)	n/a
Kentucky	**0.0 (29.5)**	**0.2 (41.7)**	*132.4 (61.4)*	n/a
Michigan	**0.3 (9.5)**	*19.6 (13.5)*	23 (19.9)	n/a

(Figs. 8a,b, 10) was also noted by Hagemeyer (1998). While the enhanced EN activity in North Carolina does not agree with our earlier speculation (section 3c), the small sample size (seven tornadoes occurring on winter tornado days) makes the applicability of the χ^2 test there questionable. Hoel (1962) notes that use of the χ^2 test with less than 4 degrees of freedom requires each category to contain "somewhat more than 5" events. Similarly, the small number of winter tornado day tornadoes during EN in North Carolina makes the result there somewhat dubious.

As a further test of the concept of ENSO driven changes in the geographic distribution of organized winter tornado activity, the DPI is examined by state (Table 4). The DPI data indicate that Florida is the only state with markedly stronger tornadoes containing longer tracks during EN winters. All other states had DPI totals lower than would be produced by an ENSO independent distribution. In LN, the axis of high DPI is oriented from the lower Mississippi Valley to the Great Lakes, and during N ENSO events the highest DPI is in a zone from Oklahoma/Kansas eastward through the Carolinas. These high DPI values generally corresponded spatially to the zone of the most frequent organized tornado activity during these phases (Figs. 7–9).

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

5. Four-tier classifications of ENSO phase

Although several definitions of ENSO exist, there is no universally accepted method for defining an ENSO event. To show the robustness of the previously identified ENSO-related shifts in areas most susceptible to organized winter tornado activity, a new classification scheme that incorporates other common definitions of the ENSO system was created.

This classification system is called the "composite 4-tier" scheme because it considers definitions of ENSO phase from four different sources:

1) the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml);
2) the Southern Oscillation index (SOI; Redmond and Koch 1991), which incorporates differences in sea level pressure between Tahiti and Darwin;
3) the bivariate ENSO time series (BEST) index (Smith and Sardeshmukh 2000), which is a bivariate combination of sea surface temperature anomalies in the Niño-3.4 region and the SOI; and
4) the multivariate ENSO Index (MEI; Wolter and

Timlin 1993, 1998), which is a nonlinear combination of sea surface temperature, surface air temperature, sea surface atmospheric pressure, zonal wind speed, meridional wind speed, and the fraction of the sky that is cloudless observed by buoy and ship observations in the equatorial Pacific.

TABLE 5. Composite four-tier classification scheme. Years classified as "LN/N" or "EN/N" were considered neutral (N).

Year	CPC	SOI	BEST	MEI	Composite 4-tier ENSO classification
1950	LN	N	N	LN	LN/N
1951	LN	LN	N	LN	LN
1952	N	EN	N	EN	EN/N
1953	N	N	N	EN	N
1954	N	EN	N	EN	EN/N
1955	LN	N	N	LN	LN/N
1956	LN	LN	N	LN	LN
1957	N	LN	N	LN	LN/N
1958	EN	EN	EN	EN	EN
1959	N	N	N	EN	N
1960	N	N	N	LN	N
1961	N	N	N	LN	N
1962	LN	N	N	LN	LN/N
1963	N	N	N	LN	N
1964	N	EN	N	EN	EN/N
1965	LN	LN	N	LN	LN
1966	EN	EN	N	EN	EN
1967	N	N	N	LN	N
1968	LN	N	N	LN	LN/N
1969	EN	N	N	EN	EN/N
1970	N	EN	N	EN	EN/N
1971	LN	LN	LN	LN	LN
1972	N	LN	N	LN	LN/N
1973	EN	EN	EN	EN	EN
1974	LN	LN	LN	LN	LN
1975	LN	LN	N	LN	LN
1976	LN	LN	N	LN	LN
1977	EN	EN	N	EN	EN
1978	N	EN	N	EN	EN/N
1979	N	N	N	EN	N
1980	N	N	N	EN	N
1981	N	N	N	EN	N
1982	N	N	N	LN	N
1983	EN	EN	EN	EN	EN
1984	N	N	N	LN	N
1985	LN	N	N	LN	LN/N
1986	N	N	N	LN	N
1987	EN	N	EN	EN	EN
1988	EN	EN	N	EN	EN
1989	LN	LN	N	LN	LN
1990	N	N	N	EN	N
1991	N	N	N	EN	N
1992	EN	EN	EN	EN	EN
1993	N	EN	N	EN	EN/N
1994	N	EN	N	EN	N
1995	EN	EN	N	EN	EN
1996	LN	N	N	LN	LN/N
1997	N	N	N	LN	N
1998	EN	EN	EN	EN	EN
1999	LN	LN	N	LN	LN
2000	LN	N	N	LN	LN/N
2001	LN	LN	N	LN	LN
2002	N	N	N	LN	N
2003	EN	EN	N	EN	EN

Applying this scheme was a two-step process. First, each winter was classified using each of the four indexes (Table 5). Then, the composite 4-tier classification was determined from the majority of individual components. For instance, if at least three of the classifications indicated EN conditions for the winter, the ENSO phase for that season was specified as EN. To be conservative in the classification, if two of the indices indicated EN (or LN) while two other sources indicated N, the ENSO phase was considered as indeterminate and that winter season was classified as N. (Note, the multivariate ENSO index only defines a bimonthly period as EN or LN.)

Under the composite 4-tier classification scheme, seven winter seasons previously classified as LN by CPC were reclassified as N (1950, 1955, 1962, 1968, 1985, 1996, and 2000), and one winter season previously classified as EN was reclassified as N (1969). All of the winters previously classified as N held their same classification under the 4-tier scheme.

Since there were no winter outbreaks in 1969, the EN phase tornado activity did not change. However, there were 11 tornado days (and 133 corresponding tornadoes) during the seven winters that were reclassified from LN to N under the 4-tier classification system (Table 6). Despite the fact that this led to some major changes in the statistical analyses, spatial shifts in tornado occurrence remained similar to those seen when CPC ENSO classifications were used. Tornado activity still appeared to be displaced to the south during the EN phase, while occurring at higher latitudes during the N phase and occurring primarily along an axis from the lower Mississippi Valley to the western Great Lakes during LN. State-by-state statistical analyses using the composite 4-tier classification (Figs. 13–15) are similar to their counterparts using the CPC classification (Figs. 10–12). State-by-state statistical analyses of DPI also show a very high ENSO phase dependence following this general pattern.

The yearly average of winter tornado days per winter changes very little under the composite 4-tier classification system (not shown) and the χ^2 statistic for the frequency of both tornado days and violent tornadoe days remains below the critical value for both classification schemes. This further justifies the hypothesis that on the national scale there is no basis for rejecting

TABLE 6. Comparison of statistics using the composite 4-tier ENSO classification and the CPC ENSO classification.

	CPC ENSO classification				Composite 4-tier ENSO classification			
	El Niño	La Niña	Neutral	χ^2 statistic	El Niño	La Niña	Neutral	χ^2 statistic
Total tornadoes	395	772	1121		395	639	1254	
Expected number of tornadoes	508.44	720.30	1059.26	32.62	466.07	423.70	1398.22	135.11
Total DPI	519.8	2586.7	6247.7		519.8	2476.4	6358	
Expected DPI	2078.71	2944.84	4330.65	2061.27	1905.49	1732.26	5716.46	1399.35
Average DPI per tornado day	14.44	51.07	84.44	14.27	14.44	62.34	74.82	54.01
Total number of tornado days	37	51	74		37	40	85	
Average per year	3.08	3.00	2.96		3.36	4.00	2.58	
Number of years	12	17	25		11	10	33	

an assumption that there is no ENSO dependence on the frequency of organized winter tornadoes. However, a state-by-state statistical analyses of DPI shows a very high ENSO dependence that is statistically significant.

6. Discussion and 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. El Niño episodes are associated with cool and wet winters in the Gulf Coast states and wet winters in Southern California. In contrast, La Niña 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 1992; Ropelewski and Halpert 1987, 1989).

However, as the scale of the meteorological phenomenon becomes smaller, the influence of synoptic-scale features decreases. The ingredients necessary for thunderstorm development (McNulty 1985) are only a small subset of those required for tornadogenesis (Johns and Doswell 1992). These differences are reflected in the findings of Galway (1979) that there is no validity to the hypothesis that tornado activity is at a minimum during dry weather regimes.

Tornado development requires not only the horizontal and vertical juxtaposing of the temperature, moisture, 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

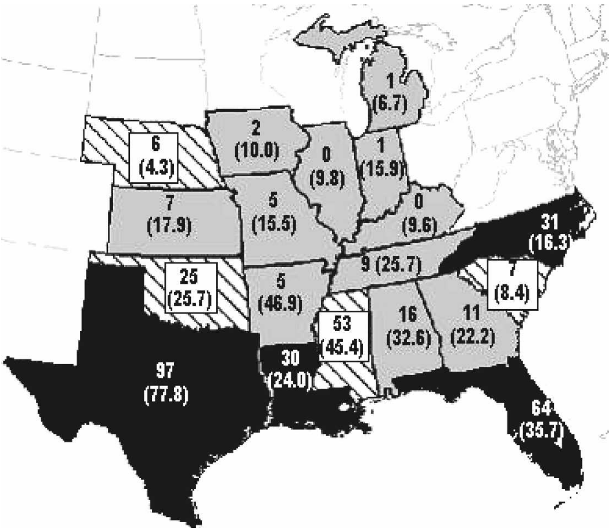

FIG. 13. Tornadoes occurring during EN winters by state. Numbers in parentheses are the expected values (independent of ENSO). Classifications of ENSO phase are made using the 4-tier scheme. States outlined in black experience greater than 125% of the expected number of tornadoes, while states outlined in gray experienced less than 75% of their expected value. States outlined in the stripes experience within 25% of their expected value of tornadoes.

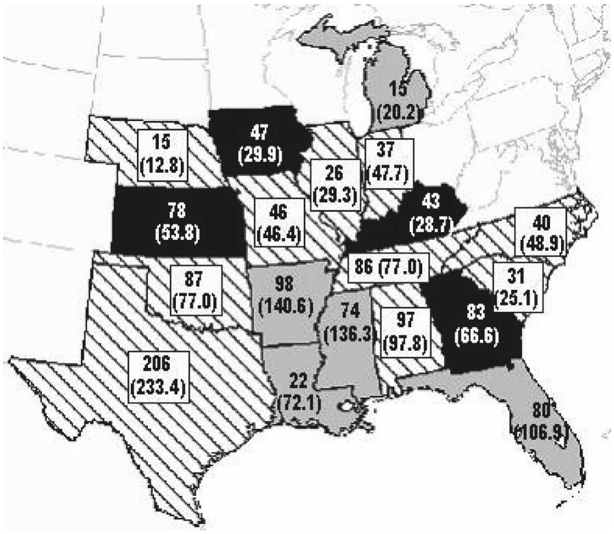

FIG. 14. Tornadoes occurring during N winters by state as in Fig. 13. The composite 4-tier ENSO classification scheme is used here.

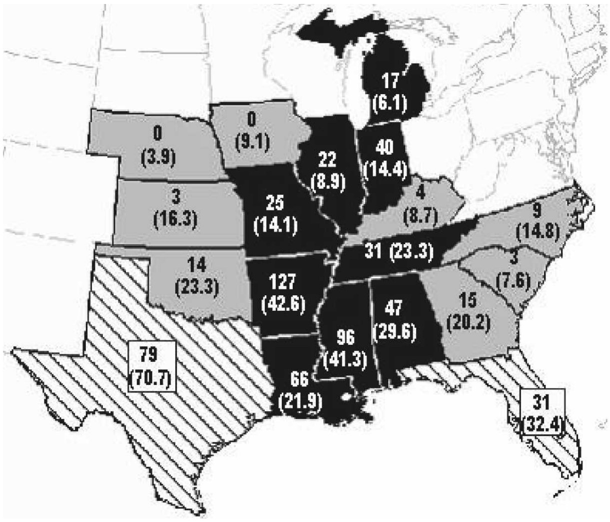

FIG. 15. Tornadoes occurring during LN winters by state as in Fig. 13. The composite 4-tier ENSO classification scheme is used here.

can be generated. Because of the importance of mesoscale and smaller processes, it is seen that tornado activity during the winter is not directly related to ENSO. However it is modulated by synoptic-scale features (i.e., jet streams) which are, in turn, affected by ENSO phase. Large-scale conditions by themselves do not set the stage for organized tornado activity.

It is well known that there was significant underreporting of tornadoes in the 1950s, 1960s, 1970s, and 1980s, and likely through the early 1990s before the deployment of Weather Surveillance Radar-1988 Doppler (WSR-88D) and increased National Weather Service (NWS) warning verification efforts (Schaefer et al. 2002). It is more difficult to speculate whether this underreporting would extend to tornado outbreaks, especially since the most significant tornadoes (causing property damage or casualties) were documented relatively well. However, it is fair to assume that some outbreaks were likely missed or were not counted because of the underreporting of individual tornadoes, with the likelihood of missed outbreaks increasing as you go back in time. The encouraging aspect of this is that a signal consistent with large-scale features observed in particular ENSO phases does exist despite the apparent weaknesses in the dataset.

Another point that needs to be addressed is the higher frequency of LN events earlier in the study period (when underreporting was most likely) and a higher frequency of EN events later in the study period (when underreporting is less of a problem). While this could skew these results, Fig. 16 indicates that there appears to be a fairly even distribution of winter tornado outbreaks regardless of ENSO phase since 1970.

The statistical analysis presented in section 4 gives credence to the following heuristic postulates:

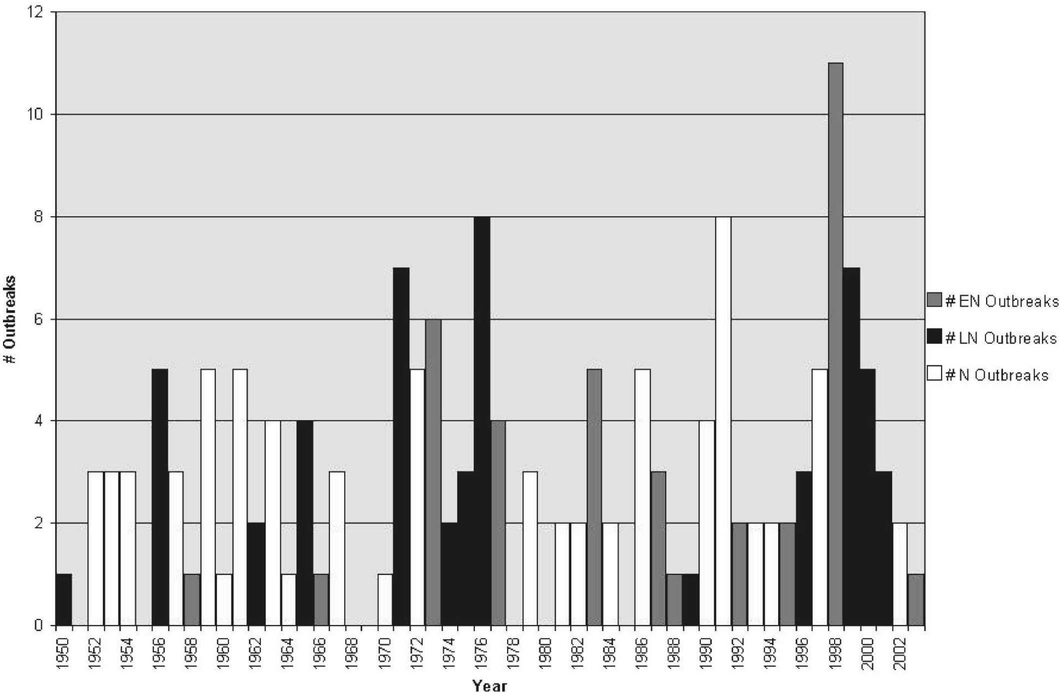

FIG. 16. Number of winter tornado days per year (CPC ENSO classifications). Shading indicates ENSO phase.

1) During El Niño winters organized tornado activity in the CONUS is generally restricted to the area immediately adjacent to the Gulf of Mexico.
2) During La Niña conditions, the states with substantially enhanced activity all lie within the southwest–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.
3) During neutral winters, organized tornado activity is most prevalent in a west–east zone across the midsection of the country. Oklahoma, Kansas, Tennessee, and Georgia (with its elongated north–south dimension) all have substantially more activity than would be expected. States to the south (Louisiana and Mississippi) had markedly fewer tornadoes on tornado days, while intervening states such as Arkansas, Missouri, Nebraska, Kentucky, and South Carolina experienced too few events in one of the ENSO phases for the χ^2 test to be valid.
4) Even though statistically significant differences in the frequency of tornadoes are not seen in examinations of pure tornado counts (Marzban and Schaefer 2001), differences become evident when the frequency of 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 La Niña and neutral winters compared to El Niño winters is seen.
5) The apparent response of organized tornado activity to ENSO phase is a nonlinear one driven by meteorological processes rather than conditions in the tropical Pacific. Neither ENSO extreme (warm nor cold phase) is related to as significant of an increase in organized tornado activity as the intermediate neutral phase is.

The last point emphasizes 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 and geographic factors cause organized tornado activity. At times, this activity will occur in atypical places. One example is the local tornado outbreak that occurred in southern Minnesota on 29 March 1998, an EN year when the climatologically preferred area for tornado activity was along the Gulf Coast. Remember, the ENSO phase by itself is not a tornado forecast tool, nor is it a historical proxy to gauge a past winter's tornado activity.

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