21st Conference on Climate Variability and Change / 89th Annual Meeting of the American Meteorological Society 11 - 25 January, 2009, Phoenix, AZ

9A.1 Can Large Scale Climate Controls Help Predict Seasonal Tornado Activity?

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1. INTRODUCTION

The occurrence of severe weather can be forecast on the short time scales by examining synoptic–scale data that is routinely available to the operational community and disseminated by the National Centers for Environmental Prediction. Over the years, several indexes and rules have been developed in order to provide guidance for short range forecasting.

Recently, attempts to quantify the interannual variability of tornado occurrences have been done in order to provide guidance about how severe a tornado season may become. But, these have had mixed degrees of success and thus, no tools have been developed in a similar manner to those of hurricanes (e.g., Lupo et al. 2008).

For example, Schaefer and Tatom (1998) found very weak and statistically insignificant relationships between ENSO and tornado occurrences across various regions of North America. Agee and Zurn-Birkhimer (1998) found that there were no significant ENSO-related interannual variations in tornado occurrences nationwide, but that there were geographical shifts in the areas of maximum occurrence. They found severe weather season to be more active in El Nino years across tornado alley. Cook and Schaefer (2008) found that tornado activity is more active during La Nina years across much of the Midwest and plains.

However, Bove (1998) found that this region experiences significantly more tornado events during La Nina (LN) years using bootstrap techniques to enlarge the data set. Marzban and Schaefer (2001) found that there was a weak, but significant, tendency for more tornado occurrences in tornado alley (the plains states) during LN months, and thus, by extension, LN seasons. Wikle and Anderson (2003) reported similar results to Marzban and Schaefer (2001) over the western plains states using a Bayesian Spatio-Temporal model.

Akyuz et al. (2004) examine tornado occurrences across a smaller region of the southern plans and found that there were more tornadoes during El Nino years, although this result was not statistically significant in the 1950 – 2002 time period. When they examined only the 1977 – 1999 period, or during the positive phase of the Pacific Decadal Oscillation (e.g. Gershunov and Barnett, 1998; Kelsey et al. 2007), they found that this correlation was stronger.

Thus, in this study an examination of the influence that large-scale climate variables have on tornado activity will be examined here. We will examine a 13 state region in the Midwest and South as well as focusing on the four state region that Akyuz et al. (2004) examined. The work of Akyuz et al. (2004) will be updated also extending their study period through the year 2008.

2. DATA AND METHODOLOGY

Multiple variables used for this study. The first and most basic dataset was the National Centers for Environmental Predication-National Center for Atmospheric Research (NCEP-NCAR) gridded reanalyses. More detail about this dataset can be found in Kalnay et al. (1996). Archived at NCAR in Boulder, Colorado, these analyses are available from their mass-store facilities. The reanalyses can be located at (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html).

The re-analyses used here were the 2.5 degrees by 2.5 degrees latitude-longitude gridded analyses available on 17 mandatory levels from 1000 to 10 hPa at 6-h intervals. These analyses include standard atmospheric variables such as geopotential height, temperature, relative humidity, vertical motion, *u* and *v* wind components and surface information

Figure 1 shows the region of concern for this study. For this region, we used all tornado counts. A climatology of tornadoes of F2 intensity or greater only were compiled for Iowa, Kansas, Nebraska, and Missouri from 1950 through 2008 using data acquired from the Storm Prediction Center (SPC) (*http://www.spc.noaa.gov/archive/*). Data from 2003–2008 were simply used to supplement that from Akyuz et al. (2004).

A synoptic and large-scale analysis was performed in order to relate tornado occurrences with the larger-scale environment. Relating the planetary-scale to the synoptic and mesoscale, however, can also be problematic due to the fact that there are complex scale interactions which cannot be accounted for using these simple techniques (e.g., Yarnal, 1993) and these interactions may be highly non-linear (e.g.,

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Yarnal, 1993; Lupo, 1997). Even with these difficulties, however, and in order to be valid, any credible statistical result regarding the interannual variability of tornado occurrence, whether they are strong or weak, should be at least physically consistent with the composite synoptic variability and the interannual variability found in large-scale patterns as found by previous studies. Finally, the 1950 – 2008 time-period is a long enough period of time to include several El Nino (14) and La Nina (15) events and to examine the interdecadal variability.

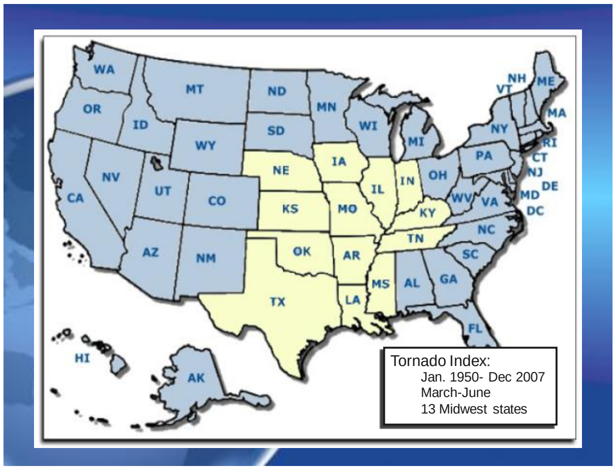


Figure 1. The large-scale study region.

2.1 definitions

All tornado occurrences were stratified by EN, neutral (NEU) and La Nina years (LN) in order to determine whether large-scale flow regime variations associated with sea surface temperature (SST) variations in the Pacific Ocean basin were reflected in the tornado climatology. See Akyuz et al. (2004) for more details regarding the complete data set. For this study, the years 2003 and 2007 were considered El Nino years, while 2004-2006 were neutral years, and 2008 was considered a La Nina year.

The reader will find a list of EN, LN, and NEU years (Table 1), as well as a more detailed description of the Japan Meteorological Agency (JMA) ENSO Index, by accessing the Center for Ocean and Atmospheric Prediction Studies (COAPS) website (http://www.coaps.fsu.edu). In summary, the index classifies years as EN, LN, and NEU based on 5-month running-mean Pacific Ocean basin sea surface temperatures (SST) anomaly thresholds bounded by the both the Nino 3 and 3.4 regions in the central and eastern tropical Pacific. The SST anomaly thresholds used to define EN and years are those greater and less than +0.5^o C, less than -0.5^o C, respectively, and NEU otherwise. For classification as an EN or LN year, these values must persist for six consecutive months including October, November, and December.

The JMA ENSO criterion defined the El Nino year as beginning on 1 October of the previous year. Thus, for example, the ENSO year 1970 begins in October of 1970 (Table 1) and ends in September 1971. Since most tornado occurrences during the spring and summer (April to June throughout the region studied is the peak time for tornado occurrences[2]), all calendar year 1971 tornadoes were considered ENSO year "1970" in order to remain consistent with the JMA criterion in our analysis. This study noted very few tornado occurrences across the region during October through December period in general, and a separate analysis of this period did not reveal any statistically significant variations and constitute a small sample. Since also the peak of tornado occurrences across this region was April to June or July[2], while ENSO typically sets in during the late fall and early winter of the previous year, the use of these annual statistics implicitly included a 4 to 6 month lag between ENSO onset and the bulk of tornado season. This was appropriate since there are many published papers which demonstrate that there is approximately a 3 to 6 month lag between the SST distributions in the Pacific region and the general circulation over North America (e.g., Namias, 1982, 1983; Hoskins et al., 1983; Park and Kung, 1988; Lee and Kung, 2000.

3. LONG TERM TRENDS AND VARIABILITY

Figure 2 shows the raw tornado counts over the 13 state region from 1950 to 2007. A strong (statistically significant) increase is shown here, which several studies have attributed to better observation techniques and increased populations making it difficult to assume natural or anthropogenic climate change would be responsible for the increase (e,g, Akyuz et al., 2004; Diffenbaugh and Trapp, 2008). Many studies, therefore, analyze F2 and stronger (significant) tornadoes only. Fig. 3 shows the trend for significant tornado occurrence in Missouri only from 1950 to 2008. A downward trend is evident here and this would be statistically significant if tornado occurrences from Iowa, Kansas, and Nebraska were included (not shown).

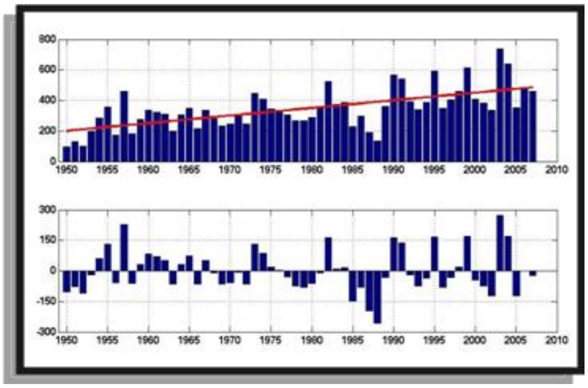


Figure 2. (top) The raw tornado counts for the 13 state region shown in Fig. 1. The red line represents the trend. (bottom) The raw tornado counts after detrending the data.

The inclusion of tornado occurrences for the year 2003-2008 did not change the character of the overall ENSO variability found by Akyuz et al. (2004) for their four state region. In short, over the region there were more tornadoes regionally and in three states (IA, MO, and KS) during El Nino years. Only in Nebraska were there more tornadoes during La Nina years, and this pattern persisted into the 2003-2008 period.

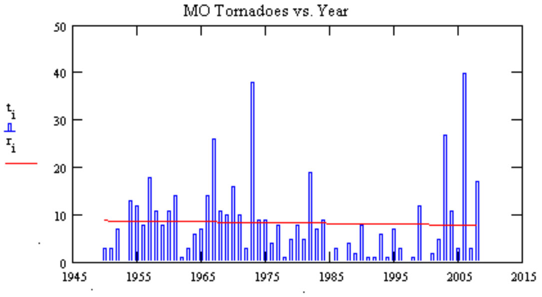


Figure 3. As in Fig. 2 (top), except for Missouri only and for significant tornadoes.

In examining interdecadal variability, Akyuz et al. (2004) showed that during PDO1 years, ENSO neutral years were more active than El Nino or La Nina years, and this relationship was significant at the 90% confidence level. They also showed that during PDO2, El Nino years were more active, but this result was not statistically significant. Table 1 shows the number of tornado occurrences for the top ten most active years during each period. The inclusion of the data after 2002 does not change this overall interpretation of the data set.

Table 1. The 10 most productive significant tornado producing years for the PDO2 and PDO1 period. The modified tornado occurrences (see Akyuz et al. 2004) are used for the earlier period.

Rank	PDO 2 (1950–76, 1999-2008)	PDO 1 (1977–98)
	Torn/Year/ENSO	Torn/Year/ENSO
1	70 / 2008 / LA	51 / 1990 / NEU
2	50 / 1964 / EL	48 / 1991 / NEU
3	48 / 2006 / NEU	45 / 1984 / NEU
4	47 / 2003 / EL	44 / 1982 / NEU
5	46 / 1967 / NEU	41 / 1993 / NEU
6	39 / 1973 / EL	32 / 1995 / NEU
7	38 / 2004 / NEU	31 / 1992 / EL
8	36 / 1965 / LA	31 / 1980 / NEU
9	35 / 2007 / EL	28 / 1977 / EL
10	33 / 1999 / LA	26 / 1986 / EL

4. COMPOSITE LARGE-SCALE ANALYSIS

An examination of the large-scale patterns will use the composite maps for the spring months (April – June) when tornado occurrence should be at a maximum. Thus, we will be able to determine if there is any significant difference between the large-scale flow in active versus non-active years.

4.1 A comparison of composites for individual seasons

The composite variables used here were sea level pressure (hPa), 925 hPa specific humidity (kg kg^{-1}), 850 hPa and 300 hPa geopotential heights (m), 850 hPa temperature (^{o}C), and 300 hPa vector winds (m s^{-1}). We used these variables to infer relevant larger-scale dynamic quantities such as upper level divergence, tropospheric directional and/or speed shear, or the importance of various quantities such as available moisture. These quantities are some examples of variables used by forecasters in assessing the threat or risk of severe weather in short range forecasting and nowcasting from the large and synoptic-scale pattern.

First, we examine the composite of the second most active year, which was an ENSO neutral year. For the 1991 composite (Fig. 4), all the favorable ingredients for severe weather formation were in place including a composite surface low along the Texas-New Mexico border (Fig. 4a), more low-level moisture (Fig. 4b), and stronger tropospheric shear than any of the other years examined for this study (Fig. 4). The upper level divergence was likely enhanced over the four-state region as it was located within the equatorward (poleward) entrance (exit) region of a downstream (upstream) and relatively poleward (equatorward) large-scale jet maximum (Fig. 4f). Rogers and Bosart (1991) also described this scenario for enhanced upper level divergence for flow regimes off the east coast of North America. Additionally, the 850-hPa temperatures were warmer in this composite than in any other composite year examined (Fig. 4d). Thus, the composite, which represents the sum total of individual days within April to June 1991 period, demonstrates this season would have a reasonably better chance at producing more severe weather events than the other three composites.

In order to demonstrate in a quantitative sense which of these composites represented a more favorable environment for the production of severe weather events, two simple and commonly used empirical severe weather indicies (Total Totals and SWeaT indicies) were estimated for three locations that launch twice-daily radiosondes within the four state region (Table 2). These indicies are empirical estimates of the stability and/or baroclinicity in the lower troposphere. We concede here that the values produced by this composite

Table 2. The Total Totals (TT)/Severe Weather Threat (SWeaT) index values for three locations within the four state region studied here for five composite tornado seasons.

Location	1956	1958	1983	1991	2000
Omaha, NE (KOAX)	43 / 197	45 / 215	46 / 202	48 / 236	44 / 218
Topeka, KS (KTOP)	45 / 207	46 / 224	46 / 209	48 / 246	44 / 236
Springfield, MO (KSGF)	44 / 240	44 / 208	44 / 199	46 / 240	43 / 245

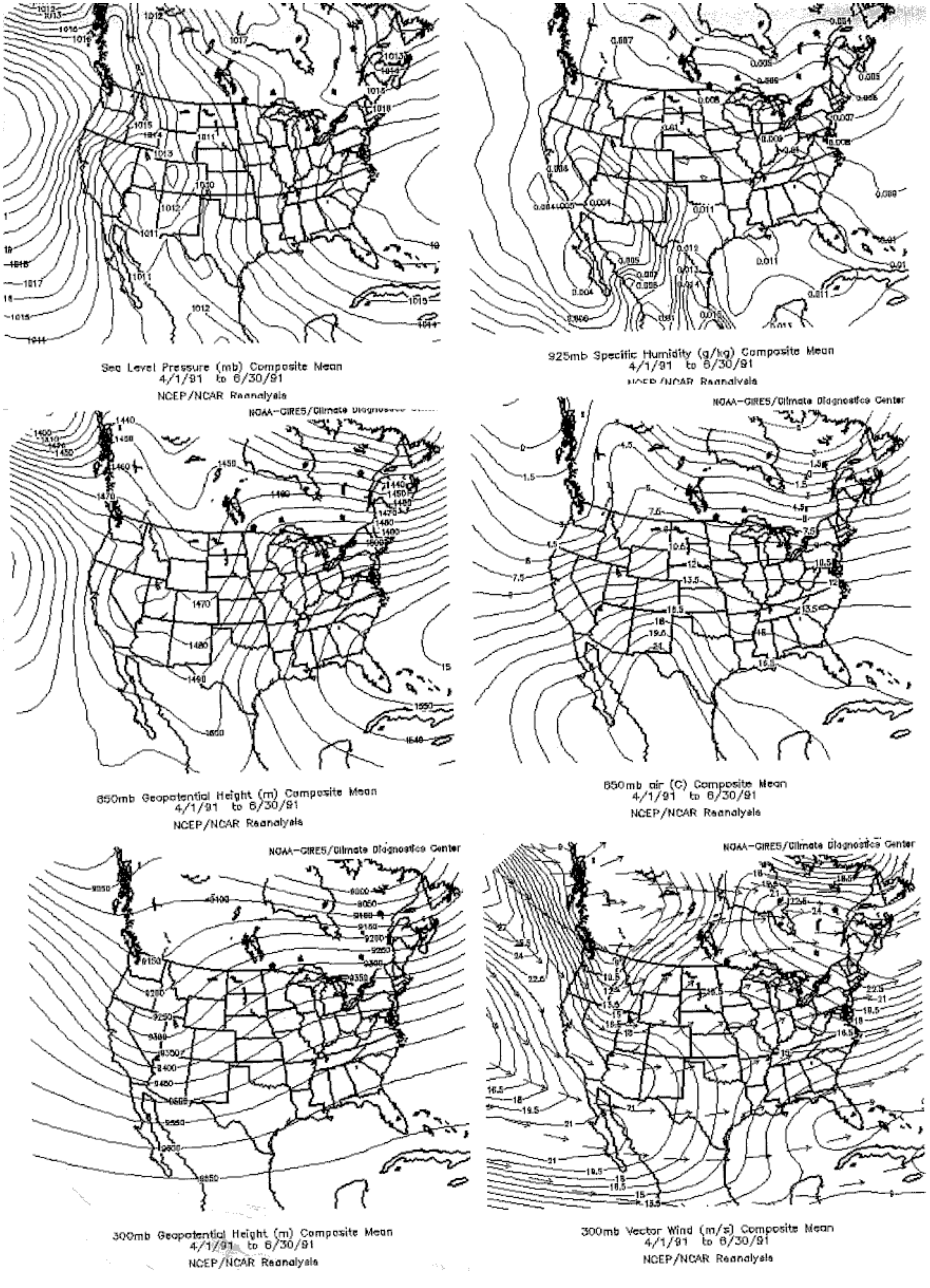
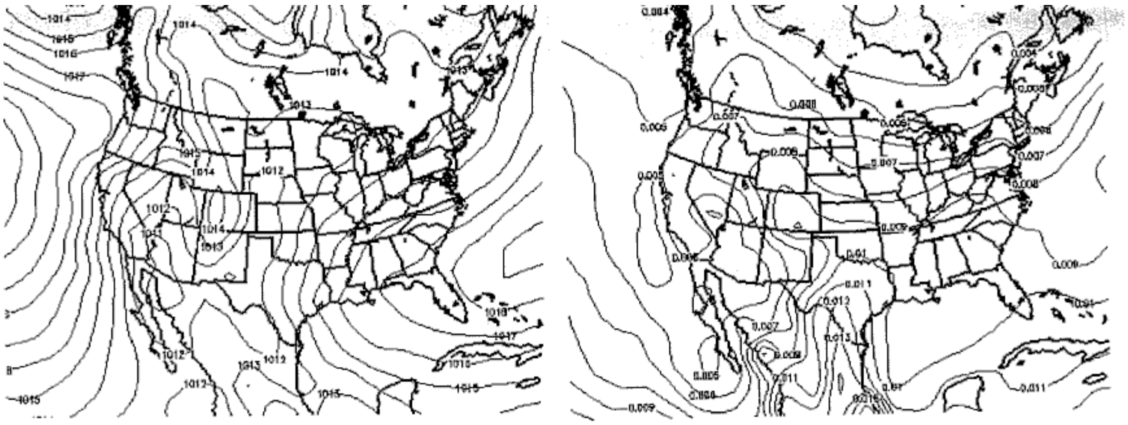
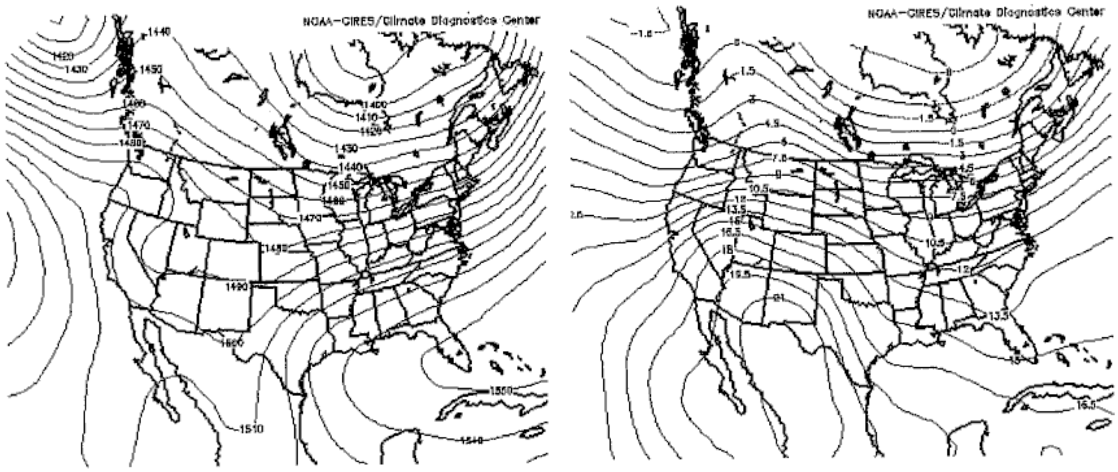


Figure 4. The synoptic composites using the NCEP re-analyses for 1 April to 30 June 1991 of a) sea level pressure (hPa, contour interval every 4 hPa), b) 925 hPa specific humidity (g kg^{-1}, 0.00025 g kg^{-1}), c) 850 hPa heights (m, 30 m), d) 850 hPa temperatures (^{o}C, 1.5 ^{o}C), e) 300 hPa heights (m, 120m), and f) winds (m s^{-1}, 1.5 m s^{-1}).



Sea Level Pressure (mb) Composite Mean
4/1/00 to 6/30/00
NCEP/NCAR Reanalysis

925mb Specific Humidity (g/kg) Composite Mean
4/1/00 to 6/30/00
NCEP/NCAR Reanalysis

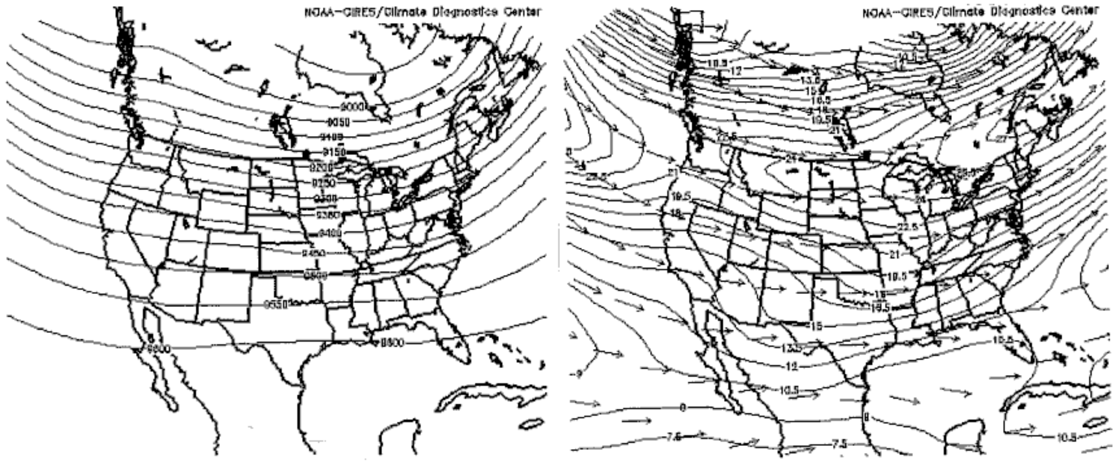


NOAA–CIRES/Climate Diagnostics Center

850mb Geopotential Height (m) Composite Mean
4/1/00 to 6/30/00
NCEP/NCAR Reanalysis

NOAA–CIRES/Climate Diagnostics Center

850mb air (C) Composite Mean
4/1/00 to 6/30/00
NCEP/NCAR Reanalysis



NOAA–CIRES/Climate Diagnostics Center

300mb Geopotential Height (m) Composite Mean
4/1/00 to 6/30/00
NCEP/NCAR Reanalysis

NOAA–CIRES/Climate Diagnostics Center

300mb Vector Wind (m/s) Composite Mean
4/1/00 to 6/30/00
NCEP/NCAR Reanalysis

Figure 5. As in Fig. 4, except for the year 2000.

analysis will not meet the threshold values for severe weather, and that the thresholds may be attained during a particular synoptic time. These index values produced for each composite did provide, however, in a relative sense, an estimate of which environment would be more favorable for producing severe weather including tornadoes. The index values for composite period of 1991 (Table 2) produced the highest values, and thus as inferred from the synoptic maps, severe weather and tornado occurrences would be most favored for producing severe weather of the composites shown.

In order to examine a composite season that stood in contrast with 1991 in terms of tornado occurrences, the spring for 2000 was chosen (Fig. 5). Only nine significant tornadoes occurred during that year, six of which occurred during the April to June period, and the year was considered to be an LN year. Table 2 also revealed that the composite Total Totals and SWeaT indicies were lower than the 1991 values. Then, as may be expected, the difference in the number of significant tornado events between the years 1956, 1958, 1983, and 2000 was controlled by smaller scale processes than could be examined here. The year 1991, nonetheless, stood out as a year where the synoptic and large-scale composite flows would reveal a more favorable background setting for severe weather production.

4.2 A comparison of multiple season composites

In this analysis, we looked at the composites over North America from March – June for the 12 most and least active tornado seasons during the 1950 – 2008 period for our 13 state region. Here, we do not consider ENSO variations per se, and this could be examined with further analysis.

Figure 6 shows the moisture flux and flux convergence for the 12 most (least) active years [top(bottom) panel]. The green color and arrows in the top panel represent strong moisture fluxes and flux convergence into our study region, while the bottom panel shows that drier air was consistently moving into the study region. The strong moisture flux in Fig. 6 (top) is especially strong within the four-state subset discussed in section 3. Thus, it would be expected that there was sufficient moisture present for the production of storms.

Tropospheric winds are shown here in Fig. 7 for the 500 hPa (925 hPa) wind vectors [top(bottom) panel] for the 12 most active tornado seasons. These figures display quite clearly that there is strong veering with height over the region indicating strong baroclinicity over the study region. Additionally, such rotational shear would be an important ingredient for generating the mesoscale helicity sufficient for the production of severe weather, including tornadoes (e.g., Johns and Doswell, 1992). Thus, between the moisture availability and the dynamic shear (Figs. 6 and 7), these composite years should be more conducive to severe weather production.

5. CONCLUSIONS

An analysis of tornado activity over 13 states within the Midwest and Southern United States has revealed the importance of considering not only interannual but also longer-term variability in severe weather occurrences and their relationship to variability in the synoptic flow regimes. This information can then be used by forecasters to generate seasonal forecasts of tornado activity in a manner similar to that of, for example, hurricanes.

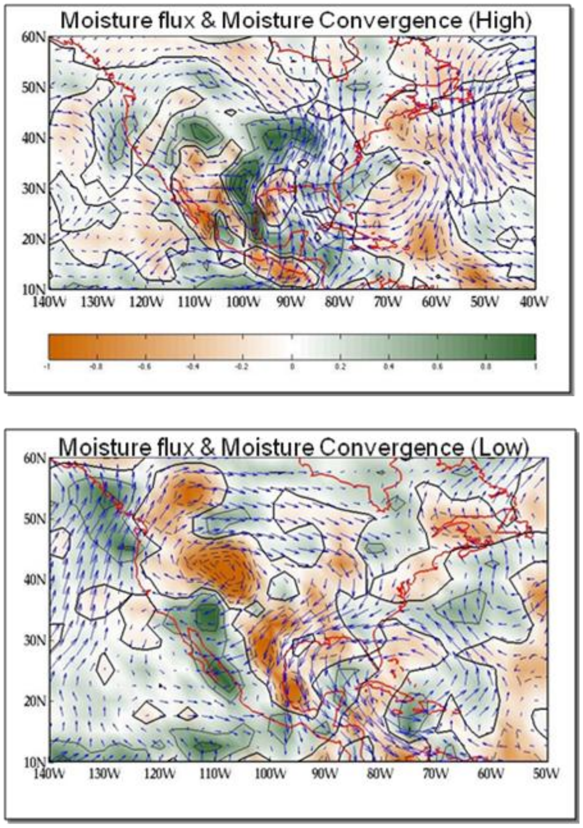


Figure 6. Moisture flux (arrows), and moisture convergence (convergence – green, and divergence – red), for the 12 (top) most and (bottom) least active tornado seasons.

The tornado climatology across the region was generated using archived tornado data from SPC for the time period 1950 through 2008. We then examined a four state region in which only F2 tornadoes were considered since F0 and F1 tornado occurrence numbers have dramatically increased due to external factors (e.g., technology, increased populations, etc). This data set was largely available from Akyuz et al. (2004) and the years 2003 – 2008 were added here.

There was little ENSO-related variability found in the 59 years of raw tornado occurrences with EL years producing slightly more events, thus the additional years did not change the results of Akyuz et al. (2004). When the modified annual tornado occurrences were used, however, there was no significant variability related to ENSO during the PDO2 period, but a likely tendency for fewer occurrences of significant tornadoes in EN years during PDO1 years.

A synoptic and dynamic analysis using composites maps of the mass and thermal distributions over the United States, and estimates of empirical severe weather indicies, reveals that there was little difference in the large-scale character of

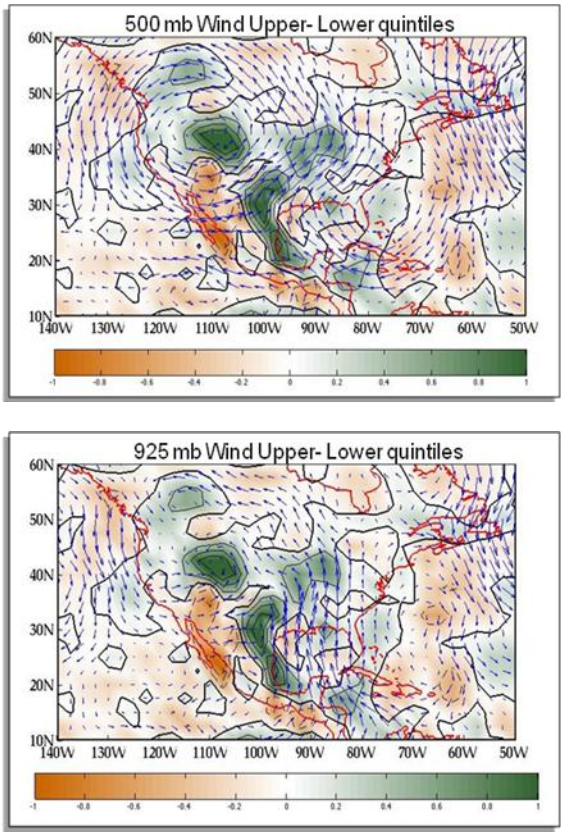


Figure 7. The wind vectors for the (top) 500 hPa and the (bottom) 925 hPa level.

the 1956, 1958, 1983, and 2000 tornado seasons. Each of these years produced most or a majority of the year's significant tornadoes during the composited period, and only the year 2000 produced noticeably fewer events than the other years. The year 1991 produced the second most tornadoes, and an examination of the synoptic maps showed that the lower troposphere was warmer and moister than for that of the other years. This season was an ENSO neutral year, and during the PDO1 period. Additionally, the character of the composite flow regime for two more of these years (1990 and 1984) appeared to be qualitatively similar to that of 1991.

Additionally, using multiple season composites shows that if you composite the 12 most active tornado seasons, there is strong moisture convergence and baroclinicity within the study region. This indicates the most active years are strongly driven by the large-scale environment being favorable for the development of severe weather, while seasons in which there was less activity are dominated by smaller-scale spatial or temporal (transient) processes.

6. ACKNOWLEDGMENTS

The authors would like to acknowledge the following individuals for their assistance with using the software and facilities and these included; S.-K. Lee, T. Heeb, J. McKeever, E. Rule, and E. Forde. We would especially like to thank the NOAA Hollings Scholarship foundation, which provided this opportunity for the first author.

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