The Short and Long-term Variability of F2 or Stronger (Significant) Tornadoes in the Central Plains

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Abstract

An analysis of the interannual and interdecadal variability of significant tornado events that occurred over a four state region in the central plains was performed over a 53 year period (1950 – 2002) using the Storm Prediction Center (SPC) archives and simple statistical techniques. A synoptic composite analysis using the National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) re-analyses was performed in order to determine whether there was support for the statistical relationships through the large-scale composite dynamics. The results showed that when the 53 year raw annual tornado occurrences are used, there was no statistically significant El Nino-related variability, and El Nino years produced slightly more tornado occurrences. However, when annual tornado occurrences were examined across different phases of the Pacific Decadal Oscillation, there was a likely tendency for more tornado occurrences in El Nino years during PDO2 and no significant interannual variability during PDO1 years. During the 1950 – 1976 period, other studies have found that significant tornado occurrences were overestimated. When a simple correction factor was applied here and the interannual variability re-examined, the strength of the statistical relationships changed such that there was now a likely tendency for fewer tornado occurrences in El Nino years during the PDO1 period, and no statistically significant relationship for PDO2 years. Finally an examination of the composite dynamics during the bulk of tornado season revealed that, out of five years examined, the large-scale flows were of similar dynamic character for four of them. The season which produced the most tornadoes qualitatively was shown to be slightly more conducive to severe weather production when using simple empirical severe weather indexes.

1. Introduction

In spite of the number of papers published addressing the long-term variability in tornado occurrences (e.g., Bove, 1998; Agee and Zurn-Birkhimer, 1998; Marzban and Schaefer, 2001) there is still uncertainty regarding this problem, and these problems include, but are not limited to, the observation of tornado events and the procedures for damage survey ratings (e.g., Marzban and Schaefer, 2001). Even with these challenges faced by researchers, recent studies have shown that mesoscale events do exhibit interannual variability that can be related, at least in part, to the El Nino and Southern Oscillation (ENSO) phenomenon. In the central plains region, for example, Browning (1998) and Berger et al. (2003) found significant interannual variations in the number of tornadoes and heavy snowfall events. This interannual variability in small-scale phenomena, especially in the Berger et al. (2003) study, was then associated with regional interannual variability in the large-scale weather regimes that occurs in conjunction with ENSO.

Recent attempts to quantify the interannual variability in tornado occurrences used a variety of statistical methodologies, examined different geographical regions, included either all or some tornadoes (e.g., F2 or greater), and using slightly differing definitions for ENSO, have yielded mixed results. 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 that the central and southern plains states (tornado alley) experienced more events during strong El Nino (EN) years. 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.

A study of interannual variability only, however, can be misleading as shown by the Berger et al. (2003) study of northwest and central Missouri snowfall events. Their work revealed that there were only slightly more snowfall events that occurred in LN winters when comparing to EN years using a 50 year data set. When this ENSO variability was analyzed in conjunction with long-term variations (e.g., the Pacific Decadal Oscillation or PDO), however, it was shown that the character of the ENSO-related variability itself changed when examined separately within each phase of the PDO. In particular, there was little ENSO variability snowfall occurrences during the middle portion of the 20th century, but very strong ENSO related variability in the latter half of the century after a change in phase of the PDO. Berger et al. (2003) also linked these changes in snowfall variability to variability in the larger-scale patterns that brought snowfalls to their study region. Thus, the changes in the behavior of ENSO variability found by their study could possibly be linked to PDO variability. Some model (Knutson et al., 1997; Collins, 2000) and observational (e.g., Gu and Philander, 1995; Mokhov et al., 2000, 2004) studies have shown that the period and amplitude of ENSO does vary on the time-scales of decades or more, and Weitlich et al. (2003) suggest that this may be related to changes in phase of the PDO.

Then, in an attempt to gain a better understanding of the interannual variability of tornado occurrences in the central plains region of the United States, this climatological study considered all tornadoes of F2 or greater that occurred across a four-state region (Iowa, Kansas, Missouri, and Nebraska) from 1950 to 2002. Once all applicable observed tornado events were collected, a statistical analysis was performed in order to examine interannual and interdecadal variations in tornado frequencies. Finally, representative composites of synoptic-scale features were examined and these demonstrate that the statistical relationships found here may result from variability in the character of these synoptic and larger-scale environments.

2. Data and Methodology

a. Data

Figure 1 shows the region of concern for this study. A climatology of all tornadoes of F2 intensity or greater from Iowa, Kansas, Nebraska, and Missouri from 1950 through 2002 was compiled using data acquired from the Storm Prediction Center (SPC)[1] in order to establish a large data set of central plains tornadoes. The multi-state region was chosen not only to enlarge the data set overall, but also since some studies (e.g., Agee and Zurn-Birhimer, 1998; Palecki and Leathers, 2000) suggested that the ENSO variability in general may be different across the western portion of this region versus that in the eastern and southeastern portion of this region. This gradient in the interannual variability was also suggested examining the results of Martins and Smith (2003), who found that the cyclone tracks (with fewer but stronger cyclones) were located further south during EN years across the eastern portion of the region and the eastern two-thirds of the U.S. overall.

This study selected the data and the time-period of 1950 – 2002 for several reasons. Climatological studies of tornadoes are sensitive to many external factors influencing their count such as; population densities, technical innovations, and individual subjectivity in damage surveys and how these damage surveys are performed (e.g., Marzban and Schaefer, 2001). As advances in technology have led to better tornado detection, it is likely that the number of F0 and F1 tornadoes have been responsible for a dramatic increase in raw tornado frequencies (e.g., Marzban and Schaefer, 2001)[2]. Thus, our study excluded these events. Other problems with tornado counts such as; the bias in tornado counts to populated areas, and differences in observation techniques (e.g., damage surveys by the National Weather Service, rather than inference from newspaper accounts – for example see Marzban and Schaefer, 2001; Ray et al., 2003) are difficult to account for in a purely objective manner. Thus, only raw counts have been examined, as done by other studies cited above.

A synoptic 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., 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 choice of the 1950 - 2002 time-period is a long enough period of time to include several El Nino (12) and La Nina (14) events and to examine the interdecadal variability.

b. definitions

After compiling all applicable tornado occurrences, the maximum intensity of each tornado was recorded as measured using the Fujita Scale (e.g., Ahrens, 2000, Table 15.1). Then, 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. The dataset was stratified also by phase of the Pacific Decadal Oscillation (PDO). Berger et al. (2003) outlined the definitions of ENSO and PDO and the methodologies for performing the analysis and we describe these briefly below.

For identifying years with respect to El Nino and Southern Oscillation, this study used the Japan Meteorological Agency (JMA) ENSO Index. This definition has been used in several published studies in order to examine the interannual variability in a variety of phenomenon (e.g., Bove, 1998, Lupo and Johnston, 2000; Berger et al., 2003), and is similar to another commonly used definition (e.g., Trenberth, 1997). Additionally, there is no consensus in the scientific community as to which ENSO index best captures ENSO as of this time (Hanley et al. 2003). The reader will find a list of EN, LN, and NEU years (Table 1), as well as a more detailed description of the JMA ENSO Index, by accessing the Center for Ocean and Atmospheric Prediction Studies (COAPS) website[3]. 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° C, less than -0.5° 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). Other climatological studies correlated monthly SST's against monthly tornado occurrences and this assumed an "instantaneous" response by the general circulation to changes in SST's. Marzban and Schaefer (2001) acknowledge, however, that an instantaneous response by the general circulation may not strictly be a valid assumption.

The PDO is a longer-term SST oscillation occurring over a 50 to 70 year period (e.g., Minobe, 1997) within the eastern Pacific Ocean basin. Gershanov and Barnett (1998) defined the positive phase of the PDO as characterized by an anomalously deep Aleutian Low. Cold western and central north Pacific waters, warm eastern Pacific coastal waters. Warm tropical Pacific waters also characterize this phase of the PDO, which we refer to as PDO1. The reverse conditions characterized the negative phase of PDO and we refer to these conditions as PDO2. Table 2 shows the period for each phase of the PDO (also see Gershanov and Barnett, 1998;

Weitlich et al., 2003; Lupo et al., 2004). Gershanov and Barnett (1998) found a correlation between PDO phase and the intensity of ENSO as they both affect the atmospheric climatological flow regimes over the United States simultaneously. In particular, they found that the PDO serves to either enhance or weaken the ENSO phenomenon, and thus the strength of the influence of the ENSO phenomenon (depending on the PDO phase). During PDO1 (PDO2), the intensity of EN and its impacts on North American atmospheric climatological flow regimes and circulation features tends to be greater (weaker), with a less (more) intense LN impact.

c. Statistical Testing

This study performed a simple statistical analysis by assuming that the distribution of annual frequencies of tornado occurrences across this region was (near) normal, in the absence of significant changes in the climate. A simple two sided "standardized test statistic" (z*) was used for the comparison of sample means for tornado frequencies and the details for this analysis can be found in any standard statistics textbook (e.g., Neter et al., 1988) In Fig. 2a, the raw annual frequencies are binned into 18 classes, each class being 5 events wide. The standard normal distribution was fitted then to the data (dotted curve). Carrying out a chi square goodness-of-fit test demonstrated that the raw annual tornado occurrences were not normally distributed. This result appeared to have occurred because of several years in which 41 – 90 tornadoes occurred, many of these seasons occurring before 1977.

Schaefer and Edwards (1999) and Marzban and Schaefer (2001) state that the occurrence of F2 tornadoes prior to the mid-1970’s may be overestimated since damage surveys were carried out based on second-hand information (newspaper reports). They also state that the National Weather Service began carrying out immediate damage surveys in the late 1970’s.

Brooks and Craven (2002), however, put this change in damage survey procedure which lead to overestimation of intensity around 1973. In a simple exercise to test the impact this problem may have on the annual distribution of tornado occurrences, while retaining a large enough sample for statistical testing, seasons with 41 or more tornadoes prior to 1977 only were discarded (17 of them). We chose the year 1977 since it was close to the time when the National Weather Service began carrying out damage surveys and this coincided with a change in phase of the PDO. Fitting a normal distribution to this dataset (Fig. 2a - solid curve) demonstrates that the annual occurrences were much closer to being normally distributed. While we concede that this simple analysis does not take into account overestimation prior to 1977 for years with fewer than 41 occurrences (in order to retain a large enough sample), it is likely that, if this overestimation could be properly accounted for and assuming no significant climate change, the dataset would be normally distributed (or close to normally distributed). Also, while this test is arbitrary, this was the simplest way that we decided to treat these data without imposing any further artificial assumptions on a dataset already fraught with potential observational problems.

Footnotes

1. *The website used is: www.spc.noaa.gov/archive/*

2. *In addition to this cited reference, one can access the High Plains Regional Climate Center at the University of Nebraska-Lincoln: www.hprcc.uni.edu/nebraska/U_S_Severe/*

3. *The COAPS website is at: http://www.coaps.fsu.edu.*

3. Climatological Analysis

a. Trends

Our study carried out an analysis of the long-term trends by examining the annual frequency of occurrence in each state (Fig.3). Each state was treated separately in order to account for the possibility of spatial inhomogeneties in long-term trend, which may be the result of real changes in climate or observing practices as discussed by some studies reference above. Observing practices could differ between National Weather Service county warning areas, which in many cases approximate state boundaries. These trends were derived using simple linear regression and tested for significance using an F-test (e.g., Neter et al., 1988). Each state exhibited a downward trend in the number of significant tornadoes, which again is likely to be the result of overestimation of the number of F2 events commented on Schaefer and Edwards (1999), Marzban and Schaefer (2001), or Brooks and Craven (2002). Thus, trend analysis here may not be reasonable. Even in the face of these problems, however, the downward trend was statistically significant (at the 95% confidence level), but only for Kansas and Missouri tornadoes (Fig. 3). Thus, the possible overestimation in the early part of this dataset additionally precluded an attempt to detect PDO-related variability (since the method of determining F-scale intensity changed at approximately the same time as the shift in phase of the PDO, or 1977) and changes in tornado counts due to climate change. Nonetheless, if tornado frequencies were overestimated prior to 1977, the degree to which this bias impacted the dataset may not have been spatially uniform. At the same time however, we must state that it would not be possible to assess what part of each state's trend may be due to bias or inherent natural variability given the information that was available to the study.

b. I*nterannual and Interdecadal Variations*

Table 3 displays the raw number of tornadoes that occurred across the entire region and the average number of events per year. These numbers demonstrate that more tornadoes occurred during NEU years across the region of study than for LN and EN years. However, an examination of the mean annual frequency of tornado occurrences revealed that more tornadoes occurred during EN years, and there was less difference in the mean number of occurrences in LN and NEU years. None of these differences rose to the level of statistical significance, and none of these differences even indicated a "likely relationship" (66-90% significance).

A state-by-state breakdown (Table 4) revealed that the interannual variability was similar across three of the four states as EN years lead LN years, however, again, none of these results are statistically significant, which is a result consistent with Agee and Zurn-Birkhimer (1998). Several of the studies referenced above found weak statistical relationships to ENSO phase using sophisticated statistical techniques, with LN years leading EN years in tornado occurrence across this region. Only in Nebraska did LN years lead EN years and this interannual variability is consistent with that found many of the studies cited above, and consistent with that found by Browning (1998) who found LN years produced more tornadoes, but in northwestern Missouri.

Our results and those of Agee and Zurn-Birkhimer (1998) would also agree with the study of Martins and Smith (2003), who showed that during EN years, there was a strong storm track across the eastern southern tier of states. More and stronger synoptic-scale cyclones in the southeastern portion of our study region during EN years would plausibly result in more opportunities for tornado occurrences in the Southern Plains. Martins and Smith (2003) indicate that LN years were associated with a storm track across the northern tier of states, and that there were more cyclone events across the eastern two-thirds of the United States as a whole during these years. Our results here also agree qualitatively with those discussed by COAPS[3] regarding the typical ENSO impacts on temperature and precipitation over this region, as they imply the storm track resides further south during the spring months across this region during EN years.

As described above, the impact of the change in the way F-scale intensities were determined which had occurred roughly during the same time as a change in phase of the PDO precluded using the raw data to determine directly a possible signal in the interdecadal variability in annual tornado occurrences. However, if it is assumed that the change in observation practice occurred approximately in a systematic way and almost concurrently with the change in phase of the PDO, then it is still possible to detect interactions between PDO and ENSO signatures. Studies cited in the introduction have shown that within this region, changes in phase of the PDO were associated with a change in the nature of ENSO-related variability in this region. It was to this end that an attempt was made to detect PDO related variations in tornado occurrence, by examining the change in ENSO variations within each phase of the PDO (Table 5 - 7).

Table 7 stratified the data by ENSO year within each phase of the PDO. During the PDO1 period, there was no significant interannual variability in the number of tornado occurrences. During these years, there were more events in NEU years as opposed to EN years. LA years were not included here since there was only one LN year during PDO1. However, during PDO2 years, the mean number of tornado occurrences was greater during EN years, and this was significant at only the 85% confidence level (indicating a likely relationship). A similar number of events occurred in both LN and NEU years. The finding that EN years generally lead in tornado occurrence during the PDO2 period is consistent with the results of Agee and Zurn-Birkhimer (1998) for the study region and the time periods of observation for PDO2 and their study have considerable overlap. This analysis demonstrates, however, that the nature of ENSO variability possibly changed within each PDO period. As suggested by Berger et al. (2003), it would be difficult to determine reliably the statistical character of the ENSO related variability within the entire 53-year period since studies have shown the character of ENSO to change significantly over the latter portion of the 20th century (Gu and Philander, 1995; Mokhov et al., 2000, 2004).

c. Modified annual tornado occurrences from 1950 – 1976: an experiment

When examining the annual frequency of tornadoes (Table 5 and 6) for the whole region and state-by-state, there were far more tornadoes in the earlier period (1950 – 1976) versus that of the later period (1977 – 2002). In an attempt to apply a simple correction to the possible overestimate in significant tornado occurrences prior to 1977, the ratio of the mean tornado occurrences from 1977 - 2002 was divided by the mean of those occurring from 1950 – 1976 (Table 8) for each state, and then multiplying this number by the raw annual frequencies during the earlier period. This had the effect of normalizing the earlier period with respect to that of the later period or imposing no long-term trend on the dataset (Fig. 2b). This can be justified by assuming that if observed trends were slight and/or statistically insignificant and if no bias in the earlier period were present, then a similar result (no-trend) could be obtained by random chance and no long-term trend at all is an equally likely outcome. If a true climate change did occur, however, then this experiment would not present credible results. Nonetheless, this simple experiment also had the effect of “detrending” the time series, a technique often applied to such data when the goal of the work is to find periodicity on time-scales smaller than that of the entire time series by using sophisticated techniques, such as Fourier or wavelet techniques (e.g., Mokhov et al., 2000, 2004).

Performing this analysis modified the interannual variability overall and/or state-by-state (Tables 9 and 10). Table 9 showed that, overall, ENSO neutral years produce more tornadoes across the region, but EN years slightly lead still LN years. Table 10 shows that in each state, EN and/or NEU years lead LA years. Then, as a result of applying the correction factor in Table 8, the average annual occurrence of tornadoes was similar across each phase of the PDO (Table 11). After application of this correction factor to the annual tornado occurrences before 1977, however, a different statistical interpretation emerges region-wide as concerns the ENSO-related variability (Table 12). During the PDO2 period, now there was no statistically significant interannual variability, but EN years still produced more events per year than NEU and LN years, regionally. During the PDO1 period, however, EN years experienced fewer significant tornado events per year across the region than ENSO NEU years, a relationship indicated to be statistically "likely" (significant at the 70% confidence level). These results were still consistent with the Martins and Smith (2003), and fewer tornado occurrences during PDO1 ENSO years region-wide. Thus, the modification did not change qualitatively the results found using the raw tornado occurrences.

d. Synoptic Composites and Discussion

The previous results demonstrate that it is difficult to determine if there is statistically significant interannual variability in tornado occurrences. Bias and subjectivity in determining whether or not a tornado event occurred, how intense the event was, and the rapid improvements in tornado detection perhaps make deriving useful climatologies of these small-scale events not possible yet. The results found here using raw tornado counts and modified counts using elementary statistical methods, however, were consistent with each other and in general with the synoptic analyses of other studies. These same techniques also demonstrated that the character of the interannual variability in tornado counts supposedly related to ENSO appears to have changed on longer time-scales, just as the frequency and character of the ENSO itself has been shown to change as well (e.g., Gu and Philander, 1995; Mokhov et al., 2000, 2004). That the character of the interannual variability of tornado occurrences seems to be different across each phase of PDO also agreed with the results of Lupo and Johnston (2000) and Berger et al. (2003), who showed similar results in their study of north Atlantic hurricanes and northwest Missouri snowfalls, respectively.

In order to determine if any of the relationships were supported by examining synoptic and/or dynamic relationships, our study performed a qualitative dynamic analysis using composites for various primary atmospheric quantities during the peak of severe weather and tornado season across the region. A lack of strong statistical relationships may not preclude relationships, which may have a synoptic or dynamic basis (e.g., Nicholls, 2001). The synoptic composites used here were for the April to June period and chosen to represent seasons in which strong EN, strong LN, or NEU conditions persisted during the late fall and into the compositing timeframe. We used observed tornado frequencies, which were representative of the climatology, to choose these years. Observed tornado frequencies were not examined, however, within the April to June period before compositing. Finally, we constructed these composites using the National Centers for Environmental Prediction (NCEP) re-analyses available through the Climate Diagnostic Center (CDC) Daily Mean Composites Page[4]. It should be noted here, however, that compositing procedures smooth out day-to-day variations and individual events. Nonetheless, compositing can demonstrate that the overall environment may have been more or less conducive to the formation or presence of strong synoptic-scale features that produce severe weather.

The NCEP - NCAR gridded re-analyses (Kalnay et al., 1996) are archived at NCAR and were obtained from the mass-store facility in Boulder, CO. 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.

The composite variables used here (e.g., Fig. 4) 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.

The first two composites examined were from the years 1956 (Fig. 4) and 1958 (Fig. 5). These two seasons occurred within the early period (PDO2) and produced a similar number of significant tornadoes (45 versus 43, respectively) region-wide. More tornadoes occurred during the April - June period than for any other period during those years (42% and 47%, respectively), and 1956 (1958) was a LN (EN) year. There was no clearly identifiable surface low in either composite (Fig. 4a, 5a) east of the Rockies, but there was southerly flow across the four state region examined. At 925 hPa (Figs. 4b and 5b), the specific humidity field indicated that the low-level moisture field was similar in each case as well, as the 0.008 kg kg-1 contour can be seen across the middle of the region and the 0.009 kg kg-1 contour nosed into the southern part of the region. Each composite period exhibited similar upper air distributions of 850 hPa height and temperature (Figs. 4c,d and 5 c,d) and 300 hPa height and vector winds (Figs 4 e,f and Figs. 5 e,f). Specifically, there was low-level baroclinicity evident over the four state region, and a low-level trough over the Rockies. There was favorable tropospheric directional shear for severe weather (assuming the 850 hPa winds are nearly geostrophic) as winds veered from southwesterly at 850 hPa to westerly at 300 hPa. The four state region was also located coincident with the equatorward entrance region of the large-scale 300 hPa jet, implying upper-level divergence over the region.

Thus, in a statistical sense and in a synoptic and dynamic sense, there did not seem to be a significant difference between these two tornado seasons, which were representative of El Nino and La Nina years during the PDO2 period. Each season produced a similar number of tornadoes and the differences in the number of events produced were likely to be attributable to individual synoptic transients and their mesoscale environments. These results regarding weaker differences between the large-scale environments during PDO2 EN and LN years for the tornado season composites would agree with those of Gershanov and Barnett (1998) and the regional study of Berger et al. (2003).

During the PDO1 period, two years were chosen using the same strategy outlined before, except that the tornado season with the second greatest number of events was included here (1991, 48 tornado events, 67% of which occurred during the April to June period). The other season chosen was 1983, which was an EN year and produced a similar number of tornadoes to the long-term EN year average (17 events) the majority of which (14 events) occurred during the compositing period. Fig. 6 demonstrates that the 1983 season was very similar to the composites in Figs 4 and 5, with the exception that there was even less low-level moisture in the northeast part of the four state region. The region was under the poleward exit region of the large-scale upper level jet, which was located across the southern part of North America. This upper level jet configuration was quite common for El Nino spring seasons, especially during the latter part (PDO1 period) of the 20th century (see COAPS website[3]).

For the 1991 composite (Fig. 7), all the favorable ingredients for severe weather formation were in place including a composite surface low along the Texas-New Mexico border (Fig. 7a), more low-level moisture (Fig. 7b), and stronger tropospheric shear than any of the other years shown here (Fig. 7). The upper level divergence was likely enhanced over the four state region as the region was located within the equatorward (poleward) entrance (exit) region of a downstream (upstream) and relatively poleward (equatorward) large-scale jet maximum (Fig. 7f). 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 shown (Fig. 7d). 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 manually estimated for three current locations that launch twice-daily radiosondes within the four state region (Table 13). 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 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 13) 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 April to June period for 2000 was chosen (Fig. 8). 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. The flow regime for the compositing period, however, does not look significantly different from Figs. 4,5, and 6. Table 13 also revealed that the composite Total Totals and SWeaT indicies were also similar to the other periods displayed. Then, as may be expected, the difference in the number of significant tornado events between the 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.

Finally, an examination of the five most productive significant tornado years from the PDO2 period (Table 14) revealed that there was no preference for these years to be associated with one phase of ENSO over another, as the statistics earlier revealed. During the PDO1 period, however, all of the five most productive seasons were ENSO neutral years, and a qualitative examination of the flow regime for two of these seasons (1984, 1990), revealed characteristics similar to those of 1991 (not shown). Thus, it would appear that during PDO1 years a more favorable large-scale background for severe weather occurrence could be associated with ENSO NEU years in general. Recall, the statistical analysis revealed a "likely" relationship for fewer annual tornado occurrences and ENSO years for this period. This contrasted with the other four years analyzed here in which there were no other seasonally composited detectable synoptic or dynamic explanation in the large-scale for any of the weak statistical results. The results of other long-term synoptic climatologies were also consistent with our statistical results found here.

Footnote:

4. *The Climate Diagnostic Center Daily Mean Composites Page is located at:* *http://www.cdc.noaa.gov/Composites/Day/*

4. Summary and Conclusions

An analysis of tornado activity in four central plains region 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. The tornado climatology across a four state region, which did not result in a homogeneous climatology, was generated using archived tornado data from SPC for the time period 1950 through 2002. 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). There was little ENSO-related variability found in the 53 years of raw tornado occurrences with LN years producing slightly more events. This agreed with the interannual variability found in related studies (e.g., Agee and Zurn-Birkhimer, 1998). These studies examined tornado occurrences across different regions and used different statistical techniques.

Other studies have shown, however, that the number of significant tornado occurrences before 1977 may have been overestimated due to the techniques used in assessing their F-scale rating. When applying a simple correction procedure to these years by assuming no long term climatic trend, the number of tornado occurrences was reduced drastically, but the interannual variability was similar to that using the raw annual tornado occurrences. Additionally, a study of the interannual variability in tornado occurrences, and how this may vary on an interdecadal scale, revealed the following results. The raw number of tornado occurrences showed a likely tendency for more tornadoes in EN years during the PDO2 period, and no significant ENSO-related variability during the PDO1 period. 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.

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 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 during the 1977 – 1999 period, 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, the five most productive tornado seasons were ENSO neutral years.

Additionally, the character of the composite flow regime for two more of these five years (1990 and 1984) appeared to be qualitatively similar to that of 1991. This implies that for PDO1 years, the large-scale flow may be predisposed to producing more severe weather events than LN or EN years. For most years within the PDO2 period, the character of the large-scale flow regime did not result in comparably favorable conditions for tornado occurrence, and smaller-scale processes controlled likely the number of tornado events that occurred during those individual years.

5. Acknowledgements

The authors would like to thank Dr. Patrick Market, Dr. Neil Fox, and Dr. Patrick Guinan for their comments and discussion of these results. We also would like to thank the anonymous reviewer, one of whose help in acquiring the SPC data set helped to produce a substantially better paper.

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Table 1. A list of years examined in this study separated by ENSO phase.

La Nina (LN)	Neutral (NEU)	El Nino (EN)
1949	1945-1948	1951
1954-1956	1950	1957
1964	1952-1953	1963
1967	1958-1962	1965
1970-1971	1966	1969
1973-1975	1968	1972
1988	1974	1976
1998-1999	1977-1981	1982
	1983-1985	1986-1987
	1989-1990	1991
	1992-1996	1997
	2000-2001	2002

Table 2. The phase of the Pacific Decadal Oscillation (PDO).

PDO PHASE	PERIOD OF RECORD
Phase 1	1933-1946
Phase 2	1947-1976
Phase 1	1977-1998
Phase 2	1999-

Table 3. All IA, KS, MO, and NE significant tornadoes from 1950 – 2002 stratified by ENSO phase.

	La Nina	Neutral	El Nino	All
Tornadoes	502	908	456	1866
Annual Average occurrence	35.8	33.6	38.0	35.2

Table 4. Average annual significant tornado occurrence in each ENSO phase for all states considered.

	La Nina	Neutral	El Nino	All
Iowa	9.9	10.0	11.2	10.2
Kansas	10.9	10.3	11.8	10.8
Missouri	7.7	6.4	9.4	7.4
Nebraska	7.3	7.0	5.6	6.8

Table 5. All IA, KS, MO, and NE significant tornadoes from 1950 – 2002 divided by PDO phase.

	PDO1	PDO2	All
Tornadoes	553	1313	1866
Annual Average occurrence	25.1	42.4	35.2

Table 6. Average annual significant tornado occurrence in each PDO phase for all states considered in this study.

	PDO1	PDO2	All
Iowa	8.2	11.7	10.2
Kansas	6.3	14.0	10.8
Missouri	4.5	9.5	7.4
Nebraska	6.2	7.2	6.8

Table 7. The total number / average annual occurrence of all significant tornadoes considered in this study stratified by PDO and ENSO phases (* represents a likely relationship).

	PDO1	PDO2
La Nina	9 / 9	493 / 37.9
Neutral	420 / 28.0	488 / 40.7
El Nino	124 / 20.7	332 / 55.3*

Table 8. Average Annual tornado occurrence from 1950 – 1976 versus 1977 – 2002, and the correction factor used to modify the earlier period.

	1950 - 1976	1977 – 2002	Correction Factor
Iowa	12.7	7.7	0.61
Kansas	15.3	6.1	0.4
Missouri	10.2	4.5	0.44
Nebraska	7.6	5.8	0.76

Table 9. As in Table 3, except using the modified tornado occurrences from 1950 – 1976.

	La Nina	Neutral	El Nino	All
Tornadoes	295	695	293	1283
Annual Average occurrence	21.1	25.7	24.4	24.2

Table 10. As in Table 4, except using the modified tornado occurrences from 1950 - 1976.

	La Nina	Neutral	El Nino	All
Iowa	6.6	8.1	8.1	7.7
Kansas	4.7	6.9	6.1	6.1
Missouri	4.1	4.5	5.1	4.5
Nebraska	5.7	6.3	5.0	5.8

Table 11. All IA, KS, MO, and NE tornadoes from 1950 – 2002 divided by PDO phase after application of the Table 8 correction factors to the 1950 – 1976 occurrences state-by-state.

	PDO1	PDO2	All
Tornadoes	553	730	1283
Annual Average occurrence	25.1	23.5	24.2

Table 12. The total number / average annual occurrence of all tornadoes considered in this study stratified by PDO and ENSO phases (* represents a "likely" relationship) after application of the simple correction factor in Table 8 to the 1950 – 1976 occurrences.

	PDO1	PDO2
La Nina	9 / 9	286 / 22.0
Neutral	420 / 28.0	275 / 22.9
El Nino	124 / 20.7*	169 / 28.2

Table 13. 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

Table 14. The five most productive significant tornado producing years for the PDO2 and PDO1 period. The modified tornado occurrences are used for the earlier period.

Rank	PDO 2 (1950 – 1976, 1999-2002)	PDO 1 (1977 – 1998)
	Number / Year / ENSO phase	Number / ENSO phase
1	50 / 1964 / El Nino	51 / 1990 / Neutral
2	46 / 1967 / Neutral	48 / 1991 / Neutral
3	39 / 1973 / El Nino	45 / 1984 / Neutral
4	36 / 1965 / La Nina	44 / 1982 / Neutral
5	33 / 1999 / La Nina	41 / 1993 / Neutral

Figure Captions

Figure 1. The four state region considered for this study – Iowa (upper right), Kansas (lower left), Missouri (lower right), and Nebraska (upper left).

Figure 2. The total annual frequency of a) raw, and b) modified central plains tornado occurrences are binned into 18 classes (bin width = 5), beginning with bin 1 (1-5 events). The dashed line in a) and b) is a normal distribution fitted (see Neter et al., 1988, p. 212, eq. 7.5) to the histogram plotted, while the solid line in a) is the normal distribution fitted by simply throwing out all occurrences greater than 41 events.

Figure 3. Long term trends in tornado occurrence per year for a) Iowa, b) Kansas, c) Missouri, and d) Nebraska.

Figure 4. The synoptic composites using the NCEP re-analyses for 1 April to 30 June 1956 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}).

Figure 5. As in Fig. 4, except for the year 1958.

Figure 6. As in Fig. 4, except for the year 1983.

Figure 7. As in Fig. 4, except for the year 1991.

Figure 8. As in Fig. 4, except for the year 2000.

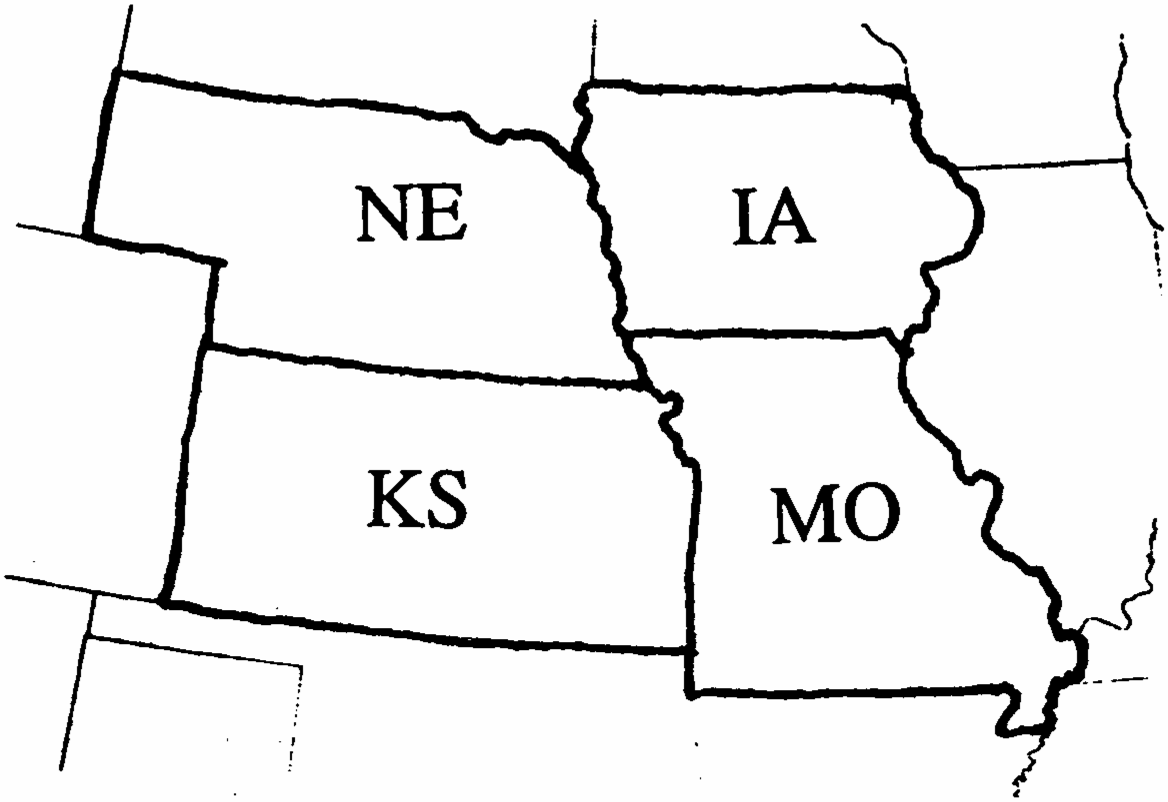
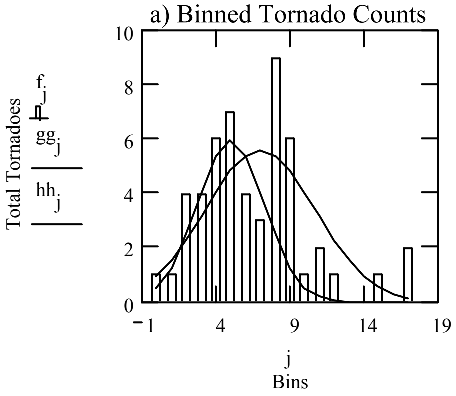


Figure 1. The four state region considered for this study – Iowa (upper right), Kansas (lower left), Missouri (lower right), and Nebraska (upper left).



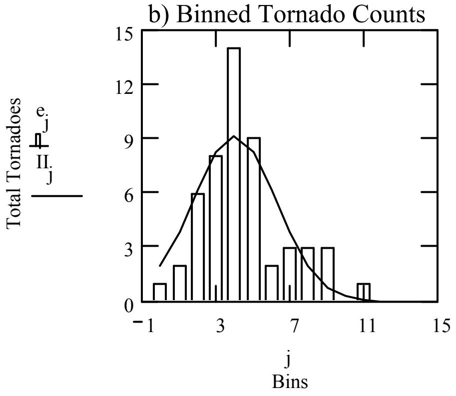
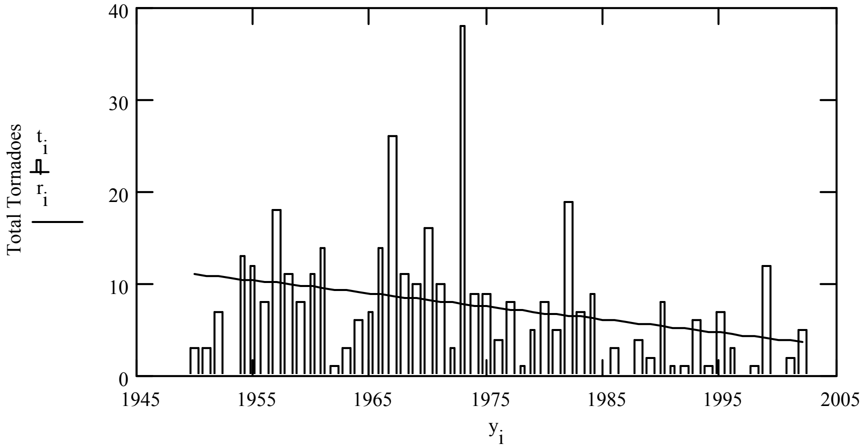
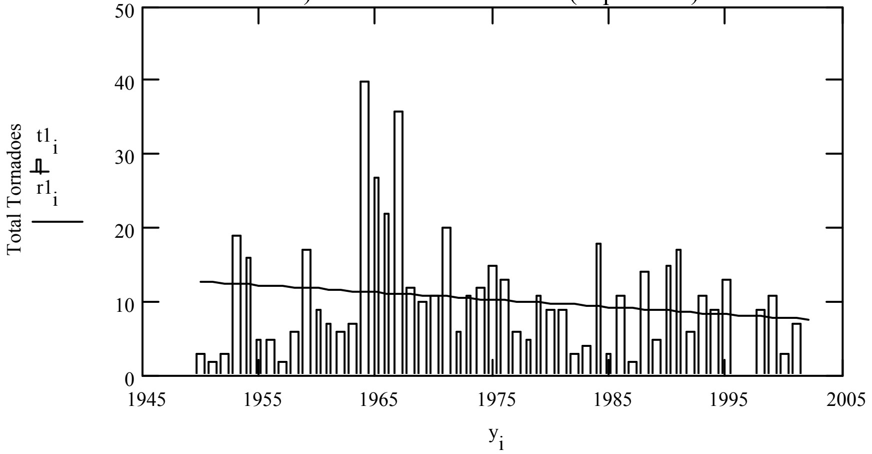


Figure 2. The total annual frequency of a) raw, and b) modified central plains tornado occurrences are binned into 18 classes (bin width = 5), beginning with bin 1 (1-5 events). The dashed line in a) and b) is a normal distribution fitted (see Neter et al., 1988, p. 212, eq. 7.5) to the histogram plotted, while the solid line in a) is the normal distribution fitted by simply throwing out all occurrences greater than 41 events.

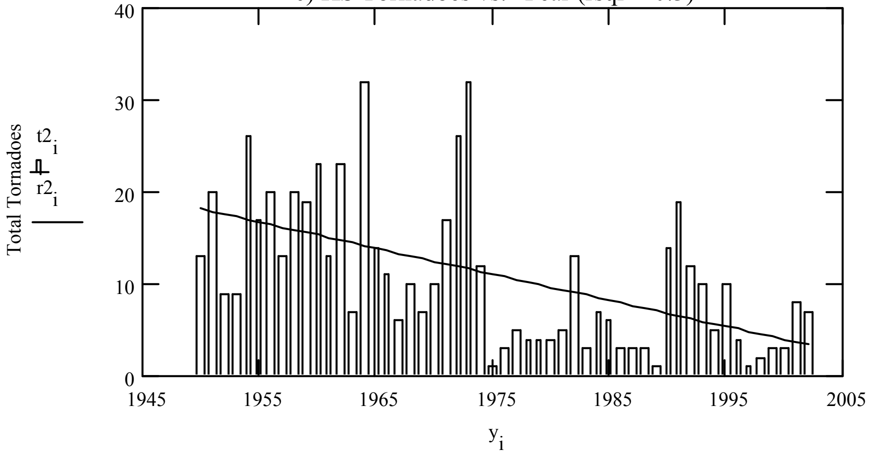
a) MO Tornadoes vs. Year (rsqr = 0.1)



b) IA Tornadoes vs. Year (rsqr = 0.04)



c) KS Tornadoes vs. Year (rsqr = 0.3)



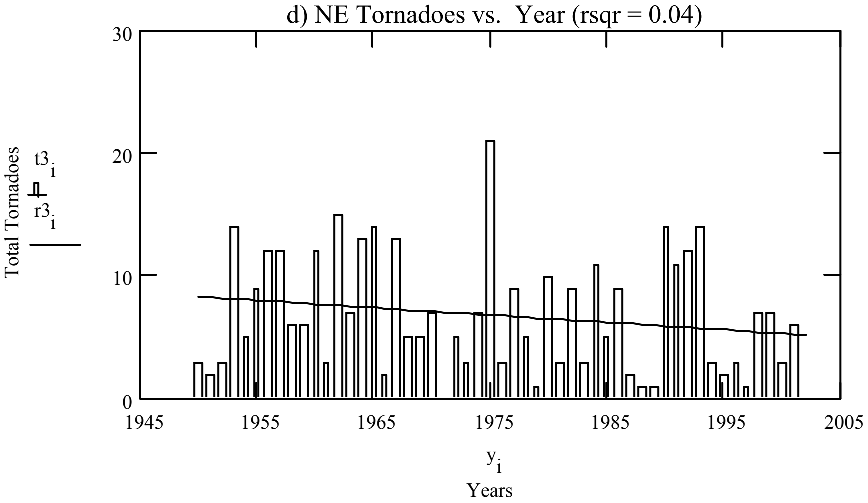
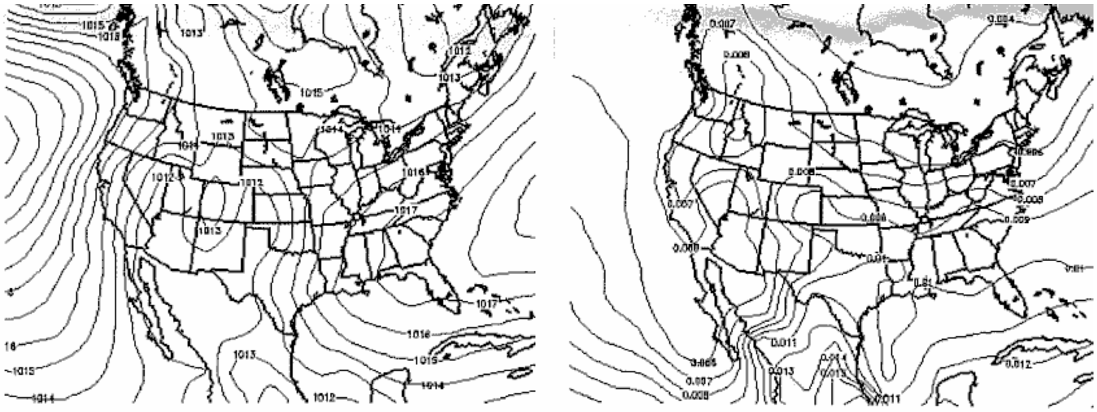
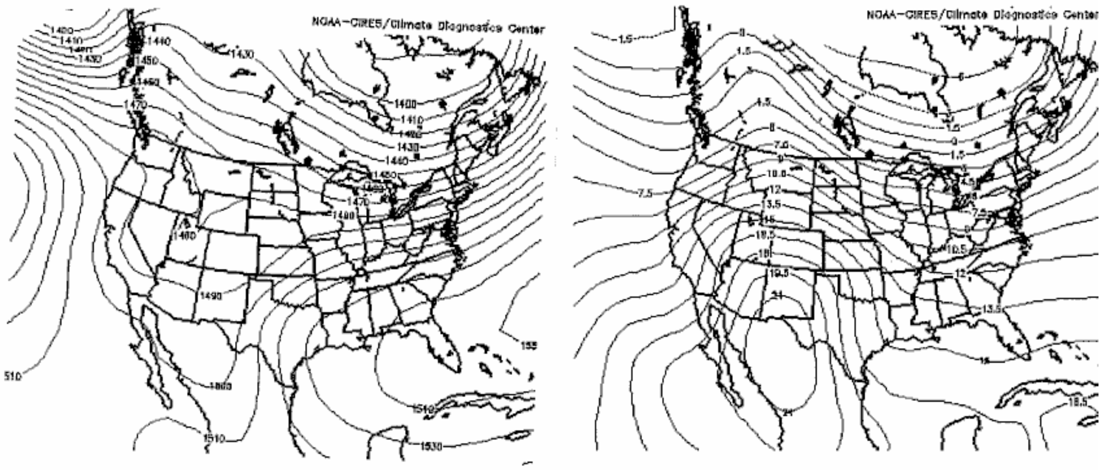


Figure 3. Long term trends in tornado occurrence per year for a) Iowa, b) Kansas, c) Missouri, and d) Nebraska.



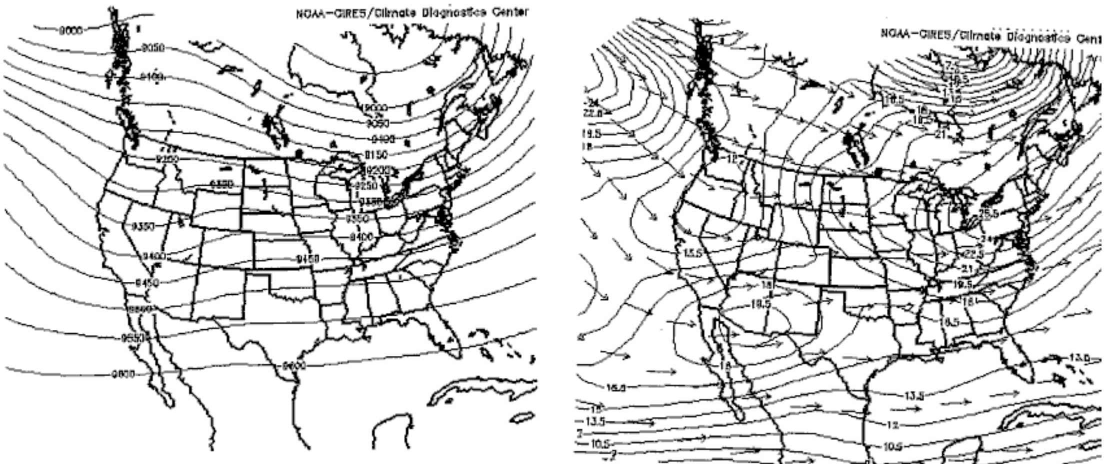
Sea Level Pressure (mb) Composite Mean
4/1/56 to 6/30/56
NCEP/NCAR Reanalysis

925mb Specific Humidity (g/kg) Composite Mean
4/1/56 to 6/30/56
NCEP/NCAR Reanalysis



850mb Geopotential Height (m) Composite Mean
4/1/56 to 6/30/56
NCEP/NCAR Reanalysis

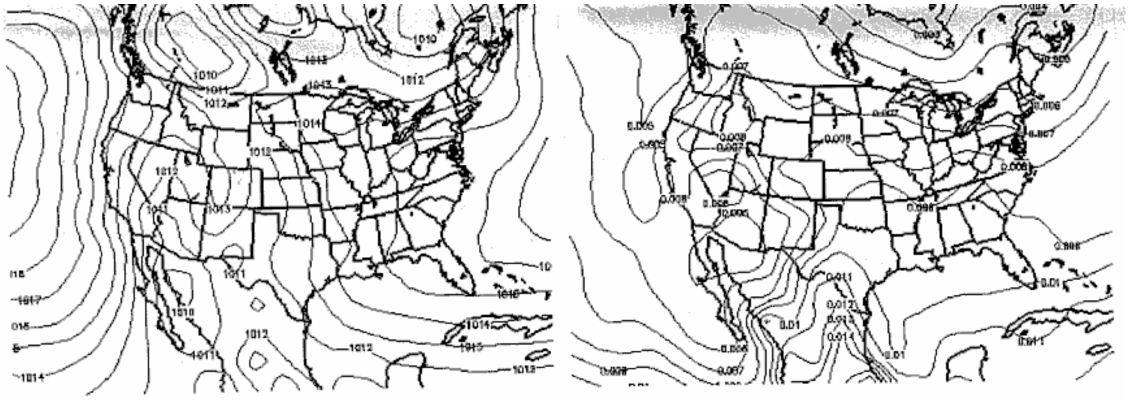
850mb air (C) Composite Mean
4/1/56 to 6/30/56
NCEP/NCAR Reanalysis



300mb Geopotential Height (m) Composite Mean
4/1/56 to 6/30/56
NCEP/NCAR Reanalysis

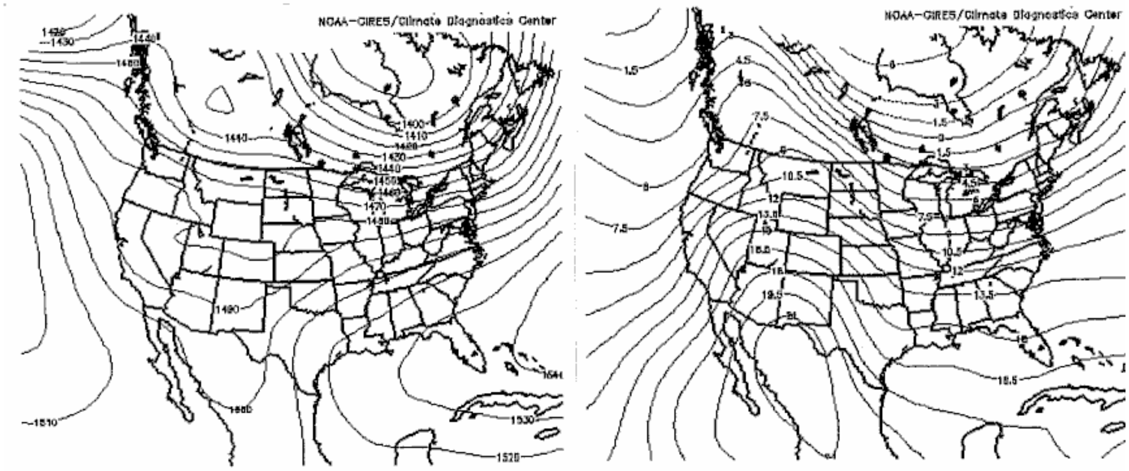
300mb Vector Wind (m/s) Composite Mean
4/1/56 to 6/30/56

Figure 4. The synoptic composites using the NCEP re-analyses for 1 April to 30 June 1956 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}).



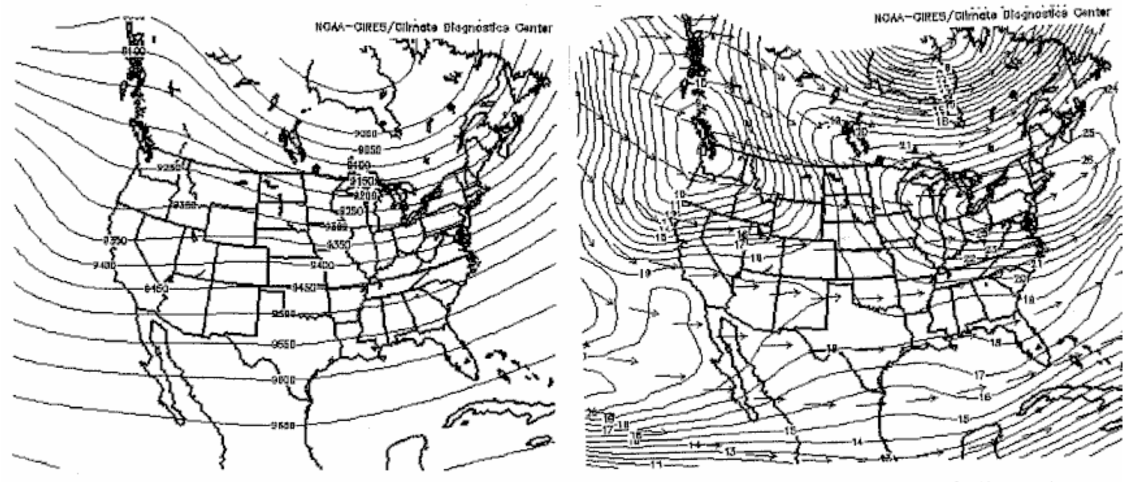
Sea Level Pressure (mb) Composite Mean
4/1/58 to 6/30/58
NCEP/NCAR Reanalysis

925mb Specific Humidity (g/kg) Composite Mean
4/1/58 to 6/30/58
NCEP/NCAR Reanalysis



850mb Geopotential Height (m) Composite Mean
4/1/58 to 6/30/58
NCEP/NCAR Reanalysis

850mb air (C) Composite Mean
4/1/58 to 6/30/58
NCEP/NCAR Reanalysis



300mb Geopotential Height (m) Composite Mean
4/1/58 to 6/30/58
NCEP/NCAR Reanalysis

300mb Vector Wind (m/s) Composite Mean
4/1/58 to 6/30/58
NCEP/NCAR Reanalysis

Figure 5. As in Fig. 4, except for the year 1958.

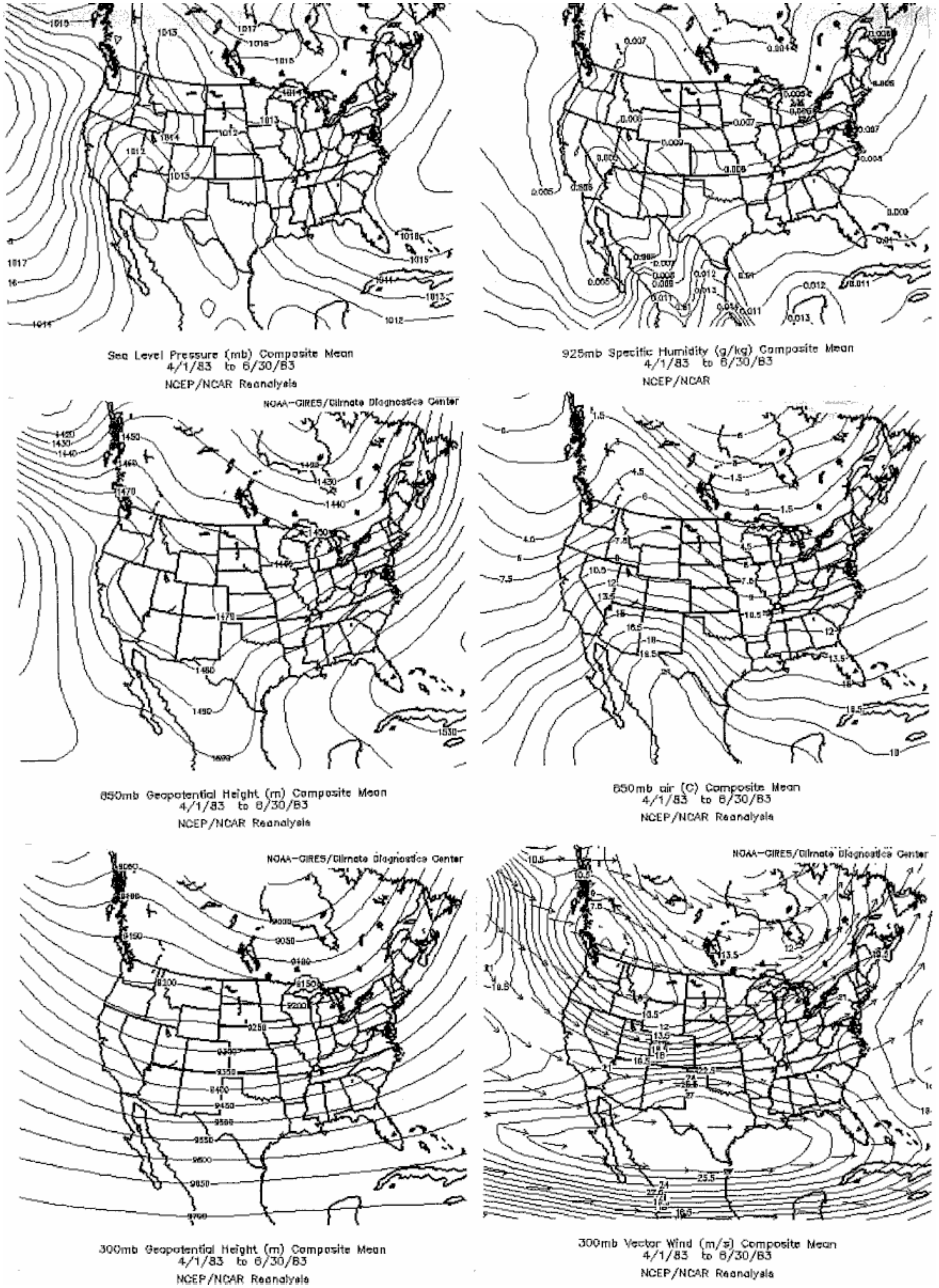
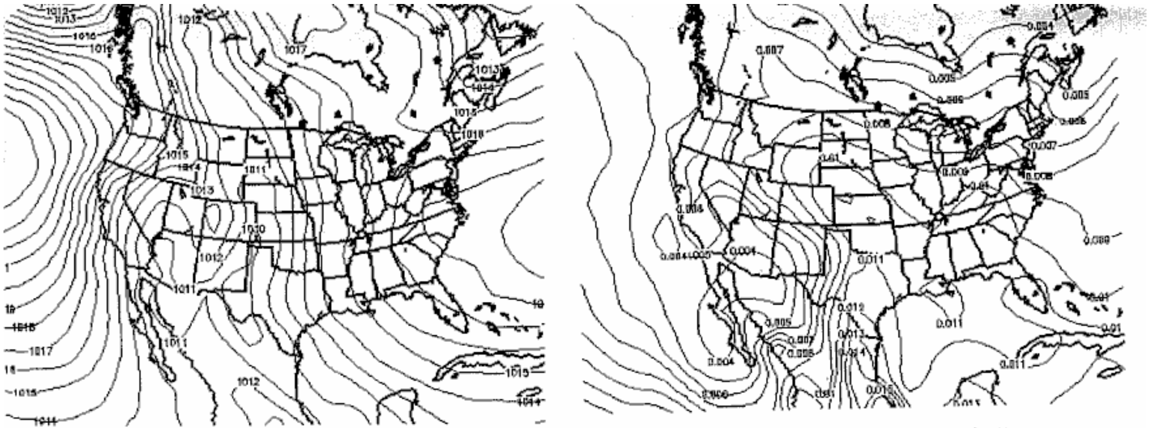
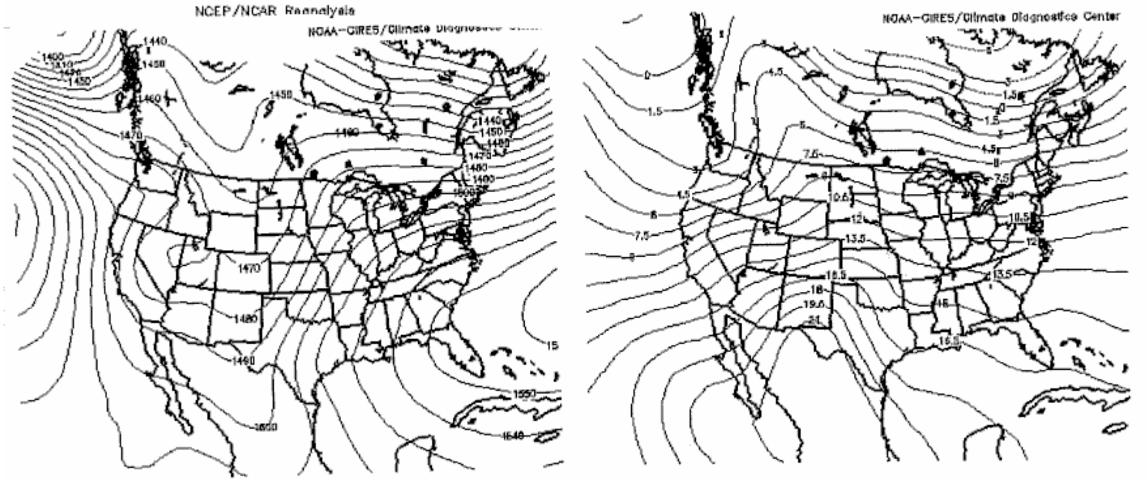


Figure 6. As in Fig. 4, except for the year 1983.



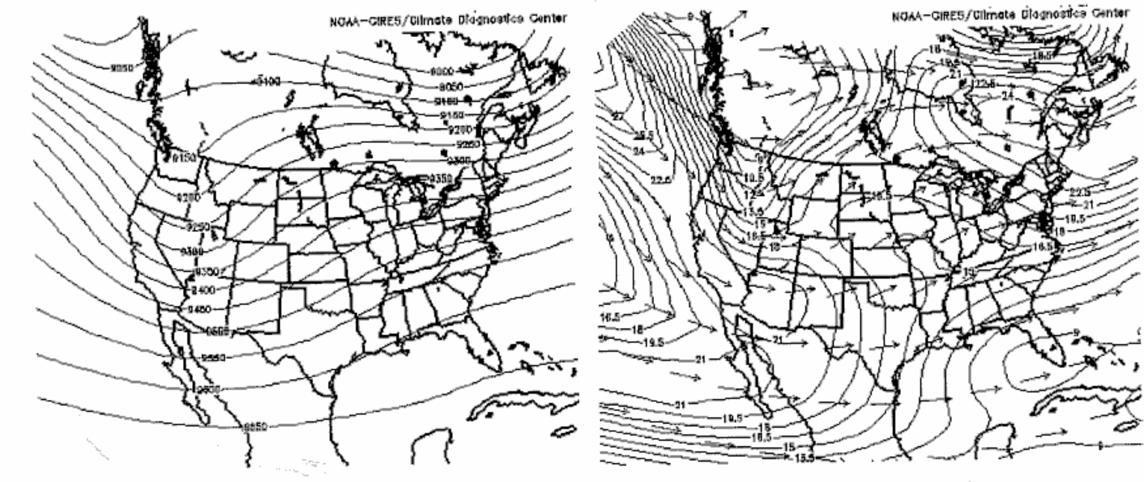
Sea Level Pressure (mb) Composite Mean
4/1/91 to 6/30/91
NCEP/NCAR Reanalysis

925mb Specific Humidity (g/kg) Composite Mean
4/1/91 to 6/30/91
NCEP/NCAR Reanalysis



850mb Geopotential Height (m) Composite Mean
4/1/91 to 6/30/91
NCEP/NCAR Reanalysis

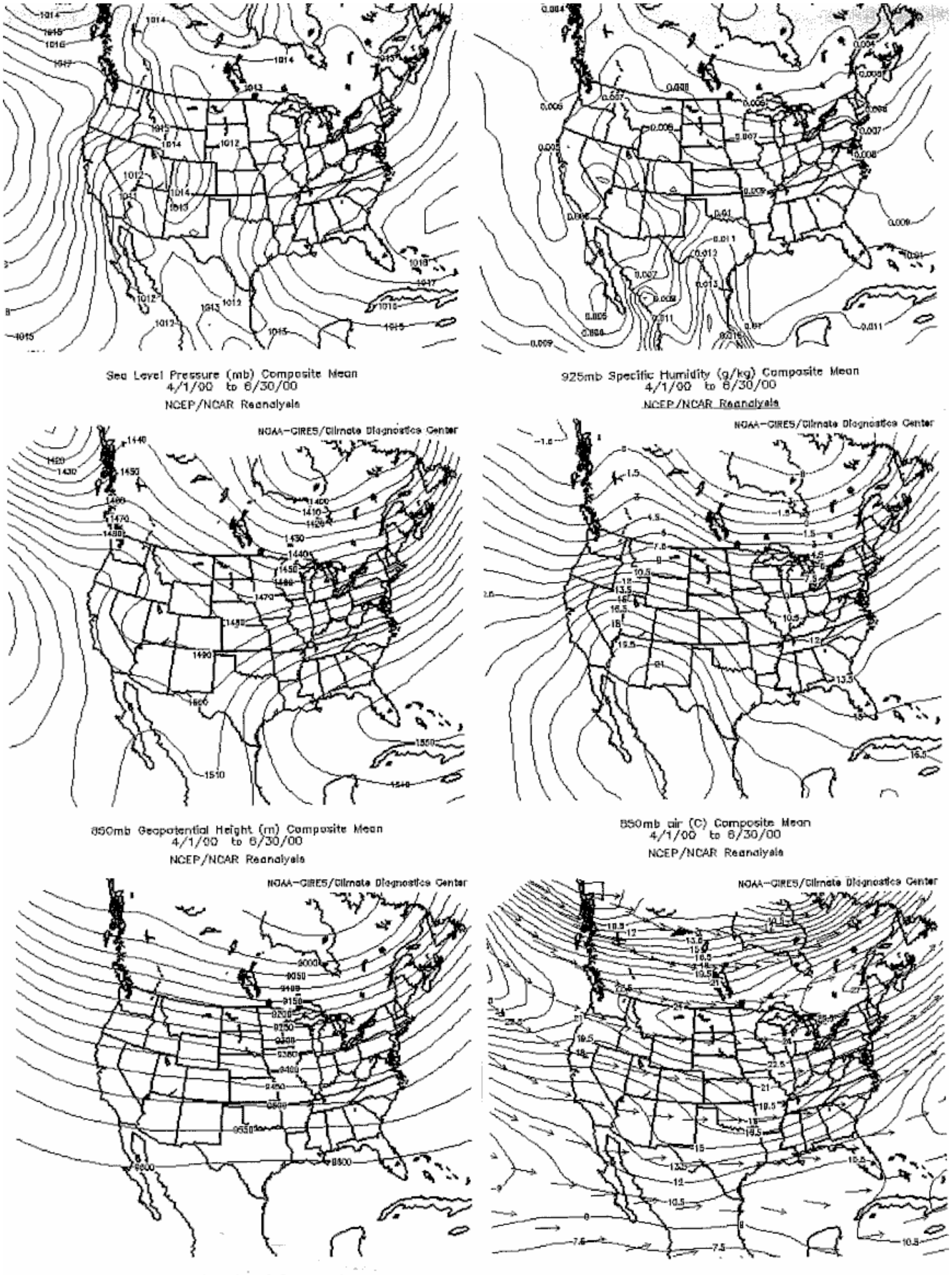
850mb air (C) Composite Mean
4/1/91 to 6/30/91
NCEP/NCAR Reanalysis



300mb Geopotential Height (m) Composite Mean
4/1/91 to 6/30/91
NCEP/NCAR Reanalysis

300mb Vector Wind (m/s) Composite Mean
4/1/91 to 6/30/91
NCEP/NCAR Reanalysis

Figure 7. As in Fig. 4, except for the year 1991.



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 8. As in Fig. 4, except for the year 2000.