The Relationship of Precursory Precipitation and Synoptic-Scale Mid-Tropospheric Flow Patterns to Spring Tornado Activity in Oklahoma

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ABSTRACT

Winter precipitation and 500 hPa geopotential height are analyzed as potential precursory predictors of spring tornado activity in Oklahoma (OK). The Storm Prediction Center (SPC) tornado database is used to calculate tornado days for each of the nine climate divisions in OK. Using daily precipitation totals from the Climate Prediction Center U.S. Unified Precipitation dataset, Dec-Feb accumulated precipitation is correlated with Mar-Jun tornado days for each climate division. Insignificant correlations are found for all climate divisions, and statistical tests affirm that there is no significant difference in OK tornadic activity following wet versus dry winters. The synoptic-scale variability in the Rossby wave pattern over the United States (US) associated with OK tornado activity may explain the ineffectiveness of precursory precipitation as a predictor, but also suggests qualitatively that precursory precipitation could be a statistically significant predictor of tornado activity in other regions of the US (Shepherd et al. 2009). Geopotential height at 500 hPa (Z500) from NCEP/NCAR reanalysis is also examined. A statistically significant and temporally consistent relationship is found between Z500 in the Pacific Northwest region and Mar-Jun statewide tornado days during 1981-2010 when Z500 is averaged over the preceding 4-month period (Nov-Feb). Persistent troughing (ridging) over the northwestern US and southwestern Canada during the winter is found to shift southeastward into the Rocky Mountains and enhance (suppress) OK tornado activity during the subsequent spring. This relationship strengthens as lead time is decreased, and may provide a method for predicting overall tornado activity in OK on a seasonal time scale.

1. Introduction

a. Motivation

Seasonal-range tornado prediction is still a new endeavor in the field of meteorology. Operationally, no tornado-related forecasts beyond a week or so in advance are currently given in any official capacity by the US government. Relatively little research has been conducted on seasonal-range tornado prediction, and the challenge of forecasting these life-threatening storms drives the need for predictive methods to be developed.

Some relationships of teleconnections and local variables to US tornado activity have been found by recent research. Muñoz and Enfield (2011) found that the low-level wind pattern associated with increased spring tornadic activity in the southeastern US is similar to the primary mode of spring variability of the Intra-Americas low-level jet. Lee et al. (2012) found a statistically significant correlation between the April-May TransNiño index and April-May intense (F3-F5) US total tornado count. While these results aid in understanding large-scale processes that contribute to tornado activity, it becomes problematic to use them for long-range tornado prediction. The aforementioned relationships are with parameters having zero lead time ahead of tornado activity, meaning they require the parameters themselves to be predicted before a seasonal tornado forecast can be derived. It is inefficient to rely on the ability to forecast variables that are only rough proxies for tornado activity. Thus, this study looks for precursory parameters related to tornado activity that can directly provide lead time on the order of months, specifically for OK.

b. Research Goals

This study first examines the relationship between precursory winter precipitation and spring tornado activity in OK. The relationship between precipitation and tornadoes has been investigated before. Galway (1979) found a very weak correlation between seasonal precipitation and tornado count in three regions of the US. A slightly stronger relationship was found between annual precipitation and tornado count, which the author noted may imply a lag correlation. However, this study was limited to data from 1953-1976, before the Doppler radar era, during which the US tornado record is known to contain biases (Doswell 2007), and these biases may have affected the results. A more recent study by Shepherd et al. (2009) found a weak positive correlation between antecedent fall-winter precipitation and spring tornado days in northern Georgia. Along the same lines, this study investigates a similar relationship, but for OK.

The relation of the wintertime mid-tropospheric flow pattern over the US to OK tornado activity is also investigated. To the author's knowledge, no recent research has been dedicated to exploring the possibility of utilizing mid-tropospheric flow as a predictor of tornado or otherwise severe weather activity, or even a zero-lag proxy for such activity. This is somewhat surprising, given that tornado and severe weather reports have been shown to be highly concentrated near upper tropospheric jet streaks in several studies (Kloth et al. 1980, Rose et al. 2004, Verbout et al. 2006), which implies that tracking the mid- or upper-level flow could be instrumental in synthesizing seasonal-scale tornado and/or severe weather outlooks. The current study, through examination of 500 hPa geopotential height, seeks to quantify the relationship of mean Rossby wave configuration over the US during the winter (Nov-Feb) to subsequent spring (Mar-Jun) tornado activity in OK.

2. Data and Methodology

a. Tornado Data

The SPC tornado database currently provides a record of each unique tornado track in the US from 1950 to 2012. There are inherent biases and inhomogeneities in US tornado data due to changes in reporting procedures and rating criteria over time, some of which are explored in Doswell (2007) and Verbout et al. (2006). Many of these biases are considered to be exacerbated before the 1980s, before the national Doppler radar network was installed, and before several procedural changes in reporting and rating tornadoes. In an effort to minimize these biases, this study restricts data analysis to the most recent 30-year standard decadal period (1981-2010). Furthermore, tornado days are chosen over tornado count as the metric to gauge tornado activity to dampen most of the reporting bias owing to spatiotemporal population variability. The SPC database is used to calculate the number of Mar-Jun tornado days for each OK climate division (Fig. 1), where a tornado day is defined as any Central Standard Time (CST) day (0000-2359 CST) during which any portion of a tornado track traveled through the climate division of interest. The Mar-Jun period was chosen because these four months are climatologically the most tornadic in OK. [1] The tornado day climatology from this period for each OK climate division is shown in Fig. 2. Not all non-meteorological bias in the tornado data can be removed, and some may still be present, evidenced by the highest climatology values occurring near the major population centers of Oklahoma City and Tulsa (climate divisions 5 and 3, respectively). However, the precautions taken in this study are expected to reduce the magnitude of the biases in the tornado data to a scale small enough so as not to overwhelm any significant relationship that might be found with the synoptic variables being studied.

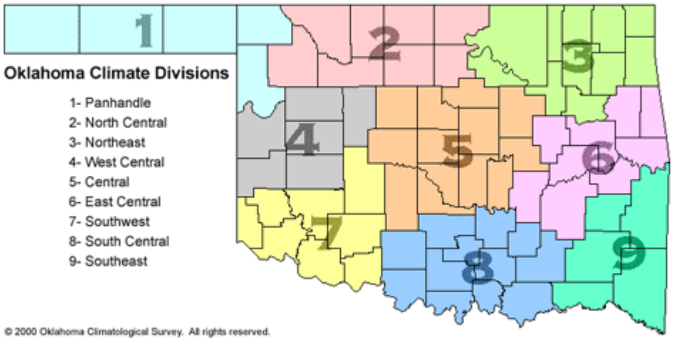

FIG. 1. The nine climate divisions of the state of Oklahoma. Taken from the Oklahoma Climate Survey.

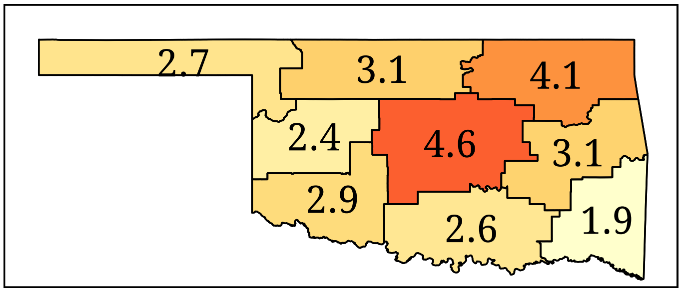

FIG. 2. Mar-Jun OK tornado days climatology (base period 1981-2010) by climate division from the SPC tornado database.

b. Precipitation Data

The Climate Prediction Center (CPC) Daily US Unified Precipitation 0.25° × 0.25° gridded dataset (Higgins 1996, 2000) is acquired from the NOAA Earth System Research Laboratory (ESRL) [2] and used to calculate Dec-Feb total accumulated precipitation for each OK climate division during 1981-2010. The climatology for this data is shown in Fig. 3, in which the spatially diverse climate of OK is evident. This large spatial variability in OK winter precipitation is the primary reason this study examines the tornado-precipitation relationship at the climate division level instead of the state level. This is done in

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[1] Monthly climatologies available from the National Climatic Data Center at http://www.ncdc.noaa.gov/oa/climate/severeweather/tornadoes.html

[2] Obtained from http://www.esrl.noaa.gov/psd/

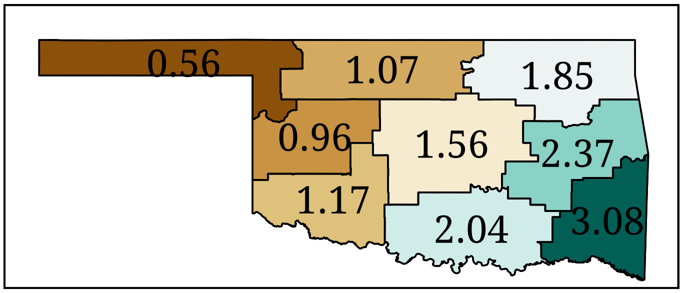

FIG. 3. Dec-Feb OK precipitation climatology ($mm\ day^{-1}$) (base period 1981-2010) by climate division from the CPC US Unified Precipitation dataset.

case the background long-term mean of accumulated precipitation has an impact on any relationship that may exist.

Percentage of climatology values for precipitation are computed and compared to percentage of climatology values for tornado days in each OK climate division. Due to the non-normal distributions of tornado activity qualitatively evident in Fig. 4, a bootstrapping technique is employed to objectively test the difference in OK tornado activity between wet and dry antecedent winters.

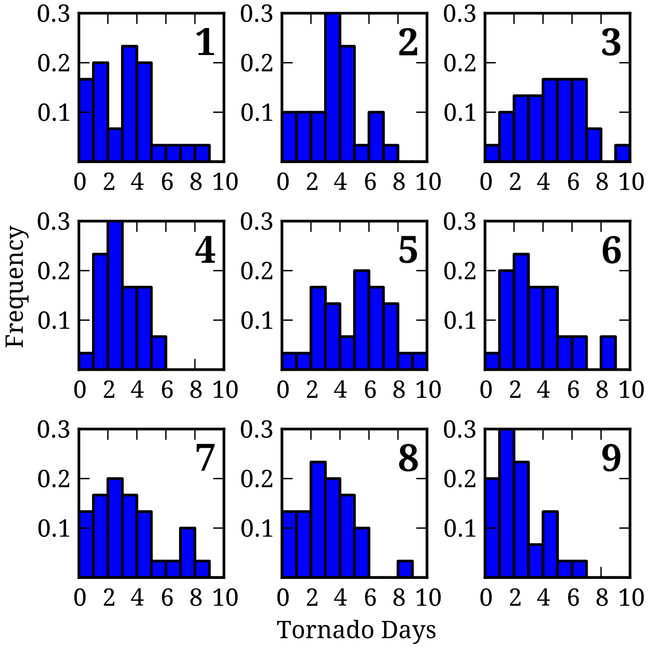

FIG. 4. Mar-Jun OK tornado days frequency distributions for each climate division for 1981-2010 from the SPC tornado database.

c. 500 hPa Geopotential Height Data

Monthly geopotential height data at 500 hPa (Z500) is extracted from NCEP/NCAR Reanalysis I (Kalnay et al. 1996) [3] for the period 1981-2010, gridded at $2.5^\circ \times 2.5^\circ$. The 500 hPa level in the middle troposphere is chosen to maximize Rossby wave variability, and thus any relationship with OK tornado activity. The average Z500 anomaly for the four months (Nov-Feb) preceding each OK tornado season (Mar-Jun) is calculated and used for the spatial correlations in section 4. Mean area-averaged values of Z500 from the region depicted in Fig. 9 are also computed and used for statistical analysis in section 4. Due to the synoptic-scale nature of the US Rossby wave pattern and its impacts on meteorological variables downstream, it is deemed prudent to examine its relationship to statewide OK tornado activity, as opposed to per climate division as with the precipitation-tornado relationship. Here, the smaller spatial scale provided by the climate divisions is not necessary, and a statewide scale is more comparable to the scale of variability associated with Rossby waves.

3. Relationship to Precursory Precipitation

a. Results

First a heuristic time series analysis is conducted to see if there is any obvious qualitative relationship between OK spring tornado activity and precursory winter precipitation. Shown in Fig. 5 are the percentage of climatology time series of Mar-Jun OK tornado days and antecedent Dec-Feb precipitation together for each climate division. No significant correlation between the two appears to exist qualitatively. The linear correlation coefficients between the two time series are very close to zero, with p-values in excess of 0.36 for all nine climate divisions. Three climate divisions have p-values in excess of 0.90, indicating (loosely) that there is a $\geq 90\%$ probability that the correlation between the two time series in these divisions arises from random variability. In addition, four of the climate divisions have a positive-signed correlation, while five have a negative-signed correlation, and there appears to be no coherent geographic pattern to the signs of the correlations. This analysis was repeated using only F2 or stronger tornado days, a second time using Sep-Feb precipitation, and a third time correlating only February precipitation to March tornado days (not shown). All of these analyses yielded little change in the significance of the correlations.

Since there appears to be no spatially-dependent connection between spring tornado activity and antecedent precipitation in OK, a composite scatter plot is created by combining the datasets from all nine climate divisions, yielding 270 total data points, in an attempt to see if there is a hidden statewide relationship (Fig. 6). The distribution of points appears fairly symmetric about the origin of the coordinate axes, qualitatively suggesting no significant relationship between the two variables

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[3] Obtained from NOAA/ESRL at http://www.esrl.noaa.gov/psd/

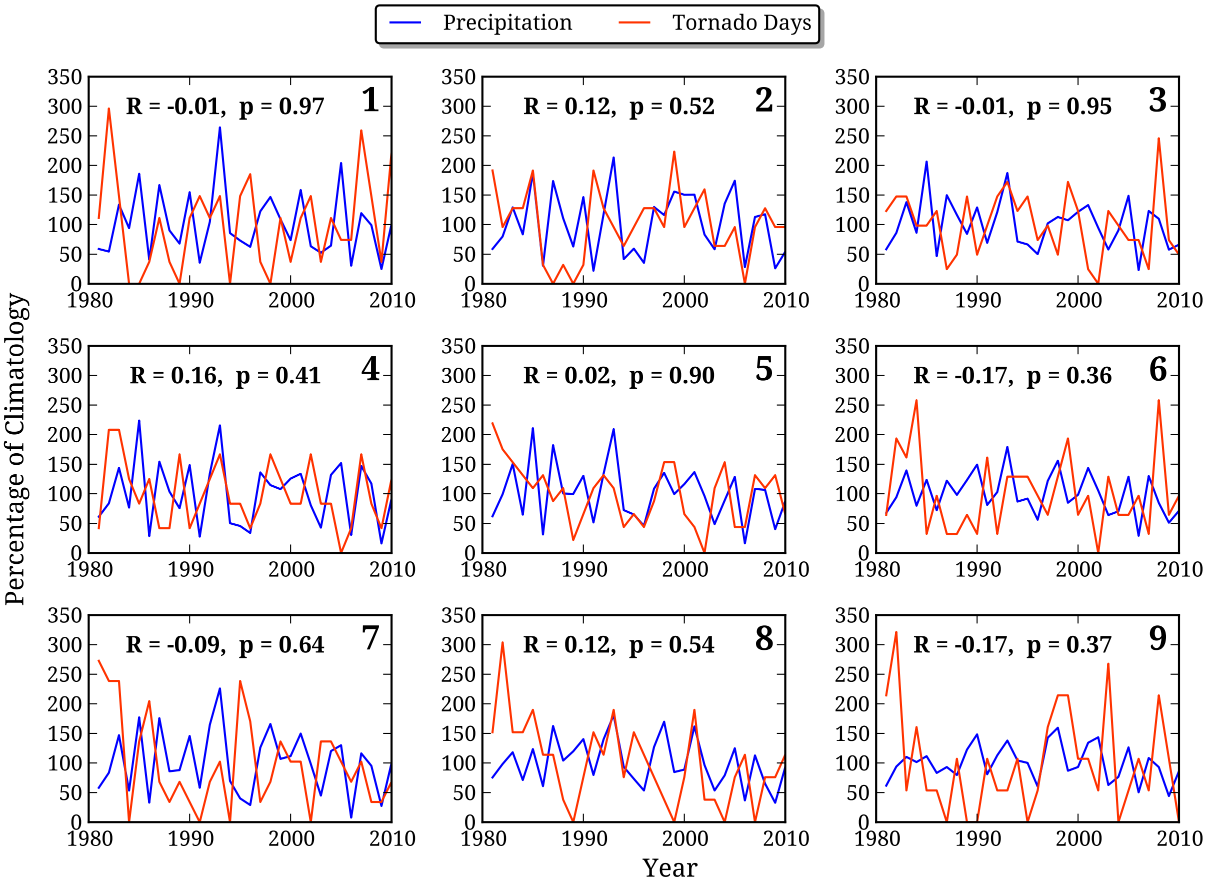

FIG. 5. Percentage of climatology time series of Dec-Feb accumulated precipitation (blue) and tornado days during the following Mar-Jun period (orange) for Oklahoma climate divisions 1-9. Pearson linear correlation coefficients and their 2-tailed p-values are shown.

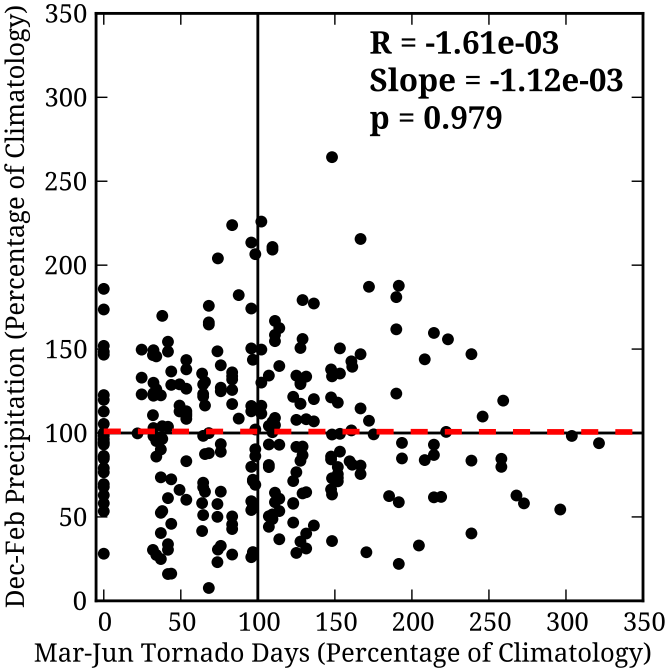

FIG. 6. Composite scatter plot of Dec-Feb precipitation versus subsequent Mar-Jun tornado days as percentage of climatology for all nine OK climate divisions (270 total points). The red, dashed line denotes the linear regression fit for the data. The correlation coefficient (R), slope, and associated p-value are shown.

in any direction. The linear regression line has a slope remarkably close to zero, with a nearly 98% ($p = 0.979$) probability that the set of points could have been obtained if the null hypothesis is true that there is no relationship between the variables.

In a final attempt to relate these two variables, a bootstrapping analysis is performed. Given the non-normal distributions seen in the tornado data (Fig. 4), standard statistical tests attempting to relate tornado activity to any other variable cannot be expected to give unbiased results, since they assume a normal distribution. Bootstrapping as a resampling technique is ideal for objectively analyzing a dataset independent of its distribution. Here, it is used to construct confidence intervals around the difference in OK spring tornado activity between years with above-normal, near-normal, and below-normal antecedent winter precipitation. The precipitation data is categorized in this manner by taking the upper, middle, and lower terciles, respectively. The differences between wet and dry years, wet and normal years, and normal and dry years are computed. The confidence intervals are determined at $\alpha = 0.95$ from 10^5 bootstrap samples. The results for each climate division are illustrated in Fig. 7. For each of the three tests, the interval around the mean difference brackets the number zero in every climate division, indicating that no statistically significant difference in OK spring tornado activity is observed between wet and dry, wet and normal, or normal and dry antecedent winters.

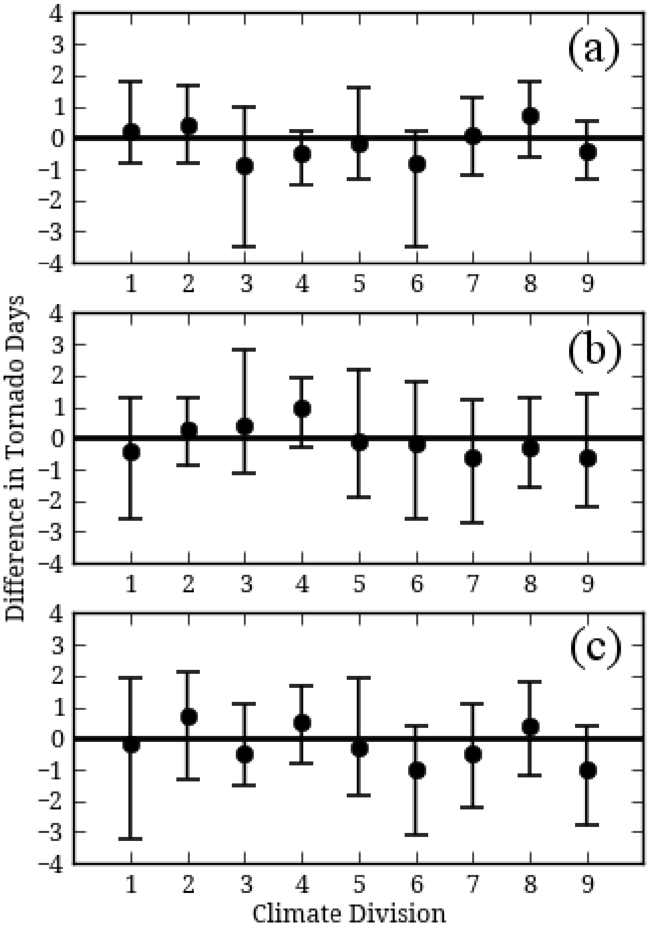

FIG. 7. Mean difference in Mar-Jun OK tornado days between years with (a) wet and dry winters, (b) wet and near-normal winters, and (c) near-normal and dry winters. The differences are calculated for each climate division in OK. Bootstrap 95% confidence intervals derived from 10^5 random samples are shown by the error bars. The zero line indicating no difference is shown in thick black.

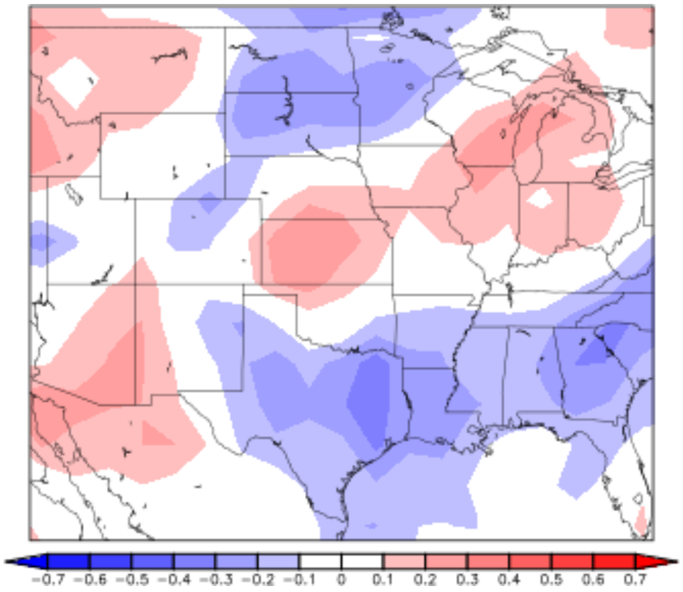

FIG. 8. Linear correlation between Mar-Jun Oklahoma tornado days and precursory Nov-Feb accumulated precipitation. Correlations are calculated over the 1981-2010 period.

b. Discussion

The analysis here indicates strongly that there is no significant relationship between OK spring tornado activity and accumulated precipitation during the preceding winter. In the context of pioneering seasonal tornado forecasting, it is worth considering the question of why no relationship exists. Figure 8 shows the spatial correlation between OK Mar-Jun tornado activity and antecedent Nov-Feb precipitation. Due to limitations in the plotting software used, it was not possible to correlate with Dec-Feb precipitation as in previous analysis, but the results with Nov-Feb precipitation are very similar, and serve to make the intended qualitative illustration. It is evident that there is not a total absence of a relationship, as there exists an area of significant non-zero correlation values south of OK, and a similar area with values of opposite sign north of OK (Fig. 8). Oklahoma itself, however, lies mostly in between these two areas of correlation, resulting in an insignificant relationship between tornado activity and local antecedent precipitation. This suggests that OK tornado activity in the spring may be associated with a synoptic-scale pattern that generates a precursory pattern in regional precipitation around the state. A potential culprit pattern in mid-tropospheric flow is investigated in section 4. It may be that a local link between tornado activity and antecedent winter precipitation does exist in other portions of the contiguous US, but that OK happens to be in a position where the relationship is minimized. This is supported by the results of Shepherd et al. (2009), which found a weak relationship between Mar-Jun tornado days and antecedent Sep-Feb precipitation in Georgia. A logical question is how useful a potential link to antecedent precipitation at any one location may be for predicting tornado activity. The analysis in section 4 does not consider a link to precipitation, but the Rossby wave pattern found there is qualitatively consistent with the spatial correlations in Fig. 8. This could indicate that any covariance between tornado activity and precipitation, such as the findings of Shepherd et al. (2009), is secondary to a more fundamental synoptic-scale pattern that created the precipitation distribution in the first place. This root process would then likely be a better predictor of seasonal tornado activity. Further research would be necessary to determine if this is the case in multiple regions of the US.

4. Relationship to Precursory Mid-Tropospheric Flow

In light of the results in section 3 revealing no significant relationship between OK spring tornado activity and local precursory precipitation, it is natural to step back and look for a more synoptic-scale pattern that might be associated with OK tornado activity. Here, geopotential height at 500 hPa (Z500) is considered as a representation of the mid-tropospheric flow in relation to OK tornado activity.

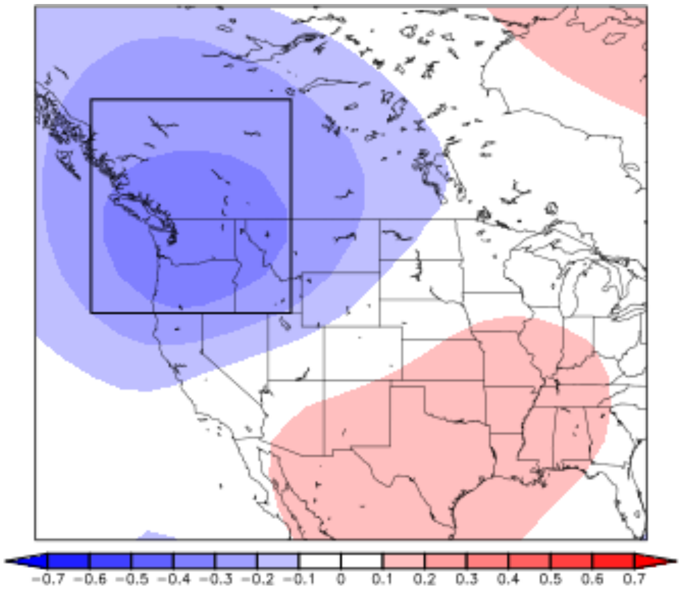

FIG. 9. Linear correlation between Mar-Jun Oklahoma tornado days and precursory Nov-Feb 500 hPa geopotential height (Z500). Correlations are calculated over the 1981-2010 period. The black box indicates the area (130°W-112°W, 42°N-58°N) over which Z500 data was extracted and spatially averaged for further analysis.

a. Analysis

Monthly $2.5^\circ \times 2.5^\circ$ grids of Z500 are extracted from NCEP-NCAR reanalysis I (Kalnay et al. 1996), and the mean Nov-Feb Z500 anomaly (relative to 1981-2010 climatology) is calculated prior to each OK tornado season (Mar-Jun) for 1981-2010. Mar-Jun tornado days are summed as in section 3, but this time for the entire state of Oklahoma, not per climate division. Mar-

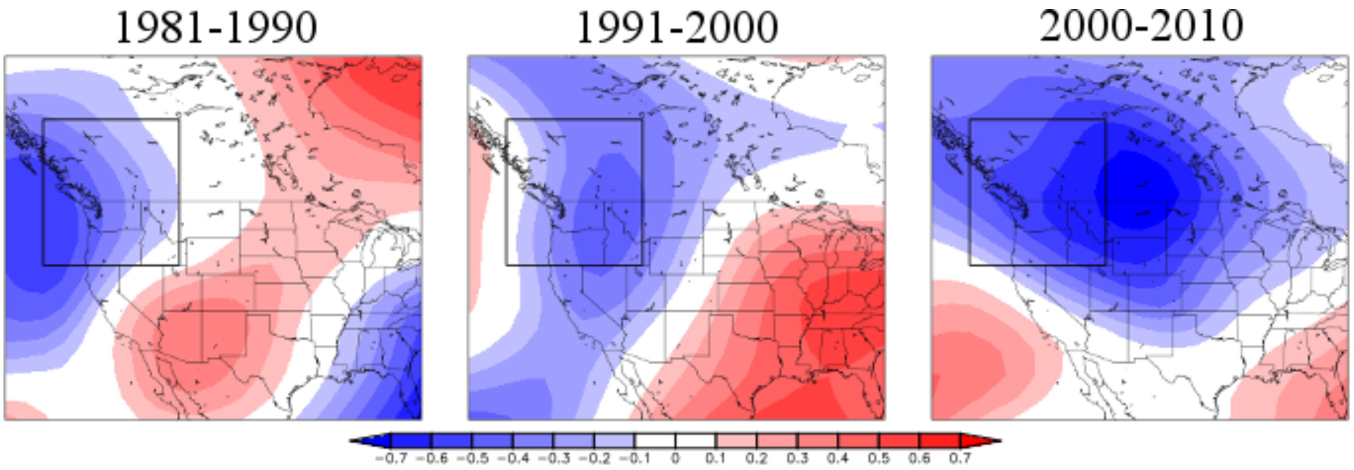

FIG. 10. As in Fig. 9, but for the periods 1981-1990, 1991-2000, and 2001-2010.

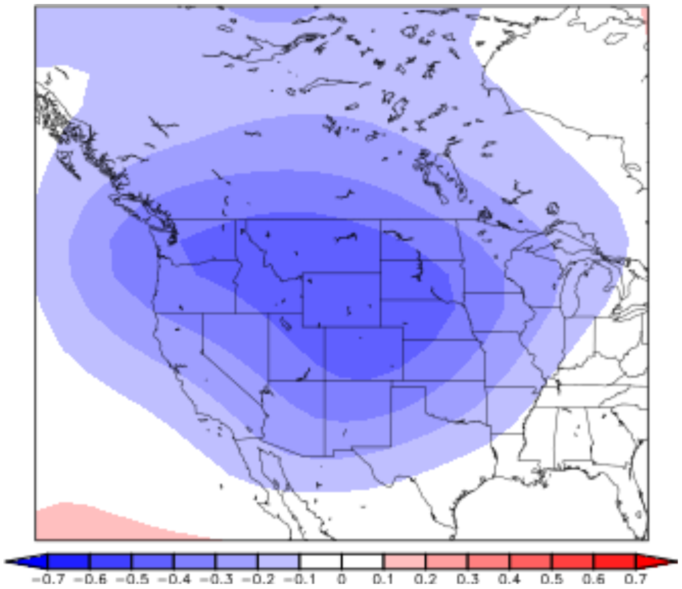

FIG. 11. As in Fig. 9, but using Mar-Jun Z500 (zero lead time).

Jun tornado days are correlated with antecedent Nov-Feb Z500 for the contiguous US region (Fig. 9). An area of significant correlation is centered over the state of Washington, extending from the northwestern US into southwestern Canada and the northeast Pacific, suggesting a tendency for troughing (ridging) there preceding active (inactive) tornado seasons in OK. To make sure this association is not a figment of an ephemeral alignment with the US winter pattern, the correlation is reproduced for the 1981-1990, 1991-2000, and 2001-2010 periods separately (Fig. 10). A qualitative analysis indicates that the mean position of the correlation maximum wobbles between decades within ±10° longitude of its 30-year position in Fig. 9, but maintains significant like-signed correlation values in the Pacific Northwest region. In contrast, although an area of opposite-signed correlation values is usually present in the southern US, it is observed to shift significantly between decades, and is generally inconsistent compared with the correlations in the Pacific Northwest. This explains the relatively low 30-year correlation values in the southern US in Fig. 9.

The correlation in Fig. 9 is repeated again in Fig. 11, but using Mar-Jun Z500, in order to examine the mode of variability associated with OK Mar-Jun tornado activity at zero lead time. The correlation values are found to be more significant and shifted to the southeast of those in Fig. 9, indicating troughing (ridging) over the Rocky Mountains during active (inactive) OK tornado seasons. This is consistent with the results of several studies which have shown that severe weather reports, including tornadoes, tend to be concentrated near upper tropospheric jet streaks (Kloth et al. 1980, Rose et al. 2004, Verbout et al. 2006). The presence of a mean trough in mid-tropospheric flow over the Rockies during the spring would be expected to advect jet streaks over the Great Plains with increased frequency. In the opposite case, the presence of a mean ridge would be expected to reduce the frequency of jet streaks downstream. To see if the relationship provides the expected result in both directions (that is, an anomalous trough over the Rockies during especially tornadic springs and an anomalous ridge during inactive springs), the mean Z500 anomaly is determined for active and inactive OK tornado seasons, defined by the upper and lower terciles of OK Mar-Jun tornado days, respectively. Panels (a) and (b) of Fig. 12 show the results at zero lead time (Mar-Jun), revealing negative Z500 anomalies over the Rockies during the ten most active years, and positive anomalies of similar magnitude over the Rockies during the ten least active years, indicating that the relationship behaves as expected in both directions. The same plots are shown in panels (c) and (d) of Fig. 12, but for Nov-Feb Z500 anomaly, a lead time of four months. The anomaly extrema over the Rockies shift slightly northwestward, similar to the change between Fig. 11 and Fig. 9. The magnitudes of

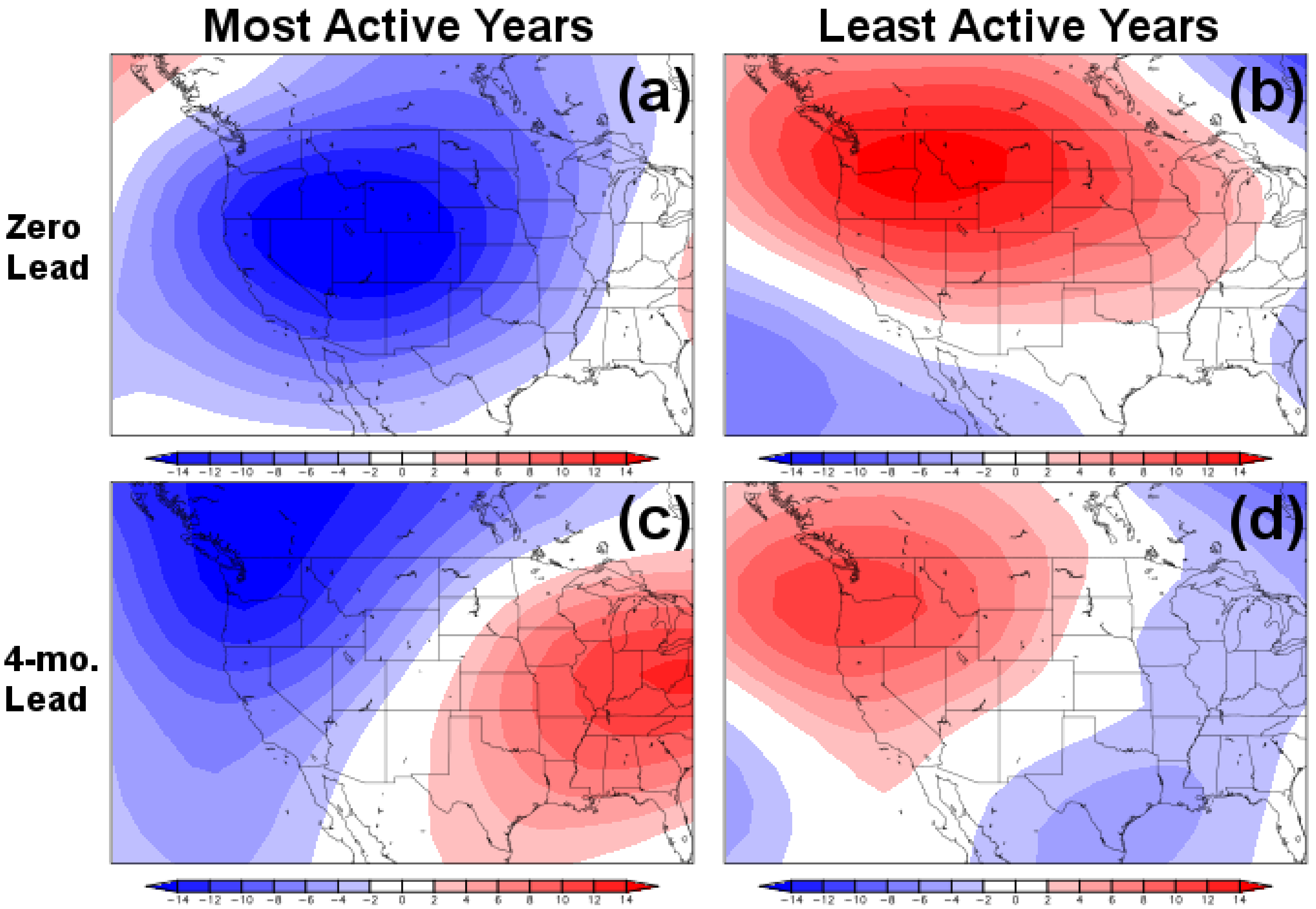

FIG. 12. Anomalous 500 hPa geopotential height (m) for the (left) 10 most active and (right) 10 least active OK tornado years in Mar-Jun during 1981-2010 for (a),(b) zero lead (Mar-Jun) and (c),(d) 4-month lead (Nov-Feb). Anomalies are relative to 1981-2010 climatology.

the anomalies are not significantly reduced from those at zero lead time, indicating that the observed relationship between the Rossby wave pattern and OK tornado activity remains robust when lagged by four months.

In order to perform further analysis, Z500 is area-averaged over the box in Fig. 9 (130°W-112°W, 42°N-58°N). Although the highest correlation values occur within the state of Washington, the box is chosen to be large enough to be representative of the general Rossby wave pattern in the region. This is done because geopotential height anomaly as a forecast tool is often examined over a region comparable in size to a typical Rossby wave. The average anomaly over a large area will also be less sensitive to the aforementioned temporal shifts in the position of the correlation maximum. Henceforth for the rest of this section, Z500 shall refer to the area-averaged values within this box.

A scatter plot of precursory Nov-Feb Z500 anomaly versus Mar-Jun OK tornado days is shown in Fig. 13. A linear regression yields a correlation of $R = -0.356$, significant at approximately 95% confidence ($p = 0.053$). While this linear correlation is not extremely significant, it seems to suffer mainly from a handful of substantial outliers. If terciles are used to bin both datasets into below-normal, near-normal, and above-normal values, the categorical correspondence between Z500 anomaly and OK tornado activity is fairly good. Out of ten years with above-normal Z500, one had an active tornado season, three had near-normal seasons, and six had inactive seasons. Out of ten years with below-normal Z500, seven had active tornado seasons, one had a near-normal season, and two had inactive seasons. Put another way, below-average Nov-Feb Z500 precluded below-average tornado seasons 8 out of 10 times, and above-average Nov-Feb Z500 precluded above-average tornado seasons 9 out of 10 times.

As in section 3 for precipitation, a bootstrapping analysis is performed to objectively characterize the difference in OK spring tornado activity between years with above-normal, near-normal, and below-normal antecedent winter Z500 in the northwestern US region, independent from the non-normal distribution of tornado days. The Z500 data is categorized in this man-

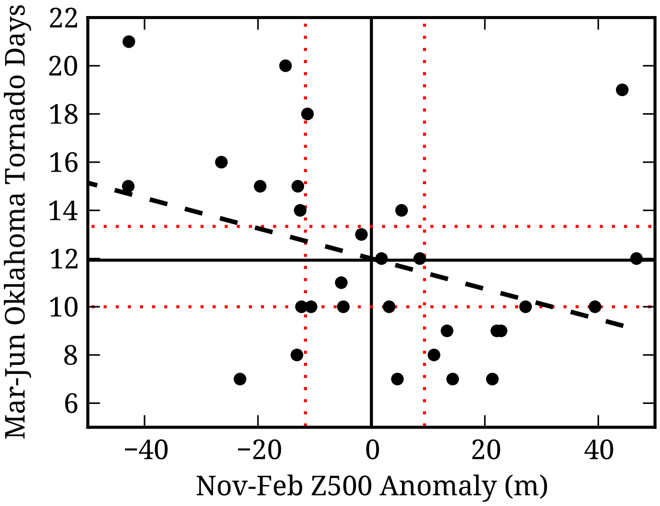

FIG. 13. Scatter plot of Mar-Jun Oklahoma tornado days versus antecedent Nov-Feb 500 hPa geopotential height (Z500) anomaly relative to 1981-2010 climatology, area-averaged over 130°W-112°W, 42°N-58°N. The dashed line represents the linear regression fit, with a correlation coefficient of $R = -0.356$ and a p-value of $p = 0.053$. The solid lines denote the means of both variables. The red, vertical lines denote the upper and lower terciles of Z500 anomaly. The red, horizontal lines denote the upper and lower terciles of tornado activity.

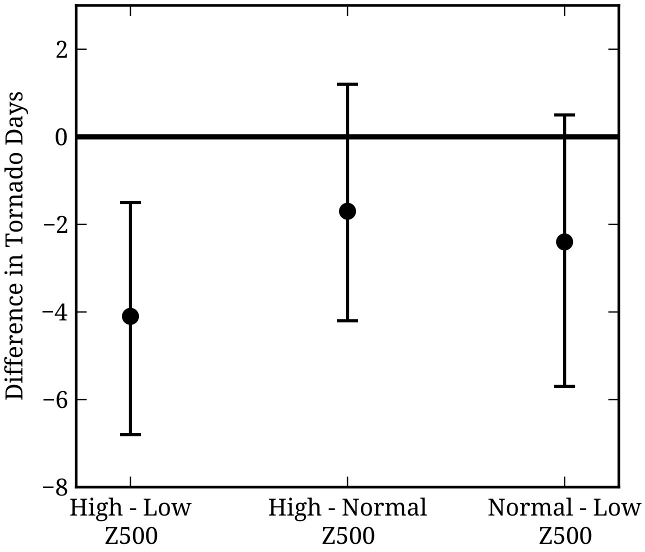

FIG. 14. Mean difference in Mar-Jun OK tornado days between years with above-normal, near-normal, and below-normal 500 hPa geopotential height (Z500) during the preceding winter within the box defined in Fig. 9. The differences are ordered from left to right as high minus low, high minus normal, and normal minus low. In other words: ridging years minus troughing years, ridging years minus normal years, and normal years minus troughing years, respectively. Bootstrap 95% confidence intervals derived from 10^5 random samples are shown by the error bars. The zero line indicating no difference is shown in thick black.

ner by taking the upper, middle, and lower terciles, respectively. Bootstrap 95% confidence intervals are constructed from 10^5 random samples around the difference in tornado days between above-average and below-average Z500, above-average and near-average Z500, and near-average and below-average Z500. The results are shown in Fig. 14. Years with above-normal winter Z500 in the Pacific Northwest are found to have 4.1 fewer OK tornado days during Mar-Jun on average than years with below-normal winter Z500 in the Pacific Northwest. The confidence interval around this value does not contain the number zero, indicating that the difference is significant at 95% confidence. In fact, this value remains significantly different from zero at up to 99.8% confidence. The differences in tornado days between above-normal and near-normal Z500 years and between near-normal and below-normal Z500 years are smaller in magnitude (-1.7 and -2.4, respectively) and not as significant, but still negative, as would be expected given the results of the analysis thus far. Unlike with local winter precipitation, these results indicate a statistically robust difference in OK tornado activity between years with opposite-signed Z500 anomalies in the Pacific Northwest region.

b. Z500 as a Predictor of OK Tornado Activity

Since a statistically significant relationship appears to exist between OK tornado activity and the US Rossby wave pattern during the preceding winter, it is natural to investigate how skillfully OK tornado activity can be predicted using this relationship. Using minimal statistical models, Mar-Jun OK tornado days are predicted and compared with observations for the 1981-2010 period. First, the linear model is tested, shown in Fig. 15a. A perfect prediction would consist of each point residing on the diagonal illustrated in the figure. The coefficient of determination (R^2) represents the fraction of the variance in the observations that is captured by the model. For the linear model, this value is 0.127, which arises from squaring the correlation coefficient of the linear regression line in Fig. 13. This means that 12.7% of the variance is explained by the model, which is rather poor. Fig. 15a illustrates that the slope of the data is not steep enough to match the diagonal, indicating that the model overpredicts inactive tornado seasons and underpredicts active seasons. Since most processes and relationships in the atmosphere are nonlinear, it was decided to test the skill of a higher order model. The 2nd-order polynomial predictor is compared with observations in Fig. 15b. A substantial jump in skill is observed, with R^2 increasing to 0.322, indicating 32.2% explained variance. However, this jump appears to be largely due to a couple of outliers making a leap closer to the diagonal between panels (a) and (b) of Fig. 15. The majority of the dataset does not appear to exhibit an appreciable increase in slope over the linear model. Thus, the skill of the quadratic model increases quantitatively, but not necessarily qualitatively.

The temptation to test even higher order models is considerable, but here we must be mindful of the potential for illusory increases in predictive skill. For any set of points, sequentially higher order polynomial fits must necessarily converge towards a perfect prediction, ultimately attaining it once the degree of the polynomial equals 1 less than the sample size. Although the sample size here is 30, models of orders higher than 2 typically quickly become part of an accelerating trend in correlation that is non-physical. That is, the character of the prediction becomes unrelatable to the physical drivers behind the atmospheric process being modeled, and any increase in skill becomes coincidental solely with the increase in the degree of the polynomial. This results in a model that is not truly useful for predicting future values.

Despite the admonition above, it is decided that valuable insight may be garnered from testing a 3rd-order model as well. It is hypothesized that there may be a natural 3rd-order signal in the relationship between OK tornado activity and the precursory US Rossby wave pattern. The reasoning behind this involves the fact that OK tornado activity is being related here to 500 hPa troughing or ridging in the northwestern US at a 4-month lead time. The magnitude of the mean Z500 anomaly in this region during the course of the tornado season (zero lead time) may play a role in the level of OK tornado activity by modulating the frequency of jet streaks in the Great Plains. However, during the four months prior to the OK tornado season (Mar-Jun), it may be that the very presence of an anomalous ridge or trough contributes more to the subsequent spring pattern than the magnitude of the Z500 anomaly within that ridge or trough. While an investigation of whether or not this is the case is beyond the scope of this study, a cursory analysis can be conducted here by examining the skill of a 3rd-order model. This is because, as an odd function, the natural shape of a cubic fit in this case will tend to dampen the impact of the magnitude of the Z500 anomaly on the tornado day prediction and exaggerate the impact of the sign of the anomaly.

The 3rd-order polynomial prediction of OK tornado activity is compared to observations in Fig. 15c. An additional increase in predictive skill over the 1st-order and 2nd-order models is found, with 37.6% of the variance explained by the 3rd-order prediction. Unlike the 2nd-order prediction, many data points are observed to shift closer to the diagonal when compared to the 1st-order prediction, and the majority of the dataset exhibits a steeper slope closer to the diagonal, indicating an overall increase in predictive skill that penetrates more than just a few outlier points. The question must be asked whether or not this increase in skill is simply due to inflating the order of the model as discussed earlier, which would result in the model not being as useful at predicting future tornado activity. To investigate this, the coefficient of determination (R^2) is computed for predictive models up to order 7 (Fig. 16). The model skill is seen to increase markedly between 1st and 3rd order, but much more slowly thereafter, reaching a near-plateau just under 0.42 as order is further increased. This is an interesting result, given that R^2 must eventually approach 1.0 as the order of the model approaches 29. The fact that model skill improves sharply until 3rd-order and then nearly stalls at higher orders suggests that there may be a natural 3rd-order signal in the relationship between OK tornado activity and antecedent Z500 that is not a purely mathematical result, but a physical one that could be useful in seasonal-scale tornado predictions.

Fig. 17 replicates the scatter plot in Fig. 13, but includes the 3rd-order model fit (green line) tested above. A couple of important observations protrude from this plot. Firstly, the cubic model appears to capture the general behavior of the middle of the distribution much better than the linear model (black line), consistent with the results in Fig. 15. Secondly, the magnitude of the derivative of the cubic fit is seen to decrease as the magnitude of Z500 anomaly increases, thereby decreasing the sensitivity of predicted tornado activity to large magnitudes of Z500 anomaly. Combined with the overall better representation of the data by the 3rd-order model, this is consistent with the conceptual hypothesis offered previously. However, the agreement with this hypothesis breaks down at Z500 anomaly values greater than about $+30$ meters, where the derivative changes sign and increases in magnitude. This right-hand tail of the cubic model appears to be pulled sharply upward in response to an outlier data point in the top right corner of the scatter plot, corresponding to the year 1981, which just happens to exhibit the largest departure from the expected outcome of having such positive antecedent Z500 anomalies. It is visually evident that without this outlier, the cubic model would likely conform to the behavior expected from our conceptual hypothesis throughout the entire distribution. However, a much larger sample size than the one used in this study would be necessary to determine if a cubic-type function is in fact a natural physical description of the relationship between OK tornado activity and the precursory Rossby wave pattern over the Pacific Northwest region.

c. Discussion

The analysis here indicates that there is a statistically significant association between Mar-Jun OK tornado activity and the precursory Nov-Feb 500 hPa flow pattern in the northwestern US region, such that troughing (ridging) tends to lead to active (inactive) OK tornado seasons. The relationship appears to be even stronger at zero lead time (compare Fig. 9 and Fig. 11), but this study is interested in seasonal prediction of tornado activity months in advance. An encouraging result is that the spatial mode of variability in Z500 associated with OK tornado activity is qualitatively consistent with previous research examining patterns in related variables (e.g. jet streaks), and is meteorologically intuitive. The synoptic scale of this relationship would make it easy to recognize and use by operational forecasters in potential long-range tornado outlooks in the future. It is evident that nonlinear statistical models can predict OK spring tornado activity with some degree of success using this relationship. However, additional research and much larger sample sizes will be necessary to determine the robustness of such predictions, and which model best represents the physical relationship being observed.

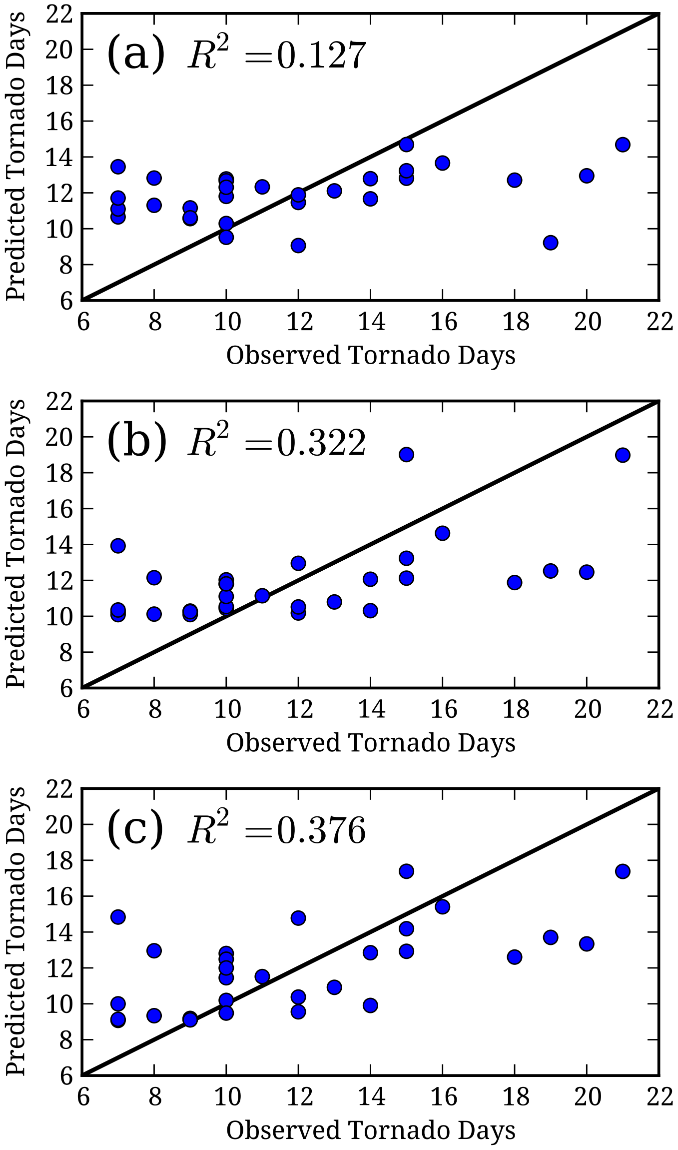

FIG. 15. Predicted versus observed Mar-Jun OK tornado days based on precursory Nov-Feb Z500 anomaly (in the region defined in Fig. 9) for (a) linear model, (b) 2nd-order model, and (c) 3rd-order model. Coefficients of determination (R^2) are shown. The black, diagonal lines represent a perfect prediction.

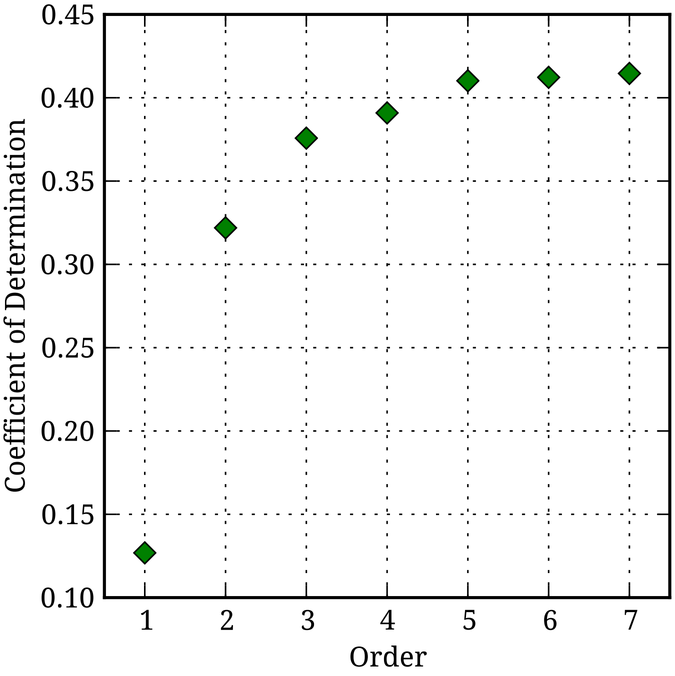

FIG. 16. Coefficients of determination (R^2) for 1st-order through 7th-order polynomial predictions of OK Mar-Jun tornado days.

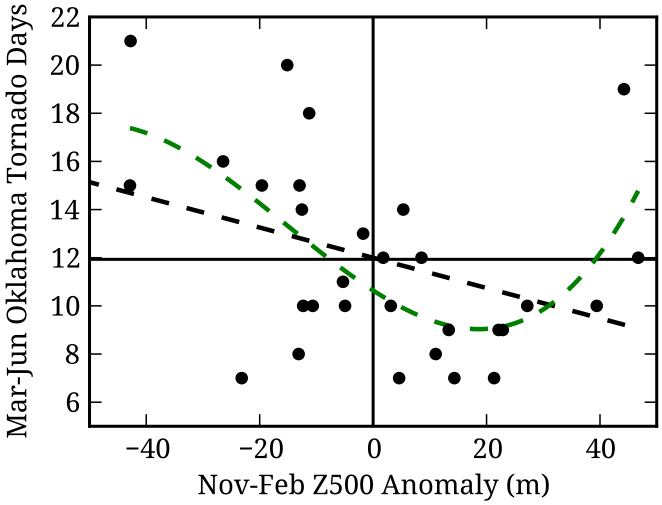

FIG. 17. As in Fig. 13, but including the 3rd-order least squares fit (green line). The red lines bounding the terciles have been removed for clarity.

5. Conclusions

This study investigated the relationship of precursory Dec-Feb local precipitation and precursory Nov-Feb mid-tropospheric flow across the US to Mar-Jun tornado activity in OK. Forecasting tornado activity is important for protecting lives and property, and there are currently no seasonal-scale tornado outlooks issued in any official capacity by the US government. Such outlooks could greatly benefit emergency managers, operational meteorologists, businesses, and the public sector, similarly to how seasonal Atlantic hurricane outlooks issued by NOAA have availed those groups.

This study has shown that local antecedent winter precipitation is useless for the purpose of seasonal tornado prediction in OK. No statistically significant relationship between Mar-Jun OK tornado days and precursory Nov-Feb precipitation is apparent during the 1981-2010 period in any of the nine climate divisions in OK. This may be due in part to Oklahoma's hapless placement in relation to the synoptic pattern that influences tornado variability in the Great Plains, and it is possible that other tornado-prone regions of the US do exhibit a connection between tornado activity and antecedent local precipitation (Shepherd et al. 2009). However, it may ultimately be more beneficial to research the precursory synoptic weather pattern that would induce any precipitation variability associated with tornado activity in the first place.

Nov-Feb mid-tropospheric flow over the US at 500 hPa was found by this study to be significantly correlated with subsequent Mar-Jun Oklahoma tornado days. In particular, the presence of an anomalous trough (ridge) over the northwestern US region was found to persist and shift southeastward into the Rocky Mountains during the Mar-Jun period, resulting in enhanced (reduced) Mar-Jun OK tornado activity. This relationship makes physical sense, as an anomalous trough persisting over the western US would act to advect dry, mid-level air into the Great Plains overlaying moist, southerly low-level flow, with enhanced wind shear and forced lift associated with jet streaks rounding the base of the trough, a setup known to promote supercells. A ridge in the same position would suppress these factors and have the opposite effect. The implications of this study lie in the fact that this intuitive synoptic setup has been shown here to be foreshadowed during the four months (Nov-Feb) preceding the OK tornado season (Mar-Jun) by the same type of pattern, simply shifted to the northwest. This finding may be able to serve as a qualitative tool for long-range forecasting of OK tornado activity. It was also shown that simple statistical models are capable of using this relationship to predict OK tornado activity with significant skill, though further research is necessary to determine the best scheme for this. It is also possible that there is a better method for quantifying the mode of variability in Z500 associated with tornado activity, such as a statistical index combining correlations from more than a singular geographic domain. Given the synoptic scale of the pattern examined here, it may be that seasonal tornado activity in other sectors of the US is subject to a similar relationship with the antecedent Rossby wave configuration. Future research could assess the strength of this relationship with regards to severe hail and wind reports, not just tornadoes. Mid-tropospheric flow as investigated in this study does not explain all seasonal tornado variability in OK, but if it is coupled with other predictors at similar lead times, a cohesive technique for forecasting seasonal tornado activity could be developed. This could then potentially be used for multiple regions of the US.

Acknowledgments.

The primary author would like to thank the mentors named as co-authors at the National Weather Service Forecast Office in Norman, OK for their support and guidance during the writing of this manuscript, and for initiating the original idea that lead to this project. The author also thanks Dr. Michael Richman at the University of Oklahoma for his helpful insight into statistical analysis techniques. The National Weather Center Research Experiences for Undergraduates program, funded by NSF grant #1062932, is thanked for making this research possible.

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