J3.7 A NEW PERSPECTIVE ON THE CLIMATOLOGY OF TORNADOES IN THE UNITED STATES

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1. Introduction

Climatological studies of severe weather hazards are beneficial to a wide variety of persons and organizations including emergency management officials, the insurance industry, engineers, and the general public. One of the more important areas of climatological research from a public safety perspective is that of tornadoes. Some previously studied aspects of tornado climatology include the reorganization of tornado records (e.g., Grazulis 1993), the establishment of a reliable damage scale (e.g., Fujita 1971; Doswell and Burgess 1988; Brooks and Doswell 2000), and the geographical threat of tornadoes (Concannon 2000). This study examines the bulk properties of tornado reports for the United States for the time period 1955-1999 to ascertain whether the dataset is suitable for use in annual, long-lead time, tornado prediction.

In studying the climatological nature of atmospheric phenomena, a long-term record of occurrence is of great importance. Temperature and precipitation records have been kept at numerous locations for well over 100 years, and in some cases 200 years, whereas the period of record for tornadoes is much shorter, with reliable records only available since approximately 1950. Knowledge of the true climatology of severe weather hazards (large hail, damaging winds, and tornadoes) is complicated by the non-systematic nature of severe weather observations. An increase in settlement and more efforts to collect information on tornadoes has led to an increase in the estimates of the number of tornadoes that occur annually in the United States. On average, tornado reports have increased by approximately 14 per year, such that the annual number of tornado reports has almost doubled since 1955 (Brooks et al. 2001).

Such dramatic changes in the climatological record of tornadoes make it much more difficult to define what is a 'normal' year, in terms of number of reported tornadoes, than it is to define what is normal for other atmospheric variables such as precipitation or temperature which have been collected systematically for long periods of time. Furthermore, the need for an appropriate definition of what is a normal tornado year becomes more important when one wishes to consider departures from normal or to answer questions concerning the expected number of tornadoes for the remaining portion of the year.

A large portion of this study focuses on overcoming these problems in order to answer questions such as, “How many more tornadoes can be expected for the rest of this year?” and “How does this year compare to normal?” and finally, “Can a slow starting tornado year, turn into a normal one, and does a large number of tornadoes early in the year always progress into a very large tornado year?” By obtaining answers to such questions, long-range prediction of tornado occurrence may be an approachable goal that is of great interest to a wide variety of groups.

Section 2 of this paper discusses the properties of the dataset used. A definition for a normal tornado year obtained from a simple model that attempts to define a normal year, and departures from normal, are presented Section 3. Discussion of the limitations and implications of this work are then presented in Section 4.

2. Data

The dataset we refer to throughout this report is the so-called ‘smooth log’ of severe weather reports that are collected by the Storm Prediction Center and archived in the National Oceanic and Atmospheric Administration (NOAA) publication, *Storm Data*.

The dataset contains all reported tornado occurrences from 1955-1999 for the continental United States. Our study focuses on these years, as well as the five-year period from 1994-1999. 1994-1999 is chosen because it allows immediate study of the aspects of recent tornado seasons that may be more representative of the true climatology of severe weather than the early years in the dataset. Even though this study works with one of the most accurate datasets about severe weather in the world, there are limitations to the quality of the observations. Recording observations of tornadoes throughout the entire United States is courtesy of National Weather Service workers throughout the country. Along with each documentation of a tornado comes a different set of standards in recordings of time, location, size, and path

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length (Grazulis 1993). Burgess and Doswell (1988) stated, “The responsibility for developing the climatological database falls on the shoulders of generally overburdened National Weather Service staff, and their training for interpreting the available data is woefully inadequate.” While dealing with the smoothed dataset eliminates some of this problem, bias can still be observed in certain aspects.

3. Results

a. Detrending the data

Perhaps the most fundamental aspect of the dataset that should be examined is the total number of tornadoes reported annually. Two major characteristics are observed from the dataset: inter-annual variability as well as a general increase in observed tornadoes throughout the time period (Fig. 1).

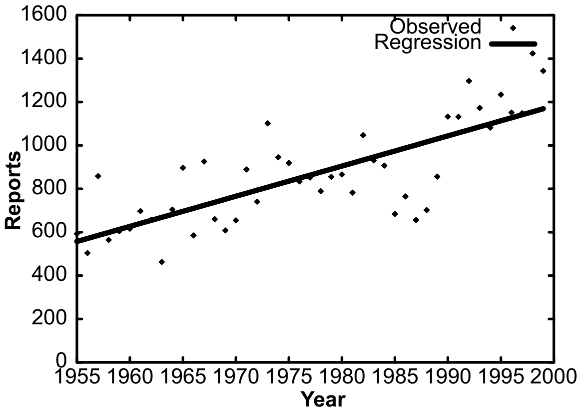

Figure 1. Raw number of tornadoes per year and regression fit to data.

A standard, least-squares regression line is fit to the data for comparison. (We are not claiming that the background increase is necessarily linear in time, but that is the simplest model and the length of the data record and questions concerning report collection make it reasonable to choose a simple model.) The slope, equivalent to an increase of 14 more tornadoes per year, signifies the increase of reports throughout the years. However, despite the increase in reports, variability is characterized by the constant fluctuation of the years about the regression line. The distance between each year and the regression line shows that all years have varying distances, indicating that if a slope didn’t exist, interannual variability would still remain. There is no clear trend for the depatures from the regression to be increasing or decreasing with time.

The regression probably provides a better answer to the frequently asked question, “How many tornadoes are there in the United States on average each year?”, than simply finding a mean over some period. The time series is non-stationary and averaging over any reasonably long period of time reduces the estimate of the number of tornadoes. Taking the mean over the entire record gives a value of about 800 tornadoes per year and, even just taking the last 30 years, the mean is about 1000 tornadoes. Given that the last time there were fewer than 1000 tornadoes reported in the United States during a year was 1989, it seems that would be a poor answer to the question of number of tornadoes. It is possible that the increase will not continue indefinitely into the future. Brooks and Doswell (2001) show that a plot of the number of tornadoes by F-scale has approached log-linear in the 1990s, after being convex in earlier years, with the increase in number of tornadoes being almost enirely in the weakest categories, F0 and F1. It is conceivable that the log-linear profile is close to the correct model of tornado occurrence, and that this increase in weak tornado reports will slow down now. It is also possible that the “true” distribution is concave and that we should expect more weak tornadoes than a log-linear profile would suggest.

Clearly, comparisons between different years are problematic, given the increase seen in Fig. 1. In order to address this, we have built a simple model of the data for each year, viewing the annual cycle of tornadoes as a cumulative distribution function (CDF). As an example, consider the number of tornadoes reported by day in 1959 (Fig. 2). A total of 612 tornadoes were reported in 1959, so the vertical axis could be rescaled from 0 to 612

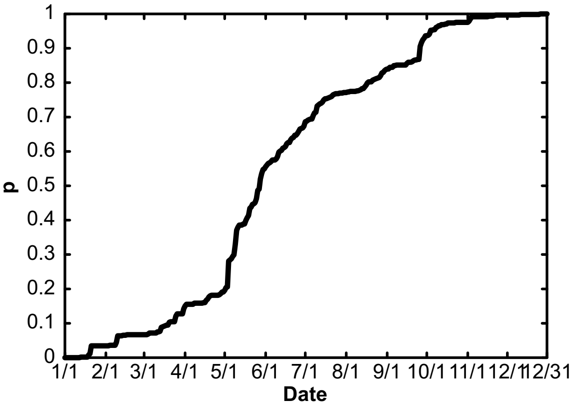

Figure 2. Annual cycle of tornado reports by day for 1959, displayed as a CDF.

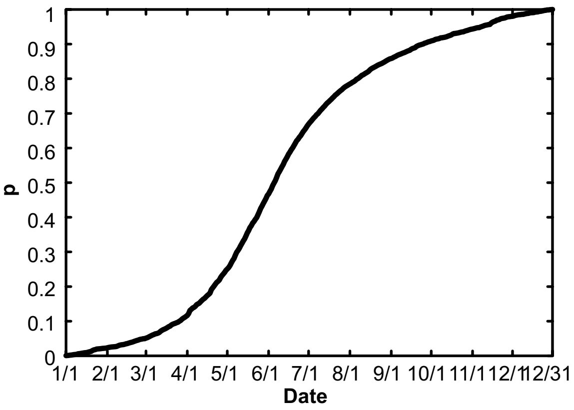

Figure 3. Mean annual CDF of tornado occurrence in the United States, based on 1955-1999.

and the plot would look identical. We have constructed such curves for each of the 45 years from 1955-1999. The mean of the curves is the mean annual CDF for tornado reports (Fig. 3). The scaling to convert the CDF to an absolute number of tornadoes is arbitrary. We have chosen to use the value of the regression line for 1999 shown in Fig. 1 as the number of tornadoes associated with p=1 on the CDF, or 1169 tornadoes. In effect, if all of the changes in the long-term are associated with improved detection, this is equivalent to looking at the number of tornadoes in “constant 1999” values, in a manner similar to adjustment for inflation in economics. Any value could have been chosen, but, since 1999 is the last complete year available, it seems useful to make the estimate in (approximately) current terms.

In order to adjust all of the years to “1999 values”, we have assumed that the difference between the observed value and the value from the regression line is represent of the departure from the “true” number of tornadoes. This difference is added to the constant 1999 value (1169 tornadoes) and that value is then an estimate of the number of tornadoes that would have been observed in that year if the observational capabilities of 1999 were available then. For instance, the 1959 season shown in Fig. 2 had a total of 612 reports. The value from the regression for 1959 was 613, so the “adjusted 1959” value is 1168. As will be discussed later, 1959 is the year closest to the normal year in the data set. 1987, on the other hand, has the fewest reports in adjusted terms. Its raw number of reports is 644 and the regression value is 902. The difference (258) is subtracted from the 1999 regression value to give an adjusted number of tornadoes of 811. All of the work that follows will use these adjusted values.

We can use the 45-year mean CDF and the linear regression estimate of 1169 tornadoes per year to estimate the mean number of tornadoes on any day of the year (Fig. 4). The CDF is fitted to the final value of 1169 tornadoes and then the increment associated with each day is rounded to the nearest integer. In the mean, the average number of tornadoes on a day in October trhough February is 2 or less. The number rapidly increases from early March into late May, to the point when an average of 9 tornadoes per day is expected and almost all days have at least 5 tornadoes on average. The decline after the peak is somewhat slower than the the increase, with it taking four months to reach the bottom instead of the three during the period of increase.

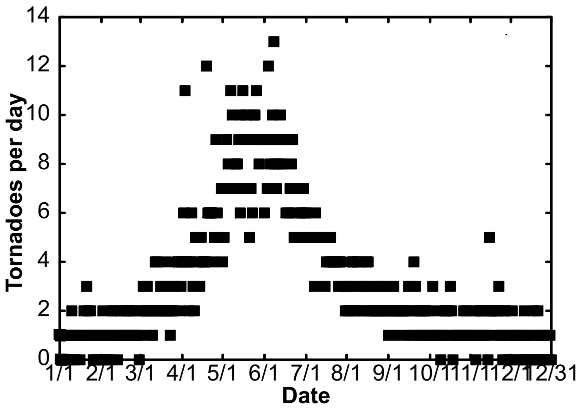

Figure 4. Expected number of tornadoes per day based off of CDF of tornado annual cycle in Fig. 3 and linear regression value of 1169 tornadoes per year from Fig. 1. Values have been rounded to the nearest integer

With the 45 adjusted years, we can now estimate the distribution of tornadoes throughout the year and begin the process of identifying “normal” and “unusual” years. A simple graphical summary of this is shown by plotting the extreme values, upper and lower deciles , and the quartiles of the distribution through the year (Fig. 5). The existence of a tornado season in the US is clear, with about 2/3 of all tornadoes occurring from April through July. The interquartile range is relatively constant for the second half of the year, ranging from 140-180 from 20 July on. The difference between the 90th and 10th percentiles is approximately twice as large as the interquartile range until the last two weeks of the year. These values give a good handle on the variability associated with tornado years. In terms of constant 1999 values, 80 percent of all years will end with with approximately 1000-1350 tornadoes.

A question of interest is where any particular year fits into the picture at any time of the year. As the project was carried out in the summer of 2001,

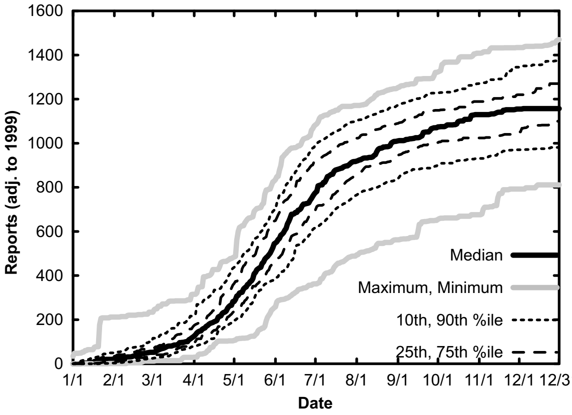

Figure 5. Distribution of tornado reports by day of year, adjusted to 1999. Thick solid line is median, thick gray lines are maximum and minimum, long dashed lines are quartiles, and dotted lines are 10th and 90th percentiles.

we monitored the progress of the 2001 season on a daily basis. Adding 2001 (through the middle of September) to Fig. 4 shows that it was well-below normal for number of tornadoes, at approximately the 10th percentile for most of the year (Fig. 6).

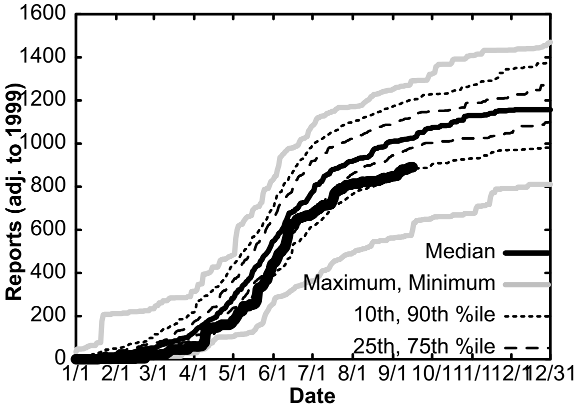

Figure 6. Same as Fig. 4, except with data for 2001 added on in heavy line. Data for 2001 are through 16 September as recorded in the smooth log data through that date.

Given how flat the distributions are in the last few months of the year, it seems unlikely, at the time of writing, that the deficit of approximately 200 tornadoes, accumulated through the middle of September, will be made up by the end of the year. 2001 is likely to finish in the lower quartile of years and may finish in the lowest decile.

The 4 biggest years on the adjusted record are 1973 (1470 tornadoes), 1998 (1440), 1957(1428), and 1992 (1385). The smallest years are 1987 (811), 1988 (850), 1985 (877), and 1986 (949). The run of small years in the late 1980s is remarkable. 1989 actually has the 6th smallest total. We can offer no explanation for this long period of suppressed tornado occurrence, but it is clearly an extraordinary period. There is no comparable extended unbroken period of above normal tornado occurrence.

b. How far ahead (behind) normal is a year?

The method described in the previous subsection allows us to look at how far ahead or behind the normal year any particular year is at any point during the year. To illustrate, consider 1992 relative to the mean season (Fig. 7). (1992 is chosen for the illustration because it is the year in the record that has the largest difference between the maximum "ahead" of normal and "behind" normal.) On 26 May, the mean tornado year has had 500 tornadoes. Only 290 tornadoes occurred in the adjusted 1992 year through 26 May, so that 1992 could be considered to be 210 tornadoes "behind" normal on that day. This is represented by the dashed line marked "t" in Fig. 7.

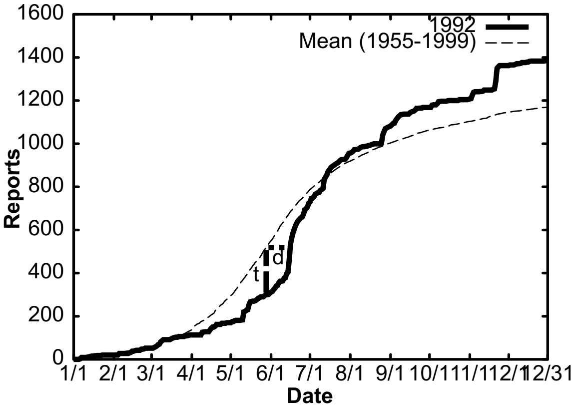

Figure 7. Tornadoes in 1992 compared to the mean tornado season, based on 1955-1999. The dashed line marked "t" represents how far behind the mean tornado season 1992 was on 26 May. The dotted line marked "d" represents how many days behind the mean tornado season 1992 was when its adjusted tornado total reached 500.

An alternate way to consider any year in comparison to the mean year is to see how many days ahead or behind the mean year the year in question reaches a particular number of tornadoes. In the case of 1992, the 500th adjusted tornado report did not occur until 16 June, 21 days after the date of occurrence in the mean record. Thus, 1992 could be considered to be 21 days behind on 16 June, as indicated by the line marked "d" on Fig. 7.

Obviously, we can plot the departure from normal in both the number of tornadoes and the number of days away from the mean throughout the year. As a notational convention, we will consider the departures to be positive if there are more tornadoes than in the mean or if the date that a cumulative number of tornadoes is reported is before the date in the mean year. On Fig. 7, this occurs if the line for a year is above (or to the left) of the line for the mean year. The departures from normal for the number of tornadoes in 1992 range from 244 below to 223 above (Fig. 8). Many features of the progression of the season are apparent in such a graph. A period when the season is exactly normal would be represented by a horizontal line. Large departures from horizonal are indicative of periods when the season is above or below normal. In the case of 1992, it can be seen that the first few months were relatively near normal. From the middle of March until the middle of June, tornado occurrence was well below normal as the “deficit” grew to 250 tornadoes. During about a one month period until the middle of July, the deficit was made up. Another brief period of above normal tornado activity is apparent around the beginning of September and a final period is clear in late November. Thus, the year can be summarized as having a single sustained period of well-below normal activity and three brief bursts of above normal activity.

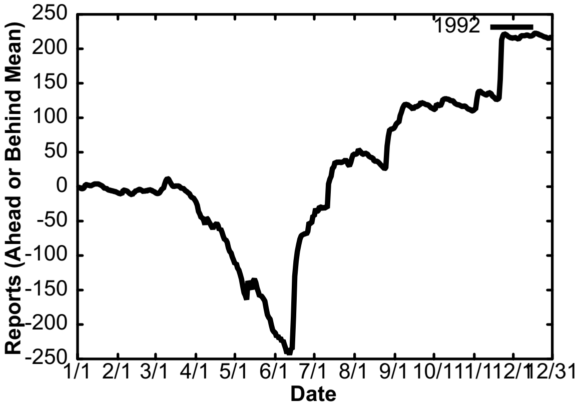

Figure 8. Number of tornadoes (adjusted) in 1992 minus the number of tornadoes in the mean year.

The depiction using the “days ahead” and “days behind” description is, of course, similar in its interpretation, although different aspects are evident (Fig. 8). Since there are more tornadoes per day, on average, in April through June (as is clear from Fig. 3), the large departures seen in Fig. 8 through the middle of July are compressed in Fig. 9. The relatively small increase in September in Fig. 8 is exaggerated in Fig. 9 because of the few tornadoes in the mean that occur then. Thus, the tornado depiction emphasizes abnormal periods near the time of maximum tornado occurrence during the year, while the day depiction emphasizes abnormal periods away from the time of maximum tornado occurrence.

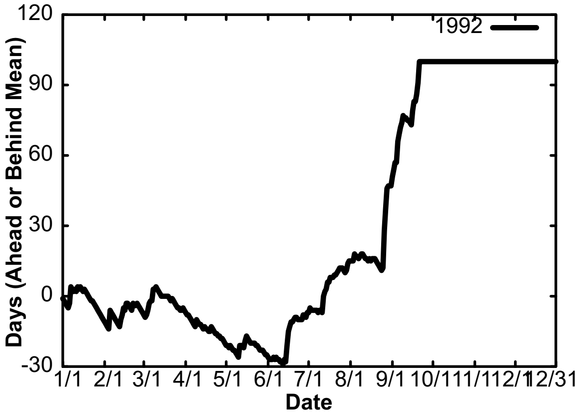

Figure 9. Number of days ahead of or behind 1992 was compared to a mean year. The line flattens out in late September after the adjusted total for 1992 reaches 1169 tornadoes, the number of mean annual tornadoes.

Small departures in both measures occur throughout the year for 1959 and 1960, making them, in a sense, the most “normal” years on the record. In contrast to 1992, when the range of departures from the mean was 467 (244 below to 223 above), those two years had a range of 91 tornadoes. 1959 was never more than 56 tornadoes away from the mean year. Similarly, those two years show the smallest range in the number of days away from normal. 1959’s range is 32 days (10 behind and 22 above) and 1960 is only 24 (17 behind and 7 ahead). In fact, 1960 never gets more than a week away from normal until 8 November and is never more than 11 days away until 21 December.

c. What’s coming next?

A topic of significant interest is whether having knowledge of what has previously occurred in the tornado season provides any information about what is likely to occur over some period of time to follow. In order to address this, we have looked at the number of tornadoes from the beginning of the year through the end of each month in comparison to the number of tornadoes after that month through the end of the year. As a starting point, we attempt to determine if extremely large or small number of tornadoes during the early part of the year are an indication of what will follow during the rest of the year.

To do this, we have broken the 45 year period into the 11th largest and smallest totals (approximately upper and lower quartiles) through the end of any particular month. Following that, we have computed the 80th and 20th percentiles (9th and 3rd values of the 11) of the number of tornadoes that occur in the rest of the year to see if they can be distinguished at all (Fig. 10). For the first few months of the year, it is apparent that there is a greater probability of a large number of tornadoes in the latter part of the year if the year has started off with many tornadoes. Through April, the 20th percentile of the number of tornadoes for the rest of the year in years that start off with many tornadoes is comparable to the 80th percentile of the number of tornadoes for the rest of the year in the years that start off slowly. By the end of May, however, the two distributions overlap almost completely.

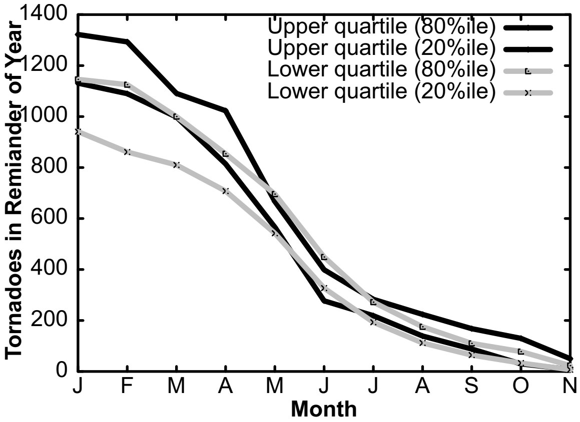

Figure 10. 80th and 20th percentiles of range of number of tornadoes occurring after the month on the abscissa given that the number of tornadoes from the beginning of the year up through the end of the month on the abscissa is in the upper quartile (bold) or lower quartile (gray) of the dataset.

Another way to consider this same issue is to to look at the effect size associated with changing from the lower quartile of the distribution to the upper quartile of the distribution. (See Cohen (1988) and Coe (2000) for detailed discussion of effect size.) Briefly, the effect size is the difference in the mean of the two different distributions associated with the different quartiles. Beyond that, however, we can make estimates of the confidence intervals associated with the effect size. Coe (2000) provides software for the calculations assuming that the distributions are normally distributed. Effect size calculations and the associated confidence intervals have advantages over null hypothesis significance testing in that they can provide values that have physical meaning (i.e., how many more tornadoes occur in one set of conditions compared to another as opposed to the probability that the two samples are not drawn from the same distribution), and they consider sample size in a more appropriate way (e.g., Cohen 1988).

We have calculated the effect size and confidence intervals on it for the change in number of tornadoes that occur during the rest of the year (months N+1 to 12) between the upper and lower quartiles of the number of tornadoes in the first N months of the year (Fig. 11). The effect size on the number of tornadoes that are reported in February through December is 195 (90% confidence interval = 103, 288) when one goes from the lower quartile to the upper quartile of January tornadoes. The effect size decreases through the first half of the year and, by April, the 90% confidence limit includes an effect size of 0. From May through November, the mean estimated effect size is essentially 0.

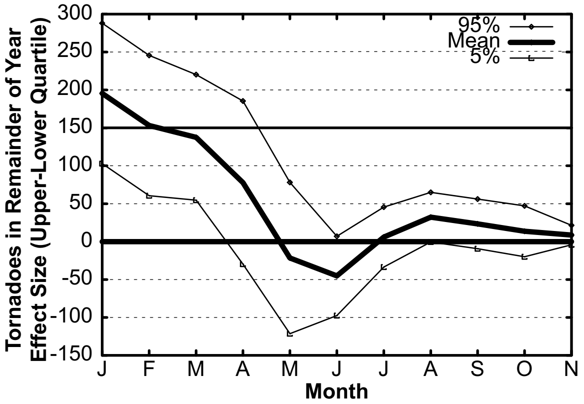

Figure 11. Estimate of effect size of tornadoes up through the end of a given month (abscissa) on number of tornadoes in rest of year (ordinate). Heavy line is best estimate of effect size, light lines give 90% confidence interval on estimate. Positive values mean that more tornadoes occur after that month if the total from the beginning of the year through the end of the month is in the upper quartile than if it is in the lower quartile.

At the same time that the effect size is decreasing in the first half of the year, the size of the 90% confidence interval of the estimate stays about the same, ranging from 165 to 215 tornadoes during January-May. After May, it dramatically narrows to 100 or less. This can be interpreted as meaning that we can have a great deal of confidence that the effect of going from the lower quartile to the upper quartile is very nearly 0 in the second half of the year. That is to say, knowledge of what has transpired in the first half of the year or longer tells us almost nothing about the likely number of tornadoes that will occur in the rest of the year.

This result implies that the first half of the year is almost completely decoupled from the second half. Given the shape of the annual cycle and the effect size, a reasonable follow-up question would be whether the first months of the year provide any information about the rest of the first half of the year. Approximately 2/3 of the tornadoes in the US occur in the first half of the calendar year, so that if we could identify a signal in the first two or three months, it might provide important public safety information for the remainder of the primary tornado threat season. Based on the small sample size, it appears that there is some information available about the April-June tornado total (Fig. 12). In particular, years that start off with few tornadoes through February or March are unlikely to have large numbers of tornadoes in the spring that follows and the years with the fewest April-June tornadoes are all associated with below average tornadoes earlier in the year. The signal is slightly better if the March data is used in the predictor, but the trade-off of additional lead time may be important. The linear correlation coefficent increases from 0.33 to 0.36 when March is included. It is also important to note that a *large* number of tornadoes in the first two or three months provides little information on what will happen in the spring. This asymmetry is of interest for future synoptic climatology work. One possible explanation is that it is more likely for the atmosphere to have a persistent large-scale pattern that is unfavorable for tornado production than for the atmosphere to have a persistent favorable pattern. In particular, persistent ridges or anomalously deep troughs over the central part of the country are both unfavorable for tornadoes, while relatively progressive systems are more favorable.

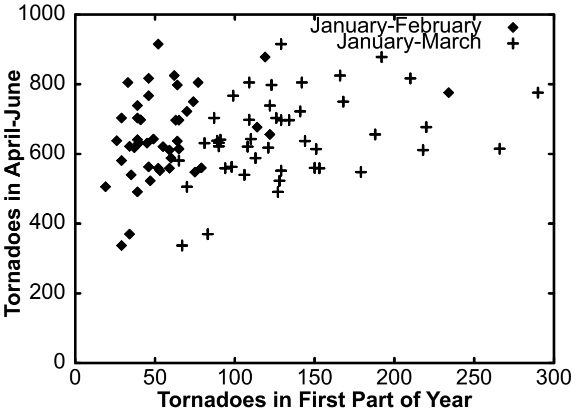

Figure 12. Scatterplot of number of tornadoes in April through June as function of number of tornadoes in first two or three months.

Even in the absence of physical understanding, the results seem to imply that there may be a possibility to do a crude form of seasonal forecasting of number of tornadoes for spring with data through February or March, particularly for those years when there are few tornadoes in the early part of the year. As an example, the first two months in 2001 had 19 tornadoes reported (adjusted to 1999 values) and April-June had 612, on the left side of the cluster in Fig. 12, and below the mean value of April-June tornadoes (650). Based on the January data alone for 2001 (4 reported tornadoes), the effect size confidence interval implies that we could have predicted with 98% confidence that 2001 would end up below the normal number of tornadoes. (This calculation is based on the mean number of February-December tornadoes from the January upper quartile, 1243, and a 98% confidence that there would be at least 78 fewer than that, or 1165, in February-December. That leads to an annual total of 1169, equal to the long-term expected value from the linear regression.) Caution has to be attached to such a calculation, but it represents an intriguing possibility, at least in some cases. It seems clear that physical understanding of the reasons behind the relationship would be helpful, and that the ability of seasonal forecasting models to predict the relevant quantities would be necessary if seasonal tornado forecasting ever became possible for more than just “above” or “below” normal.

4. Conclusions

This study has examined tornado data for the United States from 1955 through 1999 with the goal of understanding important aspects of tornado climatology. Attempts to work with the tornado database in an unmodified form are severely hampered by the increase in tornado observations for the period 1955, when reliable records began to be archived, through 1999. Before any year in the dataset can be compared to normal, a suitable definition of what is normal must be defined. To do this, we assume that the shape of the annual cycle for a particular year is correct and then adjust the amplitude so that the estimated number of tornadoes agrees with the departures from a linear regression fit to the observed number of tornadoes from 1955-1999. The regression estimates that approximately 14 more tornadoes are reported each year in the United States. The expected number of tornadoes per year currently is about 1200.

After adjustment, the years in the dataset can be compared on a more or less even basis. Variability in the number of tornadoes per year is seen by an interquartile range of about 200 tornadoes. The maximum number in any year in the data set is about 1450 (1973) and the minimum is a little over 800 (1987). We’ve also developed techniques that allow us to measure how far ahead or behind normal any tornado season is. The first, looking at the number of tornadoes, emphasizes the period of high tornado frequency during the year, while the second, focusing on the day of the year, emphasizes the lower frequency periods of the year. By these measures, 1959 and 1960 are the nearest to normal years in the record, while 1992 covers the widest range between furthest behind and furthest ahead or normal.

We have also begun to look at the statistical progression of the number of tornadoes during the year. Specifically, using the total number of tornadoes up through the end of any month, we have estimated what we know about the number of tornadoes that will occur over some later period of time. Our focus has been on unusual years, those that fall in the upper or lower quartile for the number of tornadoes in the first months of the year. Using those, we have calculated effect sizes, for the difference between beginning of the year upper quartile and lower quartile numbers of tornadoes, for the rest of the year. The effect size using January for the predictor variable is 195 tornadoes, with a 90% confidence interval of 103 to 287. The effect size lessens as more months are included in the predictor (and fewer in the predictand), until by May the effect is zero. This implies that the early part of the tornado season is decoupled from the later part, so that efforts to predict the numbers of tornadoes for a period of time, based solely on statisical grounds, will have to focus on the spring season. It appears that there may be some hope for issuing seasonal forecasts of the number of tornadoes, but only for those springs following periods of time with few tornadoes.

Another area that we have begun to explore involves the development of statistical models of tornado occurrence that will allow us to exploit the climatological data more fully. A two-stage model has been created, in which the probability of one or more tornadoes occurring on a day is first determined, either using the raw climatological probability or a Markov chain model as input. Then, the number of tornadoes that occur on that day is determined from statistical fits to the distribution of tornadoes per day given that one or more tornadoes occur. Synthetic data can then be generated from the statistical model. If realistic data can be generated, the model may prove valuable in identifying unusual tornado years. The primary difficulty at present is in fitting the tornadoes per day distributions. The raw probability of one or more tornadoes occurring on a day has not changed much over the years of the observations, but the number of tornadoes per day has. Thus, we are faced with the problem of getting a sufficiently long dataset to adequately sample the distribution while, at the same time, avoiding the nonstationarity in the data. In addition, preliminary results indicate that there are seasonal differences in the number of tornadoes per day. As a result, the sample size issue becomes even more of a problem. Mixture models using two exponential distibutions have shown some promise at fitting the data, but solutions have not been completely satisfactory. We hope to make sufficient progress to report results of this modelling effort at the conference.

5. Acknowledgments

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