CLIMATOLOGICAL CHANGES:

Meteorological Parameters Affecting the Spatial Redistribution of U.S. Tornadoes

Student Author

Ashley Dicks earned her BS in atmospheric science from Purdue University in 2017. This essay is on her undergraduate research with Professor Ernest Agee. Dicks worked with Professor Agee during her undergraduate senior year studying the climatological changes in tornadoes. Since gaining a passion for research from this project, Dicks has chosen to pursue a master's degree in atmospheric science from Purdue University. Her current research works with global climate models to explore the importance of accurately representing clouds in the models. Dicks graduated in the summer of 2019.

Mentor

Ernest Agee earned his BS in mathematics and physics from Eastern Kentucky University and his PhD in atmospheric science from the University of Missouri–Columbia. He joined the Purdue faculty in 1968 as an assistant professor and rose to full professor by 1978. Agee later served three times as department head beginning in 1990 and lastly in 2010. He has conducted research and learning with hundreds of students, leading to BS, MS, and PhD degrees, and several of his students have coauthored many of his 79 reviewed journal publications, covering an array of topics from solar physics to climate change with a focus on extreme weather and tornadoes. Agee has received the Cleveland Abbe Award from the American Meteorological Society and the Graduate School Distinguished Alumnus Award from the University of Missouri. His lectures and extended visits include the Max-Planck Institute for Meteorology at Hamburg, the University of Tokyo, and Utrecht University in the Netherlands. Teaching and mentoring student research remain Agee's top priorities.

http://dx.doi.org/https://doi.org/10.5703/1288284316927

Abstract

Climatological changes in the environments of key meteorological parameters that affect Significant Tornado Days (SigTorDs) have been determined for two active tornado regions defined as Box α and Box β, centered, respectively, over Oklahoma and Alabama and their respective environs. The North American Regional Reanalysis data was selected for 1980–2013, providing two successive 17-year periods corresponding to the last 34 years of previous research findings that focused on the aforementioned regions. This data record also corresponds to an increasing surface air temperature trend for the continental United States. Period I (1980–1996) and Period II (1997–2013) defined the years of changing environments for the two regions studied. Environmental parameters investigated and compared to SigTorDs were surface-based convective available potential energy (CAPE), storm relative helicity (0–3 km), bulk wind difference (1,000 mb to 500 mb), and lifted condensation level (LCL). Environments have changed to fewer SigTorDs (130 to 74) in Box α from Period I to Period II, dominated by decreasing frequency of storm relative helicity and slightly increasing CAPE. Box β is characterized by more SigTorDs (94 to 119) in Period II with an environment dominated by increasing frequency of storm relative helicity and minimal change in CAPE. These results support the importance of the changes in storm relative helicity (as opposed to CAPE) in explaining the eastward shift in U.S. tornado activity.

Dicks, A. (2019). Climatological changes: Meteorological parameters affecting the spatial redistribution of U.S. tornadoes. *Journal of Purdue Undergraduate Research, 9*, 9–15. https://doi.org/10.5703/1288284316927

Keywords

climate change, tornado, weather, Earth, atmospheric science

INTRODUCTION

The changing climatology of U.S. tornadoes continues to receive considerable attention within the severe storms research community, and numerous studies attest to the details of this change as well as the possible cause for change. Brooks, Carbin, and Marsh (2014) show the decline in the number of (E)F1+ tornado days since the 1970s, while the number of days with 30 or more (E)F1+ tornadoes is increasing. In spite of tornado-reporting difficulties through time, their study argues that such opposing trends relate to meteorological factors. Tippett, Lepore, and Cohen (2016) add further support to the trend of more tornadoes in the most extreme outbreaks. Tippett (2014) has also examined the volatility of tornado events indicating the effects of reporting practices, but importantly for our study he reports decreased volatility since 1975 for the annual reports of significant tornadoes, defined as (E)F2+. Brooks et al. (2014) also points out that climate modeling projections for the 21st century show increasing CAPE (supportive of more thunderstorms) but less wind shear in the first 6 km of the troposphere (suggestive of fewer rotating thunderstorms and perhaps fewer tornadoes). Tippett and Cohen (2016) have also examined tornado outbreak variability using Taylor's power law of fluctuation scaling (TL), with variance of counts increasing four times as fast as the mean. Tornado-related atmospheric proxies (CAPE and storm relative helicity [SRH]) also show conformity to TL as well as outbreak severity. Elsner, Elsner, and Jagger (2015) have addressed the increasing trend for tornado days with high tornado counts that are densely concentrated into cluster events. Agee and Childs (2014) have shown the decreasing trend in tornado counts, particularly for significant tornadoes. Farney and Dixon (2015) have examined the variability of tornado activity across the United States, as have Moore (2017) and Agee, Larson, Childs, and Marmo (2016), and their findings have all supported an eastward shift in tornado activity. The findings in Agee et al. (2016), have provided the basis for our current research, which has focused on the study of significant tornadoes and the environmental factors that might be responsible for observed trends related to climate change. The data period selected is 1980–2013, which corresponds to the last 34 years of the study period in Agee et al. (2016). This choice allows (a) the use of the North American Regional Reanalysis (NARR) data to study environmental parameters and (b) the convenient partition of the data set into two consecutive 17-year periods during a pronounced and continuously increasing warming trend (see Figure 1 in Agee et al., 2016). Based on findings in Agee et al. (2016), this study has chosen to search for changes in environmental parameters associated with Significant Tornado Days (SigTorDs), defined as those days with one or more (E)F2+ tornado events.

The spatial redistribution of U.S. tornadoes in the geographical region from 30°N-50°N to 80°W-105°W for the time period 1954–2013 has been examined by Agee et al. (2016). Two successive 30-year periods, a cool period (1954–1983) and a warm period (1984–2013) were considered based on a 2.5° x 2.5° gridded domain that contained the counts of all (E)F1–(E)F5 tornadoes. Agee et al. (2016) defined two primary regions of maximum change (each 500 x 500 km) in annual tornado activity, referred to as Box α (decreased events) and Box β (increased events and a new center of annual maximum activity), located, respectively, over the environs of Oklahoma and Alabama. The findings in Agee et al. (2016) warrant further investigation into the meteorological parameters responsible for tornado formation to determine the possible impact of any climate change effects that support the spatial redistribution of U.S. tornado activity. Parameters important to consider include thermodynamic quantities such as CAPE and dynamic quantities such as SRH. Such an investigation of key meteorological parameters requires an appropriate reanalysis data set that is sufficiently long with appropriate spatial and temporal resolution. There are different candidate data sets to consider (such as the NCEP/NCAR reanalysis data), but the one most suitable is the higher-resolution NARR data set, as described and discussed in the next section. However, the NARR data set unfortunately does not match the entire time period in Agee et al. (2016), but it does overlap with the last 34 years of this period, characterized by an increasing warming trend from 1980 to 2013 (see Figure 1 in Agee et al., 2016). Accordingly, the climatological investigation in this study has been partitioned into two successive 17-year periods of increased warming: Period I, 1980–1996, and Period II, 1997–2013. These two periods will be investigated, and meteorological trends will be compared using the NARR high-resolution data for the Box α and Box β regions. Further, the focus will be on significant tornado days, defined as those days with one or more (E)F2–(E)F5 tornadoes).

Methodology

Data and Geographical Locations

This study has focused on a meteorological analysis that attempts to address the possible impact of climatic trends in key parameters that relate to the spatial redistribution of tornadoes reported by Agee et al. (2016), focusing on SigTorDs. The combination of demands in the U.S. tornado record and the availability of matching reanalysis data resulted in choosing the time period 1980–2013 and the NARR high spatial and temporal resolution data set. Also, based on the results in Agee et al. (2016), the two domains selected for the chosen analyses are Box α (95°W-100°W and 32.5°N-37.5°N) and Box β (85°W-90°W and 32.5°N-37.5°N), the two regions of greatest change in the period 1954–2013. The NARR data resolution was chosen because of its 3-hour temporal resolution and 32-km spatial resolution as well as the availability of the relevant meteorological data. The two periods chosen for comparison of selected analyses are 1980–1996 and 1997–2013, a 34-year period of increasing surface air temperature that encompasses the domain of the tornado region of interest.

Key Environmental Parameters

The well-known significant tornado parameters formulation introduced by Thompson, Edwards, and Mead (2004) is one of several parameters of interest at the Storm Prediction Center in forecasting the real-time occurrence of significant tornadoes. This work, to be referred to as T04, developed the following equation:

$$STP = \left(\frac{CAPE}{1500\ J\ kg^{-1}}\right) \times \left(\frac{SRH}{150\ m^2\ s^{-2}}\right) \times \left(\frac{BWD}{20\ m\ s^{-1}}\right) \times \left(\frac{2000 - LCL}{1000\ m}\right)$$

This equation helps identify the four key meteorological parameters selected for this study (as provided in the NARR data set), namely CAPE, SRH, bulk wind difference (BWD), and lifted condensation level (LCL).

The daily average of surface-based CAPE was calculated using the eight 3-hour time periods. Subsequently, all positive CAPE days ≥ 75 J kg^{-1} were selected for study (cutoff due to a large number of events in the Box β region near zero CAPE). Period I (1980–1996) identified 3,031 such days out of a total of 6,205 days for Box α and similarly 2,814 positive CAPE days for Box β. Period II (1997–2013) identified an increase of 26 positive CAPE days for Box α and an increase of 88 positive CAPE days for Box β. The daily mean 0–3-km SRH provided by NARR was similarly calculated for all 3-hour time periods. The daily mean BWD was similarly calculated from the 1,000-mb level to the 500-mb level using the 3-hour data, which was adjusted for topography based on Seeley and Romps (2015).

The daily mean LCL was calculated using the 3-hour values of surface temperature and dew point temperature (2-m level). Starting with these two large sets of positive CAPE data (3,031 and 2,814), the SigTorD requirement is applied, yielding the necessary data subsets for studying the trends in the environmental parameters for Box α and Box β. Positive CAPE days are viewed as a necessary but not sufficient condition for creating a pathway to a day of significant tornadoes.

RESULTS FOR CAPE, SRH, BWD, AND LCL IN BOX α AND BOX β

The analysis and results are presented for these four environmental parameters according to the number of SigTorD for Periods I and II and for Box α and Box β. Since positive CAPE conditions (> 75 J kg^{-1}) are selected, the number of SigTorDs is slightly different than the total numbers for SRH, BWD, and LCL (but these three have all the same number of SigTorDs).

CAPE

First, as seen in Figure 1, Box α showed a decrease in the number of SigTorDs from 116 in Period I to 68 in Period II. Also, the pattern of reduced values shows a general shift to higher values of CAPE yet fewer days, suggestive of the effect of other environmental parameters in changing the frequency of SigTorDs. Box β shows the value of SigTorDs, increasing from 60 in Period I to 87 in Period II with a generally larger number of events for comparable values of CAPE (again, suggesting that other physical parameters are responsible for more SigTorDs). Although not for identical time periods but for the same regions, this trend in SigTorDs is consistent with the findings of Agee et al. (2016), with the number of days (and the number of significant tornadoes) decreasing in Box α and increasing in Box β.

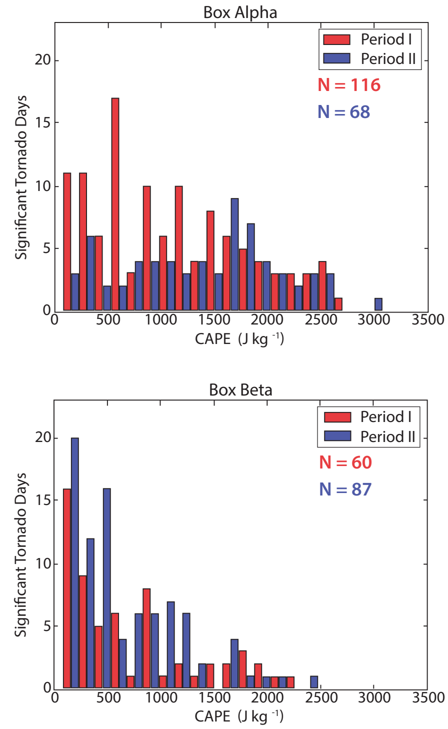

Figure 1. The total number of SigTorD (N) for each period and corresponding values of positive CAPE for (a) Box α and (b) Box β. Only the positive values of CAPE (≥ 75 J kg^{-1}) for all days have been included to show the most relevant details of the distribution.

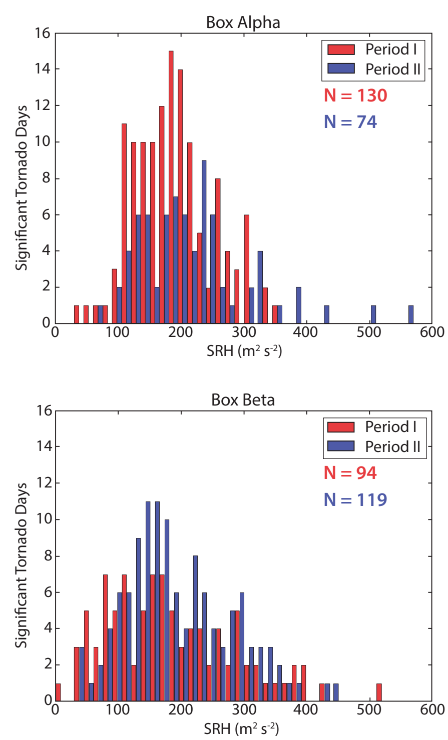

Figure 2. The total number of SigTorD (N) for each period and corresponding values of SRH for (a) Box α and (b) Box β.

SRH

The number of SigTorDs for Box α decreased from 130 in Period I to 74 in Period II, as shown in Figure 2, which also provides more meteorological evidence that supports the implication of statistical findings in Agee et al. (2016). Specifically, it is noted that the observed SRH distributions for both periods are nearly coincident, yet the supportive environment occurs less often in Period II. Box β shows the opposite result, with an increase in SigTorDs from 94 to 119 and coincident distributions for both periods but a more frequent and favorable SRH environment for Period II.

BWD

Figure 3 shows the SigTorDs for Box α from Period I to Period II decreasing, also by 56 days, but notably the BWD environments for Period II occur substantially less often (although the distributions are somewhat coincident). Box β has 25 more SigTorDs in Period II than in Period I, and the frequency and values for BWD represent more favorable environments for significant tornadoes in Period II.

LCL

Figure 4 shows for Box α that the LCL heights on SigTorDs are lower in Period I compared to Period II, which suggests that the supportive environment for SigTorDs for Period II occurs less often. The presence of larger LCL heights in Period II may suggest a drier environment (which was not investigated in this study). For Box β the distributions are similar, but the supportive environment occurs more frequently in Period II.

Summary Table

A representative set of statistics for the above distributions of the four environmental parameters, based on their number of SigTorDs, is presented in Table 1. Means, standard deviations, and quartiles for these data sets are shown; however, caution is required in the interpretation of these quantities (since N is unique for each period and each domain). The results in Table 1 are best appreciated when viewing the respective histograms in Figures 1–4. For example, in Table 1 the mean SRH change in Box α from Period I to Period II appears to have increased, but as seen in Figure 2, the mean may be higher, but the frequency distribution is substantially reduced (denoting a changing tornado environment).

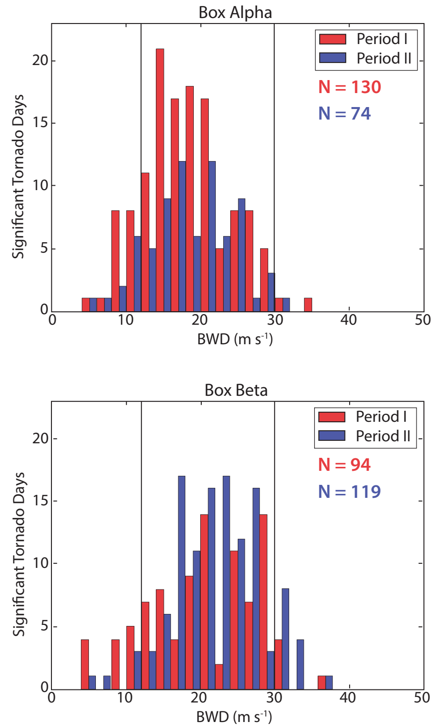

Figure 3. The total number of SigTorD (N) for each period and corresponding values of BWD for (a) Box α and (b) Box β. Lines mark the boundaries used in T04 for calculating the BWD term (and are noted here simply as a reference point).

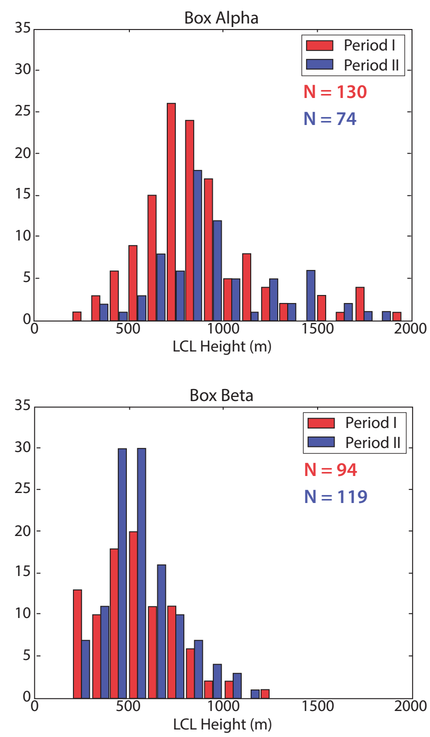

Figure 4. The total number of SigTorD (N) for each period and corresponding values of LCL for (a) Box α and (b) Box β.

		Box α		Box β	
		Period I (N = 130)	Period II (N = 74)	Period I (N= 94)	Period II (N = 119)
CAPE [J kg^{-1}]	Mean	1108	1418	726	665
	Standard Dev	742	762	618	522
	Q1	534	839	215	268
	Median	1014	1555	532	469
	Q3	1597	1893	1000	977
SRH [m^2 s^{-1}]	Mean	189	216	186	196
	Standard Dev	62.8	89.5	102.4	84.8
	Q1	144	151	103	135
	Median	185	206	170	173
	Q3	223	243	255	251
BWD [m s^{-1}]	Mean	18.1	18.6	20.5	22.1
	Standard Dev	5.75	5.45	7.20	5.76
	Q1	14.3	15.1	14.7	17.7
	Median	17.7	18.5	21.1	22.1
	Q3	21.0	22.1	27.1	26.1
LCL [m]	Mean	764	862	448	466
	Standard Dev	309	316	205	187
	Q1	569	689	302	326
	Median	718	788	434	439
	Q3	853	975	585	557

Table 1. Statistical summary of the four environmental parameters associated with SigTorDs (N). It is important to note that these results are for different values of N and are only useful when comparing results in Figures 1–4.

CONCLUSION

This investigation has succeeded in establishing reasonable documentation of *environmental changes* in four key meteorological parameters that are known to affect the occurrence of tornadoes and, more specifically, the changes in the occurrence of SigTorDs. The desire to choose the NARR high-resolution meteorological data, both in space and time, partially dictated the choice of the time period for this study (1980–2013) but still allowed the partitioning of the analysis into two successive 17-year periods. Further, this total time period was equal to the last 34 years in the study by Agee et al. (2016) and also corresponds to a 34-year period of increasing surface air temperature (see Figure 1 in Agee et al., 2016). The domains selected, Box α and Box β, have been previously documented in Agee et al. (2016) to represent the regions of greatest change in tornado counts and tornado days as well as significant tornadoes both annually and seasonally. Box α showed decreasing trends, and Box β showed increasing trends. This study has now examined four meteorological parameters (CAPE, SRH, BWD, and LCL) to help explain the SigTorD trends in Period I (1980–1996) versus Period II (1997–2013) for both Box α and Box β, based on the different environments that yield SigTorDs. Key specific conclusions are listed below:

CAPE: (1) Box α had 26 more positive CAPE days in Period II than in Period I, and Box β had 88 more positive CAPE days in Period II than in Period I, a result that is generally in agreement with climate models that predict more CAPE with global warming (see Gensini & Mote, 2015). (2) However, the decline in SigTorDs (116 to 68) from Period I to Period II in Box α revealed that weaker CAPE in Period I produced more SigTorDs than larger CAPE did in Period II. (3) It took larger values of CAPE to support the fewer days that did occur in Period II. (4) The increase in SigTorDs in Box β (60 to 87) does not appear to be related to magnitude changes in CAPE, although a favorable CAPE environment did occur more often.

SRH: (1) The decline in SigTorDs (130 to 74) from Period I to Period II in Box α reveals an environment of SRH that occurs less frequently to sustain the number of days; however, the distributions are coincident. (2) The increase in SigTorDs in Box β (94 to 119) also shows similar distributions but more frequent occurrences of favorable SRH environment. (3) These results help define and support the important role played by SRH in the occurrence of changing trends in SigTorDs (rather than CAPE), consistent with findings reported in Tippett et al. (2016) as well as Moore (2017).

BWD: Similar to the SRH distribution of changing environments that affect SigTorDs. Also, Period II shows less frequency of a favorable shear environment for Box α and more frequency of a favorable shear environment for Box β.

LCL: Similar to SRH and BWD distributions of changing environments that affect SigTorDs for both Box α and Box β, except more frequent days with lower LCL in Period I for Box α and elevated LCL heights in Period II (suggestive of a drier climate in Period II in Box α as well as other physical parameters that are driving the events).

This study for two consecutive 17-year periods and the calculation of changes in the environments of four key meteorological parameters that help produce SigTorDs have been determined, which are for the same geographical areas of focus in the spatial redistribution of U.S. tornado events presented in Agee et al. (2016). In general, it is known that the combination of adequate CAPE, SRH, BWD, and LCL is required to produce SigTorDs, and when the frequency of these conditions change on the climatological time scale, more or fewer events may happen. As summarized above, the environments have changed to yield fewer SigTorDs in the Box α region when comparing Period I to Period II. This change has happened in an *environment* of decreasing frequency of SRH, decreasing frequency of bulk wind shear, elevated height values of LCL, and larger values of CAPE for SigTorDs. Box β is characterized by a changing environment that produced more SigTorDs in Period II when compared to Period I. This change has happened in an *environment* of increasing frequency of positive CAPE, increasing frequency of SRH, increasing frequency of bulk wind shear, and a sustained frequency of LCL heights. The environments have changed in Box α, located in the Central Plains Tornado Alley, which support the statistical findings in Agee et al. (2016) of a decreasing annual trend in tornado events. The environments have also changed in Box β, located in Dixie Alley, which also supports the findings in Agee et al. (2016) of an increasing annual trend in tornado events. These results also attest to the need for climate models to resolve small-scale differences in changes in meteorological fields of information, which is especially true for impactful meteorological events such as tornadoes.

ACKNOWLEDGMENTS

The authors are grateful to the Purdue Climate Change Research Center at Purdue University for providing funds to support this study.

REFERENCES

Agee, E., & Childs, S. (2014). Adjustments in tornado counts, F-scale intensity, and path width for assessing significant tornado destruction. *Journal of Applied Meteorology and Climatology, 53,* 1494–1505.

Agee, E., Larson, J., Childs, S., & Marmo, A. (2016). Spatial redistribution of USA tornado activity between 1954 and 2013. *Journal of Applied Meteorology and Climatology, 55,* 1681–1697.

Brooks, H. E., Carbin, G. W., & Marsh, P. T. (2014). Increased variability of tornado occurrence in the United States. *Science, 346,* 349–352.

Elsner, J. B., Elsner, S. C., & Jagger, T. H. (2015). The increasing efficiency of tornado days in the United States. *Climate Dynamics, 45,* 651–659.

Farney, T. J., & Dixon, P. G. (2014). Variability of tornado climatology across the continental Unites States. *International Journal of Climatology, 35,* 2993–3006.

Gensini, V. A., & Mote, T. L. (2015). Downscaled estimates of late 21st century severe weather from CCSM3. *Climate Change, 129,* 307–321. doi:10.1007/s10584-014-1320-z

Moore, T. W. (2017). On the temporal and spatial characteristics of tornado days in the United States. *Atmospheric Research, 184,* 56–65.

Seeley, J. T., & Romps, D. M. (2015). The effect of global warming on severe thunderstorms in the United States. *Journal of Climate, 28,* 2443–2458.

Thompson, R. L., Edwards, R. & Mead, C. M. (2004). An update to the supercell composite and significant tornado parameters. Preprints, *22nd Conference on Severe Local Storms,* Hyannis, MA, *American Meteorological Society,* P8.1.

Tippett, M. K. (2014). Changing volatility of U.S. annual tornado report. *Geophysical Research Letters, 41,* 6956–6961.

Tippett, M. K, & Cohen, J. E. (2016). Tornado outbreak variability follows Taylor's power law of fluctuation scaling and increases dramatically with severity. *Nature Communications, 7,* 10668.

Tippett, M. K., Lepore C., & Cohen, J. E. (2016). More tornadoes in the most extreme U.S. tornado outbreaks. *Science, 6318,* 1419–1422.