Atmospheric Research 184 (2017) 56–65

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

On the temporal and spatial characteristics of tornado days in the United States

Todd W. Moore

Department of Geography and Environmental Planning, Towson University, 8000 York Road, Towson, MD 21252, USA

ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 28 September 2016
Accepted 12 October 2016
Available online 13 October 2016

Keywords:
United States
Tornado days
Temporal trends in tornado days
Spatial distribution of tornado days
Mann-Kendall trend test
Taylor's power law

ABSTRACT

More tornadoes are produced per year in the United States than in any other country, and these tornadoes have produced tremendous losses of life and property. Understanding how tornado activity will respond to climate change is important if we wish to prepare for future changes. Trends in various tornado and tornado day characteristics, including their annual frequencies, their temporal variability, and their spatial distributions, have been reported in the past few years. This study contributes to this body of literature by further analyzing the temporal and spatial characteristics of tornado days in the United States. The analyses performed in this study support previously reported findings in addition to providing new perspectives, including that the temporal trends are observed only in low-frequency and high-frequency tornado days and that the eastward shift in tornado activity is produced, in part, by the increasing number of high-frequency tornado days, which tend to occur to the east of the traditionally depicted tornado alley in the Great Plains.

1. Introduction

The United States (US) experiences an average of >1000 tornadoes per year, which is more than any other country on Earth (NCEI, 2016b). Tornadoes in the US often result in losses of life and property. They were responsible for an average of 70 fatalities per year over the period 1986–2015; the average fatality count is 110 over the period 2006–2015 (NWS, 2016). They also caused an average annual loss of $982 million (US dollars) over the period 1949–2006 (Changnon, 2009). These average values can be greatly exceeded, however, in extreme events when many tornadoes occur. For example, >100 tornadoes were produced on 27 April 2011 in the US across the states of Mississippi, Alabama, Georgia, Tennessee, and Virginia (NOAA, 2011; Knupp et al., 2014). These tornadoes were responsible for 316 fatalities and >2700 injuries (NOAA, 2011; Knupp et al., 2014), and they, along with the others that occurred in April in the US, resulted in more than $11 billion (US dollars) in insured losses (Simmons and Sutter, 2012).

Understanding the environmental conditions in which tornadoes occur, and when and where they occur, is imperative for mitigating their negative impacts. Over the years, research on the environment in which tornadoes occur (e.g., Doswell, 1987; Johns and Doswell, 1992; Doswell et al., 1996; Rasmussen, 2003; Doswell and Schultz, 2006; Grams et al., 2012; Garner, 2012, 2013; Mercer et al., 2012; Schultz et al., 2014; Sherburn and Parker, 2014) has highlighted various conditions, or ingredients (Doswell et al., 1996), that promote tornadogenesis. These include ample low-level humidity, high instability, high shear, and a lifting mechanism (e.g., low-level convergence or a front) (Doswell, 1987; Johns and Doswell, 1992). Thorough reviews of research on the environments in which tornadoes occur and tornado forecasting efforts are provided by Galway (1985), Schaefer (1986), Galway (1992), Doswell et al. (1993), and Doswell (2007).

The temporal and spatial distributions of tornadoes in the US have been documented in numerous climatological studies (e.g., Kelly et al., 1978; Brooks et al., 2003; Kis and Straka, 2010). The National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) and Storm Prediction Center (SPC) also provide information about tornado climatology and tornado data (NCEI, 2016a, 2016b; SPC, 2016). This information and these data sources have been particularly useful to analyses of tornado hazard and to the development of tornado risk and vulnerability models (e.g., Boruff et al., 2003; Ashley et al., 2008; Dixon et al., 2011; Simmons and Sutter, 2011; Dixon and Moore, 2012; Widen et al., 2013; Ashley et al., 2014; Coleman and Dixon, 2014; Jagger et al., 2015; Rosencrants and Ashley, 2015; Shen and Hwang, 2015; Elsner et al., 2016; Romanić et al., 2016; Standohar-Alfano and van de Lindt, 2015).

In addition to understanding the environmental conditions that were and are favorable for tornadoes, and their climatological distributions, it also is important to consider how they may change in response to global climate change. In multiple studies, the environmental conditions that are known to promote tornadoes have been modeled (i.e., they examined the tornado-favorable ingredients rather than tornadoes) to determine if atmospheric conditions in the future will be more or less favorable for them (e.g., Brooks et al., 2003; Trapp et al., 2009; Gensini and Ashley, 2011; Diffenbaugh et al., 2013; Robinson et al., 2013; Gensini and Mote,

E-mail address: tmoore@towson.edu.

http://dx.doi.org/10.1016/j.atmosres.2016.10.007

2014; Gensini et al., 2014; Gensini and Mote, 2015; Seely and Romps, 2015; Tippett et al., 2015). This approach is taken because it is currently not possible to project whether tornadoes will become more or less frequent, or more or less intense, in a warmer atmosphere with physics-based climate models because their spatial and temporal resolutions are too coarse (Tippett et al., 2015). Although uncertainty still exists, studies have reported that environmental conditions will likely favor more severe weather, and possibly tornadoes, in the future, largely because of an increase in atmospheric instability and low-level humidity.

Recent empirical studies have searched for changes in the temporal and spatial distributions of tornadoes in the US. Some have shown that the annual numbers of tornadoes in the US have not increased (Brooks et al., 2014; Elsner et al., 2015; Tippett and Cohen, 2016; NCEI, 2016a), despite the projections for an increase in tornado-favorable environments (Diffenbaugh et al., 2013; Gensini and Mote, 2015; Seely and Romps, 2015; Tippett et al., 2015). Others have reported trends in tornado day frequencies and in various statistical characteristics of tornado activity. Brooks et al. (2014), for example, reported that the number of days per year with 1+ tornadoes declined since the 1970s, but that the number of days with >30 tornadoes increased. Elsner et al. (2015), similarly, reported that the number of days per year with 4+ tornadoes decreased whereas the number of days with 8+, 16+, and 32+ increased over time. They also found similar trends when looking at the annual probability of tornado days and the annual proportion of tornadoes occurring on days meeting these frequency thresholds. Tippett and Cohen (2016) reported an upward trend in the mean number of tornadoes per outbreak per year.

Studies also have shown that several tornado metrics have become more variable over time. Brooks et al. (2014) reported an increase in the standard deviation of the ranks of monthly tornado frequency between 1954 and 2013. Tippett (2014) reported an increase, primarily in the 2000s, in the volatility of annual tornado frequency, defined as the standard deviation of the difference between the annual tornado frequencies of successive years. Tippett and Cohen (2016) showed that the variance of the number of tornadoes per outbreak increased at a rate of 2.89% per year over the period 1954–2014.

Temporal changes in the spatial distribution of tornadoes in the US also have been reported. Farney and Dixon (2014) plotted the annual average number of tornado days for the periods 1960–1989 and 1990–2011. Their plots show an increase in tornado day frequencies in the latter period throughout the Middle and Lower Mississippi, Ohio, and Tennessee River Valleys, and in a few places to the east of the Appalachian Mountains. Elsner et al. (2015) analyzed tornado density and found that tornadoes became more clustered in space over the period 1954–2013, leading to an increase in tornado density. Most recently, Agee et al. (2016) analyzed the spatial distribution of tornadoes in the periods 1954–1983 and 1984–2013 and reported a decrease in tornado activity in the latter period in Texas and Oklahoma and an increase to the east in Tennessee and Alabama.

Understanding the environments in which tornadoes occur as well as their temporal and spatial distributions is important to many, including operational forecasters, emergency managers, and insurance companies. Continued study is needed to advance our understanding as new data become available. This is especially true in the context of climate change. This study builds upon the array of empirical studies on this topic by further analyzing the temporal and spatial trends of tornado days in the US.

2. Data and methods

2.1. Data sources and processing

Tornado reports were obtained from the SPC's Severe Weather Database (SWD; SPC, 2016). The SWD provides two tornado files. One has raw data and includes all state and county segments of a tornado track, meaning that a tornado could have multiple entries depending on the number of states and counties/parishes through which it tracked. The second includes only one entry per tornado, and therefore minimizes the overcount that results from long-tracked tornadoes that intersect multiple counties/parishes and/or states (there are 61,209 tornado entries in the raw database and 60,114 in the second). The second database ("Actual_tornadoes.csv" from SPC (2016)) is used in this study.

The tornadoes in the database have multiple attributes, including information on their date, time, location, and estimated intensity. Intensity is estimated with the Fujita (F) or Enhanced Fujita (EF) Scale, both of which range from 0 (minimum damage) to 5 (maximum damage). The EF Scale replaced in the F Scale in 2007. An increasing trend in the number of (E)F0 tornadoes per year has been documented and attributed largely to non-meteorological factors such as changes in reporting practices and technology, whereas the (E)F1+ record is more stationary owing to the fact that stronger tornadoes have likely been observed and reported more consistently over time (Brooks and Doswell, 2001; Brooks, 2004; Doswell et al., 2005; Verbout et al., 2006; Kunkel et al., 2013). As a result, recent studies (e.g., Brooks et al., 2014; Elsner et al., 2015; Tippett and Cohen, 2016) have limited their analyses to (E)F1+ tornadoes. In line with these studies, only tornadoes rated (E)F1+ are analyzed here. The database was further narrowed by omitting tornadoes that occurred outside of the contiguous US; tornadoes in Hawaii (41), Alaska (4), and Puerto Rico (24) were excluded.

Beginning the analysis in 1974 reduces the under- and over-counts of F1 and F2 tornadoes, respectively, prior to 1974 (Agee and Childs, 2014). Other studies have shown that the number of tornadoes rated E(F)2+ declined after the 1970s when the National Weather Service began to systematically rate tornado intensity (Verbout et al., 2006; Edwards et al., 2013; Romanić et al., 2015). Multiple others have limited their analyses to tornado data from the 1970s and onward to reduce the effect of secular trends (e.g., Coleman and Dixon, 2014; Fuhrmann et al., 2014; Elsner et al., 2016; Standohar-Alfano and van de Lindt, 2015). Beginning the analysis in 1974 also enables future work that will combine environmental data from the North American Regional Reanalysis, which begins in 1974, with the datasets generated here. This future work will focus on the synoptic patterns and the kinematic and thermodynamic environments associated with low- and high-frequency tornado days.

The analyses in this study are focused on tornado days, which are defined as days with 1+ tornadoes. Annual frequencies of tornado days were derived and recorded. Tornado days of different magnitudes also were derived and recorded on the basis of (1) exceedance thresholds, including 10+ tornadoes, 20+ tornadoes, 30+ tornadoes, and 50+ tornadoes, and (2) mutually exclusive groups, including 1–9 tornadoes, 10–19 tornadoes, 20–29 tornadoes, and 30+ tornadoes.

2.2. Methods of analysis

Recent studies that reported trends in the frequencies and statistical metrics of tornado days have used generalized linear models, including ordinary least squares linear regression (Brooks et al., 2014; Elsner et al., 2015; Tippett and Cohen, 2016). In this study, I employ a previously-unused method, a combination of the nonparametric Mann-Kendall test and Theil-Sen slope estimate, to verify and further analyze trends in tornado day time series. These methods are appropriate given the asymmetry of the frequency distribution of tornado day magnitude (i.e., the number of tornadoes per day; Elsner et al., 2014), and they are commonly used to detect monotonic trends in the time series of extreme weather and climate events (e.g., Burn and Elnur, 2002; Webster et al., 2005; Kossin et al., 2007; Gocic and Trajkovic, 2013; Kunkel et al., 2013; Sonali and Kumar, 2013; Westra et al., 2013; Araghi et al., 2016; Bari et al., 2016; Pingale et al., 2016; Romanić et al., 2015). The trend statistics and parameters reported in this study are the Mann-Kendall statistic (S) and the Theil-Sen slope estimate (β) (Mann, 1945; Kendall, 1975).