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What Is a Tornado Outbreak?

Perspectives through Time

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ABSTRACT: The term "tornado outbreak" appeared in the meteorological literature in the 1950s and was used to highlight severe weather events with multiple tornadoes. The exact meaning of "tornado outbreak," however, evolved over the years. Depending on the availability of scientific data, technological advancements, and the intended purpose of these definitions, authors offered a diverse set of approaches to shape the perception and applications of the term "tornado outbreak." This paper reviews over 200 peer-reviewed publications—by decade—to outline the evolving nature of the "tornado outbreak" definition and to examine the changes in the "tornado outbreak" definition or its perception. A final discussion highlights the importance, limitations, and potential future evolution of what defines a "tornado outbreak."

KEYWORDS: Atmosphere; North America; Extreme events; Tornadoes; History

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Annually, the United States experiences at least a few days with clusters of tornadoes (Doswell and Schultz 2006) that extensively damage property and infrastructure and threaten people's lives. Most tornado-related fatalities in the United States result from these types of tornado days (Galway 1975). These events can be particularly dangerous because they usually comprise multiple, long-track tornadoes (EF2–EF3) that persist for tens of minutes and, thus, can affect populated areas (Brooks 2004). Over the years, numerous studies have used the notion of "tornado outbreaks" to describe these spatiotemporal complexes of multiple tornadoes, leading to common use of this phrase.

The term "tornado outbreak," however, has been inconsistently defined (Doswell et al. 2006; Foglietti et al. 2020). Some definitions fail to describe measurable or quantifiable characteristics. For example, the *Glossary of Meteorology* from the American Meteorological Society defines a tornado outbreak as "multiple tornado occurrences associated with a particular synoptic-scale system," but it does not mention how many tornadoes are "multiple" tornadoes (American Meteorological Society 2021). Other definitions focus on selective characteristics, such as a threshold number of tornadoes (Galway 1977), or apply statistical modeling techniques on multiple variables to distinguish tornado outbreaks (Mercer et al. 2009; Shafer and Doswell 2010; Mercer et al. 2012). Consequently, the term "tornado outbreak" has been attributed to events with a different number of reported tornadoes, magnitudes, durations, or spatial distribution, as well as in the context of famous events, such as the "jumbo outbreak" of 3 April 1974 (Fujita 1974). Further, the term "outbreak" has been used not only exclusively in the context of tornadic storms but also to describe other extreme weather events, such as cold-air outbreaks (e.g., Walsh et al. 2001) or (nontornadic) severe storm outbreaks (e.g., Doswell et al. 2006). Also, depending on the availability of scientific data, technological advancements, and the intended purpose of their definitions, authors have diverse set of approaches that shape the perception and applications of the term "tornado outbreak." In fact, there is no universal definition of a tornado outbreak, and the definition remains adaptable depending on the requirements of a given research project.

This article will provide an extensive review of the changing nature of "tornado outbreak" definitions and classifications. We highlight over 200 manuscripts that contributed to changes in the "tornado outbreak" definition or its perception, providing the first comprehensive, chronological review. For space restrictions and direct comparisons, we limited our review in the second section to use of the term in the United States. The third section highlights the importance, limitations, and potential future evolution of what defines a "tornado outbreak."

Tornado outbreak definitions in historic literature

As research into tornado development and impacts grew over time, a diversity and abundance of definitions of "tornado outbreak" arose, resulting from several reasons. First, over the past 70 years, the availability and quality of tornado-related meteorological data have changed tremendously as a collective result of 1) an increase in observations with each new year in the historical record, 2) changes in tornado detection techniques, such as the introduction of Weather Surveillance Radar-1988 Doppler (WSR-88D; Verbout et al. 2006), 3) recent rises in the proportion of reported tornadoes attributable to quasi-linear convective systems (Smith et al. 2012; Ashley et al. 2019), and 4) changes in the official National Weather Service tornado survey practices (Edwards et al. 2013; Burgess et al. 2014), such as the modification of methods that guided the process of collecting reports [e.g., establishment of the Fujita (Fujita 1981) and enhanced Fujita scales (Doswell et al. 2009)]. Second, the ways tornadoes are observed and recorded have resulted in a significant increase in tornado reporting statistics (Fig. 1), especially the number of weak tornado reports (Brooks and Dotzek 2008). Namely, an increase in population density, urbanization, and better public severe weather awareness has increased people's attention to weather conditions (Verbout et al. 2005). More trained storm spotters and weather enthusiasts who visually detect and confirm tornadoes have led to an increase in the number of reported tornadoes (McCarthy 2002; Bass et al. 2009; League et al. 2010).

Furthermore, the recent proliferation of photo and video-recording equipment, including smartphones, digital cameras (with time lapse, video, zoom lenses, etc.), and drones, provides high-quality visual material used to improve identification and documentation of tornadoes (Seimon et al. 2016). Fast internet connections and social media platforms have enabled almost instant confirmation of tornado existence and, in some recent cases, live streaming of tornado development and life cycle, even from remote places in the United States. Many authors have discussed this evolution of tornado reporting (Doswell and Burgess 1988; Diffenbaugh et al. 2008; Doswell et al. 2012; Brooks et al. 2014; Tippett 2014; Foglietti et al. 2020), noting that nonmeteorological factors influence the increase in reported tornadoes in the historical record. By extension, changes in the tornado database have influenced how to define a tornado outbreak simply by offering a longer, more specific record of individual tornadoes used in new types of analyses. Importantly, although the ability to document and detect tornadoes has improved substantially, the overall quality of recorded information has lagged. For instance, wind-related tornado data collected by the Doppler-on-Wheels (Wurman et al. 2013) are excluded from records of tornado intensity. These and other data are formatted as text or comma-separated values that, while easy to read or edit manually, pose problems to import into relational databases. Finally, improvements in computational power, software, and programming tools over the years have drastically increased the speed of data processing. Consequently, mining large datasets has become more approachable and time efficient, offering new ways to explore tornado datasets with sophisticated statistical techniques.

In light of this dynamic progress, we review the evolving nature of the "tornado outbreak" definitions over the decades in the United States. In the late sixteenth century, reports of

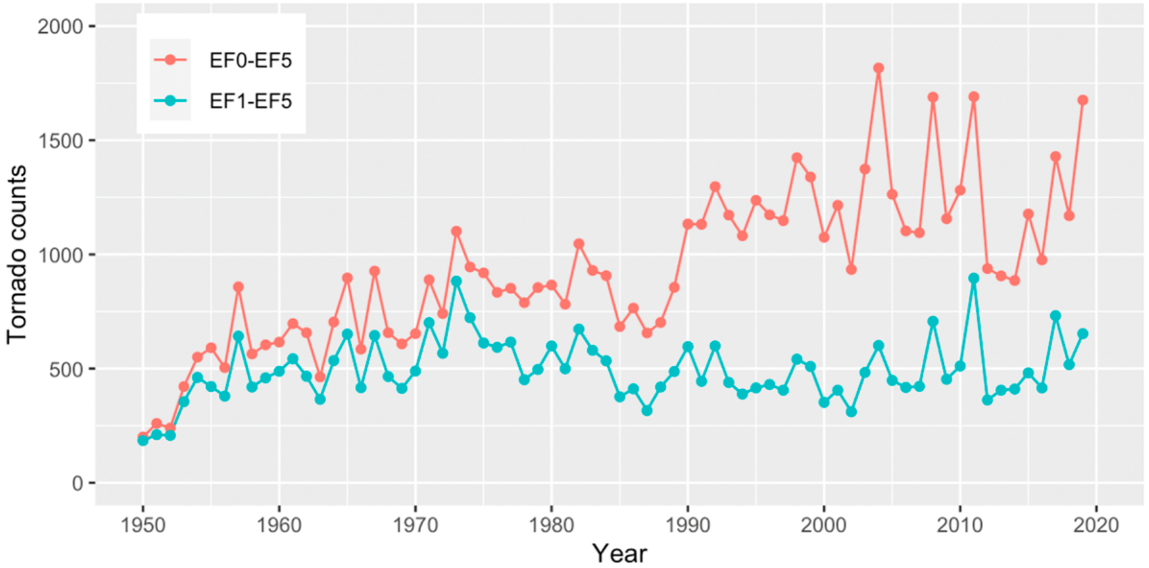


Fig. 1. Annual number of reported tornadoes (coral) and annual number of EF1 and greater reported tornadoes (turquoise) from 1950 to 2019.

tornadoes and tornado outbreaks by New World explorers and weather enthusiasts were referred to as "whirlwinds" (Redfield 1857), "hurricanes" (Brocklesby 1859), "cyclones" (Brooks 1949), or "tornado swarms" (Ludlum 1970). Although the provenance of "tornado outbreak" is difficult to establish, it may result from a cross-pollination of the terms "tornado" and "cold-air outbreak," which were frequently used in mid-twentieth-century publications (e.g., Miller 1946; Saucier 1949; Hsieh 1949; Tepper 1950).

1950–59. The wide appearance of the term "tornado outbreak" in the scientific literature can be first traced to the early 1950s. Major Fawbush, Captain Miller, and Captain Starrett, from the U.S. Air Force and the Air Weather Service of Tinker Air Force Base in Oklahoma City, presented empirical methods of tornado development forecasting in 1951 (Fawbush et al. 1951). The forecasters described a synoptic-scale frontal system where the U.S. Weather Bureau recorded "seven individual tornadoes, with paths up to 30 miles in length" (p. 8). Fawbush et al. (1951) used the term "outbreak of tornadoes" interchangeably with "outbreak of storms"; it is unclear if the authors applied "outbreak" in association with tornadoes only or to emphasize the unusual scale of a storm event. One year later, Carr (1952) reported on the tornadoes of 21–22 March 1952 that affected the lower Mississippi and Tennessee valley, using the term "outbreak" only in association with "a series of tornadoes" (p. 50). Thus, that work is one of the first to use "outbreak" only in reference to a specific event with multiple tornadoes.

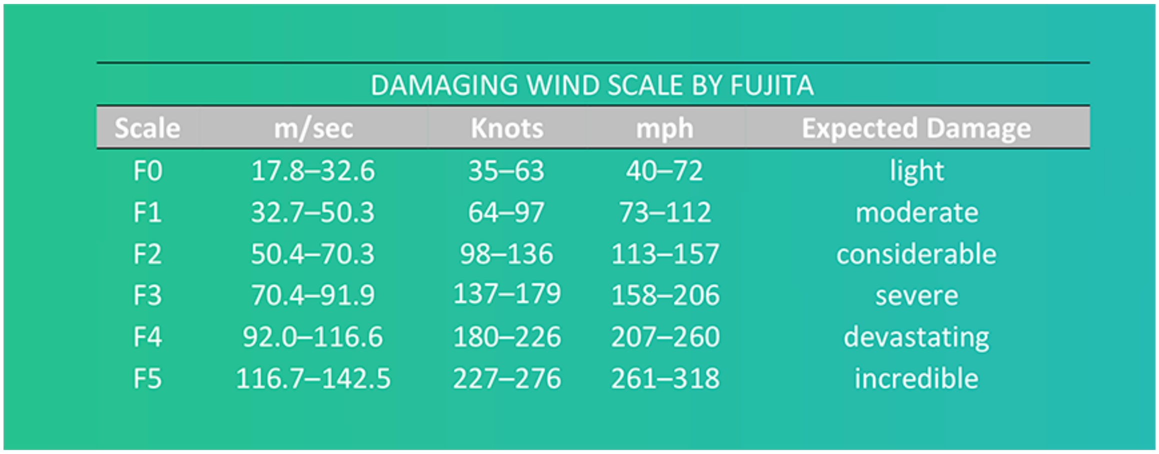
The first extensive listing of tornado outbreaks appeared in the 1953 book titled, *Tornadoes of the United States* (Flora 1953). Here, Flora stated that an "outbreak" was a "family or series of tornadoes … that occur in groups that break out approximately the same hour or within a few hours of each other" (p. 207). This and other contemporary publications that used the term "tornado outbreak" (Brooks 1953; Van Tassel 1955) did not detail how many tornadoes constitute a "family" or "series." Beebe (1956) was the first author to do so, defining an outbreak as "one in which 3 or more tornadoes occurred within a specific area and at least 2 of these tornadoes were separated by a distance of 100 miles or more" (p. 140). By the end of the decade, the term "tornado outbreak" had been used in association with severe weather events that had multiple tornadoes, but no specific definition had been adopted (Whiting and Bailey 1957; Beebe 1958; Ludlum 1959; Beebe 1959; Smith 1959), leading to even more definitions in the 1960s.

1960–69. Literature in the 1960s offered new insights to the tornado outbreak definitions, as scientists included more spatiotemporal characteristics than seen in the prior decade. For example, Wolford (1960) proposed that a tornado outbreak was a "family-type series of tornadoes, that travel in the same direction, following parallel paths that are rather close together, within a space of few hours in the same state or section of the country" (p. 12). The term "family-type" associated with tornado outbreaks was commonly used during this decade (e.g., Beebe 1961; Ludlum 1961; Hardy 1962, 1963). It is not clear, however, if authors referred to Wolford's definition that suggested parallel tornado paths or to the previous definition from Flora (1953) that named any group of tornadoes (including multiple tornadoes from a single storm) as a family of tornadoes. Judging from their characterizations of the published events, most authors seemed to distinguish multiple independent events as "family-like tornado outbreaks" and instances when multiple tornadoes occurred from a single storm as a "multiple tornado outbreak" (Galway 1966). When an event was exceptionally memorable, scientists adopted the practice of referring to that event by a specific nickname rather than by its date of occurrence. This practice started with O'Connor (1965), who first detailed the "Palm Sunday tornado outbreak," which at the time was considered "the second greatest tornado disaster in the nation's history in terms of the number dead (271)" (p. 465). The Palm Sunday tornado outbreak was one of only a few tornado outbreaks that were nicknamed due to the unusual magnitude of destruction that they caused (Bradbury and Fujita 1966; Andrews 1966; Fujita 1967; Pearson 1968; Agee 1969; Fujita et al. 1970).

At the decade's end, Pautz (1969) grouped tornado outbreaks into three categories: a "small family outbreak" with 6 to 10 tornadoes, a "moderate family outbreak" with 11 to 20 tornadoes, and a "large family outbreak" with more than 20 tornadoes. He also defined the term "family outbreak" as the occurrence of six or more tornadoes on one tornado day over a relatively small area, with no clarification what "tornado day" or "small area" meant. Thus, at the end of the decade arose the first definition of tornado outbreak based on a number of observed tornadoes and some general guidance for classifying the sizes of outbreaks. This quantitative approach was expanded widely in the 1970s.

1970–79. New understanding of tornadoes that arose in the 1970s modernized the approaches to characterizing individual tornadoes and, consequently, helped to generate new tornado outbreak classifications. Fujita (1971) documented results from the Tornado Watch Experiment project, which investigated satellite-viewed cloud characteristics in relation to tornado occurrences. His report suggested that individual tornadoes should be characterized by tornado intensity and area of impact, and he proposed a new 13-level scale based on damaging wind ranges (though only six levels were relevant for tornado activity). The Fujita scale, or F scale (Table 1), assigned a tornado intensity using estimates of wind speeds from structural or tree damage and classified tornadoes as gale (F0), weak (F1), strong (F2), severe (F3), devastating (F4), and incredible (F5) (Fujita 1971). Tornado-affected areas also were categorized by size (Table 1) as trace (TR), decimicro (DM), micro (MI), meso (ME), macro (MA), giant (GI), and decagiant (DG). The adoption of the Fujita scale in tornado research allowed scientists to compare one aspect of the damage magnitude among tornadoes within an outbreak. For example, the scale was applied to study individual tornadoes in one of the most famous outbreaks in U.S. history—the "jumbo" tornado outbreak of 3 April 1974 (Fujita 1974; Hoxit and Chappell 1974; Purdom 1974; Agee et al. 1975, 1976). This storm-damage classification transformed how tornadoes were reported and created opportunities to explore new tornado outbreak definitions.

Table 1. The "Fujita scale" adopted from Fujita (1971).



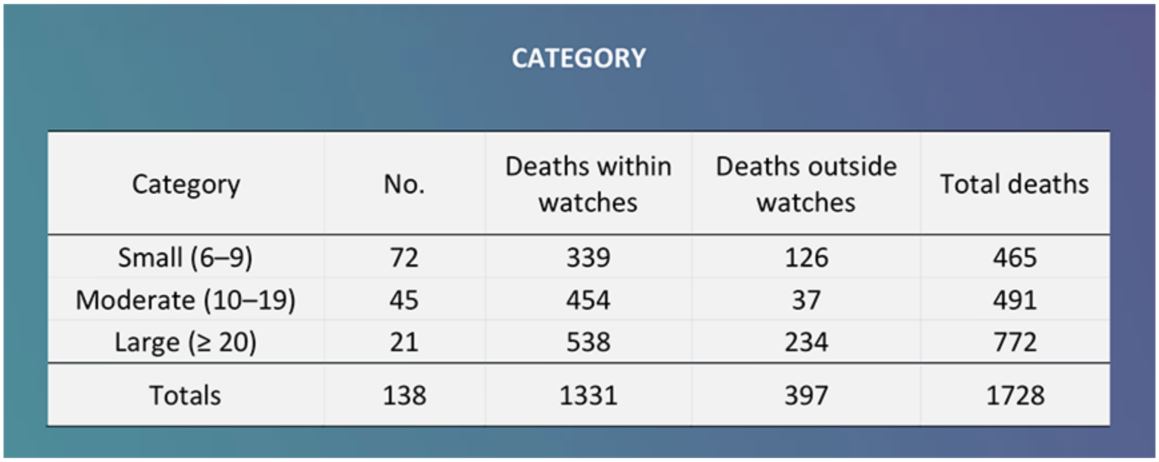
DAMAGING WIND SCALE BY FUJITA

Scale	m/sec	Knots	mph	Expected Damage
F0	17.8–32.6	35–63	40–72	light
F1	32.7–50.3	64–97	73–112	moderate
F2	50.4–70.3	98–136	113–157	considerable
F3	70.4–91.9	137–179	158–206	severe
F4	92.0–116.6	180–226	207–260	devastating
F5	116.7–142.5	227–276	261–318	incredible

Maddox and Gray (1973) grouped tornadoes into "tornado outbreak days" to analyze associated atmospheric conditions using proximity soundings. They defined the "tornado outbreak day" as "a day on which an unusually large number (roughly twenty or more) of destructive tornadoes occurred over a contiguous region of radius approximately 200 nautical miles" (1 n mi = 1.852 km) (Maddox and Gray 1973, p. 2). This work was the first to specify the number of tornadoes with specific temporal and spatial characteristics in its tornado outbreak definition.

Two years later, Galway (1975) slightly modified number of tornadoes in the existing tornado outbreak definition of Pautz (1969), so that small tornado outbreaks had 6 to 9 tornadoes, moderate had 10 to 19 tornadoes, and large had 20 or more (Table 2).

Table 2. Example of tornado outbreak classification adopted from Galway (1975, p. 741).



CATEGORY

Category	No.	Deaths within watches	Deaths outside watches	Total deaths
Small (6–9)	72	339	126	465
Moderate (10–19)	45	454	37	491
Large (≥ 20)	21	538	234	772
Totals	138	1331	397	1728

Subsequently, Galway (1977) presented yet another approach whereby an "outbreak" was defined as 10 or more tornadoes from a single, organized weather system. Further, tornado outbreaks were categorized as local, progressive, and line. The "local outbreak" had a maximum duration of seven hours and area of activity confined to a circular envelope of ~1.0×10^4 n mi^2 (square nautical miles). A "progressive outbreak" advanced (or progressed) from west to east within a duration of 9.5 h on average, where the distance between first and last tornado report was greater than 350 nm and the activity envelope was at least 5.4×10^4 n mi^2. Finally, a "line outbreak" had "a limited eastward progression that forms on an axis, generally oriented north-south" (p. 478), with a duration of about 8 h and an area of 5.9×10^4 n mi^2. This classification, conceptually close to that of Maddox and Gray (1973), was the first to include *temporal* characteristics to capture more detail in the character of tornado outbreaks. His work highlighted an emerging pattern of applying the outbreak definition as a tool to study the precursor conditions leading to tornado outbreak development—a pattern that dominated the next decade.

1980–89. At the turn of the 1980s, comprehensive studies of the statistical properties of tornadoes, such as the average number of tornadoes within a certain distance of given point, became popular (McNulty et al. 1979; Schaefer et al. 1980a). Scientists analyzed data from various tornado databases to acquire new information about U.S. tornado probabilities, develop climatologies, and perform risk assessments (Schaefer et al. 1980b; Reinhold and Ellingwood 1982; Twisdale and Dunn 1983; Grazulis and Abbey 1983; Grazulis 1984). By the end of the 1970s, researchers noticed inconsistencies in those tornado databases (Kelly et al. 1978; Tecson et al. 1979); namely, some of the early data contained spatial and temporal inconsistencies in the tornado reports of the same events. For example, one long-track tornado passed simultaneously through two cities separated by almost 70 miles (Forbes and Wakimoto 1983)! Another matter that generated lively discussions among scholars was the use of the Fujita scale rating and viability of its assigned categories (Minor et al. 1977; Schaefer and Galway 1982; Colquhoun and Shepherd 1985). Consequently, there emerged an increased need to verify tornado databases and improve the quality of the tornado record (Fujita 1981; Schaefer et al. 1986).

New definitions also arose. Forbes and Wakimoto (1983) introduced an idea of a "concentrated" tornado outbreak, characterized by many weak tornadoes that did not have to be associated with cumulonimbus clouds. This concept was not popular, and many researchers continued using the prior definitions of tornado outbreaks (Galway and Pearson 1981; Galway 1981; Schaefer and Doswell 1984) or applied the term to major events characterized by multiple strong tornadoes, fatalities, and property damage (Ostby and Wilson 1981; Witten 1985; Myers 1987).

1990–1999.

In the early 1990s, the study of tornado outbreaks gravitated toward concepts inspired by the research of the preceding decade. While analyzing past major tornado outbreaks, Grazulis (1990a) noted limitations in the tornado database such as a "bias in both tornado documentation and the Fujita scale rating process" (p. 131), concluding that the distribution of tornado risk still was not well understood. In this work (Grazulis 1990a), major tornado outbreaks were defined as outbreaks of significant tornadoes (F2+) with total pathlengths exceeding 100 miles. Grazulis (1990b) expanded the definition to include any tornado that caused death and was applied to produce a dataset of all historic "significant" tornadoes from 1880 to 1989. Later, Grazulis (1993) based a tornado outbreak on Galway (1975), defining it as "a group or a family of six or more tornadoes which are spawned by the same general weather system" (p. 13). Here, a small outbreak could include six tornadoes from two different thunderstorms associated with a cold front; however, if the six tornadoes resulted from different weather systems, they would not be treated as an outbreak. Simultaneously, Grazulis (1993) extended the definition to mark the gap between the end of one outbreak and the start of another as a "six-hour lull in tornado activity" and underscored that an outbreak did not have to be confined to one calendar day. Still, previous tornado outbreak definitions (e.g., Galway 1977) continued to be used during this time (Johns and Doswell 1992; Spector et al. 1993).

Measurements of severe weather events were significantly improved in the 1990s due to implementation of the WSR-88D (Crum and Alberty 1993). The WSR-88D system helped differentiate tornadic and nontornadic storms, resulting in increased probability of tornado detection (Polger et al. 1994). Operated in tandem with other instrumentation, the WSR-88D system supported extensive scientific field experiments, such as the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX), conducted to evaluate hypothesis on tornadogenesis and tornado dynamics (Rasmussen et al. 1994). Consequently, these efforts led to improvements in the tornado record, tornado databases, and tornado outbreak analyses.

The proliferation of popular and inexpensive video cameras (Davies et al. 1994) caused a surge in photogrammetric analyses of tornadoes. New or evolving observational capabilities and enhanced computational resources led to the advent of improved computer modeling, resulting in more detailed numerical weather simulations (e.g., Wicker and Wilhelmson 1995). That advancement benefitted research on tornado outbreaks by improving prediction (Kaplan et al. 1998) and enhancing the understanding of the environmental conditions favoring the evolution of tornado outbreaks, especially kinematic and thermodynamic conditions (Corfidi 1998; Hamilton et al. 1998; Koch et al. 1998; Langmaid and Riordan 1998).

A regional lens in distinctive geographic locations (e.g., Florida; Schmocker et al. 1990) was used to examine tornado outbreaks (Johns and Dorr 1996; Hales and Vescuo 1997), with a focus to improve regional knowledge, forecasts, and warnings of those events. For example, Hagemeyer and Matney (1994) noted that because peninsular Florida was isolated from surrounding states, a tornado outbreak required a regional approach and was defined as "four or more tornadoes in four hours or less at, or south of, 30° latitude" (p. 3). Hagemeyer (1997) used this definition to analyze the tornado-outbreak climatology for peninsular Florida, distinguishing three outbreak environments: extratropical, tropical, and a hybrid of those two. Subsequently, outbreaks associated with tropical environments and hurricanes continued to be researched, contributing to a broader understanding of the influence of different environmental factors on tornado outbreak evolution (McCaul 1991; Hagemeyer and Hodanish 1995; Vescio et al. 1996; Edwards 1998).

By the end of the decade, scientific interests expanded to tornado outbreak simulations for analyses of damage paths (Lee and Wilhelmson 1997; Adlerman et al. 1999) and damage potential. Doswell et al. (1993) found that outbreak-related tornadoes were capable of the highest damage potential of any tornadoes, and these tornadoes usually were produced by supercells. Also, Thompson and Vescio (1998) observed that it was difficult to compare different tornado outbreaks with each other because the existing Fujita scale relied on damage to manmade structures and thus tended to "preclude high ratings for tornadoes occurring in sparsely populated areas." To address this issue, the authors proposed categorizing tornadoes with a destruction potential index (DPI) that measured the potential for damages and casualties for any chosen time period during a tornado outbreak. It was calculated as the total tornado damage area multiplied by the weighted mean F scale for all tornadoes that occurred during the time period of interest. In general, this work embodied a broader effort undertaken by researchers in the 1990s to aid tornado forecasting and provide greater accuracy in the prediction of tornado outbreaks across the United States.

2000–09. The considerable technological changes during the 1990s contributed to a substantial increase in the number of reported tornadoes, especially those of F0 and F1 ratings (Brooks and Doswell 2001). This increase, caused by nonmeteorological factors, became important to consider when defining tornado outbreaks based only on damage thresholds, and scientists found additional sources of potential biases and errors in the data. For instance, Verbout et al. (2006) observed inconsistencies in the tornado reporting system, wherein tornado reporting prior to the mid-1970s underestimated the fraction of F1 tornadoes and overestimated the fraction of F2 and higher tornadoes.

Environmental characteristics (such as instability, shear, storm-relative flow, and mean jet stream position) and their roles in tornado outbreak development were investigated frequently in the 2000s (Thompson and Edwards 2000; Markowski 2002; Hamill et al. 2005; Lee et al. 2006a,b). Scholars sought to find what environmental factors controlled tornado outbreaks (e.g., factors influencing winter outbreaks; Cook and Schaefer 2008). Consequently, the research results supported more detailed information for both high-resolution modeling and numerical weather prediction (Zupanski et al. 2002; Xue et al. 2003; Roebber 2004) in operational forecasting. This focus provided potentially useful information for forecasters to better diagnose environmental settings that supported tornado outbreaks at different spatial ranges: mesoscale (Egentowich et al. 2000a,b,c; Stensrud and Weiss 2002; McCaul et al. 2004; Seko et al. 2009), synoptic scale (Roebber et al. 2002; Rose et al. 2004; Curtis 2004; Verbout et al. 2005; Watson et al. 2005; Verbout et al. 2007; Belanger et al. 2009), or a mix of both scales (Rogash and Smith 2000; Darbe and Medlin 2005). Also, to improve real-time tornado detection, scientists utilized diverse techniques and data, such as three-dimensional visualization software (Nietfeld 2003), satellite imagery (Bikos et al. 2002), remote sensing (Myint et al. 2008), and enhanced-resolution radar data (Brown et al. 2002). Technological innovation led also to the development of a tornado-debris recognition method (e.g., polarimetric radars; Ryzhkov et al. 2005) and various tornado-damage estimation methods (Yuan et al. 2002; Yuan 2005; Camp 2008), resulting in enhanced tornado detection and assessment capabilities. This collective scientific effort applied various methods and techniques that challenged and improved the conceptual ideas and perceptions of tornado outbreaks (Miller 2006).

As the tornado record improved and lengthened, Brooks et al. (2003) analyzed the climatology of tornado days, and Schneider et al. (2004a) investigated the climatology of "tornado outbreak days." A "tornado outbreak day" was defined as a calendar day when a tornado outbreak (based on Galway 1977) occurred, applying a summary database they developed with severity categories based on tornado counts. The database included the F-scale ratings, tornado counts, total pathlength, and "destructive potential index," and it identified both major and minor tornado outbreak events (Fig. 2). They also analyzed "tornado outbreak day sequences," defined as a continuous or near-continuous sequence of tornado outbreaks (Schneider et al. 2004b), such as during the outbreaks from 3 to 11 May 2003 (also described as an extended tornado outbreak; Hamill et al. 2005).

Without a means to measure "density," "importance," or "quality" of tornado outbreaks on a nationwide basis, Edwards et al. (2004) adopted a new strategy to assess and define tornado outbreaks. As part of a broader project, the team proposed a set of criteria for tornado outbreaks, including the number of tornadoes, number of violent (F4+) tornadoes, number of significant (F2+) tornadoes, DPI, cumulative pathlength (km), and number of deaths to develop a "tornado outbreak index" (O index). Severe weather days characterized by positive O-index values (i.e., O index > 0) were classified as tornado outbreak days and ranked. The higher the ranked position, the more significant an event was. Although the new approach provided a useful means to compare tornado outbreaks, the authors recognized that some elements were subjective, leading to a certain amount of arbitrariness in the classification.

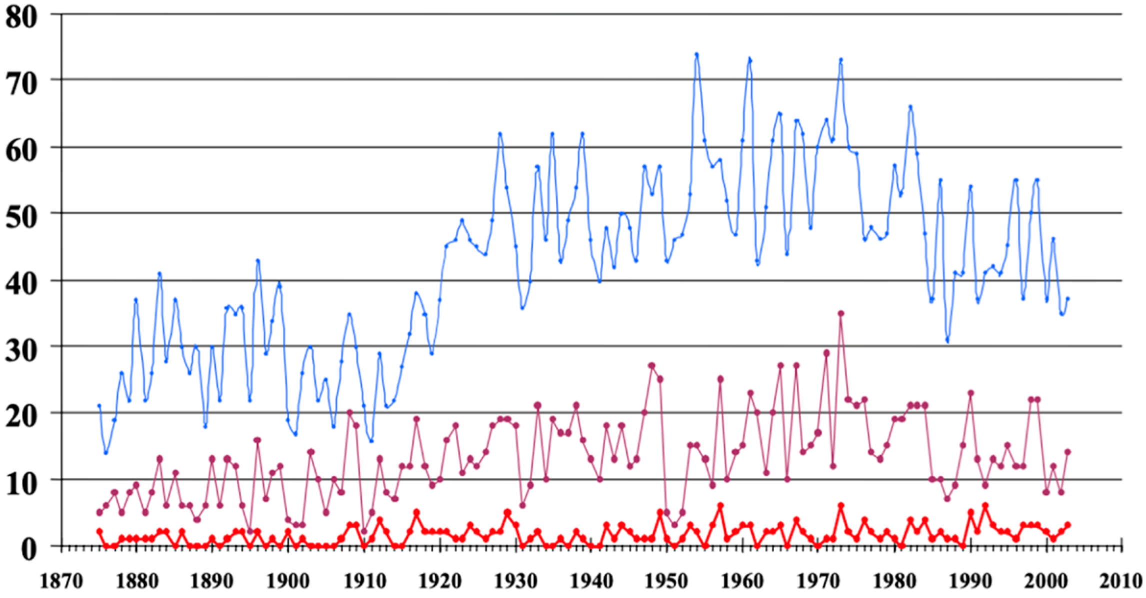


Fig. 2. Annual number of significant tornado days (solid blue), tornado outbreak days (categories 1–6, solid maroon), and major outbreak days (categories 3–6, solid red) for the period from 1875 to 2003. Adopted from Schneider et al. (2004b).

Verbout et al. (2006) also expressed that the criteria defining tornado outbreaks were dependent on user decisions. They analyzed tornado outbreaks through the lens of "big tornado days," defined as "a single day when numerous tornadoes and/or many tornadoes exceeding a specified intensity threshold were reported anywhere in the country" (p. 1). To identify a "big tornado day," Verbout et al. (2006) used 1) "convective days" (i.e., 1200–1200 UTC), rather than calendar days, to match the diurnal cycle of convection and the SPC forecasting day, 2) a minimum number of reported tornadoes determined from a fraction of the annual value associated with a simple least squares linear regression (i.e., the minimum depended on the year under investigation), and 3) a minimum number of F1 tornadoes or higher. Using a least squares linear regression, they accounted for almost 50% of the increase in the number of reported tornadoes from 1950 to 2000. Many threshold combinations were possible, depending on the user's research objectives, and hence, the definition of "big tornado days" never was completely objective. This flexible definition was practical if one research team wanted to analyze a small number of case studies in great detail (bigger threshold) and another research team wanted to develop a robust statistical model requiring a large number of "big tornado days" (smaller threshold).

Another approach to define and rank tornado outbreaks was the "Forbes impact index," developed by Forbes (2006) to rank tornado outbreaks depending on their impact. In this work, a tornado outbreak was defined as an event with at least 45 tornado reports occurring in adjoining states and with no tornado-free gap of six hours or longer during the outbreak. Next, 11 attributes (including number of fatalities and injuries, number of significant tornadoes, and amount of total damage) were used to calculate the Forbes impact index. Each attribute was assigned an integer value from 0 to 10 points (with two attributes of 5 points maximum); the points total across all attributes determined the ranked position of a tornado outbreak. Forbes (2006) applied this scheme to analyze the 15 highest-ranked outbreaks and determine the large-scale meteorological patterns for these events.

The aforementioned outbreak rankings focused either on societal impacts or meteorological significance. Yet not all meteorologically significant events would strongly affect society; conversely, not all outbreaks of large societal impact would be unusual meteorologically. Doswell et al. (2006) noted that there was no convincing rationale of attaching greater importance to one criterion. Hence, they developed a multivariate index to account for *both* meteorological and societal impact variables for tornado outbreaks, yielding a ranking that would be robust to any parameter choices. First, they identified days when seven tornadoes or more occurred during 1970–2003. Then they ranked these days according to the linearly weighted average of eight variables, resulting in the 20 highest-ranked tornado outbreaks events. Mercer et al. (2009) applied this ranking in combination with statistical modeling and synoptic-scale numerical weather prediction to test if model-predicted covariates could determine the type of severe weather outbreak that occurred. Their results displayed a high probability of outbreak detection, even several days prior to the event. The various approaches to define and classify tornado outbreaks at the beginning of the twenty-first century demonstrated the desire for more accurate long-term forecasts while preserving considerable flexibility depending on the user's research goals. These approaches further developed the perception and prediction of tornado outbreaks.

2010–19. In the 2010s, the literature mainly focused on different statistical approaches to classify and rank tornado outbreaks. For example, Shafer and Doswell (2010, 2011) used kernel density estimation to group tornadoes into regionally separated outbreaks (Fig. 3) and then applied multivariate linear-weighting method to rank resulting outbreaks. This research offered a standardized approach to identify the relative severity of the outbreaks. Other studies quantified the severity of tornado outbreaks using different methods. For instance, Malamud and Turcotte (2012) suggested that the statistics of tornado touchdown pathlengths could serve as a quantitative measure of tornado intensity. In their research, the strength of a tornado outbreak was calculated from the total pathlength of all "severe tornadoes" (i.e., those with a pathlength equal to or greater than 10 km) during a "convective day" (i.e., 24-h period starting at 1200 CST). Using pathlength data for 1952–2011, they estimated that, on average, one convective-day tornado outbreak would have a total pathlength of at least 480 km yr^{-1} and 1,200 km decade^{-1}.

Fuhrmann et al. (2014) proposed a new metric to measure the strength or "physical magnitude" (p. 1) of tornado outbreaks, defined as the sum of the wind force across the area of impact (i.e., the work, in joules, generated by all tornadoes in the outbreak). They defined a tornado outbreak as a sequence of at least six tornadoes of F1 or greater intensity that had a maximum gap of 6 h between consecutive tornadoes in the sequence. They computed an outbreak strength based on the intensity (Fujita/EF-scale rating) of each tornado over its distance traveled and found this measure, called “adjusted Fujita miles,” to be correlated with the number of fatalities (correlation coefficient = 0.80) and injuries (correlation coefficient = 0.81). The authors suggested that “adjusted Fujita miles” could assess potential lethality of tornado outbreaks. Tippett and Cohen (2016) applied the tornado outbreak definition by Fuhrmann et al. (2014) to document a significant increase in the annual variance and a gradual increase in the mean number of tornadoes during 1954–2014. They also found an increase in the number of tornadoes per outbreak and that extreme tornado outbreaks were more frequent than originally anticipated (Tippett et al. 2016).

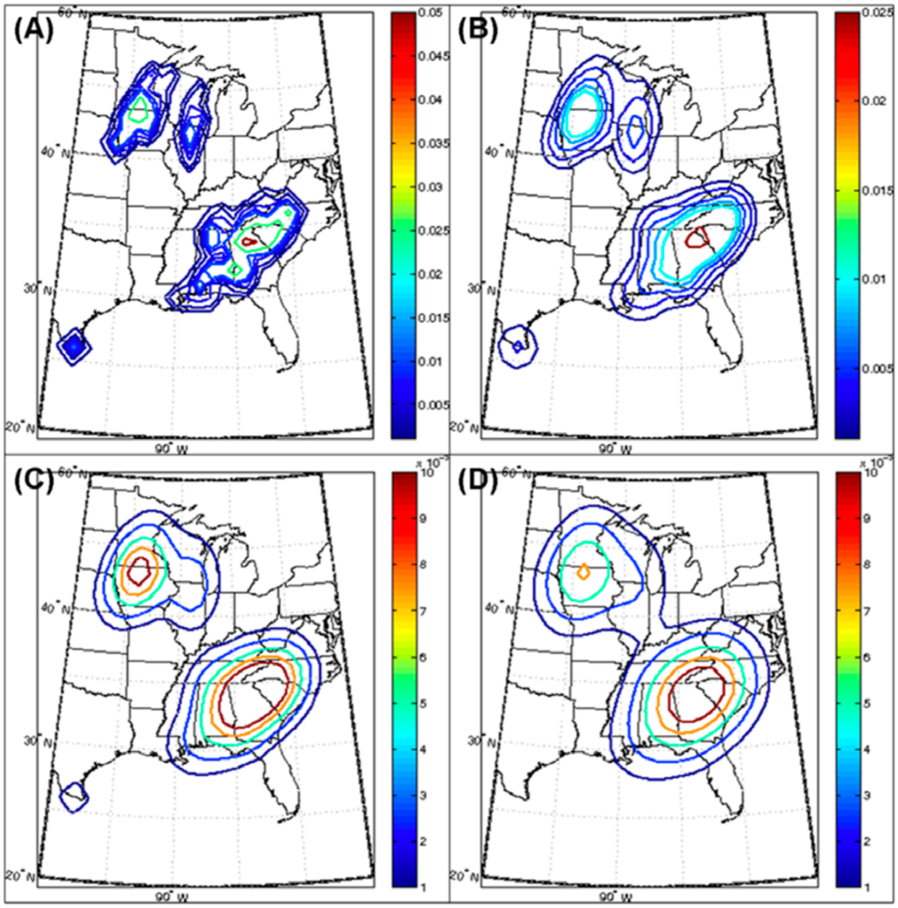


Fig. 3. Representations of two separate regions of severe convective activity from 1200 UTC 29 Apr to 1159 UTC 30 Apr 1991 using four different bandwidths in a kernel density estimation (KDE) function. Plots use National Weather Service severe reports. Adopted from Shafer and Doswell (2011).

Finally, to minimize risks associated with tornado outbreaks and improve forecasts, many researchers studied the environmental conditions associated with tornado outbreaks (Corfidi et al. 2010; Schumacher and Boustead 2011; Knupp et al. 2014; Trapp 2014; Yussouf et al. 2015; Tochimoto and Niino 2016; Anderson-Frey et al. 2018; Flynn and Islam 2019; Gray and Frame 2019; Mercer and Bates 2019). In particular, research focused on the relationship between tornado outbreak occurrence and specific environmental indices (Saide et al. 2015; Megnia et al. 2019) or their associated global-scale weather patterns (Thompson and Roundy 2013; Lee et al. 2013, 2016; Sparrow and Mercer 2016; Cook et al. 2017; Tippett 2018). For instance, Gensini and Marinaro (2016) defined “tornado outbreak” as a single day when 15 or more tornadoes occurred east of the Rocky Mountains. Using 285 (90th percentile) out of 2,440 outbreak days, they showed that tornado outbreaks were more common during periods when the time tendency of atmospheric angular momentum was negative [i.e., global wind oscillation (GWO) phases 1, 2, and 8; see Gensini and Marinaro (2016) for more information on GWO phases]. They suggested that the GWO framework might be useful in subseasonal forecasts of tornado outbreaks. Gensini et al. (2019) documented that phases of the GWO could help predict an extended period with favorable severe weather conditions, such as the May 2003 period from Schneider et al. (2004b), 3–4 weeks prior to any event. Gensini et al. (2019) was the first to document a successful forecast of an unusually active period for tornadic thunderstorms, including tornado outbreaks, at subseasonal lead times. That work, as well as others cited above, are examples of dynamical and innovative statistical approaches that were undertaken during the 2010s to analyze tornado outbreaks. The changes to techniques and methods across the decades, driven by improvements in both knowledge and technologies, helped to overcome initial challenges associated with the concept of a tornado outbreak and most likely will continue to do so into the future.

Discussion and final remarks

The term "tornado outbreak" used over the past several decades has proven to be diverse and ambiguous. As noted by Galway (1977), "A tornado 'outbreak' can mean many things to many people." Here, we review the transformations of the term from 1950 to 2019 in the United States, emphasizing how these definitions were shaped and resulted in new knowledge on tornado outbreaks. Sorting the publications by decade may not be useful for some applications, so we also arranged them into six general categories in Table 3: 1) definition and ranking, 2) observational record, 3) climatology and statistics, 4) mesoscale conditions, 5) synoptic conditions, and finally, 6) technology, hazard assessment and global-scale patterns. It is important to add that, although not discussed herein, "tornado outbreak" is a term that has been widely adopted by international scholars (e.g., Dotzek 2001; Oprea and Bell 2009; Allen and Allen 2016; Antonescu et al. 2017, 2018; Chernokulsky and Shikhov 2018; Louis 2018) for their own research needs, resulting in substantial discussion about tornado outbreaks across continents. All of this work has been aimed at knowledge to reduce tornado risks or impacts across society.

The selection of one universal approach or an attempt to create a new "tornado outbreak" definition is challenging. Some difficulties relate to subjective thresholds that can be applied

Table 3. Classification of literature on tornado outbreak definitions from 1950 to 2020.

Tornado outbreak	Definition, ranking	Observational record	Climatology, statistics	Mesoscale conditions	Synoptic conditions	Technology, hazard assessment, global-scale patterns
1950–59	Flora (1953) Beebe (1956)	Brooks (1953) Van Tassel (1955) Ludlum (1959)	Beebe (1958)	Smith (1959)	Tepper (1950) Fawbush et al. (1951) Carr (1952) Whiting and Bailey (1957)	Beebe (1959)
1960–69	Wolford (1960) Pautz (1969)	Beebe (1961) Ludlum (1961) Hardy (1963) Galway (1966)	Agee (1969)	O'Connor (1965) Fujita (1967)	Andrews (1966)	Hardy (1962) Bradbury and Fujita (1966) Pearson (1968)
1970–79	Fujita (1971) Maddox and Gray (1973) Galway (1975, 1977)	Minor et al. (1977)	Fujita (1974) Kelly et al. (1978) McNulty et al. (1979) Tecson et al. (1979)	Agee et al. (1976)	Fujita et al. (1970) Hoxit and Chappell (1974) Agee et al. (1975)	Purdom (1974)
1980–89	Forbes and Wakimoto (1983)	Ostby and Wilson (1981) Galway (1981) Grazulis (1984) Witten (1985)	Schaefer (1980a) Schaefer and Galway (1982) Schaefer and Doswell (1984)	Fujita (1981) Grazulis and Abbey (1983) Colquhoun and Shepherd (1985)	Galway and Pearson (1981) Myers (1987)	Schaefer (1980b) Reinhold and Ellingwood (1982) Twisdale and Dunn (1983) Schaefer et al. (1986)

Table 3. (*Continued*).

Tornado outbreak	Definition, ranking	Observational record	Climatology, statistics	Mesoscale conditions	Synoptic conditions	Technology, hazard assessment, global-scale patterns
1990–99	Grazulis (1990a,b, 1993)	Spector et al. (1993)	Schmocker et al. (1990)	McCaul (1991)	Johns and Doswell (1992)	Crum and Alberty (1993)
				Polger et al. (1994)	Johns and Dorr (1996)	Davies et al. (1994)
		Hagemeyer and Hodanish (1995)		Rasmussen et al. (1994)	Hales and Vescuo (1997)	Lee and Wilhelmson (1997)
	Hagemeyer and Matney (1994)			Corfidi (1998)	Kaplan et al. (1998)	Adlerman et al. (1999)
			Hagemeyer and Matney (1994)	Hamilton (1998)		Doswell et al. (1993)
	Thompson and Vescio (1998)	Edwards (1998)		Koch et al. (1998)	Vescio et al. (1996)	Wicker and Wilhelmson (1995)
				Langmaid and Riordan (1998)		
2000–09	Edwards et al. (2004)	—	Brooks and Doswell (2001)	Egentowich et al. (2000a,b,c)	Rogash and Smith (2000)	Brown et al. (2002)
			Brooks et al. (2003)	Thompson and Edwards (2000)	Roebber et al. (2002)	Bikos et al. (2002)
	Schneider et al. (2004a,b)		Rose et al. (2004)	Markowski (2002)	Nietfeld (2003)	
			Verbout et al. (2005, 2007)	Stensrud and Weiss (2002)	Curtis (2004)	Yuan et al. (2002)
	Doswell et al. (2006)			McCaul et al. (2004)	Roebber (2004)	Zupanski et al. (2002)
				Lee et al. (2006a,b)	Darbe and Medlin (2005)	Xue et al. (2003)
	Forbes (2006)		Belanger et al. (2009)		Hamill et al. (2005)	Ryzhkov et al. (2005)
				Miller (2006)	Watson et al. (2005)	
	Verbout et al. (2006)		Mercer et al. (2009)	Seko et al. (2009)	Cook and Schaefer (2008)	Camp (2008)
						Myint et al. (2008)
2010–20	Shafer and Doswell (2010)	—	Shafer and Doswell (2011)	Knupp et al. (2014)	Corfidi et al. (2010)	Lee et al. (2013)
			Malamud and Turcotte (2012)	Trapp (2014)	Schumacher and Boustead (2011)	Thompson and Roundy (2013)
	Fuhrmann et al. (2014)		Tippett and Cohen (2016)	Yussouf et al. (2015)	Saide et al. (2015)	Lee at al. (2016)
			Tippett et al. (2016)	Anderson-Frey et al. (2018)	Tochimoto and Niino (2016)	Sparrow and Mercer (2016)
	Gensini and Marinaro (2016)			Flynn and Islam (2019)		Cook et al. (2017)
			Mercer and Bates (2019)	Gray and Frame (2019)	Brown and Nowotarski (2020)	Tippett (2018)
				Megnia et al. (2019)		Gensini et al. (2019)

to the physical characteristics of tornado outbreaks (e.g., at least seven tornadoes within 24 h). Such a definition can include a threshold of intensity expressed by the minimum magnitude of tornadoes occurring within the outbreak (e.g., tornadoes rated EF1 and higher). Scientists also have considered these thresholds within a defined spatial range, perhaps also including a minimal threshold of tornado pathlength or width. Another layer of complexity to a definition can be added by incorporating a number of deaths and injuries or the economic impact (expressed as costs and losses). To make the task even harder, exposure, vulnerability, and perception of the risk associated with tornado outbreaks across the country vary considerably (Hoekstra et al. 2011; Klockow et al. 2014; Jauernic and Van Den Broeke 2017; Sanders et al. 2020). An event with few tornadoes may be considered an outbreak in the northeastern United States, but "just an average spring day" in the U.S. southern Great Plains. Further, local beliefs about tornadoes and tornado risk, known as "folk science" or place-based environmental knowledge (Klockow et al. 2014), influence the perception of a tornado outbreak threat. Klockow et al. (2014) noted that unique, place-based understandings of tornadoes are unlikely to be resolved by universally defining a tornado outbreak.

Perhaps to the dismay of some scholars, there is no one consistent, unequivocal definition of a tornado outbreak—nor, we believe, should there be. Differences in use of "tornado outbreak" term in research, forecasting, or common societal usage make it virtually impossible to create a definition to fit all purposes. It is our viewpoint that a definition should depend on the user's purpose and appropriate to the data and technologies available for a particular time. Regardless, researchers and forecasters must clearly define the term and their reason to use it so as to avoid confusion, and it becomes particularly important to ensure "apples to apples" comparison between studies looking at tornado climate variability (e.g., Brown and Nowotarski 2020; Molina et al. 2018). A clear definition helps turn our attention to learning about the events, their individual characteristics, and how to better prepare for them in the future.

Fig. 4. A depiction of "Man-ka-ih." Adopted from Momaday (1969).

Although defining and categorizing phenomena are hallmarks of Western science, it is important to recognize the vast knowledge and experience of other cultures to fully embrace the opportunity of serving and protecting those in harm's way. Still today, the perspectives of Native American peoples on many scientific topics are rarely acknowledged, attributed to them, or understood in a meaningful way. Tornadoes and tornado outbreaks are no different. Indigenous peoples have witnessed the devastating power of tornadoes over thousands of years across the landscape. These experiences and the generational stories they produce have shaped diverse perceptions, beliefs, and understandings on what a tornado is. For instance, Kiowa people have a special relationship with tornadoes, referred to as "Man-ka-ih" (Fig. 4) or "Storm-Maker Red Horse" (NPR 2014); they use their language to communicate with this storm spirit (Momaday 1969). For many Native Americans, each object in nature has a spirit, and thus, each tornado may be considered as an individual, rather than a group or an outbreak (Vogel 2001; Peppler 2011). Regardless of the definition used, we need to recognize and appreciate the differences in tornado outbreak definitions if we wish to communicate outbreak-related research and forecasts effectively across different peoples and places.

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