Spatial and Temporal Characteristics of Tornado Path Direction*

Philip W. Suckling
Texas State University–San Marcos

Walker S. Ashley
Northern Illinois University

Common perception is that tornadoes travel in paths from the southwest quadrant of directions toward the northeast. This study examines path directions for 6,194 tornadoes that occurred in the eastern two-thirds of the United States during the twenty-three-year period 1980–2002. At the national scale, nearly 70 percent of tornadoes included in the study propagated from the west, west-southwest, and southwest, with west-southwest being the highest frequency origin direction. Nevertheless, distinct seasonal and regional variations were found. In central and northern areas of the country, a more westerly or northwesterly path origin prevails during late spring and summer. The midtropospheric flow, convective typology, and synoptic patterns of tornado outbreaks are thought to contribute to the distributions observed in the climatology. **Key Words: natural hazards, tornadoes, tornado path.**

Introduction

Hazard mitigation studies indicate that over the past half century improved warning technologies and community preparedness have substantially reduced fatalities and injuries associated with tornadoes (Boruff et al. 2003). Tornado hazard studies and associated risk-assessment models frequently focus on spatial characteristics such as track length and track width, but often overlook path direction (e.g., Schaefer, Kelly, and Abbey 1986; Grazulis, Schaefer, and Abbey 1993; Brooks 2004). Tornado path direction, however, is not a trivial matter for tornado hazard mitigation. When considering the safest location within a building in the event of a tornado, at one time the southwest corner of a basement was considered the safest, on the theory that wind-blown debris from the damaged building would accumulate in the northeast corner of the basement as the tornado moved from the southwest toward the northeast (Finley 1887; Flora 1954). Although tornado path direction, as we will show, is indeed generally from the southwest, research by Eagleman (1967) and others has shown that the safest location is opposite to the southwest corner since debris actually accumulates nearest to the initial impact (Eagleman, Muirhead, and Williams 1975; Grazulis 2001).

Current tornado safety recommendations for buildings assert that one should seek shelter in an interior, reinforced room or corridor in the lowest level of a structure (AMS 2000; FEMA 2004; NWS 2004). In addition to this primary rule, safety guidelines, research, and accounts continue to indicate that the "downstream" portion of a building will be somewhat safer than the "upstream," relative to the approaching tornado (Eagleman 1967; Eagleman, Muirhead, and Williams 1975; Tornado Project Online 1999; AMS 2000). Clearly, such guidelines need to be revaluated in light of recent wind engineering research, advancements, and techniques. For example, should "safe rooms" and shelters be constructed away from the west-, southwest-, and south-facing walls, which, based on climatological data, have a higher probability of receiving the highest wind loads and therefore have a higher chance of collapse (Eagleman 1967)? Clearly, microscale vortex and structure interactions make it difficult to

*The assistance of Jamie Dyer (Climatology Research Laboratory, University of Georgia) is gratefully acknowledged. The authors thank the anonymous reviewers, whose comments helped us clarify and improve the manuscript.

The Professional Geographer, 58(1) 2006, pages 20–38
Initial submission, March 2004; revised submission, November 2004; final acceptance, December 2004.
Published by Blackwell Publishing, 350 Main Street, Malden, MA 02148, and 9600 Garsington Road, Oxford OX4 2DQ, U.K.

determine where debris will fall. However, climatological information such as that derived from this study can be utilized in future engineering studies to investigate the safest location in structures for different tornado scenarios.

Additionally, data on tornado path direction are also extremely important to public officials and information managers at local emergency operational facilities who must determine the distribution of resources and storm spotters in severe weather situations. Results from this study show that spotters should be positioned to have an unobstructed view to the west and southwest horizons, where a majority of tornadoes originate. Understanding climatological features such as predominant tornado path direction can aid in general tornado awareness and in obtaining critical information quickly so that officials can make timely local warning dissemination decisions.

Common perception is that U.S. tornadoes travel in paths from the southwest toward the northeast (Eagleman, Muirhead, and Williams 1975; Eagleman 1990; Grazulis 2001). However, there has been very limited research on tornado path direction for the United States, and most studies that have examined tornado path direction have only considered specific states. For example, estimates from the early twentieth century indicated that in Kansas 61 percent of tornadoes came from the southwest, 16 percent from the west, and 11 percent from the northwest (U.S. Department of Commerce 1953). It was shown that in Illinois more than 80 percent of tornadoes traveled from the southwest through west directions (Wilson and Changnon 1971). In a study of the state of Iowa based on the thirteen-year period 1959–1971, Notis and Stanford (1973) reported that almost 70 percent of Iowa tornadoes traveled from the southwest quadrant, but about 30 percent came from the west or northwest directions. The descriptive climatology by Schaefer et al. (1980) examined national tornado path direction, albeit briefly, and concluded that 87 percent of conterminous U.S. tornadoes travel from the southwest quadrant. Schaefer et al. (1980) also noted that when tornado motion is considered on a seasonal basis, only summertime storms differ markedly from this general pattern, with one of four summer tornadoes traveling from the northwest quadrant of directions. Fujita (1987) briefly examined tornado path direction in a climatological study of tornado data from the period 1916–1985 and concluded that 59 percent of tornadoes moved from the southwest.

As illustrated in this review, there is limited research on tornado path direction for the United States, especially during the past twenty years. Recent enhancement of tornado reporting procedures by the National Weather Service (NWS), the development and enhancement of an integrated warning system (Doswell, Moller, and Brooks 1999), increased population, increased public awareness, and the proliferation of video cameras have led to improvements in the accuracy and consistency of the tornado report database. Despite inherent limitations of the raw tornado report database (e.g., see Doswell and Burgess 1988; Grazulis 1993; Brooks, Doswell, and Kay 2003), these recent improvements and enhancements in the data allow for detailed examination of the more recent portion of the database to uncover characteristics of tornado path directions. Given the potential importance of tornado path direction to hazard mitigation recommendations, this study seeks to provide a comprehensive geographic study of path direction for tornadoes occurring in the central and eastern United States. We also speculate that the interaction of processes across a multitude of scales, including storm-scale dynamics and synoptic-scale steering winds, are important controls on the distributions described.

Data and Methods

Data regarding U.S. tornadoes are now much more reliable and complete than ever before (Burgess, Donaldson, and Desrochers 1993; Schaefer et al. 1993; Grazulis 2001). Several factors account for the improvement in the tornado report database. These include emphasis on and improvement of warning verification practices by the NWS since the early 1980s (Johns and Evans 2000), increased use and improvement of spotter networks (Doswell, Moller, and Brooks 1999), modernization of the NWS during the early 1990s with improved technologies including deployment of Doppler radar (Friday 1994), and improved communications (e.g., cell phones) and documenting media (e.g., video cameras). Despite improvement in the quality and consistency of the data, there

Figure 1 *Map of the six regions selected for the regional-scale study. Tornadoes that occurred within these six regions were utilized for the national-scale analysis.*

remain a number of limitations and biases in the raw tornado report dataset. These limitations and biases in the tornado and other severe weather datasets have been described elsewhere (e.g., Doswell and Burgess 1988; Grazulis 1993; Brooks, Doswell, and Kay 2003; Schaefer, Weiss, and Levit 2003) and involve such factors as basic errors in reporting or recording of time and location information, spatial and temporal variability in the efforts to collect severe weather reports for warning verification programs, adjustments in the nature of detailed damage surveys, and population changes.

Detailed characteristics of tornadoes in the United States are collected by local NWS offices and, thereafter, published in the National Climatic Data Center (NCDC) publication *Storm Data* and made available on the NCDC storm events Web page[1] or in the *SeverePlot* software package[2] (Hart 1993). For this study, we restricted our analyses to 1980–2002 for two reasons: (1) prior to this period the data become increasingly suspect and incomplete (e.g., see Kelly et al. 1978) and (2) a twenty-three-year period should provide a long enough record to account for any climatological shifts in favorable synoptic patterns for severe weather development (e.g., see the effects of favorable, long-term severe weather pattern shifts on derecho climatologies presented by Bentley and Sparks 2003 and Coniglio and Stensrud 2004).

Because tornadoes are rare west of the Continental Divide, we restricted our analysis to a thirty-seven-state area across the central and eastern United States. In an attempt to examine possible region-specific shifts in the climatology, we divided that area into six regions (Figure 1). The regions were divided primarily along state lines due to the state-by-state reporting strategy utilized by *Storm Data* and because mitigation efforts are often implemented on a state-by-state basis. Subdividing the thirty-sev-

Table 1 *Number of tornadoes during the twenty-three-year period 1980–2002*

F-scale	Total number	Track information incomplete	≥ 1.61 km path length	≥ 1.61 km length with complete track information
F0	11754	10140	2615	349
F1	7017	4474	4195	2452
F2	2438	826	2060	1598
F3	708	77	691	629
F4	158	5	156	153
F5	13	0	13	13
Total	22088	15522	6730	6194

en-state area into regions was a somewhat subjective process and we realize that some differences of opinion may arise as to which states belong in which regions.

To analyze tornado path direction, detailed latitude and longitude coordinate information for the start and end points of each individual tornado is needed. Many tornadoes in the database are either small, short-lived, or lack post-storm survey team analysis and, therefore, include only "touchdown" locations. In fact, more than 70 percent of tornadoes in the study period lacked full track information (Table 1), and in a number of cases where a track length was indicated no tornado end-point information was available. Since 97 percent of the tornadoes with a length of less than 1.61 km (1 mile) had incomplete track data, we restricted our analyses to tornado events greater than or equal to this length. More than 6,000 tornadoes meeting the start and end-point and minimal length criteria were available for analysis (Table 1). Tracks for these tornadoes are plotted in Figure 1, revealing the distribution of events across the nation.

A tornado can indeed change path direction during its life span. Nevertheless, for the purposes of this study, a straight path from start location to end location is assumed. We believe this is a safe assumption because tornadoes characteristically have much smaller "side-to-side" deviation along the track in comparison to the overall length of the along-track vector. Path directions according to path origin (i.e., the direction from which the tornado is traveling) are categorized into sixteen directions (N, NNE, NE, ENE, etc.). Again, these directions refer to the direction from which the tornado is approaching (i.e., WSW means that the tornado is traveling from the west-southwest and moving toward the east-northeast).

Path direction origin is illustrated using a figure similar to a wind-rose diagram, known as a "radar diagram," with the frequency of tornado events plotted according to the sixteen cardinal directions (e.g., Figure 2). The radar diagrams in this study utilize a floating scale of actual frequency numbers, instead of percentages, for the period in question. The actual magnitudes are employed in the diagrams rather than percentages because they illustrate the importance of seasonality and sample size on developing a tornado climatology. Nonetheless, noteworthy percentages are indicated throughout the text.

Results: National Scale

At the national scale, tornadoes travel in paths dominantly from the W, WSW, and SW directions (69.3 percent of tornadoes included in the study) with WSW having the modal frequency (Figure 2). The frequency of tornadoes traveling from the NW (3.2 percent) and WNW (7.0 percent), and from the SSW (8.1 percent) and S (4.5 percent) is notable, but these directions are far less common than the three main directions of W (21.6 percent), WSW (26.2 percent), and SW (21.5 percent). Tornadoes do travel in paths from all nine of the remaining cardinal directions, but far less often. In the thirty-seven-state region, 65.1 percent of all tornadoes move into the northeast quadrant. This percentage is far less than the 87 percent indicated for nationwide tornadoes from 1950–1978 by Schaefer et al. (1980). From 1980–2002, 28.2 percent of tornadoes propagated into the southeast quadrant. Tornadoes moving toward the west were extremely rare during this period, with only 4.0 percent of events moving into the northwest quadrant and 2.7 percent of tornadoes moving into the southwest quadrant.

The dominant easterly and northeasterly motion of tornadoes described in our twenty-three-year climatology is likely due to several factors, including the predominance of the midlatitude westerlies across the study region, tornado-producing storm typology, and the tendency for tornado outbreaks in the eastern two-thirds of the United States to occur in areas of southwesterly flow at 500 hPa with a long wave trough to the west of the outbreak area (Beebe 1956; Miller 1972; Galway and Pearson 1981).

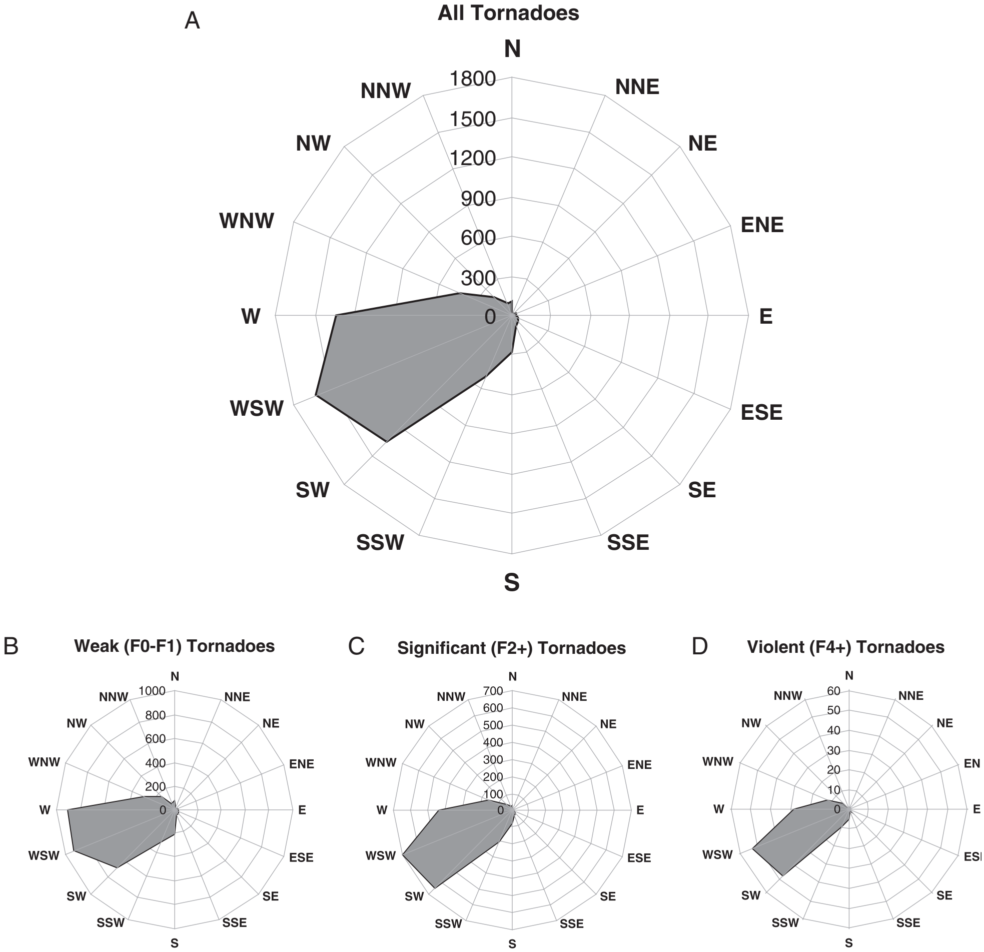

Figure 2 *Radar diagrams illustrating the frequency of tornado path direction origin for (A) all, (B) weak, (C) significant, and (D) violent tornadoes.*

The motion of tornadoes is undoubtedly affected by the parent convective storms that spawn them. In turn, the parent convective storms are steered by the prevailing winds in which they are embedded (Fujita 1987). Notis and Stanford (1973) discovered that Iowa tornado directions of propagation were closely tied to 500-hPa flow. The mean 500-hPa flow for the 1,927 days during which tornadoes occurred in our dataset was predominantly westerly to southwesterly across the United States except for a small portion of the north-central region (Figure 3A). Most storm systems producing tornadoes would have propagated to the east or northeast assuming that the 500-hPa level is a good indicator for steering-level flow.

In addition, it is important to understand the factors that determine cellular and, in particular, supercellular convective propagations since most tornadoes are produced by these convective typologies (Moller et al. 1994; Tessendorf and Trapp 2000). Weisman and Klemp (1986) determined that supercell motion is primarily due to the advection of the storm by the mean wind and the internal storm dynamics that form when convective updrafts develop in a vertically sheared environment (e.g., see Bunkers et al. 2000). In many cases, supercells, including

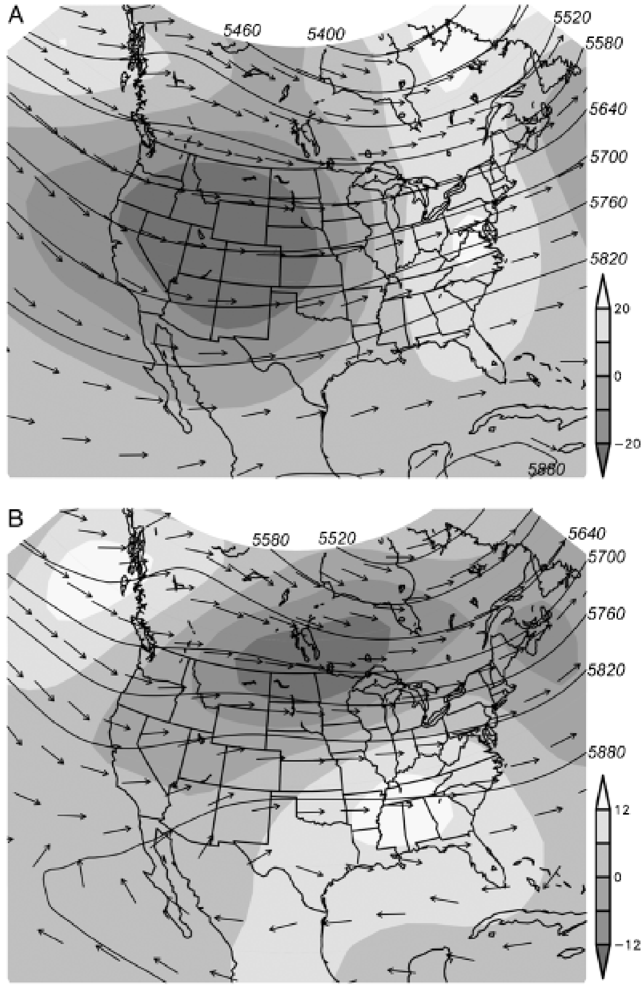

Figure 3 *Mean 500-hPa heights, winds, and anomalies for days in which a tornado occurred (A) during the entire twenty-three-year period of study, and (B) during the summer months of June, July, and August over the twenty-three-year period.*

those producing tornadoes, have been observed moving slower and at 20°, 30°, or greater to the right of the mean wind—so called, right-turning supercells (Maddox 1976). In fact, the deviant motion (in terms of mean flow) of supercells is a distinct characteristic of this storm type and specific techniques for calculating supercell motion have been developed (e.g., see Bunkers et al. 2000). We hypothesize that the unique motion of right-turning supercells likely accounts for some shift in the path climatology to a more westerly direction. Additionally, there are likely a number of noncellular tornadoes in our dataset. Tessendorf and Trapp (2000) illustrated that quasi-linear convective systems and hurricane rain bands may account for nearly 24 percent of all tornadoes in the contiguous United States. It is likely that tornadoes spawned by hurricanes may account for some of the more unusual directions identified in our study.

Finally, eighty-one tornado outbreaks[3] occurred during the study period—an outbreak being defined as a day with at least five F2 + tornadoes and a Destruction Potential Index (Thompson and Vescio 1998) of 50 or greater. All but ten of these tornado outbreaks (i.e., 86 percent) occurred within 500-hPa flow that contained a southwesterly component across the outbreak region. Nearly 81 percent of all tornadoes in the dataset that occurred during tornado outbreak days propagated from the southwesterly quadrant, indicating that tornado directions of motion do appear to be closely tied to midtropospheric flow, as suggested by Notis and Stanford (1973).

Comparing "weak" (F0–F1) tornadoes with significant (F2 +) and extreme (F4 +) events illustrates that weak tornadoes have a greater concentration of W path direction than more severe tornadoes (Figures 2B–2D). Significant and extreme tornadoes are tightly clustered, with most of these events traveling from the WSW or SW. Nevertheless, there are several examples of strong tornadoes that have propagated in directions different from these typical path directions. For example, the F5 Jarrell, Texas, tornado that occurred on 27 May 1997 propagated from the northeast toward the southwest.

To illustrate variations through the year, tornado path direction origin is plotted in radar diagrams for monthly pairs (Figure 4). The diagrams are designed to illustrate dominant direction rather than total frequency, therefore the frequency scale varies: the March–April and May–June monthly pairs have greater total frequency of tornadoes, the January–February and September–October pairs have the least frequency. For January–February, tornado paths are dominantly from the SW (31.8 percent), followed by WSW (29.5 percent) and, to a lesser extent, W (17.9 percent) directions. By March–April, there is a slight shift to a greater westerly component, with WSW and W accounting for 31.0 percent and 21.0 percent of all tornado paths, respectively. As spring progresses toward summer, a shift in dominant origin direction to W is evident in the May–June diagram with W and SW path origins accounting for 25 percent each. For the summer months of July–August, tornado paths are primarily from the northwestern quadrant rather than from the southwestern quadrant. During July–August, the modal frequency is W (26.0 percent), however WNW (15.7 percent) and NW (7.8 percent) frequencies remain relatively high. By fall, tornado path origins shift back to the southwestern quadrant. For September–October, WSW (21.2 percent) and SW (20.5 percent) are modal, with a wide swath of directions being evident including WNW (5.3 percent) and W (17.4 percent), through SSW (11.5 percent) and S (10.6 percent). For November–December, tornado path direction origins return to a narrower range, similar to the January–February case, with SW (35.2 percent) and WSW (29.2 percent) dominant, followed by SSW (13.2 percent) and W (11.8 percent).

The bimonthly and monthly (not shown) analyses illustrate subtle, yet distinct, seasonal shifts in the tornado path climatology. Tornado paths propagate from a primarily southwesterly direction during January, February, and March, then from a predominantly westerly direction for the next six months (April–September), before returning to again propagating from the southwesterly direction toward the end of the annual cycle. Previous research has suggested that the seasonal shifts in tornado occurrence are strongly linked to upper-air synoptic-scale meteorological patterns (Notis and Stanford 1973; Bluestein and Golden 1993; Davis, Stanmeyer, and Jones 1997; Monfredo 1999; Brown 2002). As previously illustrated, Notis and Stanford (1973) noted seasonal shifts in Iowa tornadoes and suggested that direction of tornado movement is intimately related to the 500-hPa flow. Indeed, mean 500-hPa charts for the tornado days in the bimonthly cases (not shown) indicate a distinct association between the 500-hPa flow across the study domain and the highest frequency path directions. For example, during June, July, and August, tornadoes from the N, NNW, NW, and WNW account for 25.3 percent of all events during this period, but during the remainder of the year only 8.8 percent of tornadoes propagate from these directions. These warm-weather months are the only period where the mean tornado day 500-hPa analysis is from the west-to-northwest across the majority of the study area (Figure 3B). Johns (1982) discovered that during the summer months a large number of severe weather outbreaks, including those producing tornadoes, occur with west-northwest and northwest flow in the midtroposphere. Hence, the climatological maximum in northwest-flow severe weather outbreaks during the summertime (c.f., Figure 3 in Johns 1982) is likely responsible for the distinct shift toward more easterly and southeasterly moving tornadoes during this warm-weather period.

Results: Regional Scale

The national-scale results illustrate that there are potentially important seasonal dynamics involved with the analysis of tornado path direction. Tornado season varies considerably by

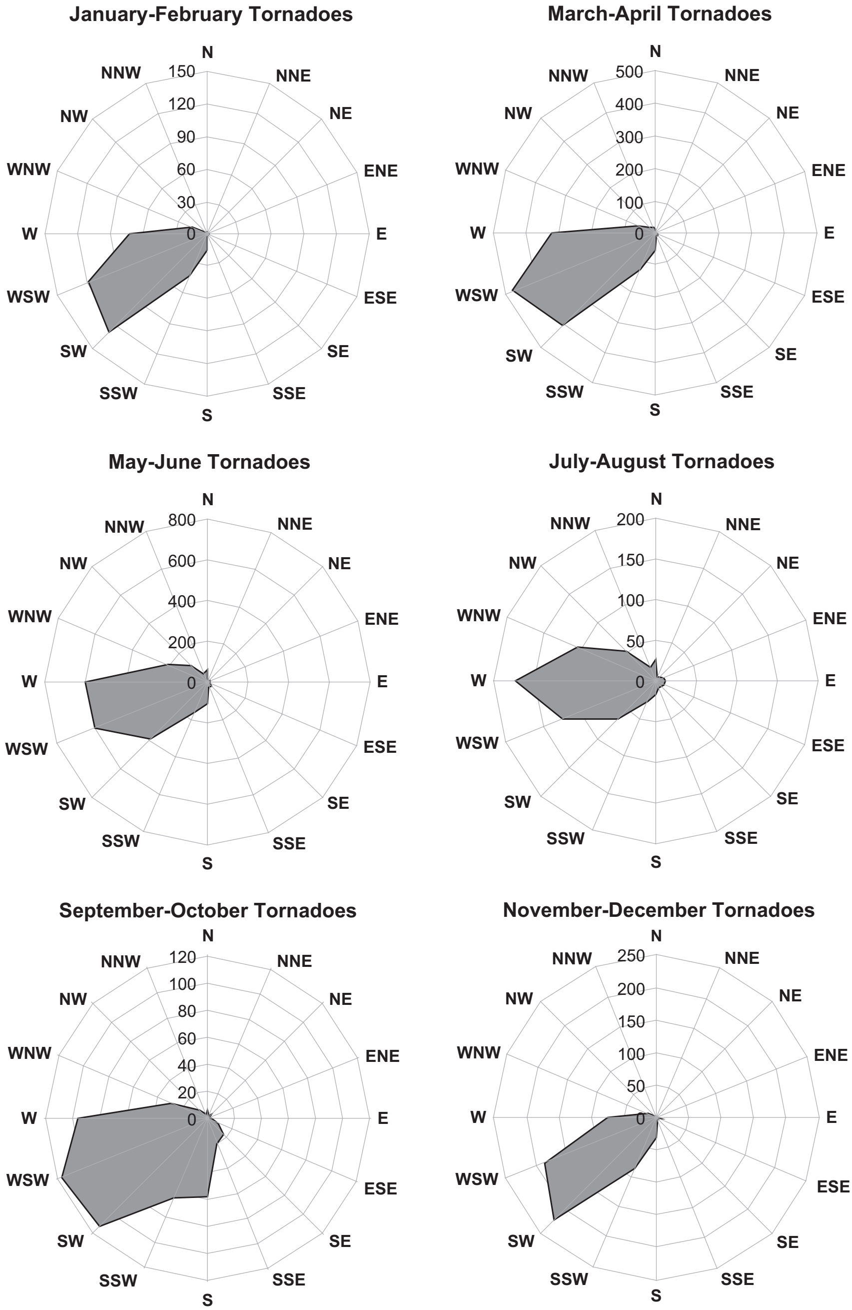

Figure 4 *Radar diagrams illustrating the frequency of tornado path direction origin for monthly pairs.*

location (region) within the country, governed by changes in synoptic-scale meteorological controls (Bluestein and Golden 1993; Davis, Stanmeyer, and Jones 1997; Monfredo 1999; Brown 2002). Therefore, we repeated the analysis of tornado path direction for six similar-

Table 2 *Number of tornadoes, by region, during the twenty-three-year period 1980–2002 with path length ≥ 1.61 km and complete track information*

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
South Central	126	52	177	298	465	154	14	20	44	119	119	100	1688
Southeast	80	110	230	223	154	95	27	37	65	56	235	64	1376
Central	7	11	87	325	460	375	122	44	38	76	32	22	1599
Ohio V/Mid Atlantic	11	4	52	78	126	162	91	40	38	37	46	1	686
Northeast	1	1	3	11	41	65	69	22	16	5	12	0	246
North Central	0	0	14	34	100	210	131	52	32	21	5	0	599
Total	225	178	563	969	1364	1061	454	215	233	314	499	187	6194

sized regions (Figure 1). The total number of tornadoes and the monthly frequency for each of these regions are presented in Table 2.

Tornado season peaks in March, April, and May for the southernmost regions (South Central, Southeast), nevertheless many tornadoes are still evident during January and February. Tornadoes also are experienced throughout the fall in both of these regions, with November in fact being the overall peak month for tornado occurrence in the Southeast. Very few tornadoes occur in either region during the summer months of July and August.

In contrast, the northernmost regions (North Central, Ohio Valley–Mid Atlantic, Northeast) experience few tornadoes during the winter (December, January, February). Tornado season peaks during spring and summer (May, June, July for the North Central region; April through July for the Ohio Valley–Mid Atlantic region; May through July for the Northeast). An April, May, June peak is evident for the Central region, but summer and fall tornadoes are also experienced. Similar to the northernmost regions, the Central region has few winter tornadoes.

In the following sections, diagrams for each of the six regions illustrate the seasonal distribution of tornadoes, and radar diagrams plot tornado path direction for monthly pairs.

South Central Region

Spring is the peak tornado season in the South Central region (Figure 5, top left). For March–April, tornado paths are dominantly from the W, WSW, and SW directions (Figure 5), which is quite similar to the national scale for these months illustrated previously in Figure 4. Other monthly pairs illustrated in Figure 5 do not vary much from the March–April case. However, the path origin directions for September–October indicate a wide distribution among directions in the southwest quadrant. This relatively broad distribution could be an artifact of the weak tropospheric flow that occurs across this region before the strong westerlies return during the winter season. Supercell motion, when the mean wind is relatively weak, has been observed to deviate by greater than 30° to the right of the mean wind (Davies 1998; Bunkers et al. 2000), and that deviant motion might explain this unique distribution. Moreover, tornadoes generated by tropical storms or hurricanes could account for the increase in tornadoes with a southerly component during this period. Path direction origins are from a narrower range for the other monthly pairs, especially November–December. Because summer tornadoes are rare, no radar diagram is presented for July–August. The rarity of tornadic events during this period is likely caused by an increasingly capped environment in this region (Farrell and Carlson 1989), a decrease in the thermodynamic instability of the atmosphere (Johns 1982), and a general weakening of the midtropospheric westerlies leading to an overall decrease in the deep-layer shear needed to facilitate the growth of tornado-producing convection (Johns 1982).

Southeast Region

For the Southeast region, March–April is again the bimonthly period with the greatest number of tornadoes (Figure 6, top left). To an even greater extent than in the South Central region, March–April tornado paths in the Southeast are dominantly from the W, WSW, and SW directions (Figure 6). This pattern is also prevalent for the late fall and winter months of November–December and January–February.

Fewer tornadoes occur during the summer, and tornado paths are somewhat more variable for May–June (with a W dominance) and September–October (with greater variation from WNW through to SSE and SE). Some of the

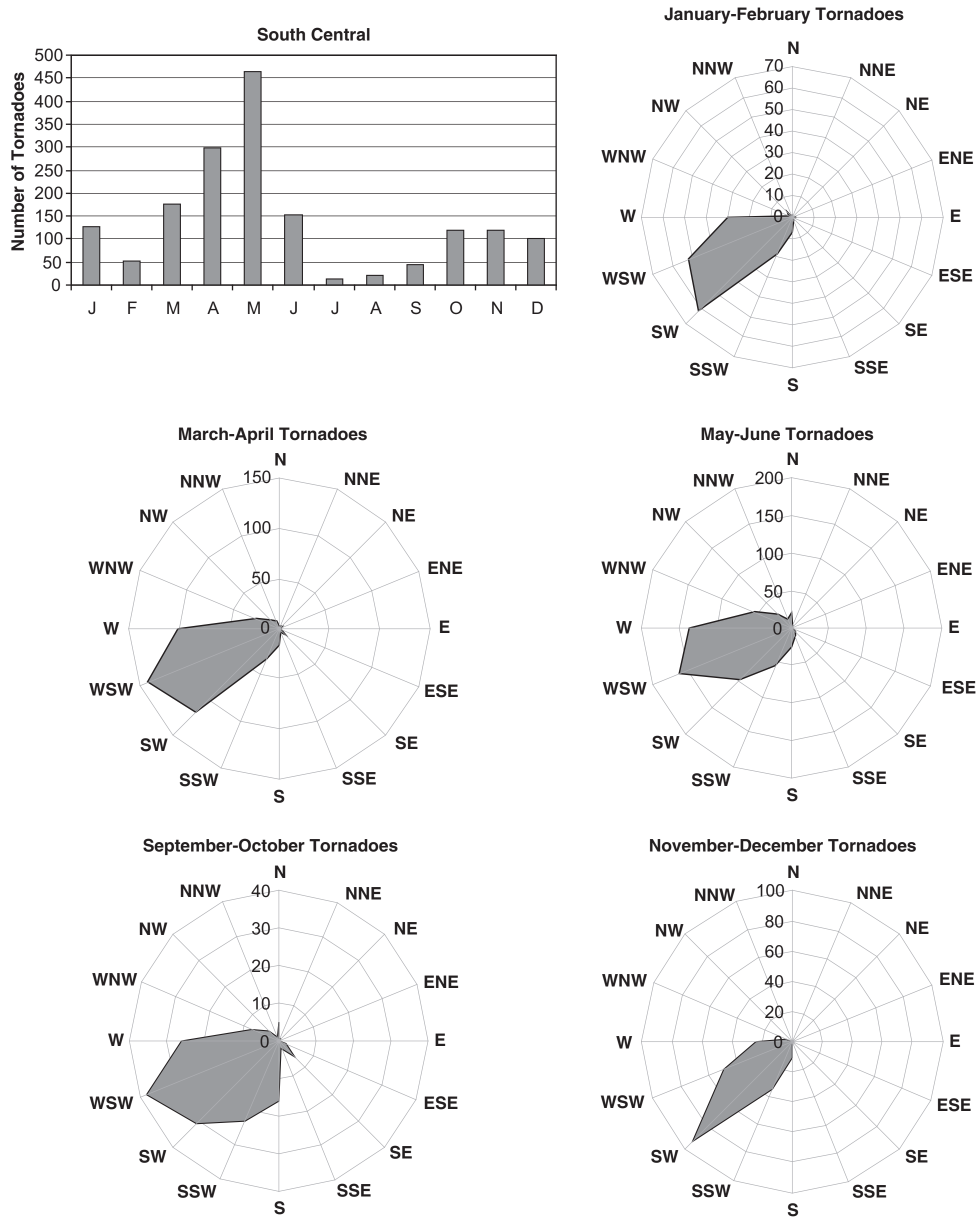

Figure 5 *Seasonal distribution of tornadoes (top left) and radar diagrams illustrating the frequency of tornado path direction origin for monthly pairs, for the South Central region.*

latter events were associated with tropical system-generated tornadoes rather than being the more common supercell-generated tornadoes. In addition, the relatively wide variation in path directions during the late warm season in the Southeast may be attributable to waterspouts coming onshore or from tornadoes forming in low-shear environments on convergence lines associated with sea breezes (Brooks, Doswell, and Kay 2003). Again, no radar diagram is presented for July–August given the rarity of summer tornadoes in this region.

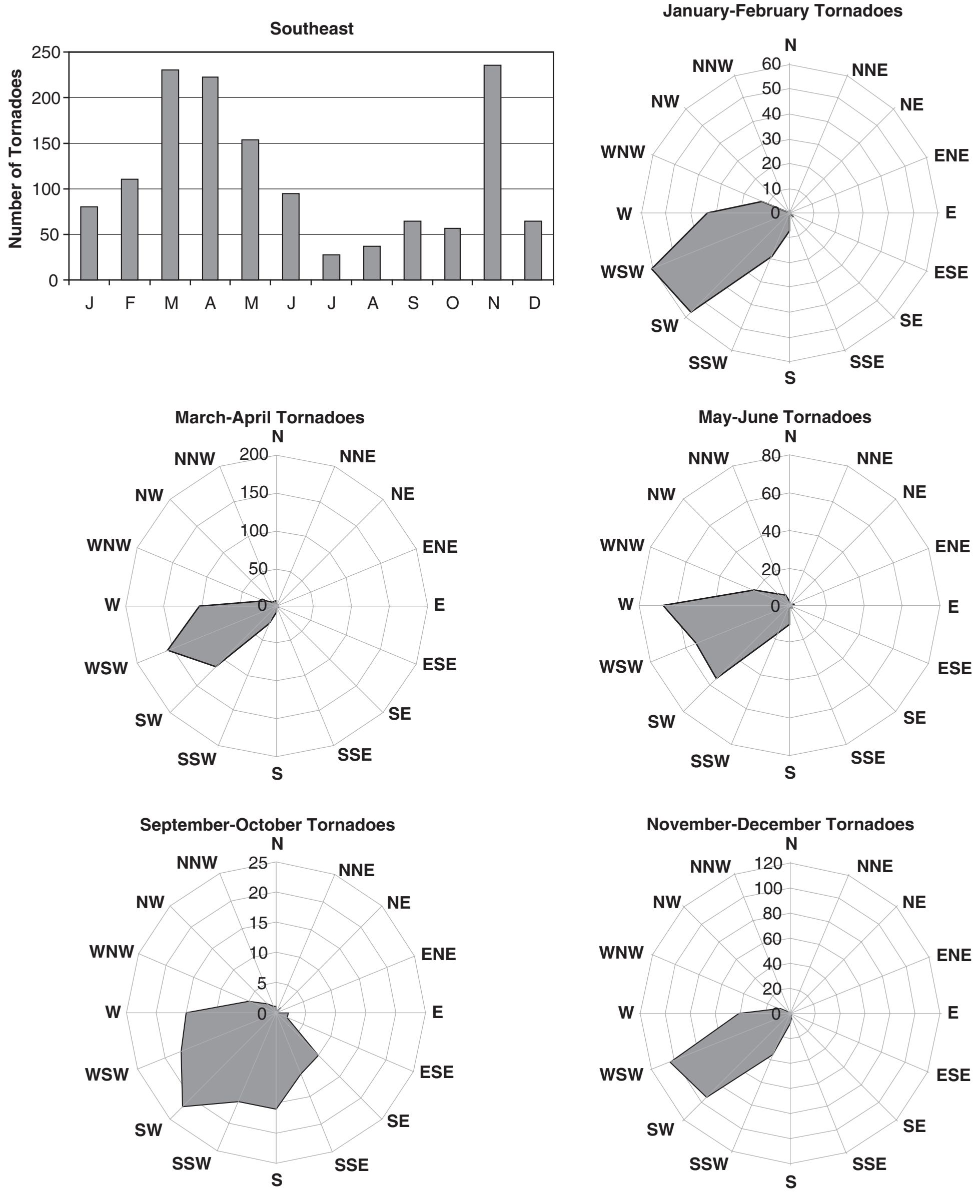

Figure 6 *Seasonal distribution of tornadoes (top left) and radar diagrams illustrating the frequency of tornado path direction origin for monthly pairs, for the Southeast region.*

Central Region

The peak months for tornado events in the Central Region are April, May, and June (Figure 7, top left). Tornado paths for March–April are again dominantly from the southwestern quadrant including W, WSW, and SW directions, but also with a significant number from the SSW and some from the S (Figure 7). For the smaller number of tornadoes occurring in the preceding winter months (not shown), tornado paths are from a very narrow range of directions dominated by SW.

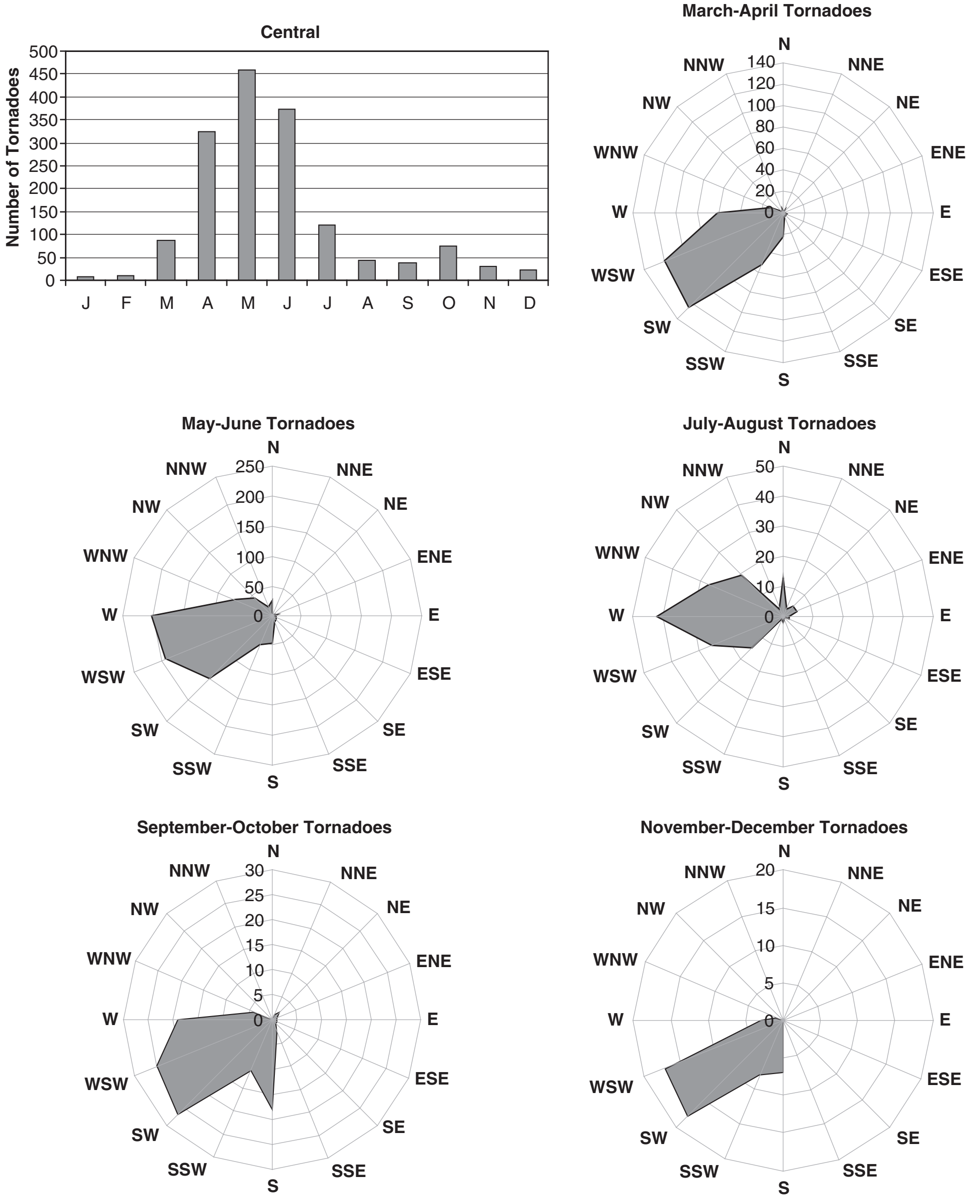

Figure 7 *Seasonal distribution of tornadoes (top left) and radar diagrams illustrating the frequency of tornado path direction origin for monthly pairs, for the Central region.*

The May–June monthly pair experiences the most tornadoes for this region. The modal path direction is from the W, with a notable number of events occurring in a wider swath from the NW and WNW, and from the WSW, SW, SSW through to S directions. For this region, July–August summer tornadoes are more numerous than in the South Central and Southeast regions, although still much smaller in number than the March–April and May–June time periods. Path direction origins are notably different during the summer months of July and

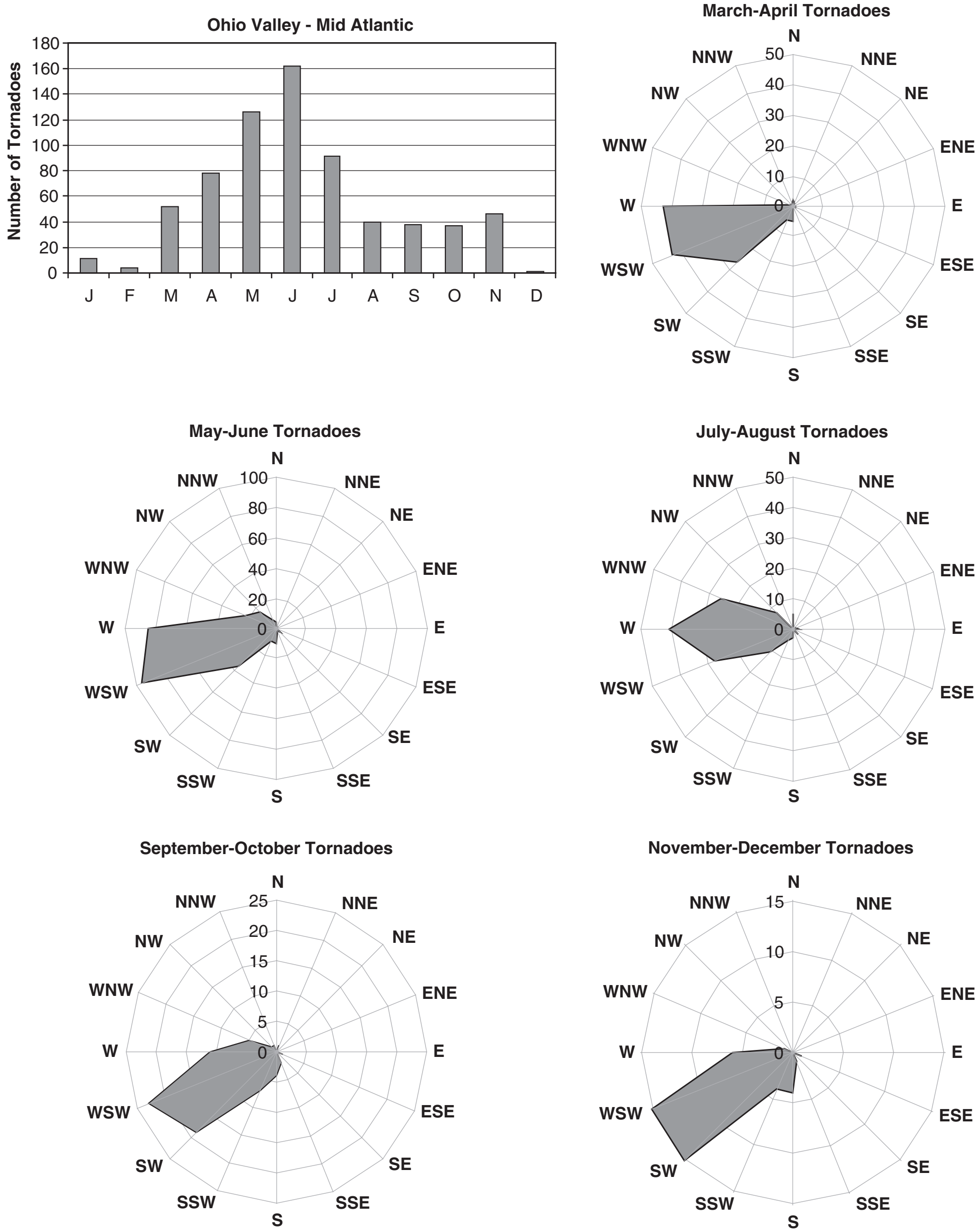

Figure 8 *Seasonal distribution of tornadoes (top left) and radar diagrams illustrating the frequency of tornado path direction origin for monthly pairs, for the Ohio Valley–Mid Atlantic region.*

August with W, NW, and even a N spike in the number of events. The unique shift to more westerly and northwesterly path origins during these summer months is likely due to the climatological maximum in northwest flow outbreaks across the region during this period (see, e.g., Figures 4, 7, and 8 in Johns 1982). By fall, there is a dramatic shift back to tornado paths from the WSW through S directions. Similarly, the mean midtropospheric flow during this time

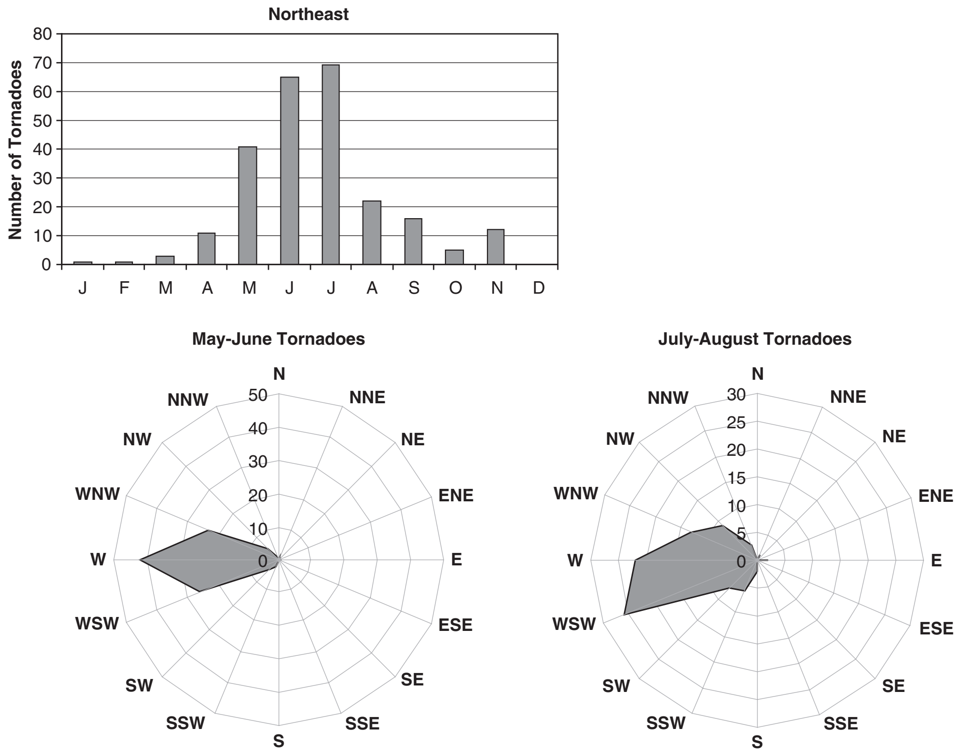

Figure 9 *Seasonal distribution of tornadoes (top left) and radar diagrams illustrating the frequency of tornado path direction origin for monthly pairs, for the Northeast region.*

period for tornado days in the dataset shifts back predominantly from the southwest, indicating that this shift in the path direction climatology is governed primarily by the upper-level steering flow. Finally, although November–December tornadoes are rare, they primarily have path origins from the WSW and SW in this region.

Ohio Valley–Mid Atlantic Region

Tornado events for the Ohio Valley–Mid Atlantic region are most numerous during the spring and early summer months of April, May, June, and July (Figure 8, top left). Notable numbers of tornadoes also are evident for the months of August through November, but winter tornadoes are rare.

Path direction origins illustrated in the radar diagram sequence indicate a gradual shift from the March–April case dominated by the W and WSW directions to more westerly to northwesterly origin directions in July and August (Figure 8). Similar to the Central region, the increase in W and WNW directions during July and August is likely the result of an increase in northwest flow severe weather outbreaks that tend to occur across the region during these two months (e.g., see Figures 7 and 8 in Johns 1982). By fall, path directions shift back to the southwestern quadrant for both the September–October and November–December radar diagrams (the latter diagram really represents November since there is only one December event). Tornadoes are also quite rare during the winter months of January and February.

Northeast Region

Illustrative of the climatological return of low-level moisture and low static stability to the Northeast during late spring and summer, tornado events for this region are most numerous during the months of May, June, and July (Figure 9, top left). Throughout May and June in the Northeast, tornado paths originate from primarily the W. During July and August, the tornado path direction shifts, with the modal origin becoming WSW. Nevertheless, a large number of Northeast tornadoes arrive from the northwest quadrant of motion during the summer. Tornadoes during the remainder of the year in this region are rare.

North Central Region

Tornadoes are very rare during the winter half of the year for the North Central region (Figure 10, top left). Only two monthly pairs (May–June, July–August) have a sizeable number of torna-

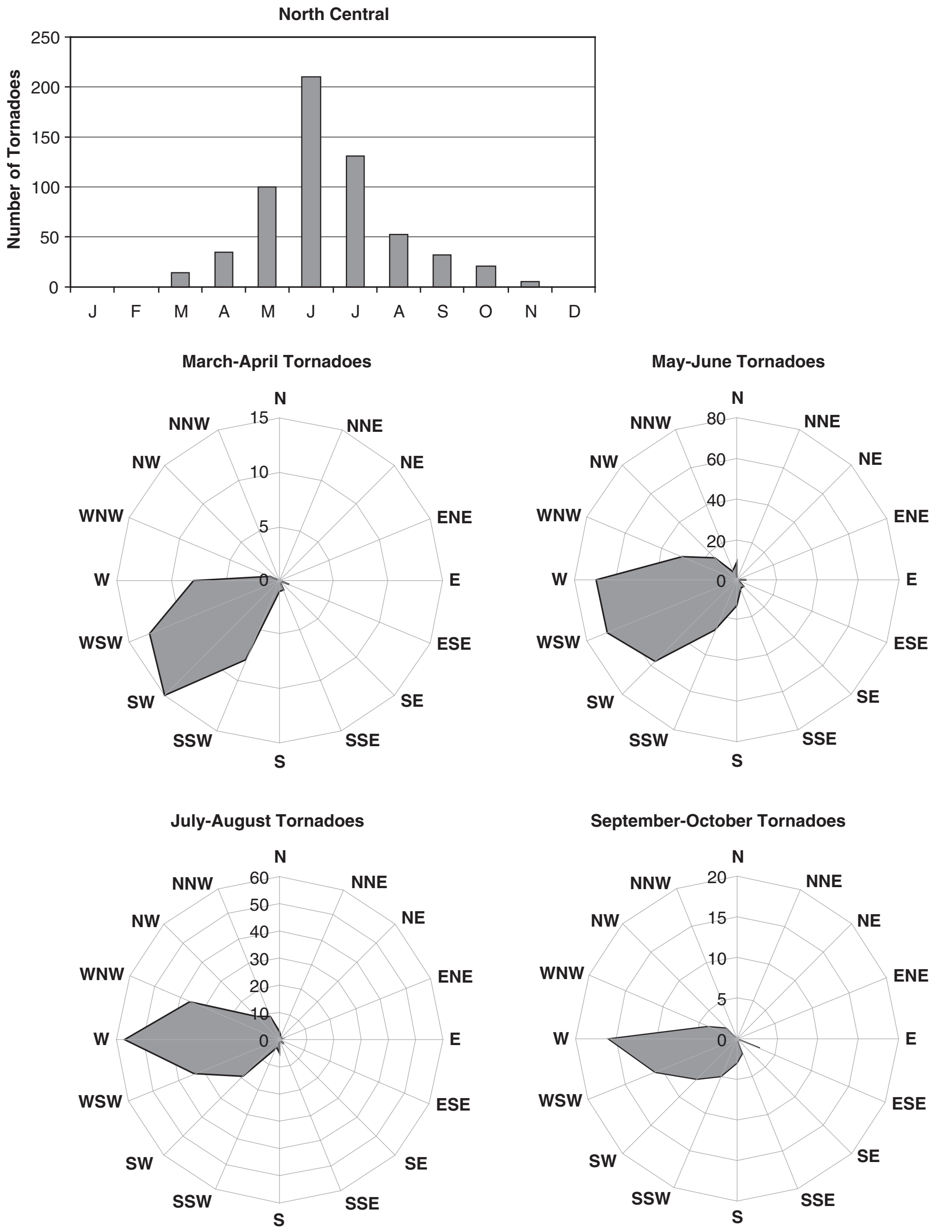

Figure 10 *Seasonal distribution of tornadoes (top left) and radar diagrams illustrating the frequency of tornado path direction origin for monthly pairs, for the North Central region.*

does. Nevertheless, four radar diagrams are presented in order to illustrate changes in tornado path direction for this region (Figure 10).

The small numbers of events that occur during March–April have paths from the SSW, SW, WSW, and, to a lesser extent, W. For May–June, when there are far more tornadoes, origins shift a bit and are primarily from the W and WSW. This shift to a more westerly and northwesterly direction continues through July and August, where W and WNW are the predominant path origin directions. The modal travel direction for these summer events is from the WNW, with paths ranging from the NNW and NW through to W, WSW, SW, and SSW. Unique to this region, the primary path origin for the six-month period May–October is from the W. The predominance of westerly midtropospheric flow (Figure 3) and the influence of northwesterly flow severe weather outbreaks are the probable reasons for this unique distribution.

Conclusions

Although forecasters and atmospheric scientists are aware of the generalization that tornadoes typically propagate from the southwest quadrant, no study has comprehensively examined the characteristics of U.S. tornado path directions. Such research has important implications for hazard mitigation and engineering studies. For example, knowledge about tornado path direction can be useful when deciphering the safest location within a structure.

Results from this study illustrate that the common perception that most U.S. tornadoes travel from the southwest quadrant of directions is generally valid. For the thirty-seven-state region, tornadoes moving from the west-southwest toward the east-northeast were the most frequent, with tornadoes traveling from the southwest and west directions also having high frequencies. Even on this national scale, subtle seasonal shifts in tornado path direction are evident. In late spring (May–June), west and west-southwest are the modal origin directions for tornado paths. By the summer months (July–August), when tornadoes are far less common nationally, path directions are dominantly from the west, west-northwest, and northwest directions. The climatological maximum in northwest flow severe weather outbreaks (Johns 1982) and a shift in the mean tornado day tropospheric flow to the west-to-northwest across the study area during summer may be the primary contributing factors leading to this observed shift in tornado path directions.

Regionally, important variations occur in tornado path direction origins. In the North Central and Northeast regions, most tornadoes occur in late spring (May–June) and summer (July–August). Tornadoes during these monthly pairs travel dominantly from the west and west-southwest during May and June, and primarily from the northwest quadrant of directions during July and August. Additionally, although tornado path direction is most commonly from the southwestern quadrant for both the Central and Ohio Valley–Mid Atlantic regions, variations do occur. The months of April, May, and June represent peak tornado season for these regions. By May–June, the modal direction for tornado path origin is west or west-southwest, similar to the case for the North Central and Northeast regions. Although summer tornadoes are far less frequent in the Central and Ohio Valley–Mid Atlantic regions, path directions are dominantly from the west and the northwest quadrant of directions when they do occur. For the remaining seasons in these regions, the commonly perceived southwest quadrant of directions dominates.

For the southernmost regions (South Central and Southeast), spring and winter tornadoes dominate. Summer tornadoes are very rare. Tornado path direction, as expected, is predominantly from the southwest quadrant; therefore the common perception that tornadoes travel from the southwest quadrant of directions is most valid for these southern regions.

Seasonal shifts in tornado occurrence are strongly linked to upper tropospheric synoptic-scale meteorological patterns (Bluestein and Golden 1993; Davis, Stanmeyer, and Jones 1997; Monfredo 1999; Brown 2002). Notis and Stanford (1973) demonstrated that tornado path direction is closely linked to the 500-hPa level flow pattern. The results from our study support Notis and Stanford's conclusions and illustrate further that the midtropospheric flow is the primary control on the overall tornado direction climatology. In addition, more than 23 percent of tornadoes in the dataset were associated with one of eighty-one tornado outbreaks. In a large majority of these outbreaks, the steering-level flow was from the southwest.

In fact, 90 percent of all tornadoes that occurred during these outbreaks propagated from the SSW, SW, WSW, or W, indicating that the midlevel tropospheric flow is a controlling factor in tornado path direction in these scenarios. Finally, right-turning supercells and their associated tornadoes in the climatology are speculated to have contributed to a greater easterly propagation of direction of motion. However, until a climatology of supercells and their various typologies is developed, such hypotheses will remain unsupported.

Additional study, incorporating synoptic climatological methods, could be useful in identifying the progression of atmospheric features that lead to the character and seasonality identified in the climatological distributions shown in this research. Such research would be useful in confirming the potential consistency of tornado path direction in summer versus other times of the year.

This study concludes that the common perception that tornadoes travel from the southwest quadrant of directions (especially SW, WSW, and W) is generally valid for the southern United States, and also valid for other parts of the country especially during spring, fall, and winter. However, by late spring, a more westerly component often dominates tornado path direction origin. Where summer tornadoes occur in significant numbers, a westerly to northwesterly directional origin is most prevalent. Since most tornadoes in the North Central region occur during late spring and summer, tornadoes in this area often travel from the northwest quadrant of directions (including west). It is essential that these seasonal and regional variations in tornado path directions be incorporated into future engineering and hazard studies to further improve tornado mitigation efforts. ■

Notes

[1] Available online at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms.

[2] *SeverePlot v2* is freely available online at http://www.spc.noaa.gov/software/svrplot2/.

[3] These tornado outbreak days have been identified by John Hart of the NWS's Storm Prediction Center. The list is available online at http://www.crh.noaa.gov/mkx/climate/torout.htm.

Literature Cited

American Meteorological Society (AMS). 2000. Policy statement: Tornado preparedness and safety. *Bulletin of the American Meteorological Society* 81:1061–65.

Beebe, R. G. 1956. Tornado composite charts. *Monthly Weather Review* 84:127–42.

Bentley, M. L., and J. A. Sparks. 2003. A 15 yr climatology of derecho-producing mesoscale convective systems over the central and eastern United States. *Climate Research* 24:129–39.

Bluestein, H. B., and J. H. Golden. 1993. A review of tornado observations. In *The tornado: Its structure, dynamics, prediction, and hazards*, ed. C. Church, D. Burgess, C. Doswell, and R. Davies-Jones, 319–52. Geophysical Monograph 79. Washington, DC: American Geophysical Union.

Boruff, B. J., J. A. Easoz, S. D. Jones, H. R. Landry, J. D. Mitchem, and S. L. Cutter. 2003. Tornado hazards in the United States. *Climate Research* 24:103–17.

Brooks, H. E. 2004. On the relationship of tornado path length and width to intensity. *Weather and Forecasting* 19:310–19.

Brooks, H. E., C. A. Doswell, and M. P. Kay. 2003. Climatological estimates of local daily tornado probability for the United States. *Weather and Forecasting* 18:626–40.

Brown, M. E. 2002. The spatial, temporal, and thermodynamic characteristics of southern-Atlantic United States tornado events. *Physical Geography* 23:401–17.

Bunkers, M. J., B. A. Klimowski, J. W. Zeitler, R. L. Thompson, and M. L. Weismanm. 2000. Predicting supercell motion using a new hodograph technique. *Weather and Forecasting* 15:61–79.

Burgess, D. W., R. J. Donaldson Jr., and P. R. Desrochers. 1993. Tornado detection and warning by radar. In *The tornado: Its structure, dynamics, prediction, and hazards*, ed. C. Church, D. Burgess, C. Doswell, and R. Davies-Jones, 203–21. Geophysical Monograph 79. Washington, DC: American Geophysical Union.

Coniglio, M. C., and D. J. Stensrud. 2004. Interpreting the climatology of derechos. *Weather and Forecasting* 19:595–605.

Davies, J. M. 1998. On supercell motion in weaker wind environments. *Preprints, 19th Conference on Severe Local Storms*, 685–88. Minneapolis, MN: American Meteorological Society.

Davis, R. E., T. M. Stanmeyer, and G. V. Jones. 1997. A synoptic climatology of tornadoes in Virginia. *Physical Geography* 18:383–407.

Doswell, C. A., III, and D. W. Burgess. 1988. On some issues of United States tornado climatology. *Monthly Weather Review* 116:495–501.

Doswell, C. A. III, A. R. Moller, and H. E. Brooks. 1999. Storm spotting and public awareness since the first tornado forecasts of 1948. *Weather and Forecasting* 14:544–57.

Eagleman, J. R. 1967. Tornado damage pattern in Topeka, Kansas, June 8, 1966. *Monthly Weather Review* 95:370–74.

———. 1990. *Severe and unusual weather*, 2nd ed. Lenexa, KS: Trimedia Publishing.

Eagleman, J. R., V. U. Muirhead, and N. Williams. 1975. *Thunderstorms, tornadoes, and building damage*. Lexington, MA: D. C. Heath.

Farrell, R. J., and T. N. Carlson. 1989. Evidence for the role of the lid and underunning in an outbreak of tornadic thunderstorms. *Monthly Weather Review* 117:857–71.

FEMA (Federal Emegency Management Association). 2004. Surviving the storm, tornadoes. Available online at: http://www.fema.gov/pdf/hazards/survtorn.pdf (last accessed 13 October 2005).

Finley, J. P. 1887. Tornadoes. New York: The Insurance Monitor. Available online at: http://hsci.cas.ou.edu/exhibits/exhibit.php?exbid=30&exbpg (last accessed 13 October 2005).

Flora, S. D. 1954. *Tornadoes of the United States*. Norman: University of Oklahoma Press.

Friday, E. W. 1994. The modernization and associated restructuring of the National Weather Service: An overview. *Bulletin of the American Meteorological Society* 75:43–52.

Fujita, T. T. 1987. *U.S. tornadoes Part 1 70-year statistics*. Satellite and Mesometeorology Research Project (SMRP) Research Paper No. 218, University of Chicago, 122 pp.

Galway, J. G., and A. Pearson. 1981. Winter tornado outbreaks. *Monthly Weather Review* 109:1072–80.

Grazulis, T. P. 1993. *Significant tornadoes 1680–1991*. St. Johnsbury, VT: Environmental Films.

———. 2001. *The tornado: Nature's ultimate windstorm*. Norman: University of Oklahoma Press.

Grazulis, T. P., J. T. Schaefer, and R. F. Abbey Jr. 1993. Advances in tornado climatology, hazards, and risk assessment since tornado symposium II. In *The tornado: Its structure, dynamics, prediction, and hazards*, ed. C. Church, D. Burgess, C. Doswell, and R. Davies-Jones, 408–26. Geophysical Monograph 79. Washington, DC: American Geophysical Union.

Hart, J. 1993. SVRPLOT: A new method of accessing and manipulating the NSSFC severe weather database. *Preprints, 17th Conference on Severe Local Storms*, 40–41. St. Louis: American Meteorological Society.

Johns, R. H. 1982. A synoptic climatology of northwest flow severe weather outbreaks. Part I: Nature and significance. *Monthly Weather Review* 112: 449–64.

Johns, R. H., and J. S. Evans. 2000. Comments on "A climatology of derecho-producing mesoscale convective systems in the central and eastern United States, 1986–95. Part I: Temporal and spatial distribution." *Bulletin of the American Meteorological Society* 81:1049–54.

Kelly, D. L., J. T. Schaefer, R. P. McNulty, C. A. Doswell III, and R. F. Abbey Jr. 1978. An augmented tornado climatology. *Monthly Weather Review* 106:1172–83.

Maddox, R. A. 1976. An evaluation of tornado proximity wind and stability data. *Monthly Weather Review* 104:133–42.

Miller, R. C. 1972. *Notes on the analysis and severe-storm forecasting procedures of the Air Force Global Weather Central*. Air Weather Service Tech. Rept. 200 (Rev.), Air Weather Service, Scott Air Force Base, IL, 190 pp.

Moller, A. R., C. A. Doswell III, M. P. Foster, and G. R. Woodall. 1994. The operational recognition of supercell thunderstorm environments and storm structures. *Weather and Forecasting* 9:327–47.

Monfredo, W. 1999. Relationships between phases of the El Nino–southern oscillation and character of the tornado season in the south-central United States. *Physical Geography* 20:413–21.

Notis, C., and J. L. Stanford. 1973. The contrasting synoptic and physical character of northeast and southeast advancing tornadoes in Iowa. *Journal of Applied Meteorology* 12:1163–73.

NWS (National Weather Service). 2004. *Thunderstorm, tornadoes, lightning: A preparedness guide*. Available online at: http://www.nws.noaa.gov/om/brochures/ttl.pdf (last accessed 13 October 2005).

Schaefer, J. T., D. L. Kelly, and R. F. Abbey. 1986. A minimum assumption tornado-hazard probability model. *Journal of Climate and Applied Meteorology* 25:1934–45.

Schaefer, J. T., D. L. Kelly, C. A. Doswell III, J. G. Galway, R. J. Williams, R. P. McNulty, L. R. Lemon, and B. D. Lambert. 1980. Tornadoes. When, where, how often: A study of 29 years of tornado data. *Weatherwise* 33:52–9.

Schaefer, J. T., R. L. Livingston, F. P. Ostby, and P. W. Leftwich. 1993. The stability of climatological tornado data. In *The tornado: Its structure, dynamics, prediction, and hazards*, ed. C. Church, D. Burgess, C. Doswell, and R. Davies-Jones, 459–66. Geophysical Monograph 79. Washington, DC: American Geophysical Union.

Schaefer, J. T., S. J. Weiss, and J. J. Levit. 2003. The frequency of severe thunderstorm winds over the contiguous United States. *11th International Conference On Wind Engineering*, Lubbock, TX, 8 pp.

Tessendorf, S. A., and R. J. Trapp. 2000. On the climatological distribution of tornadoes within quasi-linear convective systems. *Preprints, 20th Conference on Severe Local Storms*, Orlando, FL, American Meteorological Society, 134–73.

Thompson, R. L., and M. D. Vescio. 1998. The Destruction Potential Index—A method for comparing tornado days. *Preprints, 19th Conference on Severe Local Storms*, Minneapolis, MN. American Meteorological Society, 280–82.

Tornado Project Online. 1999. *Safety.* Available online at: http://www.tornadoproject.com/safety/safety.htm (last accessed 13 October 2005).

U.S. Department of Commerce. 1953. *Tornado occurrences in the United States*. Technical paper no. 20. Washington, DC: U.S. Government Printing Office.

Weisman, M. L., and J. B. Klemp. 1986. Characteristics of convective storms. In *Mesoscale meteorology and forecasting*, ed. P. S. Ray, 331–58. Boston: American Meteorological Society.

Wilson, J. W., and S. A. Changnon Jr. 1971. *Illinois tornadoes*. Circular 103. Champaign: Illinois State Water Survey.

PHILIP W. SUCKLING is Professor and Chair of the Department of Geography at Texas State University–San Marcos, San Marcos, TX 78666. E-mail: ps33@txstate.edu. His research interests involve climatology and natural hazards.

WALKER S. ASHLEY is Assistant Professor in the Meteorology Program, Department of Geography at Northern Illinois University, DeKalb, IL 60115. E-mail: washley@niu.edu. His research interests involve synoptic and mesoscale climatology/meteorology, especially with respect to severe weather.