A 10-Yr Climatology Relating the Locations of Reported Tornadoes to the Quadrants of Upper-Level Jet Streaks

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(Manuscript received 3 March 2003, in final form 24 June 2003)

ABSTRACT

Observations and numerical model simulations associate rising motions below the right-entrance and left-exit quadrants of an upper-level straight jet streak with the development of convection and severe weather. The occurrence of tornadoes in relation to the jet quadrants is investigated for the continental United States for the spring months of 1990–99. Tornadoes occurred primarily within the two exit quadrants, with the left-exit quadrant favored over the right-exit quadrant. While fewer tornadoes were located below the two entrance quadrants, the right-entrance quadrant was favored over the left-entrance quadrant. For those days on which many tornadoes occurred (''outbreak'' days), a greater percentage of tornadoes occurred below the left-exit and right-entrance quadrants than for those days on which only a few tornadoes were reported. Composite diagrams are presented to clarify the relationship between the quadrants of a jet streak, severe weather, and synoptic features such as low pressure centers and frontal boundaries.

1. Introduction

Operational forecasts of severe weather often make reference to upper-tropospheric ''jet streaks'' (i.e., wind maxima) as factors that influence the development of severe weather, including tornadoes. The importance placed on jet streaks in severe weather forecasting arises from theoretical considerations of straight jet streaks (Namias and Clapp 1949), which predict a characteristic middle-tropospheric vertical velocity pattern beneath the quadrants of jet streaks. Based on these ideas, it is commonly assumed that severe weather is more likely to occur within regions of upward motion beneath the right-entrance and left-exit quadrants of a jet streak. In this paper, we examine this assumption as it applies to the occurrence of tornadoes over the United States. Our study makes use of a 10-yr climatology of tornadoes, including over 1000 separate tornado reports, to examine the robustness of the relationship between the occurrence of tornadoes and their location with respect to the quadrants of nearby jet streaks.

2. Background

A jet is a region of relatively strong winds that is concentrated in a narrow stream in the atmosphere. A wind speed maximum within a jet stream is called a jet streak (Fig. 1). Since the movement of a jet streak is typically slower than the wind speed within the jet, air parcels accelerate in the upstream or entrance region of a jet streak, and decelerate in the downstream or exit region of a jet streak (Bluestein 1993). The entrance and exit regions of a jet streak can be divided into their left and right sides, with respect to an observer looking downstream along the jet axis. This yields the four quadrants of a jet streak illustrated in Fig. 1. For a straight zonal jet streak near the tropopause in the midlatitude Northern Hemisphere, the acceleration pattern associated with a jet streak implies ageostrophic flow across the jet, right to left in the entrance region and left to right in the exit region. This ageostrophic flow, in turn, is associated with convergence in the left-entrance and right-exit quadrants, and divergence in the right-entrance and left-exit quadrants. The constraints of mass continuity require that a vertical circulation accompany the jet-level convergence–divergence pattern. This vertical circulation is most pronounced in the underlying troposphere due to the stability of the overlying stratosphere. Consequently, beneath the divergence quadrants (i.e., the right entrance and left exit) there is implied upward motion, and beneath the convergence quadrants (i.e., the left entrance and right exit) there is implied downward motion. We refer to this pattern of vertical velocity as the ''four-quadrant rule.'' The vertical–ageostrophic circulations beneath the entrance and exit regions are often referred to as thermally direct and indirect, respectively, because with colder tropospheric air situated on the left side of the jet (as required by

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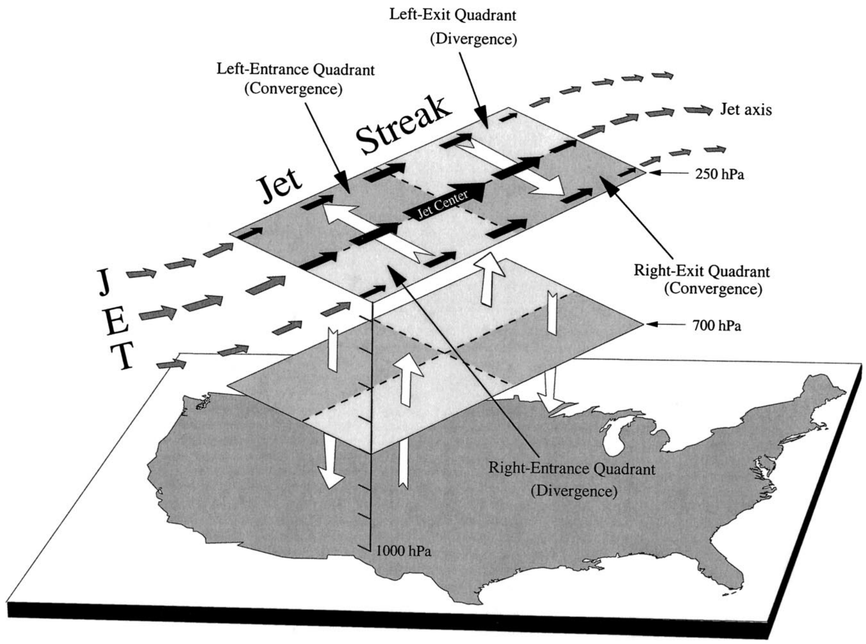

FIG. 1. Idealized jet model demonstrating the four quadrants of a jet streak and the areas of divergence and convergence at the level of the jet streak. The white horizontal arrows indicate the implied ageostrophic wind at the level of a jet streak, and the white vertical arrows indicate the implied midtropospheric vertical motions.

thermal wind balance), cold air sinks and warm air rises in the circulation of the entrance region, whereas the opposite is the case for the exit region. These ideas were discussed by Namias and Clapp (1949), Bjerknes (1951), Riehl et al. (1952), and Murray and Daniels (1953).

A natural extension of the jet streak dynamics model outlined above is the possibility of a causal relationship between propagating upper-level jet streaks and severe weather, as proposed by Beebe and Bates (1955). They hypothesized that the rising branches of jet streak circulations could destabilize the atmosphere by lifting a potentially unstable atmospheric layer. In addition, Uccellini and Johnson (1979) proposed that mass adjustments associated with a propagating upper-level jet streak can enhance the low-level jet, a feature that is often present in the lower troposphere in severe weather situations. They postulated that this process creates a more favorable thermodynamic environment for severe weather through the differential advection of warm moist air at low levels beneath cooler, drier air aloft.

These and other studies take into account many complexities of jet streak dynamical theory, such as interactions between lower- and upper-level jets (Uccellini and Johnson 1979), multiple jets at the same level (Uccellini and Kocin 1987; Hakim and Uccellini 1992; Kaplan et al. 1998), jet streak curvature (Riehl et al. 1952; Beebe and Bates 1955; Shapiro and Kennedy 1981), varying spatial scale of jet streaks (Kaplan et al. 1998), along-jet thermal advection (Shapiro 1981; Keyser and Shapiro 1986), and the sloped nature of the ageostrophic response to a propagating jet streak (Uccellini and Johnson 1979; Homan and Uccellini 1987). However, an examination of forecast discussions produced by various units of the National Weather Service (NWS) reveals that the simple four-quadrant rule, as applied to the jet structure at a single pressure level, is a commonly used tool in the forecasting of severe weather. This usage motivates the present study, which examines the climatological relationship (over a period of 10 yr) between tornado occurrence and the four quadrants of nearby jet streaks at 250 hPa. While we do not consider all of the complexities of jet streak dynamics listed above, our approach takes into account the time constraints of operational forecasting. Thus, the intent here is to evaluate the tool most commonly used by forecasters, rather than more complex dynamical models.

Several studies have examined the relationship between severe convection and upper-tropospheric jet patterns. Some early studies (Lee and Galway 1956, 1958; Ludlam 1963) concluded that tornadoes were more likely to occur in the vicinity of the upper-tropospheric jet, but they did not discuss tornado occurrence with respect to the location of jet streaks or jet streak quadrants. Other studies that have specifically examined tornado locations with respect to jet streak quadrants have been constrained by limited sample sizes, in most cases examining only a single season or partial season, or a limited region. Newton and Newton (1959) plotted tornado locations in the United States for the spring of 1949 in relation to jet streak quadrants and the maximum

TABLE 1. Results of some prior studies correlating tornado reports to the quadrants of a jet streak: N, Newton and Newton (1959); K, Kloth and Davies-Jones (1980). Numbers are number of tornadoes found below the designated quadrant.

Left-entrance quadrant	Left-exit quadrant
N: 2 K: 4	N: 10 K: 54
Right-entrance quadrant	**Right-exit quadrant**
N: 4 K: 39	N: 9 K: 17

winds at 500 hPa (Table 1). However, the small sample size, the use of 500-hPa winds rather than winds closer to the tropopause, and the lack of an explicit methodology yielded inconclusive results. Whitney (1977) examined five cases of severe weather in the United States from the spring of 1975 and concluded that severe convection was more likely to occur north of the subtropical jet. He found that most of the severe weather occurred in the left-exit quadrant of a jet streak, although in one of the five cases he studied severe weather was prevalent in the left-entrance quadrant. McNulty (1978) utilized a limited dataset from the spring of 1976 to demonstrate a relationship between severe weather in the central United States and upper-tropospheric divergence associated with jet streaks at 300 hPa. Bluestein and Thomas (1984) suggested that an upper-level jet streak played a role in the formation and maintenance of severe storms that occurred in Texas in May 1978.

Kloth and Davies-Jones (1980) studied the distribution of tornadoes in relation to jet streaks at 300 hPa for 143 tornadoes that occurred within 3 h of 0000 UTC during the month of May 1977 in the central United States. They found that 80% of the tornadoes in their sample occurred within 1250 km of a jet streak (defined as a closed isotach of 25 m s^{-1} or more). For that 80%, they classified under which quadrant of the jet streak each tornado occurred, and the results are summarized in our Table 1. Curvature of the jet streak was not taken into account, and the authors do not clarify how a ''crosshair'' was oriented to delineate the quadrants of a jet streak. This study had a sample size of 1 month, and many of the tornadoes occurred on just a few days.

Harnack and Quinlan (1989) studied the distribution of tornadoes in relation to jet streaks at 850 and 300 hPa for the period 1980–84, but only in the northeastern United States. They used National Centers for Environmental Prediction (NCEP) objectively analyzed upper-level charts from 1200 UTC, and severe weather events that occurred 3–15 h later (1500–0300 UTC). Their results showed an overwhelming preponderance of tornadoes in the right-entrance and the left-exit quadrants of jet streaks.

Few papers have challenged the widely held view that severe weather is significantly more likely to occur under the right-entrance and left-exit quadrants of a jet streak. Maddox and Doswell (1982) illustrated several cases of severe weather that occurred in locations generally considered to be unfavorable for the development of storms, for example, under areas of upper-level convergence and negative vorticity advection. They emphasized the importance of low-level warm advection as the mechanism for generating upward vertical motions in the cases they examined.

3. Methodology

The NCEP–National Center for Atmospheric Research (NCAR) ''reanalysis'' was used for the analysis of jet streaks. The reanalysis is an objective gridded reanalysis of historical data for the years 1948–2000. It uses a global spectral model with a horizontal resolution of 209 km that assimilates data with a three-dimensional variational scheme cast in spectral space. The model has 28 vertical levels in sigma coordinates, and provides pressure-level data every 6 h. Sources of data utilized by the model include surface, ship, and aircraft observations, as well as rawinsonde data and satellite soundings. Documentation of the reanalysis project is given by Kistler et al. (2001) and at the reanalysis Web site (wesley.wwb.noaa.gov/reanalysis.html).

In this study the gridded data analysis was displayed using the Grid Analysis and Display System (GrADS). Data for the months of April, May, and June were analyzed for the 10-yr period from 1990 to 1999. In each case, the wind field was plotted as isotachs (in increments from 2.5 or 5 m s^{-1}) for the 250-hPa level. The total domain considered was from 20° to 55°N latitude and from 60° to 130°W longitude, which covers most of the contiguous United States and surrounding regions.

Tornado reports were obtained from the National Climatic Data Center (NCDC) Storm Event database (maintained online at www4.ncdc.noaa.gov). Since the 0000 UTC reanalysis was used to reconstruct the 250-hPa wind field, only those tornadoes that occurred within 3 h of 0000 UTC (from 2100 to 0300 UTC) on each day were used in this study. To reduce the likelihood of considering multiple reports of the same tornado, or multiple touchdowns of the same vortex, tornadoes that occurred within 10 min and 10 km of another tornado were considered as one tornado occurrence. We used reports of only those tornadoes rated F1 or higher on the Fujita scale, since such reports are usually confirmed by formal damage assessments.

An example of the analysis technique described below is shown in Fig. 2. Jet exit and entrance quadrants were hand analyzed and compared to the reported locations of tornadoes using the following protocol:

1) The jet streak was defined as the region enclosed by the highest isotach greater than 25 m s^{-1}. The isotach could either be an enclosed curve or a curve closed by the borders of the domain.
2) The jet axis (i.e., the axis of strongest winds; see

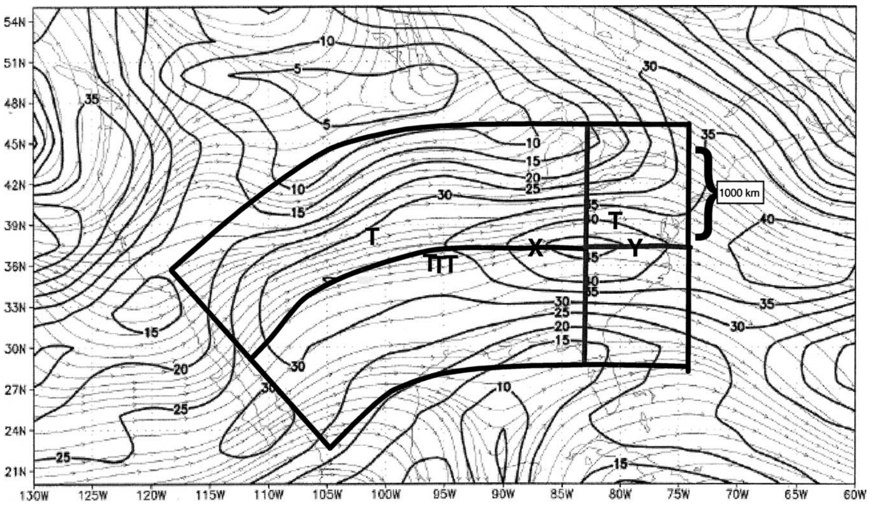

FIG. 2. Example of jet-quadrant analysis. The thick black lines delineate the quadrants of the jet streak. Tornado locations are indicated by Ts. Isotachs are solid black lines and are labeled in m s^{-1}; streamlines are the light lines with arrows. In this case, one tornado occurred in the left-exit quadrant and in the left-entrance quadrant, and three tornadoes occurred in the right-entrance quadrant. Note that X and Y are defined in Fig. 3.

Fig. 1) was determined by following an elongation or ''ridge'' in the closed isotachs, provided the isotachs did not deviate significantly from the plotted streamlines. If there was a significant deviation from the streamlines, the streamline that passed through the centroid of the jet streak was taken to be the jet axis. If the isotach ridge became ambiguous at some point, the jet axis was continued along the streamline from that point forward or backward. The ''beginning'' and ''end'' of a jet streak were taken to be the locations where the gradient of the winds became 0 along the jet axis. For the purpose of determining the quadrants of a jet streak, the jet axis was extended for 300 km (tangential to the streamline) before the beginning and beyond the end of the jet streak.

3) The quadrants of a jet streak were determined by drawing a straight line perpendicular to the jet axis at the centroid of the maximum closed isotach. This perpendicular was extended 1000 km on either side of the jet axis. All points forward (downstream) from this perpendicular, to the left of the jet axis, within 1000 km of the jet axis, and up to the end of the jet plus 300 km, were considered to be in the left-exit quadrant of the jet streak. The analysis of the other three quadrants was carried out in a similar manner. A distance of 1000 km was chosen as an outer bound because numerical studies indicate that this is about the greatest distance from the jet axis where associated vertical motions occur (e.g., Keyser and Pecnick 1985; Moore and Vanknowe 1992).
4) Starting from the maximum closed isotach defining the jet streak, and moving along the jet axis toward either the entrance or exit region, the wind speed along the jet axis has to decrease by at least 5 m s^{-1} below the value of the maximum closed isotach for a region to qualify as either an entrance or exit.
5) If a tornado was reported at a location that could be associated with two or more jet streaks, the following procedure was used to determine the appropriate jet streak. First, for each jet streak we determined the closest point along its associated jet axis to the tornado location. We then determined the magnitude of the acceleration along the jet axis (given by the isotach gradient) at this point. The largest isotach gradient determined which jet streak was used in the analysis. An exception was when one of the jet axes was closer to a tornado than another by a difference of 500 km or more; in this case, the jet axis closest to the tornado determined the appropriate jet streak.
6) Tornadoes that occurred within 1000 km of a jet axis, but not in a designated entrance or exit region, were classified as ''north of jet'' or ''south of jet'' (or ''right'' or ''left'' of the jet if the jet axis was predominately meridional).

The data were separated into those days on which a large number of tornadoes were reported, and those days on which few tornadoes were reported. This was done to determine if there were any qualitative or quantitative differences between days on which synoptic conditions favored the occurrence of many or a few tornadoes. The NWS defines an ''outbreak'' as a day on which six or more tornadoes are reported in association with one storm system, a definition endorsed by Grazulis (1993). While the present study was confined to tornadoes that occurred from 2100 to 0300 UTC, the NWS definition was adopted to distinguish outbreak from ''nonoutbreak'' days.

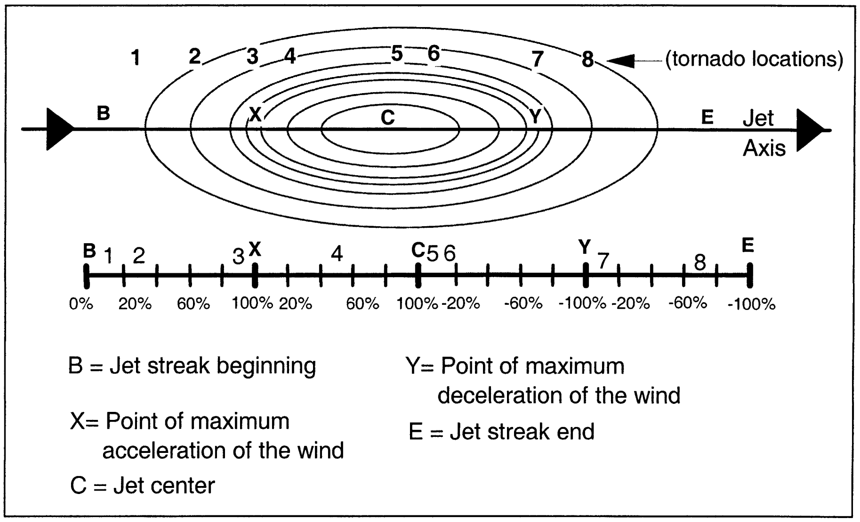

FIG. 3. Idealized jet streak model for determining the *x* axis in Figs. 4–6. The ovals are isotachs. The horizontal scale shows the percentage increase in wind speed from point B to point X, and from point X to point C; and, the percentage decrease in wind speed from point C to point Y, and from point Y to point E.

To show quantitatively the locations of a large number of tornadoes with respect to the quadrants of jet streaks that covered a range of lengths, suitable *x* and *y* axes of a Cartesian coordinate system had to be devised. The *y* axis was chosen to be the distance of the tornado to the right or left of the jet axis. The dynamics of a jet streak are more dependent on the acceleration and deceleration of air parcels as they move through the jet streak than they are on the length of a jet streak. Therefore, the scale on the *x* axis was normalized to be a percentage of the increase (or decrease) in wind speed from the point of maximum acceleration (or deceleration) in the jet streak, as illustrated in Fig. 3. In addition to the points along the jet axis previously defined as the jet streak beginning (marked B in Fig. 3) and the jet streak end (marked E in Fig. 3), we define two other points along the jet axis. Point X is the location of the maximum acceleration in wind speed, and point Y is the location of the maximum deceleration in wind speed. Hence, in the entrance region of a jet streak, the horizontal coordinate in Fig. 3 is the percent increase in wind speed along the jet axis from the jet streak beginning (B in Fig. 3) to point X, and from point X to the jet streak center (C in Fig. 3). In the exit region of a jet streak, the scale on the *x* axis is the percent decrease in wind speed along the jet axis from the jet streak center (C in Fig. 3) to point Y, and from point Y to the jet streak end (E in Fig. 3). For example, if the innermost isotach in Fig. 3 is 50 m s^{-1} and the isotach interval is 5 m s^{-1}, the outermost isotach is 20 m s^{-1}. Point Y falls midway between the 35 and 40 m s^{-1} isotachs or ~37.5 m s^{-1}. The jet streak end (point E) falls at approximately 17.5 m s^{-1} (lowest isotach minus one-half an interval). Extending a perpendicular from the tornado located at point 8 to the jet axis determines that location 8 falls at approximately the 25 m s^{-1} isotach, which is a 63% reduction in wind speed from point Y (37.5 m s^{-1}) to the jet streak end (17.5 m s^{-1}). Location 8 is therefore placed between −60% and −80% on the horizontal axis. In contrast, extending a perpendicular from location 6 to the horizontal axis demonstrates that location 6 falls within the innermost isotach. This is a reduction of less than 10% from the maximum wind speed in the jet streak, so location 6 is placed within the −20% line on the horizontal axis.

4. Results

For the period and locations of this study, a total of 774 tornadoes were reported on 65 outbreak days, and a total of 646 tornadoes were reported on 216 nonoutbreak days. The occurrence of the tornadoes with respect to outbreak and nonoutbreak days, and their locations relative to jet streaks, are shown in Table 2.

Most tornadoes (97%) were classified as being associated with a jet or jet streak, consistent with early studies (Lee and Galway 1956, 1958; Ludlam 1963). Also, by our classification scheme, most (94%) of the tornadoes associated with upper-level jet streaks could be classified as occurring in either an entrance or exit region, rather than north or south of the jet axis. However, this result is probably dependent on the inclusive nature of the classification scheme. Overall, the dominant quadrant is the left exit, and the quadrant of least frequent tornado occurrence is the left entrance, for both outbreak and nonoutbreak days.

With regard to the four-quadrant rule, if tornado occurrence is examined on the jet-entrance side only, the four-quadrant rule correctly predicts the favored region: tornadoes occurred twice as frequently under the right-

TABLE 2. Location of tornadoes with respect to jet streak quadrants in the United States between the hours of 2100–0300 UTC from Apr through Jun 1990–99. For each category, tornado occurrence is expressed as an absolute number (in parentheses), as well as a percentage of the total number of tornadoes that occurred.

Outbreak days (i.e., six or more tornadoes: 65 days)	Left-entrance quadrant (54) 7%	Left-exit quadrant (338) 44%	North of jet (7) <1%	Unclassified (6) <1%	Total (774)
	Right-entrance quadrant (123) 16%	Right-exit quadrant (213) 28%	South of jet (33) 4%		
Nonoutbreak days (one–six tornadoes; 216 days)	Left-entrance quadrant (73) 11%	Left-exit quadrant (1191) 30%	North of jet (18) 3%	Unclassified (42) 6%	Total (646)
	Right-entrance quadrant (160) 25%	Right-exit quadrant (137) 21%	South of jet (25) 4%		
Total (outbreak plus nonoutbreak days; 281 days)	Left-entrance quadrant (127) 9%	Left-exit quadrant (529) 37%	North of jet (25) 2%	Unclassified (48) 3%	Total (1420)
	Right-entrance quadrant (283) 20%	Right-exit quadrant (350) 25%	South of jet (58) 4%		

entrance region as under the left-entrance region for both outbreak and nonoutbreak days. Similarly, if tornado occurrence is examined on the jet-exit side only, the four-quadrant rule correctly predicts the favored region: tornadoes occurred 60% more often under the left-exit region than under the right-exit region on outbreak days, and 40% more often under the left-exit region than under the right-exit region on nonoutbreak days.

However, another clear pattern is a predominance of tornado occurrence in the exit region as a whole rather than the entrance region. Twice as many tornadoes occurred in the exit region for all of the study days. This tendency is even more pronounced on outbreak days, with 3 times as many tornadoes occurring in the exit region. The favoring of the exit region is not limited to the conventionally favored left-exit quadrant, as a substantial number of tornadoes also occurred in the right-exit quadrant. In fact, on outbreak days, 73% more tornadoes occurred in the conventionally unfavored right-exit quadrant than in the conventionally favored right-entrance quadrant. Several studies, beginning with Riehl et al. (1952) and Beebe and Bates (1955), have considered the effects of flow curvature on jet streak dynamics. In addition to the divergence and upward motion pattern that leads to the four-quadrant rule, the divergence pattern implied by gradient wind balance in a cyclonically curved jet streak requires upward motion under the exit region as a whole, thereby favoring the exit region for destabilization and severe weather. Hence, one might conclude that the favoring of the exit region seen in the present study is due to a dominance of cyclonically curved jet streaks. However, most of the jet streaks examined in the present study were straight or minimally curved (approximately 52%). The remaining 48% of the jet streaks exhibited sufficient curvature to be visually characterized, but of those 58% had *anticyclonic* curvature. Thus, it does not appear that flow curvature offers a ready explanation for the favoring of the exit region over the entrance region. Another possibility is that surface characteristics that strongly influence convective stability (e.g., the locations of low pressure centers, warm sectors, and warm, moist southerly airflows) may occur more frequently under exit regions of jet streaks in the central United States, the most tornado-prone region of the country. This issue is addressed in more detail in the next section.

L. Uccellini (2003, personal communication) has suggested that the significant number of tornadoes in the right-exit region is not inconsistent with the theory of secondary circulations associated with jet streaks, provided that the sloped nature of those circulations (Uccellini and Johnson 1979; Homan and Uccellini 1987) is taken into account. In other words, the tropospheric ascent regions associated with upper-level jet streaks should occur along sloping isentropic layers rather than in vertical columns. Therefore, the low-level return branch of the exit-region circulation slopes upward to the north beneath both the left and right quadrants, and sufficient lifting for the release of deep convection may occur before the low-level air parcels cross the upper-level jet axis, when they are still beneath the right-exit quadrant. While this explanation may reconcile the results of the present study with theory, it further dilutes the utility of the simple four-quadrant rule, which would have to be amended to include a favored right-exit quadrant, in addition to the favored left-exit and right-entrance quadrants.

Figure 4 shows the total distribution of tornadoes during the study period. Two maxima in the distribution are apparent. The first is in the exit region of the jet streak, from about 500 km left of the jet axis to about 300 km to the right. A secondary maximum, more diffuse than the first, is seen in the right-entrance quadrant of the jet streak. A noticeable absence of tornadoes is seen in the left-entrance quadrant, away from the jet axis.

Figure 5 shows the distribution of tornadoes that were reported on the 65 outbreak days of this study. The exit region of the jet streak clearly dominates the distribution, and the maximum in the distribution is below the left-exit quadrant of the jet streak. However, as stated earlier, a significant number of tornadoes were reported below the right-exit quadrant.

For the outbreak days, a secondary maximum in tornado reports is again observed in the right-entrance quadrant of the jet streak, and it is better defined than

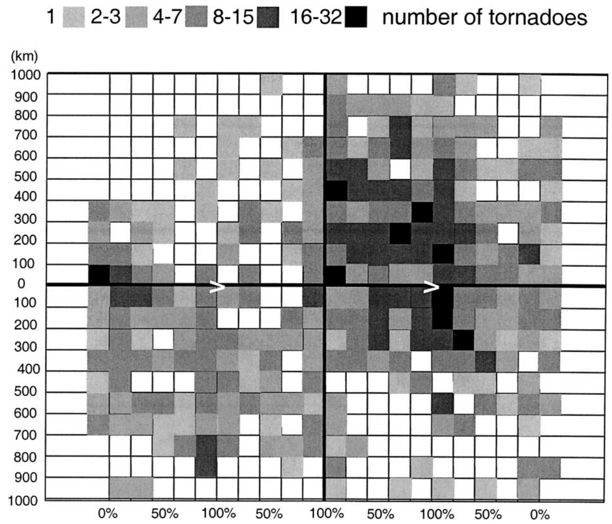

FIG. 4. Total number of tornadoes with intensity F1 or greater that occurred from Apr to Jun 1990–99. The *y* axis is the distance (in km) from the jet axis (the thick black line at 0 km). The *x* axis is defined in Fig. 3. The direction of the wind is given by the arrowheads, which are located on the jet axis at the points of maximum acceleration and deceleration of the wind.

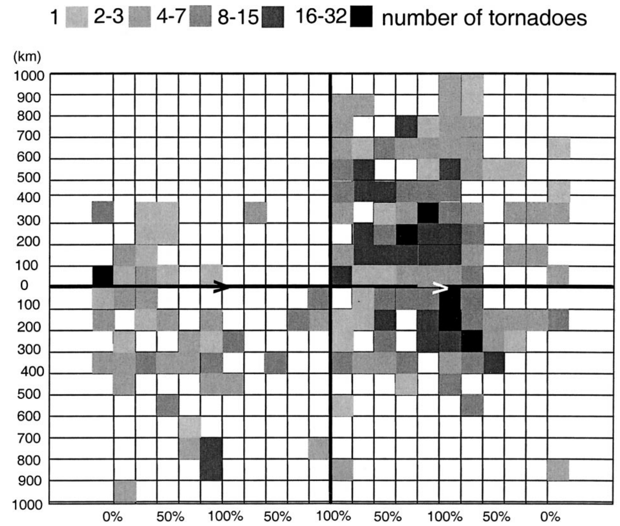

FIG. 5. As in Fig. 4 but for tornadoes occurring on outbreak days.

it is for the nonoutbreak days. Tornadoes occurring below the exit region were most likely to occur between the jet center and jet exit (i.e., close to the jet center). In contrast, tornadoes occurring upstream of the jet center were prevalent upstream of the entrance region to the jet streak. The sharp cutoff in tornadoes below the center of the jet is likely an artifact of the normalization procedure for the horizontal axis (see section 3), since many jet streaks exhibited elongated centers along which the isotach gradient was zero. For example, in Fig. 3 the tornadoes numbered 5 and 6 are placed within the first increment on the horizontal axis (labeled −20%). In Figs. 4–6, tornadoes falling anywhere within the innermost isotach were plotted within the first 10% of deceleration following the jet center, but before the point of maximum deceleration along the jet axis.

Figure 6 shows the distribution of tornadoes for nonoutbreak days. The pattern is similar to the pattern for total tornadoes, but it is slightly more diffuse. Two maxima in tornado occurrence are still evident: one centered below the left-exit quadrant and the other below the right-entrance quadrant. However, many of the tornadoes below the exit region of a jet streak are close to the jet center, while for the outbreak days the maximum is closer to the point of maximum deceleration along the jet axis.

5. Synoptic environments

Composite sketches, illustrating common surface synoptic features for tornadoes occurring below each of the quadrants of a jet streak, are shown in Fig. 7. These figures are for days on which tornadoes occurred below just one of the quadrants, and the relevant jet streak was isolated from other jet streaks. The sketches show common synoptic features associated with tornadoes that occurred within the various quadrant.

A relatively small number of tornadoes were reported below the left-entrance quadrant of a jet streak. The composite for this quadrant illustrates that the synoptic environment for these storms was not conducive to the development of severe weather (Fig. 7 top left). Severe thunderstorms require the presence of relatively warm and moist low-level air, and a sufficient lifting mechanism to raise a parcel to its level of free convection. Tornadoes are usually found in the warm sectors of midlatitude cyclones, or near-surface fronts or boundaries. Warm sectors are not usually found beneath the left-entrance quadrant of a jet streak. Strong surface cold

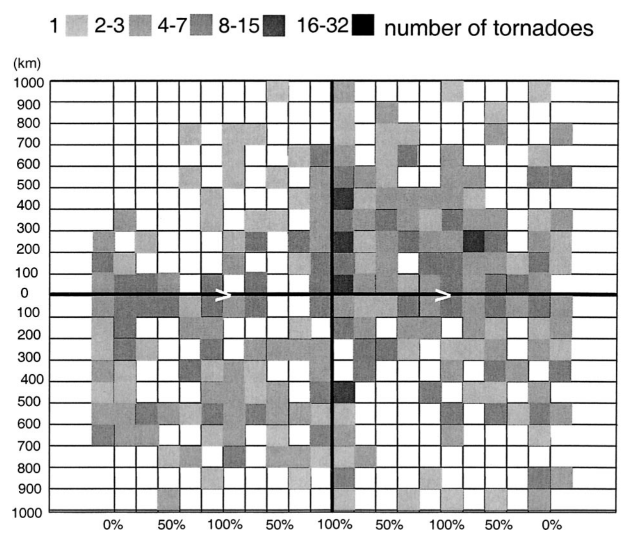

FIG. 6. As in Fig. 4 but for tornadoes occurring on nonoutbreak days.

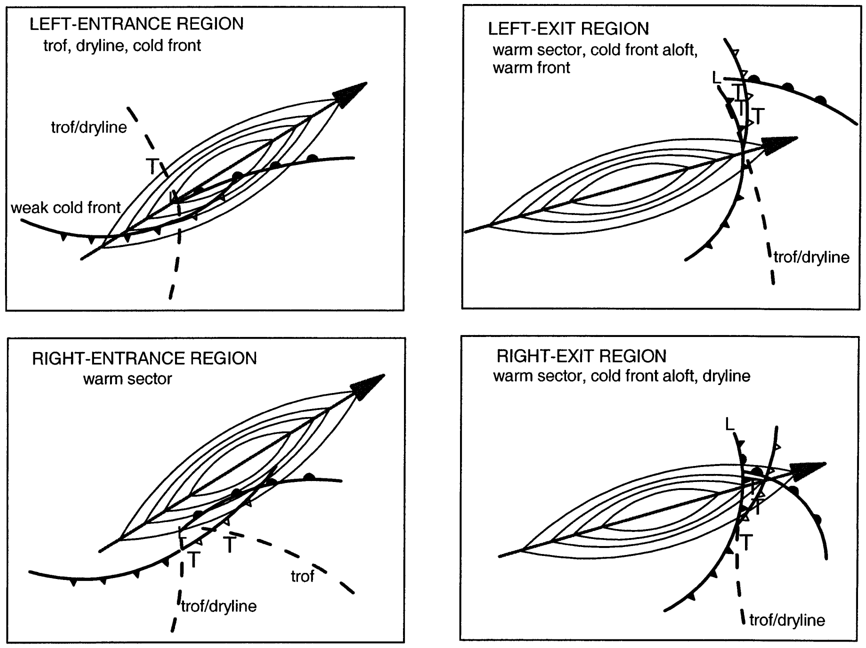

FIG. 7. Composite sketches for the quadrants of a jet streak. Typical tornado locations are marked by a T. Jet axes and wind direction are shown by the arrows, and isotachs are shown as concentric closed curves. Tornadoes located below each quadrant are typically associated with the features listed below the name of the quadrant in each sketch.

fronts are infrequent to the north and beneath the entrance of a jet streak. The left-entrance quadrant of a jet streak is more frequently associated with cold, dry air at the surface, and weak surface boundaries, as can be seen in Fig. 7. In the few cases in which tornadoes were unambiguously located below the left-entrance quadrant, they generally occurred in regions of relatively weak warm advection and in the vicinity of a surface boundary, generally a trough or dryline. These tornadoes were also found beneath the jet axis, where the surface air was relatively warm and moist.

The composites for the left-exit and right-exit quadrants (Fig. 7) illustrate classic scenarios for the occurrence of severe weather, and they show the dominance of the exit region for both outbreak and nonoutbreak days. Strong surface lows were most common below the left-exit quadrant of jet streaks, and tornadoes most commonly developed in the vicinity of strong surface lows. The surface low was generally located below the left-exit region, regardless of whether the tornadoes occurred in the left-exit or right-exit quadrants. Tornadoes commonly occurred near a ''triple point,'' that is, where a warm front intersected a cold front or dryline/trough. Tornadoes below the left-exit quadrant were often associated with a favorable combination of strong low-level warm advection and southerly flow, juxtaposed with relatively cold air aloft and a westerly component to the flow at upper levels. Tornadoes below the right-exit quadrant were generally associated with more mature, often occluded frontal systems.

Tornadoes below the right-entrance quadrant often involved surface lows and warm-sector convection. The surface lows often appeared to be in the process of developing along a previously existing frontal boundary. The dryline or lee trough appeared to be a significant feature for these cases.

6. Conclusions

The identification of regions that are conducive to the development of severe weather is a challenging problem in weather forecasting. In this paper, we have shown a significant correlation between one type of severe weather, namely tornadoes, and the quadrants of upper-level jet streaks. Tornadoes occurred most frequently below the exit region of a jet streak. Figures 4–6 show that this maximum in tornado occurrence appears as a fairly uniform, elliptical area approximately 1000 km wide, centered below the left side of the jet axis. Most of the tornadoes occurred below the left-exit quadrant, but a significant number also occurred below the right-exit quadrant. Most of the tornadoes that occurred below the exit region of a jet streak were located significantly closer to the jet center than tornadoes that occurred below the entrance region. In the entrance region, tornado occurrence was strongly favored below the right-entrance quadrant, although this maximum was not as well defined as that below the right- and left-exit quadrants. Regardless of the quadrant of the jet involved, tornadoes generally occurred in proximity to frontal, trough, or dryline boundaries and/or surface low pressure systems.

Acknowledgments. This research was supported by Grant ATM-9632580 from the Mesoscale Dynamic Meteorology Program, Atmospheric Research Division, National Science Foundation.

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