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Climatology of Storm Reports Relative to Upper-Level Jet Streaks

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Abstract
Using quasigeostrophic arguments and numerical simulations, past works have developed conceptual models of vertical circulations induced by linear and curved jet streaks. Because jet-induced vertical motion could influence the development of severe weather, these conceptual models, especially the “four quadrant” model for linear jet streaks, are often applied by operational forecasters. The present study examines the climatology of tornado, hail, and severe wind reports relative to upper-level jet streaks, along with temporal trends in storm report frequencies and changes in report distributions for different jet streak directions. In addition, composite fields (e.g., divergence, vertical velocity) are analyzed for jet streak regions to examine whether the fields correspond to what is expected from conceptual models of curved or linear jet streaks, and whether the fields help explain the storm report distributions. During the period analyzed, 84% of storm reports were associated with upper-level jet streaks, with June-August having the lowest percentages. In March and April the left-exit quadrant had the most storm reports, while after April the right-entrance quadrant was associated with the most reports. Composites revealed that tornado and hail reports are concentrated in the jet-exit region along the major jet axis and in the rightentrance quadrant. Wind reports have similar maxima, but the right-entrance quadrant maximum is more pronounced. Upper-level composite divergence fields generally correspond to what would be expected from the four-quadrant model, but differences in the magnitudes of the vertical velocity between the quadrants and locations of divergent-convergent centers may have resulted from jet curvature. The maxima in the storm report distributions are not well collocated with the maxima in the upper-level divergence fields, but are much better collocated with low-level convergence maxima that exist in both exit regions and extend into the right-entrance region. Composites of divergence-convergence with linear, cyclonic, and anticyclonic jet streaks also generally matched conceptual models for curved jet streaks, and it was found that wind reports have a notable maximum in the right-entrance quadrant of both anticyclonic and linear jet streaks. Finally, it was found that the upper-level divergence and vertical velocity in all jet-quadrants have a tendency to decrease as jet streak directions shift from SSW to NNW.

Keywords
composite fields, conceptual model, divergence field, entrance region, four quadrant, jet axis, jet streaks, numerical simulation, operations forecasters, severe weather, temporal trends, vertical circulation, computer simulation, precipitation (meteorology), storms, tornadoes

Disciplines
Atmospheric Sciences | Geology

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Climatology of Storm Reports Relative to Upper-Level Jet Streaks

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ABSTRACT

Using quasigeostrophic arguments and numerical simulations, past works have developed conceptual models of vertical circulations induced by linear and curved jet streaks. Because jet-induced vertical motion could influence the development of severe weather, these conceptual models, especially the “four quadrant” model for linear jet streaks, are often applied by operational forecasters. The present study examines the climatology of tornado, hail, and severe wind reports relative to upper-level jet streaks, along with temporal trends in storm report frequencies and changes in report distributions for different jet streak directions. In addition, composite fields (e.g., divergence, vertical velocity) are analyzed for jet streak regions to examine whether the fields correspond to what is expected from conceptual models of curved or linear jet streaks, and whether the fields help explain the storm report distributions.

During the period analyzed, 84% of storm reports were associated with upper-level jet streaks, with June–August having the lowest percentages. In March and April the left-exit quadrant had the most storm reports, while after April the right-entrance quadrant was associated with the most reports. Composites revealed that tornado and hail reports are concentrated in the jet-exit region along the major jet axis and in the right-entrance quadrant. Wind reports have similar maxima, but the right-entrance quadrant maximum is more pronounced. Upper-level composite divergence fields generally correspond to what would be expected from the four-quadrant model, but differences in the magnitudes of the vertical velocity between the quadrants and locations of divergent–convergent centers may have resulted from jet curvature. The maxima in the storm report distributions are not well collocated with the maxima in the upper-level divergence fields, but are much better collocated with low-level convergence maxima that exist in both exit regions and extend into the right-entrance region. Composites of divergence–convergence with linear, cyclonic, and anticyclonic jet streaks also generally matched conceptual models for curved jet streaks, and it was found that wind reports have a notable maximum in the right-entrance quadrant of both anticyclonic and linear jet streaks. Finally, it was found that the upper-level divergence and vertical velocity in all jet-quadrants have a tendency to decrease as jet streak directions shift from SSW to NNW.

1. Introduction

A conceptual “four quadrant” model (4QM hereafter; e.g., Bluestein 1993; Rose et al. 2004) of upper-tropospheric linear jet streak circulations was first hypothesized by Namias and Clapp (1949) and later inferred through observations by Murray and Daniels (1953). Using the quasigeostrophic momentum equation, it easily can be shown that the ageostrophic wind is directed perpendicular and to the left (in the Northern Hemisphere) of the acceleration of the wind. The ageostrophic flow results in upper-level horizontal divergence (convergence) in the right-entrance and left-exit (left entrance and right exit) regions, resulting in a vertical circulation with upward (downward) motion occurring in quadrants with upper-level divergence (convergence), which satisfies mass conservation. The vertical circulation in the entrance quadrants is “thermally direct” with warm air rising and cool air sinking, while that in the exit region is “thermally indirect” (e.g., Bluestein 1993; Holton 2004).

The jet-induced secondary circulation was first recognized by Beebe and Bates (1955) to be a potential contributing mechanism for severe weather, which later case studies (e.g., Uccellini and Johnson 1979; Bluestein and Thomas 1984; Sanders and Blanchard 1993) and a few climatological studies (e.g., Kloth and Davies-Jones 1980; Harnack and Quinlan 1989; Rose et al. 2004) also evinced. The possible mechanisms by which jet-induced vertical circulations contribute to severe weather include
decreasing the static stability, cooling a layer of air to saturation and thus releasing convective available potential energy (CAPE), enhancing moisture convergence at low levels, and increasing CAPE in the exit region through differential temperature and moisture advection with height (Bluestein and Thomas 1984 and references therein). In addition, Bluestein and Thomas (1984) recognize that jet streaks are intrinsically linked to severe weather because they enhance vertical wind shear, which is important in sustaining long-lived convection (e.g., Weisman and Klemp 1982).

In the atmosphere, jet streaks often do not fit the four-quadrant conceptual model. Beebe and Bates (1955) recognized that centripetal acceleration caused by curvature in the flow changes the orientation of the ageostrophic wind, modifying the jet-induced vertical circulation. Later, studies using numerical models of idealized jet streaks (e.g., Newton and Trevisan 1984; Moore and VanKnowe 1992) quantified the expected changes in jet-induced circulations caused by curved flow, and a conceptual model for curved jet streaks was described by Keyser and Shapiro (1986). In general, it is expected that curved flow (i.e., flow with a strong along-contour component of the ageostrophic wind) containing a jet streak centered at the base of a trough (top of a ridge) will have enhanced divergence (convergence) east of the trough (ridge), resulting in a two-cell, rather than four-cell, pattern of divergent–convergent centers. Numerical simulations conducted by Moore and VanKnowe (1992) showed that the two-cell pattern for cyclonically and anticyclonically curved jets is aligned with the jet axis rather than on either side of the axis, and the magnitude of the vertical motion should be the strongest with cyclonically curved jet streaks, more modest with anticyclonically curved jet streaks, and weakest with linear jet streaks. Further modifications to the four-quadrant conceptual model are required in the presence of thermal advection (Shapiro 1983), which can cause jet-induced circulations to be laterally displaced toward either side of the jet axis (e.g., Cammas and Ramond 1989; Lackmann et al. 1997; Pyle et al. 2004).

Regardless of how well the 4QM fits typical atmospheric jet streaks, an analysis of forecast discussions by Rose et al. (2004) produced by various units of the National Weather Service (NWS) revealed that the model was often used as a forecasting tool when generating forecasts of severe weather. This analysis motivated Rose et al.’s (2004) 10-yr climatological study of F1 and above tornado occurrences relative to quadrants of 250-hPa jet streaks without considering all the complexities of jet streak dynamics. They found that the majority of tornadoes occurred within the exit quadrants, with the left-exit quadrant favored over the right-exit quadrant. Fewer tornadoes occurred in the entrance quadrants, but the right-entrance quadrant was favored over the left-entrance quadrant. Rose et al. (2004) concluded discrepancies in the observed tornado distribution with the 4QM likely occurred because surface features that are closely tied to the development of convection, like low pressure centers and warm sectors, tend to occur most frequently in the exit quadrants.

The goal of the current study is to extend the results of Rose et al. (2004) by analyzing the climatology of hail and wind reports, as well as tornado reports, relative to linear and curved upper-level jet streaks, as lateral boundary conditions for a version of the NCEP–DOE Global Reanalysis (Kanamitsu et al. 2002) as lateral boundary conditions for a version of the NCEP Eta Model (Mesinger et al. 1988; Mesinger 2000; Black 1988; Janjić 1994) and Eta Data Assimilation System (EDAS; Rogers et al. 2001). Storm reports (hail, wind, and tornado), as compiled in the National Climatic Data Center (NCDC) publication Storm Data, were obtained from the Storm Prediction Center Web site (http://www.spc.noaa.gov/climo/historical.html). Bias and quality problems inherent in the NCDC’s Storm Events Database are discussed in Gallus et al. (2008 and references therein). Problems relevant to this study include the fact that some tornadoes are assigned a pathlength and width while wind and hail reports are treated as point events, despite occurring in swaths that also have diverse geometrical properties (Doswell et al.
For this study, only the beginning points of tornado paths are used to assign locations relative to jet streaks. In addition, human and population biases are largely responsible for marked increases in weaker tornado, wind, and hail reports observed in the dataset over the last few decades (e.g., Billet et al. 1997; Weiss et al. 2002, Verbout et al. 2006). The time period March–September of 1994–2004 was analyzed in this study, which is more recent than the 1990–99 period analyzed by Rose et al. (2004), and only jet streaks occurring at 0000 UTC that had one or more associated storm reports valid ±3 h from 0000 UTC were considered, following Rose et al. (2004). Storm reports occurring within this 6-h time window, but not associated with any jet streak, were classified as non-jet-related reports.

To identify upper-level jet streaks, the Grid Analysis and Display System (GrADS) was used to display isotachs at the 250-hPa level overlaid by streamlines, as well as the locations of storm reports for each case. In addition, accelerations in wind speed (computed using the isotach gradient) were displayed with isotachs, streamlines, and storm report locations overlaid. An example of a case that was analyzed for 1 June 1995 is provided in Fig. 1. For each case, if storm reports occurred within the specified time period, a plot similar to Fig. 1a was examined to identify jet streaks. The criterion for jet streak classification was an enclosed area of wind speeds exceeding 25 m s$^{-1}$, as in Rose et al. (2004). Each jet streak that appeared to contain storm reports in any of its quadrants was then hand analyzed using an interactive GrADS script, which required a user to mark the location of the jet core and jet endpoints, as well as the orientation of the minor axis that went through the jet core and jet endpoints and extended 1000 km in both directions perpendicular to the major jet axis. Rose et al. (2004) noted that 1000 km is approximately the maximum distance from the jet axis where jet-induced vertical motions occur (Keyser and Pecnick 1985; Moore and Vanknowe 1992). The jet core was defined as a point within the area of maximum wind speed where the acceleration became zero, while the jet ends were defined by following the streamlines nearest to the jet core downstream (upstream) through the exit (entrance) region until the acceleration became zero. In addition, the GrADS script required that the user mark one point, or a sequence of points, following the streamline nearest to the jet core within the exit and entrance regions that defined the extension of the major jet axis. The positions of the remaining points defining the jet streak that mark the boundaries of the cyclonically (left) and anticyclonically (right) sheared sides of the jet streak were calculated by the GrADS script.

These remaining points are basically projections of the user-defined major jet axis points to the left and right sides of the jet streak. A schematic illustrating the anchor points defining the jet streak region is shown in Fig. 2.

After each jet streak was defined, it was divided into a 77 × 37 grid so that composites could be generated. The jet core was used as the center grid point. Because the strongest cross-jet ageostrophic flow that induces vertical motions coincides with the maximum and minimum accelerations of the geostrophic wind in the entrance and exit regions, respectively (e.g., Bluestein 1993), the center grid point in the entrance (exit) region was taken to be the point along the major jet axis with the maximum (minimum) acceleration.

It should be noted that the composite fields, in particular upper-level divergence, could be affected by convection present at the time of the jet streak analysis. An attempt was made to quantify the influence of ongoing convection by comparing the composite upper-level divergence of cases in which storm reports did not occur until after 0000 UTC to cases in which reports occurred before and after 0000 UTC (not shown). These two composites were very similar; thus, no further attempts were made to account for the influence of convection on composite fields.

3. Results

a. Jet streak climatology and composite storm report distributions

For the 11 yr analyzed in this study, a total of 3179 jet streaks containing 105 987 storm reports were analyzed, accounting for 84% of the total (126 864) number of storm reports that occurred during this period. Of the jet-streak-related storm reports, 13.8% (14 672) were counted more than once because they were located in quadrants of more than one jet streak. A full summary of monthly and total storm report statistics is provided in Table 1.

In general, the monthly distribution of jet cores associated with storm reports follows the seasonal northward migration of the jet stream (Figs. 3a–g). The peak month for storm reports, including jet-and non-jet-related reports, is June, with May having only slightly less reports than June (Fig. 3h; Table 1). During the warm season (June–August), the percentage of jet-related storm reports (top-right panels in Figs. 3a–g) decreases, so that May is the peak month for jet-related storm reports, with June having the second-most jet-related reports. A number of factors likely contribute to the decrease in jet-related reports during the warm season. First, strong solar insolation and high humidity often result in high values of CAPE favorable for severe
weather despite the presence of weak vertical wind shear in areas far removed from upper-level jet streaks. Maddox and Doswell (1982) provide examples of such cases and provide evidence that low-level warm advection was the primary forcing mechanism for severe convection occurring well south of an upper-level jet streak. Second, as the North American monsoon (NAM; Higgins et al. 1997) becomes established and the average position of the jet stream shifts northward, jet streaks occur more often at latitudes to the north of the United States, decreasing the area evaluated in the contiguous United States so that jet-related reports decrease, while non-jet-related reports may increase or remain relatively constant. Third, the decrease in baroclinicity (and associated shear) during the warm season results in a lower likelihood for exceedence of the minimum jet streak criteria. Finally, when the large upper-level anticyclone associated with the NAM is established during the warm season, midtropospheric perturbations (MPs; Wang and Chen 2008, manuscript

![Fig. 1. Example of the GrADS interface used to define jet streaks: (a) 250-hPa streamlines and isotachs (m s$^{-1}$; shaded), (b) 250-hPa acceleration (m s$^{-2}$; shaded), streamlines, storm reports (circles, squares, triangles), and isotachs (m s$^{-1}$; black contours); and (c) numbers of each type of storm report in each jet quadrant.](image-url)
submitted to Mon. Wea. Rev., hereafter WC) that are restricted in their vertical development to below the 250-mb level often provide synoptic-scale (or sub-synoptic scale) forcing to initiate and sustain long-lived severe weather episodes. These episodes are often associated with progressive mesoscale convective systems (MCSs) or derechos (Hinrichs 1888; Johns and Hirt 1987) that are characterized by long swaths (>400 km) of damaging wind reports, although hail and tornadoes can also occur. Because MPs originate in the mid-troposphere, associated storm reports may occur without an upper-level jet streak being present. WC found that MPs are most frequent in July and August, the time when non-jet-streak-related storm reports are most frequent, and are concentrated in a corridor stretching across the upper Midwest south of the polar jet axis.

During March and April the majority of storm reports occur in the left-exit quadrant, while after April most reports occur in the right-entrance quadrant (bottom-right portion of Figs. 3a–f; Table 1). Thus, the quadrant containing the most reports is always one of the quadrants favored for upward motion according to the 4QM. The shift in the maximum from the left-exit to right-entrance region occurring in April may simply be attributed to the jet stream shifting northward. During March and April (after April), the mean jet stream position over the southern (northern) United States would place most of the right-entrance (left exit) region outside of the United States, with the left-exit (right entrance) region remaining in the United States. If the different types of storm reports are considered separately, there are a few instances when the majority of reports occur in a quadrant not favored for upward motion. For example, the right-exit region is favored for wind reports during March and tornado reports during June and July.

Considering the distribution of reports over all four jet streak quadrants, only March and April have distributions that would be consistent with the circulations predicted by the 4QM. After April, the right-exit quadrant (not favored for upward motion by the 4QM) always contains more reports than the left-exit quadrant (favored for upward motion). If only the quadrant entrance quadrants are considered, all months have a storm report distribution matching that predicted by the 4QM with the right-entrance region always having more reports than the left-exit region (Figs. 3a–f).

The distribution of tornado reports over jet streak quadrants for the period April–June is found to be generally similar to that observed in Rose et al. (2004) for the same months. Both studies ranked the quadrants in order of decreasing tornado reports as left exit, right exit, right entrance, and left entrance. However, storm reports were more evenly distributed over the jet streak quadrants in our study relative to Rose et al. (2004) [31% (37%), 30% (25%), 28% (20%), and 11% (9%) for the left-exit, right-exit, right-entrance, and left-entrance quadrants, respectively, in the current study (Rose et al. 2004)]. Rose et al. (2004) found that non-outbreak days (defined as having between one and six F1 or stronger tornadoes) had tornadoes that were more evenly distributed over jet quadrants than outbreak days (defined as having 6 or more F1 or stronger tornadoes). The inclusion of F0 tornadoes in our study, along with allowing storm reports to be counted in more than one jet streak [which was not done in Rose et al. (2004)], likely account for some of the differences between our study and that of Rose et al. (2004). However, it should be noted that the tornado report distribution in our study (e.g., Fig. 4c; discussed later) is quite similar to that of Rose et al. (2004).

Overall, the percentages of “repeated” storm reports (i.e., reports located in quadrants of more than one jet streak) were 12.5%, 13.4%, and 9.3% for tornadoes,
hail, and wind, respectively (Table 1). During July the percentage of repeats tended to be the least (6.3, 7.3, and 4.0 for tornado, hail, and wind, respectively) and during May (September) the percentage of repeats was highest [17.1 (8.7), 16.5 (24.4), and 13.8 (21.5), for tornado, hail, and wind, respectively]. Because May and September are immediately before and after, respectively, the NAM, they may be particularly favorable months for these repeated reports. During these months, a subtropical upper-level jet still exists over the southwest United States, which can couple/coexist with the northward-(southward-) migrating polar jet in May (September). The occurrence of severe weather north of the subtropical jet and south of the polar jet during spring was discussed by Whitney (1977). In addition, Ramaswamy (1956) linked severe convection to pre-monsoon intrusions of the subtropical jet stream in northern India and Pakistan, speculating that analogous intrusions in the United States during spring help facilitate tornado outbreaks.

Composite storm report distributions (Figs. 4a–d) show that storm reports are concentrated in a region along the major jet axis in the exit region east of the point with maximum deceleration, and in another region roughly centered over the right-entrance quadrant. Tornado reports appear to be more concentrated in the exit region, while hail reports are relatively evenly distributed between the two regions, and wind reports are more concentrated in the right-entrance region. The x axis used in these composites represents the average length of the major jet axis, which was 2600 km (the distribution of lengths is shown in Fig. 4f). Thus, the average dimension of the jet streak area was 2600 km × 2000 km (Fig. 4e). Because the grid used to normalize

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* Torn = Tornado.
the jet streak regions had $77 \times 33$ points, each point represents an average area of $34 \text{ km} \times 61 \text{ km}$.

**b. Jet streak composite fields**

The composite 250-hPa divergence (Fig. 5a) generally matches what would be expected from the 4QM, with divergence generally occurring in the right-entrance and left-exit quadrants and convergence in the left-entrance and right-exit quadrants. However, the convergence–divergence dipoles are not centered directly along the jet axis as expected by the 4QM, but rather are slightly displaced toward the cyclonically sheared side of the jet streak. The jet-transverse vertical circulation in the thermally direct entrance region (Fig. 5e) is stronger than that in the thermally indirect exit region (Fig. 5f), which is consistent with the average jet streak curvature being anticyclonic (shown later). The jet-transverse vertical circulation in the entrance region (Fig. 5e) also generally matches what would be expected from the 4QM, with upward (downward) motion occurring over most of the troposphere in the right-entrance (left entrance) region and maxima–minima vertical velocities
FIG. 4. Composite storm report frequencies within a jet streak for (a) all reports, (b) hail, (c) tornadoes, and (d) wind. Black lines define the jet streak quadrants. (e) A jet streak with the average dimensions analyzed in this study overlaid with the United States for reference. (f) Distribution of the jet streak lengths analyzed.
around 400 hPa. The jet-transverse vertical circulation in the exit region (Fig. 5f) only matches the 4QM in the left-exit region where upward motion occurs over the depth of the troposphere. In the right-exit region, only a small area between about 600 and 300 hPa and near the major jet-axis experiences the downward motion expected from the 4QM, while upward motion occurs in much of the lower to midtroposphere.

Composite mean sea level pressure (MSLP; Fig. 5b) reveals a closed surface low centered in the left-exit...
quadrant. For a jet streak located at the base of a baroclinic wave, this surface low appears to match the region where quasigeostrophic forcings (i.e., differential temperature and vorticity advection) would contribute to its formation. A trough of low pressure extends from the surface low into the right-entrance quadrant, which implies the average location of surface fronts. The presence of fronts is also implied by the change in wind direction and convergence along the low pressure trough. Note that the quadrants with upper-level divergence both have low-level convergence (Fig. 5b, shaded). However, the right-exit quadrant, which has upper-level convergence, also has low-level convergence.

The distribution of storm reports (Figs. 4a–d) coincides with what would be expected from the composite upper-level divergence fields (Fig. 5a) only if the entrance regions are considered (i.e., most of the storm reports in the entrance region occur in the right-entrance region where there is upper-level divergence). In the exit region, the area of strongest upper-level divergence is north of the area with the most storm reports, and the maximum in storm reports located along the major jet axis occurs in the presence of upper-level convergence. In addition, areas with high densities of storm reports extend into the right-exit region where there is also upper-level convergence. The exit-region storm reports appear to coincide much more closely with low-level convergence than with upper-level divergence.

In addition to support from low-level convergence, the high relative frequency of storm reports in the right-exit region is also explained by composites of basic severe weather parameters, which show that CAPE (Fig. 5c) tends to be highest in the right-exit region, as well as 0–3-km storm relative helicity (SRH; Fig. 5d). Thus, although the jet-induced vertical circulation is not conducive to severe weather in the right-exit region, this region often overlays the warm sector, and other processes counteract the jet streak processes, making storm reports in this region very common, which was also discussed by Rose et al. (2004).

c. Effects of jet streak curvature

A procedure was devised to estimate the radius of curvature of the jet streaks analyzed in this study to examine the effects of jet streak curvature. The change in jet streak direction [Δd(radians)] along the major jet axis was calculated using the midpoints of the exit and entrance regions, and the distance between these two midpoints, L, along the major jet axis was computed. Using the formula for the circumference of a circle, C = 2πR, it is easily shown by substituting (2π/Δd) × L for C that R = L/Δd, which estimates the radius of curvature. Note that this estimate is for the radius of curvature of streamlines, not trajectories, so that large errors could be introduced during computation of fields dependent on R, like centripetal acceleration (Holton 2004). However, for the purposes of this study, this estimate should be adequate. For convenience, a curvature parameter, \( R^* = (1/R) \times 10^3 \), is used to describe the different degrees of jet streak curvature. Large relative magnitudes of \( R^* \) indicate large relative curvature, with \( R^* < 0 \) indicating anticlockwise and \( R^* > 0 \) indicating clockwise curvature.

The distribution of jet curvatures (Fig. 6) is slightly weighted toward jet streaks with anticlockwise curvature, with an average \( R^* = -0.56 \). To examine the effects of jet streak curvature on storm report distributions, jet streaks with \( R^* \geq 5.0 \) are classified as cyclonically curved, those with \( R^* \leq -5.0 \) are classified as anticlockwise curved, and those with \( -1.5 \leq R^* \leq 1.5 \) are classified as linear. Values of \( 1.5 \leq |R^*| \leq 5.0 \) are not used so that features of cyclonically and anticlockwise curved jet streaks are clearly distinguishable from linear jet streaks. Note that when using these thresholds, the average \( R^* \) is classified as linear. Composite storm report distributions for each class of \( R^* \) (Fig. 7) show that the distributions vary according to the classifications of curvature. Tornado, wind, and hail reports are all more frequent in the exit quadrants of cyclonically curved jet streaks than the entrance quadrants (Figs. 7a, 7d, 7g, and 7j), with maxima centered approximately along the major jet axis, while the opposite is apparent for anticlockwise curved jets (Figs. 7b, 7e, 7h, and 7k), with maxima within the right-entrance region. For linear jet streaks (Figs. 7c, 7f, 7i, and 7l), the distributions are much more equally distributed between the exit and entrance regions than for anticlockwise and cyclonically curved jet streaks, with the exception of wind reports. The distribution of wind reports for linear jet streaks is similar to that for anticlockwise curved jets with a maximum occurring in the right-entrance region.

Generally, the distribution of storm reports for different classes of \( R^* \) matches what would be expected from conceptual models (e.g., Beebe and Bates 1955; Shapiro and Kennedy 1981) and numerical simulations (e.g., Moore and VanKnowe 1992) of curved jet streaks. These models predict two-cell rather than four-cell patterns of vertical velocity, with an area of upward (downward) motion centered along the jet axis in the exit quadrant (entrance quadrant) for cyclonically curved jet streaks, and the opposite pattern for anticlockwise curvature. Thus, maxima in storm report frequencies for each class of curvature correspond to the region where the strongest vertical velocities are predicted. However, note that for anticlockwise curved jet streaks, maxima in storm report frequencies are not...
centered along the major axis, where divergence should be maximized, like they are for the cyclonically curved jet streaks.

The composite 250-hPa divergence for each class of $R^*$ (Figs. 8a–c) also generally matches what would be expected from conceptual and numerical models, except that divergent–convergent centers are displaced toward the cyclonically sheared side of the jet streak away from the major jet axis. For cyclonically curved jet streaks (Fig. 8a), a maximum in divergence (convergence) occurs in the left-exit (left entrance) region. For anticyclonically curved jet streaks (Fig. 8b), the divergence and convergence maxima are stronger than for cyclonically curved jet streaks, with the divergence (convergence) maxima in the right-exit (right entrance) quadrant. The jet-transverse cross sections also show stronger vertical velocity magnitudes in the anticyclonic jet streaks than in the cyclonic jet streaks, which seems to contradict the results from Moore and VanKnowe (1992). However, anticyclonically curved jet streaks in the present study tended to be stronger than cyclonic jet streaks with average jet core speeds of 49.0 and 46.1 m s$^{-1}$, respectively, which implies that stronger accelerations likely occur in the anticyclonic jet streaks with stronger ageostrophic components driving the vertical circulations.

For linear jet streaks, the familiar four-cell pattern of divergent–convergent centers is apparent (Fig. 8c). The strongest vertical velocities in linear jet streaks, which occur in the left-exit quadrant (Fig. 8f), are weaker than the strongest vertical velocities that occur in the left-exit quadrant of cyclonically curved jet streaks (Fig. 8d), and weaker than those that occur in the right-exit quadrant of anticyclonically curved jet streaks (Fig. 8h). These results are consistent with Moore and VanKnowe (1992).

For cyclonically curved jet streaks (Fig. 9a), a closed center of low pressure is centered along the major axis in the center of the exit region. An area of strong relative convergence coincides with this surface low, as well as a maximum in storm report frequency (Figs. 7a, 7d, 7g, and 7j). It is worth noting that the maximum in low-level convergence is located exactly where it would be predicted by conceptual models of curved jet streaks. The surface low in the composite cyclonic jet streak is located where quasigeostrophic processes like differential temperature and vorticity advection would contribute to lowering surface pressure. Also, note that the area where relatively strong low-level convergence occurs also tends to have low-level wind shear (Fig. 9g) and CAPE (Fig. 9d) sufficient for severe storms.

For anticyclonically curved jet streaks (Fig. 9b), an area of surface low pressure exists in the right-entrance quadrant. Similar to the cyclonic jet streaks, an area of strong relative convergence coincides with this area of low pressure, except it is not as strong as in the cyclonic jet streak composite. Also similar to the cyclonic jet streak composites, the storm report distributions for anticyclonic jet streaks correspond very closely to the area of relatively strong low-level convergence in the anticyclonic jet streak composite. The surface low in the anticyclonic jet streak composite is located where quasigeostrophic forcings would contribute to lowering surface pressure in a jet streak that had rounded the base of a trough and was entering the top of a ridge. Relatively high values of CAPE (Fig. 9e) and SRH (Fig. 9h) extend farther rearward and toward the cyclonically sheared side of the jet streak in the right-entrance region than for the cyclonic jet streak composite (Fig. 9d and 9g), which likely reflects warm sectors extending farther rearward in anticyclonic relative to cyclonic jet streaks. In general, combinations of favorable shear and

![Diagram](image-url)
instability for severe storms cover the largest area in the anticyclonic jet streaks. However, the coverage of severe reports (Fig. 7) is similar to that in linear jet streaks, which have a larger region favored for severe weather by upward motion as inferred from the jet-transverse cross sections of vertical velocity (Figs. 8d–i). The composite MSLP for linear jet streaks (Fig. 9c) resembles that for cyclonically curved jet streaks, except...

Fig. 7. Distribution of total storm report frequencies associated with (a) cyclonic, (b) anticyclonic, and (c) linear jet streaks. (d–f), (g–i), and (j–l) Same as in (a–c) but for tornado, hail, and wind reports, respectively.
the low pressure center is slightly farther toward the cyclonically sheared side of the jet streak and the associated low-level convergence is weaker. Also, low-level convergence and relatively high values of SRH (Fig. 9f) extend farther rearward into the right-entrance region than in cyclonically curved jet streaks, but not as much as in the anticyclonically curved jet streaks.

d. Effects of jet streak direction

To examine what impact the direction of the jet streak may have on severe weather reports, jet streaks are categorized into six ranges of directions: SSW (180°–210°), SW (210°–240°), WSW (240°–270°), WNW (270°–300°), NW (300°–330°), and NNW (330°–360°). Ninety-eight percent of the jet streaks analyzed fell within these ranges. The remaining 2% of jet streaks, which had directions with easterly components, were not analyzed because they represented such a small sample of cases.

WSW jet streaks were most frequent (27.1%), closely followed by SW jet streaks (24.0%), and then WNW (18.5%), NW (12.3%), SSW (11.8%), and NNW jet streaks (4%; Fig. 10). Generally, the ranking of percentages of storm reports associated with each jet streak direction followed the ranking of jet streak percentages, but the SW and WSW directions were especially active with the percentage of storm reports higher than the percentage of jet streaks (Fig. 10).

For SSW jet streaks, storm reports are concentrated in the right-entrance region with many fewer reports occurring in other quadrants (Figs. 11a, 11g, 11m, and 11s). For the other two directions with southerly components (SW and WSW), the frequency of storm reports increases...
noticeably relative to SSW jet streaks in all jet quadrants (Figs. 11b and 11c, 11h and 11i, 11n and 11o, and 11t and 11u), and the distribution of storm reports appears much more uniform. However, wind reports associated with these two directions are most concentrated in the right quadrants, and high relative frequencies of all storm reports tend to extend farther toward the cyclonically sheared side of the WSW jet streaks compared to SW jet streaks. As jet streak directions rotate from WNW to NNW, storm report frequencies decrease markedly and there is a tendency for reports to be increasingly concentrated in the exit regions.

Jet streak composites of divergence for SSW/SW jet streaks (180°–240°; Fig. 12a) show two centers of maximum divergence located in the right-entrance and left-exit regions. The divergence center in the right-entrance region extends forward along the jet streak into the right-exit region, so that almost the entire right-exit region experiences divergence. As the jet streak directions rotate from the SSW/SW (240°–300°) to the NW/NNW (300°–360°; Figs. 12b and 12c), the area of divergence in the right-exit and entrance regions shrinks and decreases in intensity, as does the divergence center in the left-exit region. In addition, areas of convergence in the left-entrance and right-exit regions expand and extend into areas of the right-entrance and left-exit regions, while also increasing in intensity. Generally, as jet streak directions rotate clockwise, there is a trend toward increasing convergence within the entire jet streak. The exit and entrance region jet-transverse cross sections of vertical velocity (Figs. 12d–i) reflect these changes in divergence–convergence. For SSW/SW jet streaks, the jet-exit region (Fig. 12d) experiences upward vertical motion throughout most of the troposphere. As the directions rotate clockwise (Figs. 12e and 12f), this upward motion decreases in intensity and is replaced by increasing downward motion, especially in the right-exit region. The jet-entrance region
jet-transverse cross sections (Figs. 12g–i) reveal similar trends. For SSW/SW jet streak directions, maxima in upward and downward vertical velocities in the left- and right-entrance regions, respectively, occur in the mid-troposphere, with the upward motion maximum being most intense (Fig. 12g). However, as the directions rotate clockwise (Figs. 12h and 12i), the downward maximum in vertical velocity becomes more intense and expands, and the upward motion maximum disappears. The upper-level divergence pattern for WSW/WNW jet streaks (Fig. 12b) most closely resembles that of the 4QM and appears very similar to that of linear jet streak composites, respectively. Thus, it does not appear that only changes in curvature explain the divergence–vertical velocity patterns as jet streak directions change.

To more clearly show the trends in vertical velocities as jet streaks shift from SSW to NNW, direction–distance diagrams of 500-hPa vertical velocity averaged in the along-jet direction (similar to time–latitude or Hovmöller diagrams often used in diagnostic studies) are constructed for jet streak exit and entrance regions (Fig. 13). In the entrance region (Fig. 13a), as jet streak directions rotate clockwise, an upward–downward motion dipole, with the upward motion component in the right-entrance quadrant being most intense, transitions to a dipole with the downward motion component in the left-entrance quadrant being most intense. In the exit region (Fig. 13b), as jet streak directions rotate clockwise, upward motion in both the left and right quadrants weakens and begins to transition to downward motion when jet streaks begin having a northerly component. These changes in vertical velocity with shifting jet streak directions may imply that the vertical velocities within jet streaks are partially a function of jet streak position relative to a long-wave trough. In other words, jet streaks with a northerly (southerly) component are likely located on the backside (frontside) of a long-wave trough where differential vorticity and temperature advection on larger scales contribute to downward (upward) motion.

The trends in storm report distributions with changing jet streak direction (Fig. 11) are not completely consistent with the trends in upper-level divergence or vertical velocities (Fig. 12). For example, the strongest upward vertical velocities occur with SSW jet streaks, but a disproportionately large number of storm reports occur with SW and WSW jet streaks (Fig. 10), which have weaker upward vertical velocities. This inconsistency may be explained by examining composites of CAPE and SRH. For SSW jet streaks, a maximum in SRH (Fig. 14m) is located in the right-exit region, not collocated with relatively high values of CAPE (Fig. 14g) found in the right-entrance region. However, for SW and especially WSW jet streaks, there is much more overlap between relatively large values of CAPE (Fig. 14h and 14i) and SRH (Fig. 14m and 14n) in the
right-exit region. For WNW jet streaks, the collocation of CAPE (Fig. 14j) and SRH (Fig. 14p) is similar to that of SW and WSW jet streaks, but the magnitude of SRH is smaller in the WNW jet streaks. In addition, low-level convergence is weaker and MSLP is higher in WNW relative to SW and WSW jet streaks, which likely explains the drop in storm report frequencies as the jet streak direction shifts from WSW to WNW. For NW and NNW jet streaks, relatively high values of CAPE are located in the right-exit region, but the maximum in SRH shifts rearward into the right-entrance region, so that the two parameters are not collocated.

Generally, the analysis in Fig. 14 indicates that SW and WSW jet streaks result in the most favorable configuration of low-level winds and instability for severe weather, so that even though these jet streaks do not have upward vertical velocity as strong as SSW jet streaks, these jet streak directions are associated with the majority of storm reports. Also notice that, as the jet streak direction rotates clockwise, a closed area of surface low pressure centered along the major jet axis in the exit region (Fig. 14a) weakens and shifts downstream and toward the cyclonically sheared side of the jet streak. A trough of low pressure trailing from this closed surface low (implying the average location of cold fronts) into the right-exit and right-entrance regions also shifts farther downstream, suggesting that warm sectors occupy a decreasing area within the jet streak as the direction shifts clockwise.

### 4. Summary and discussion

The climatology of storm reports (tornado, hail, and wind) relative to upper-level (250 hPa) jet streaks was analyzed, and composites of upper- and low-level wind and divergence fields and other severe weather parameters were generated. The correspondence of the storm report distributions relative to features in the composite analyses was examined, and comparisons were made to the vertical circulations predicted by conceptual models and idealized numerical simulations of curved and linear jet streaks. The time period March–September 1994–2004 was used in the analysis, and jet streaks occurring at 0000 UTC with associated storm reports...
occurring ±3 h from 0000 UTC were considered. The results obtained are summarized below.

The most storm reports (jet- and non-jet-related) occurred in June, but the peak month for jet-related storm reports was May. On average, 84% of storm reports were associated with jet streaks, but this percentage was markedly lower during the warm season months of June–August than in other months analyzed.

In March and April (after April) the left-exit (right entrance) region was the jet quadrant with the most storm reports. The right-entrance region always had more reports than the left-entrance region, and the left-exit region had more (less) reports than the right-exit region during March and April (after April).

Composite storm report distributions revealed that reports were concentrated in one region along the major jet axis in the exit region, and in another region in the right-entrance quadrant. Tornado reports were most concentrated in the exit region, hail reports were about evenly distributed between the two regions, and wind reports were mostly concentrated in the right-entrance region.

Composite upper-level divergence fields and jet-transverse cross sections of vertical motion were generally consistent with the 4QM, although differences in the intensities of the divergent–convergent centers and locations of the vertical circulations relative to the jet streak implied that jet curvature may have had some effects. Also, downward vertical velocities were relatively weak and only extended down to the midtroposphere in the right-exit quadrant of the composite jet streak, with upward motion in the lower to midtroposphere. Composites of MSLP, low-level convergence, CAPE–convective inhibition (CIN), and SRH were all favorable for severe weather in the right-exit region,
which counteracted the jet-induced downward vertical motion favored in this quadrant, and explained the relatively high frequency of storm reports.

Composites for cyclonic, anticyclonic, and linear classifications of jet streak curvature were also generally consistent with conceptual models for jet streaks. Rather than the four-cell pattern of upward–downward vertical motion in linear jet streaks, the cyclonic and anticyclonic jet streaks had two main areas of upward and downward motion. The composite for anticyclonic jet streaks had the strongest vertical motion, and linear jet streak composites had the weakest vertical motion. Despite having the weakest vertical motion, linear jet streaks had storm report frequencies comparable to cyclonically and anticyclonically curved jet streaks. In general, the distribution of storm reports for the different classifications of curved jet streaks coincided with the regions where the upward vertical velocities were largest. However, for linear jet streaks, wind reports were much more frequent in the right-entrance region than in the left-exit region, where upward vertical velocities were slightly weaker. It is speculated that the wind report maxima in the right-entrance region for linear and anticyclonic jets may reflect occurrences of long-lived MCSs (i.e., derechos) that may be most frequent in this quadrant. This speculation is supported by cluster analyses of 250-hPa geopotential height and wind patterns associated with derecho events (Coniglio et al. 2004). For the three main patterns associated with derecho events (500-hPa upstream trough, ridge, and zonal patterns), “clusters” with an average derecho location in the right-entrance region of an anticyclonic or
linear 250-hPa jet streak accounted for 60 of 114 cases in Coniglio et al. (2004).

Composites for different jet streak directions revealed that SSW jet streaks were associated with the strongest upward vertical velocities, and there was a trend for decreasing upward vertical velocities as jet streak directions rotated clockwise. These trends in vertical velocity with shifting jet streak direction likely reflect the jet streak position relative to a long-wave trough [i.e., northerly jets are typically between a ridge (trough) and downstream trough (ridge), where largescale processes favor descent (ascent)]. The majority of storm reports were associated with SW and WSW jet streaks, which were associated with modest jet-induced upward vertical velocities and the best combination of winds and instability for severe weather.

Identifying favorable regions for the development of severe weather is a challenging aspect of operational forecasting, and many different fields/parameters must be considered when generating severe weather forecasts. Consideration of the 4QM and the position of upper-level jet streaks relative to low-level features is helpful when determining risk areas, and the results from this study should provide additional insight to forecasters when considering the influence of upper-level jet streaks on severe weather potential.

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FIG. 14. (a)–(f) Same as in Fig. 5b but for (a) SSW, (b) SW, (c) WSW, (d) WNW, (e) NW, and (f) NNW. (g)–(l) Same as in (a)–(f) but for surface-based CAPE (J kg$^{-1}$; shaded) and CIN (J kg$^{-1}$; dashed contours). (m)–(r) Same as in (a)–(f) but for 0–3 km SRH (m$^2$ s$^{-2}$).


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