A Synoptic Analysis of the First AVE-SESAME '79 Period

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Abstract

Fields of divergence, vertical motion, stability, and surface pressure tendency are examined at 3 h intervals for the first regional scale AVE-SESAME '79 (Atmospheric Variability Experiment—Severe Environmental Storms and Mesoscale Experiment) day. Two areas of severe storms formed during the period from 1200 GMT 10 April through 1200 GMT 11 April. The Red River Valley outbreak began during the afternoon of 10 April, while a second area formed in southwestern Texas during the early evening hours. Results show the rapid changes in environmental conditions associated with these two storm areas.

The propagation of an upper level jet streak into the region was a major factor in producing the Red River Valley outbreak. This streak was associated with the formation of a strong low-level jet and a small-scale surface pressure perturbation. The sudden development of a strong upper tropospheric wind maximum over Oklahoma and Kansas corresponded with major changes in kinematic parameters at that level. Instability over the Red River Valley was released by strong upward motion producing intense convection.

Similar features were responsible for the storms in southwestern Texas. Although this area was quite unstable, forcing mechanisms appear somewhat weaker than in the earlier outbreak.

1. Introduction

During the spring of 1979, NASA, NOAA, NSF, and other governmental agencies participated in a field experiment to learn more about the structure and dynamics of mesoscale systems. This project has been called AVE-SESAME '79 (Atmospheric Variability Experiment—Severe Environmental Storms and Mesoscale Experiment). The first regional scale day of AVE-SESAME '79, 10-11 April, coincided with the formation of two major areas of severe local storms. Figure 1 shows locations of these storms and reporting stations in the region. The first area occurred between approximately 1800 and 0200 GMT in the Red River Valley region of Texas and Oklahoma. Alberty et al. (1980) have documented 12 tornadoes in this area, including deadly storms of F3 intensity or greater at Wichita Falls (SPS); Vernon, Tex.; and Lawton, Okla. By the end of the day on 10 April, 56 people had died, 1916 were injured, and damage estimates totaled several hundred million dollars (NOAA, 1980). Later in the evening, a new area of storm activity formed in southwestern Texas near San Angelo (SJT). This activity resulted in several tornadoes that caused injuries and heavy rural damage (Alberty et al., 1980). Thunderstorm activity became less violent as it moved into eastern Texas and Arkansas during the early morning of 10-11 April.

Three hourly regional-scale rawinsonde data, along with other specialized data (e.g., aircraft, Doppler radar, satellite, etc.) collected during AVE-SESAME '79 ensure that many detailed studies will be conducted to unravel the mysteries of this period. Results from several investigations already have been reported (e.g., Moller, 1980; Carlson et al., 1980). The objective of this article is to provide a general scenario of those key features that are believed to have played signifi-
common release time by performing linear time interpolation similar to that used by Fankhauser (1969). As part of the process, missing data were interpolated in time from available soundings if the time interval was 6 h or less; otherwise, the sounding remained missing. The reconstituted data were transferred to a 127 km grid at the surface, and at 50 mb intervals from 900 mb to 100 mb, by using the Barnes (1964) objective analysis scheme. Adjustments for balloon drift downwind from release, which averaged 90 km at 100 mb but reached 153 km in some cases, were included in the procedure. The kinematic method then was used to compute vertical motion. Surface values of ω incorporated the effects of terrain, local pressure changes, and cross-isobaric flow; however, their combined effects generally were less than 1 μb s⁻¹, except over mountainous terrain. Vertical motion and divergence were adjusted using the O'Brien (1970) technique, with values of ω at 100 mb assumed to be zero. The adjustments to divergence were a linear function of pressure in this procedure. Before application of O'Brien's technique, the mean and standard deviation of vertical motion at 100 mb were 0.5 and 10.2 μb s⁻¹, respectively. Since these values were nearly an order of magnitude larger than corresponding adiabatic vertical motions, a feature also noted by Fankhauser (1969), the adjustment was deemed appropriate.

3. Synoptic analyses
   a. Initial conditions

Synoptic conditions at 1200 GMT 10 April are shown in Fig. 2. At the surface (Fig. 2a), an anticyclone centered over the upper Great Lakes bathed the eastern half of the country with cool, dry air. A deep cyclone having a 988 mb center was located over the Colorado–Wyoming border, and was the pivot point for a cold front extending southward into New Mexico, and a stationary front extending into Nebraska and Kansas. A stationary front was positioned along the Gulf Coast. During the day, the circulation around the low carried warm, moist air over southern Texas, as the stationary front along the Gulf moved northward as a warm front. A dry line seemed to be developing in western Texas, since dew points of 21°F at El Paso and 9°F at Marfa were juxtaposed with values in the 50s and 60s in central Texas. West Texas and Oklahoma are climatologically favored regions for dry line development, because dry air from the west often meets warm, moist air from the Gulf region. Further study will be necessary to determine whether the dry air mass was due to subsidence (Schaeffer, 1974) and/or transport from the Mexican plateau as proposed by Carlson et al. (1980).

At 850 mb (Fig. 2b), a closed low was located over southern Colorado, while a ridge stretched from the southeastern states through the Mississippi River Valley. As at the surface, warm, moist air from the Gulf of Mexico was being advected northward into Texas and Oklahoma. Further aloft at 700 mb (not shown), southwesterly flow carried dry air over the Red River Valley. This differential advection in the vertical, due to directional shear, helped
create a region of convective instability over southern Texas. An amplifying baroclinic wave was the dominant feature at 300 mb (Fig. 2c). This system exhibited a negative horizontal tilt as it stretched from Washington into southwestern New Mexico. A weakening short wave extended in a northwest to southeast direction through the Midwest, while a ridge was located from the middle Mississippi River Valley into the Dakotas. Although poorly resolved because of a sparsity of Mexican radiosonde reports, a jet streak with maximum winds greater than 110 kt can be seen in northern Mexico, moving around the base of the trough. This jet streak moved northeastward, eventually passing into southwestern Oklahoma by the end of the AVE–SESAME period (1200 GMT 11 April). The subtropical jet stream was centered between 200–150 mb and stretched from southern Texas to along the Gulf Coast states. At 300 mb, it appears only as a region of strong winds.

b. Upper-level 3 h variability

The special three hourly rawinsonde data now will be used to describe regional conditions that led to the Red River Valley outbreak. The discussion begins at 1800 GMT 10 April and includes conditions at 2100, 0000, and 0300 GMT. At 1800 GMT, the main jet streak with peak winds greater than 100 kt at 300 mb is located over the southwestern edge of the region (Fig. 3a). This streak is just west of a short wave trough whose axis lies from near Albuquerque through the Big Bend of Texas. Wind speeds decreasing to around 65 kt and strong contour diffluence can be noted in the exit region of the streak located over north-central Texas.

Dramatic changes occur in the flow at 300 mb during the next 3 h ending at 2100 GMT (Fig. 3b). The most striking difference is the increase in wind speed over Oklahoma. Winds increase from 75 kt over both Gage (GAG) and Oklahoma City (OKC) at 1800 GMT, to 115 kt and 125 kt, respectively, at 2100 GMT. The short wave over western Texas is located between the newly-formed wind maximum over Oklahoma, and the main jet streak farther west. A later section will suggest that the wind maximum was associated with enhanced upward vertical motion and strong upper-tropospheric divergence. Although this apparently non-convective change in wind speed is hard to explain at this time, it and the associated variations in kinematic parameters have similarities to environmental changes, attributed to convective storm inducement (e.g., Fritsch and Maddox, 1981a, b; Fuelberg and Scoggins, 1978). Unfortunately, it is not a trivial task to isolate the suspected feedback mechanisms from variations that are not storm-induced. More detailed analyses are underway to explain the sudden formation of this wind maximum. At 0000 GMT 11 April (Fig. 3c) the isotach analysis shows the movement of the wind anomaly into Kansas. Finally, by 0300 GMT (Fig. 3d) the main jet core is advancing into southwestern Texas as wind speeds over north-central Texas increase.

c. Low-level 3 h variability

The sequence of 850 mb maps shown in Fig. 4 reveals the development of a pronounced low-level jet (LLJ). At 1800 GMT, the regional scale chart (Fig. 4a) reveals a 60 kt wind maximum over El Paso, but this is probably a lower extension of the major jet core aloft, since the winds have more of a westerly component than at other nearby stations. A secondary wind maximum of 35 kt occurs over southeastern Texas. Continuity suggests that this is the region of LLJ development. By 2100 GMT (Fig. 4b), a significant southerly LLJ core of 45 kt is located over northeastern Texas. LLJ formation apparently follows the mechanism proposed by Uccellini and Johnson (1979) and Uccellini (1980) in
which upper- and lower-level jet streaks are coupled through mass and momentum adjustments. Strong surface-pressure falls occurring in northern Texas (see Section 3f) support this hypothesis. In addition, strong upper tropospheric divergence occurs over the region. At 1800 GMT (not shown) the 300 mb divergence over the Red River Valley area was $4 \times 10^{-5} \text{s}^{-1}$, but this increases to $10 \times 10^{-5} \text{s}^{-1}$ only 3 h later (Fig. 5b). It is difficult to relate the divergence patterns to specific quadrants of the upper-level wind maxima, as was done by Sechrist and Whittaker (1979). We hope future studies will unravel the complex interactions in this highly ageostrophic region.

The developing LLJ induces the formation of strong low-level convergence over north-central Texas and Oklahoma, with values as great as $6 \times 10^{-5} \text{s}^{-1}$ (see Fig. 5a). This is the result of speed convergence to the north and west of the jet core, and directional convergence (confluence) between central and western Texas. Thus, it appears that the LLJ interacts with the low-level extension of the main jet core found farther west, to create a significant low-level convergence zone over the Red River Valley.

The LLJ moves northward and develops an eastward extension by 0000 GMT (Fig. 4c). Westerly momentum continues to move into southwestern Texas, leading to continued strong directional convergence over the same area. Finally, by 0300 GMT (Fig. 4d), the LLJ shows an eastward shift toward Arkansas, along with strengthening to 70 kt.

The analyses reveal that the LLJ is not confined to the boundary layer, and does not have significant diurnal variability. The appearance of a new wind maximum near Abilene, Texas (ABI) should be noted. This weaker, more confined perturbation apparently plays a role in the development of convective activity over southwestern Texas between 0000 and 0300 GMT.

\section*{d. Stability}

Dramatic changes in stability occurring between 1800 and 0000 GMT help produce an area which is conducive to
severe storm development. Fields of lifted index (LI) for 1800, 2100, 0000, and 0300 GMT are shown in Fig. 6. At 1800 GMT (Fig. 6a), values of LI less than zero cover most of Texas, with greater instability (LI < -4) over south-central Texas. Strongly stable conditions dominate the region to the north and east over Missouri and Tennessee. By 2100 GMT (Fig. 6b), the -2 and -4 contours have shifted northward toward the Red River Valley. The initial convection forming near Lubbock (LBB) and Stephenville (SEP) between 1700 and 1900 GMT develops on the northern fringes of the most unstable region near strong low-level convergence. Significant stability changes occur between 2100 and 0000 GMT (Fig. 6c), when the -2 isopleth moves northward into western Oklahoma, while values of -4 lie just south of the Red River Valley. An examination of individual soundings reveals that decreasing values of LI primarily result from low-level warming, which is associated with surface heating and the LLJ. The even greater instability (LI ≤ -6) covering southern and central Texas is associated with the second area of storms that developed between 0000 and 0300 GMT. By 0300 GMT (Fig. 6d), values in this area have decreased to -8.

e. Vertical motion

Fields of vertical motion at 500 mb show the rapidly evolving conditions that are conducive to severe storm development over the Red River Valley. At 1800 GMT (Fig. 7a), two centers of upward motion are located over the AVE–SESAME region. The strongest, having values near -9 μb s⁻¹, is located over New Mexico, while a secondary maximum of -6 μb s⁻¹ occurs near the Red River Valley. Downward motion stretches from Arkansas into the Ohio River Valley.

Vertical motion changes dramatically between 1800 and 2100 GMT (Fig. 7b), especially over the Red River Valley, where magnitudes nearly triple, now being -18 μb s⁻¹. This increase is closely related to the sudden appearance of the upper-level wind maximum over Oklahoma that was noted...
earlier (Fig. 3b). The area of strongest upward motion is located near the wind maximum, and is supported by strong low-level convergence and upper-level divergence (Fig. 5). These dynamic forcing mechanisms, coupled with decreasing stability (Fig. 6), create ideal conditions for intense convection.

By 0000 GMT 11 April (Fig. 7c), the magnitude of upward motion increases to near \(-20\) \(\mu b\) s\(^{-1}\), as the area moves northeastward into central Oklahoma. Upward motion over southwestern Missouri increases from \(-2\) \(\mu b\) s\(^{-1}\) at 2100 GMT to \(-11\) \(\mu b\) s\(^{-1}\) at the present time. During the preceding 6 h, an area of downward motion develops over southern Texas and merges with a pre-existing area over Arkansas. Two areas of ascent are apparent at 0300 GMT (Fig. 7d). One is located over the Red River Valley, while the second is found over central Kansas. Maximum values decrease slightly to near \(-14\) \(\mu b\) s\(^{-1}\).

f. Surface developments

The importance of regional maps of surface pressure and pressure tendency for diagnosing and forecasting severe convection has been noted in numerous studies (e.g., Moller, 1980; Whiting, 1957). Their importance stems from sensitivity to changes in net integrated divergence and density advection within a vertical column. This section will consider variations in surface pressure and dew point that occurred on 10 and 11 April, and will give brief descriptions of storm developments. Only highlights will be presented at this time, since additional, more detailed analyses are underway. Altimeter settings will be used to describe pressure and its changes. The values were obtained from the Service A teletypewriter sequences, and then subjectively checked for accuracy. Since they are determined by adding to each station pressure a factor that is based on the standard atmosphere, the settings are not affected by local variations in surface temperature, as are sea level pressures.

The surface pressure field changed little between 1200 and 1400 GMT (not shown). By 1500 GMT, a trough was forming along a northwest–southeast line from New Mexico into western Texas (not shown). To the west of the trough, surface winds were westerly at about 20 kt gusting to 34 kt. In addition, the dry line was undergoing rapid development nearby. For example, the dew point gradient between Roswell, New Mexico, and Lubbock (LBB) increases from 4°F/100 km at 1200 GMT to 11.3°F/100 km at 1500 GMT, apparently because of moisture convergence associated with the developing pressure perturbation. The isallobaric chart for the 1500–1800 GMT period (Fig. 8a) shows a negative maximum of \(-0.10\) in./3 h \((-3.4\) mb/3 h) in the Texas panhandle. Corresponding to these falls, the surface trough shows continued development near the Texas–New Mexico border at 1800 GMT (Fig. 9a). The dry line shifts eastward as westerly flow continues to the rear of the trough (Fig. 9a). Midland reports an 18°F decrease in dew point during this 3 h period.

As noted by Carlson et al. (1980), surface pressure tendencies between 1800 and 2100 GMT are the most dramatic of the 24 h AVE–SESAME period. Two axes of falls, with magnitudes near \(-0.20\) in./3 h \((-6.8\) mb/3 h) are observed (Fig. 8b). Semidiurnal pressure variations contribute approximately \(-0.04\) to \(-0.06\) in./3 h \((-1.5\) to \(-2.0\) mb/3 h) to these falls. One axis extends from near Amarillo (AMA) to Wichita Falls (SPS), while the other stretches from near Wichita Falls into northeastern Oklahoma. The pressure tendency equation indicates that pressure falls are the result of net integrated mass divergence in a column. In this case, the falls may be related to strong upper-level divergence (Fig. 5b) occurring downwind of the jet streak over Mexico, and near the smaller-scale wind maximum over Oklahoma (Fig. 3b), but more detailed studies are underway to evaluate the hypothesis. The pressure falls produce a closed perturbation over the Texas panhandle near 2100 GMT (Fig. 9b). Tegtmeier (1974) has noted that similar small-scale pressure perturbations, which he terms surface, subsynoptic-scale lows, are not infrequent during severe storm outbreaks. Moller (1980) has described the role of the current low in organizing strong surface
gradients of temperature and moisture.

Severe thunderstorm activity began at approximately 1735 GMT near Stephenville, Texas (SEP) where echo tops reached 50000 ft. An area of storms, which spawned several weak tornadoes, formed near Lubbock (LBB) around 1900 GMT. The radar summary for 2035 GMT (Fig. 10a) reveals strong convective activity in the vicinity of the pressure perturbation and to the northeast into Oklahoma, with both areas having maximum cell tops greater than 45000 ft. Weaker convection is located farther north and over Louisiana. The storms over Texas and Oklahoma are closely correlated with the area of maximum upward motion (Fig. 7b). GOES visible imagery for 2100 GMT (Fig. 11a) reveals several interesting features: 1) the strong dryline in central Texas, 2) blowing dust in the lower Texas panhandle and southern New Mexico, and 3) strong convective clusters over southwestern Oklahoma and the Texas panhandle. Severe tornado activity began in the Red River Valley near 2100 GMT. A discussion of these storm events is given by Alberty et al. (1980).

The isallobaric chart for the 2100–0000 GMT period reveals less impressive patterns than at earlier times (Fig. 8c). A broad region of rises is seen over southern portions of the Texas panhandle and New Mexico as cooler, drier air advances eastward. Complex patterns of pressure falls are found over much of the remainder of the area. Some of this complexity probably is induced by the thunderstorm activity. Figure 9c shows altimeter settings for 0000 GMT 11 April. Interestingly, the low neither deepens nor fills between 2100 and 0000 GMT; central values remain near 29.25 in. (991 mb) as it moves eastward to a position just west of Wichita Falls. The dryline now exhibits an eastward bulge (Fig. 9c) that previously has been related to severe storm development (Tegtmeier, 1974).

The radar summary for 2335 GMT (Fig. 10b) and GOES image for 2300 GMT (Fig. 11b) show a short line of thunderstorms extending from the Red River Valley toward the northeast, where it merges with a general area of

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FIG. 6. Lifted Index analyses.
thunderstorms stretching from southern Missouri into Colorado. The storms near Wichita Falls contained maximum tops up to 58000 ft. A "V" shaped area of cirrus outflow from these storms is evident in the GOES image. The Wichita Falls tornado touched down near 0000 GMT. That area is located slightly southeast of the area of maximum upward motion at 0000 GMT (Fig. 7c).

The three-hourly isallobaric chart for 0000–0300 GMT 11 April (Fig. 8d) shows rises over the southern Texas panhandle and complex patterns over Oklahoma and Kansas. The one-hourly isallobaric chart for 0100–0200 GMT, however, indicates a small-scale fall center near San Angelo (SJT) (Fig. 12). The surface map for 0200 GMT (Fig. 9d) reveals a narrow trough of low pressure extending southward from the weakening perturbation near Wichita Falls to the new fall center. The sparsity of surface data in the area makes a complete description of this new feature very difficult. The enhanced pressure gradient and strong directional shear over the area suggest a resurgence of surface moisture convergence.

Additional information about conditions over southwestern Texas is available from rawinsonde data at 0300 GMT. At 300 mb (Fig. 3d), there is only weak evidence in the height and wind fields to support the diagnosis of a short wave over the San Angelo area. At 850 mb (Fig. 4d), a wind maximum of 55 kt is located over Abilene (ABI). Although it is tempting to call this a second LLJ, it does not have the spatial or temporal continuity that was displayed by the LLJ that formed over northeastern Texas, now seen over the Oklahoma–Arkansas border.

Strong southerly flow over eastern Texas, juxtaposed with westerly flow over western regions, creates a zone of strong low-level convergence, resulting in upward vertical motions at 700 mb (Fig. 13). Two areas of ascent form along an axis from Del Rio to Wichita Falls. Magnitudes are as great as $-17 \mu b s^{-1}$ in the northernmost area, where convection associated with the Red River Valley outbreak continues; smaller values are found over the area toward the southwest.
Vertical motions near San Angelo at 500 mb (Fig. 7d) are somewhat weaker than those at 700 mb, suggesting that the dynamic forcing for the new storm area is confined to the lower portions of the troposphere. The upward motion, together with strong instability in the area (Fig. 6d), creates ideal conditions for additional severe storm development.

The earliest stages of new storm development are seen in the GOES image for 2300 GMT (Fig. 11b), which shows a narrow line of cumulus clouds in west-central Texas. The radar summary for 0235 GMT (Fig. 10c) shows the new storm area near San Angelo and the storms over the Red River Valley, with both regions having maximum tops greater than 50000 ft. GOES infrared imagery at 0303 GMT (Fig. 14) shows later developments. Three tornadoes in southwestern Texas had path lengths over 20 miles, and two paths were greater than 0.5 miles wide. In addition, there were numerous reports of hail >0.75 in. in diameter (Alberty et al., 1980). By 0300 GMT (Fig. 9e) strong pressure rises >0.12 in./3 h (>3.7 mb/3 h) near San Angelo considerably weaken the trough in that region.
4. Later conditions

Conditions during the later part of the AVE-SESAME period were less severe than those previously described. The thunderstorms of the Red River Valley outbreak near 0000 GMT moved northeastward into Oklahoma, with maximum echo tops remaining at or above 50000 ft. Several tornadoes were spawned from these storms until approximately 0600 GMT. Near 0700 GMT, as the storms over Oklahoma began to weaken, new development occurred in extreme southeastern Oklahoma and northeastern Texas. The most intense storms moved into central Arkansas by 1200 GMT, the end of the AVE-SESAME period. The secondary activity that formed near San Angelo between 0000 and 0300 GMT moved eastward across south-central Texas and
FIG. 11. GOES visible images for a) 2100 GMT and b) 2300 GMT 10 April.


Fig. 10. National Meteorological Center radar summaries.

First AVE-SESAME period are given in Fig. 15. At the surface (Fig. 15a), the low that was over northern Colorado 24 h earlier (Fig. 2a) has deepened 4 mb to 984 mb. A cold front stretches southward from near Oklahoma City to San Antonio, while the stationary front along the Gulf Coast at 1200 GMT 10 April, has moved northward as a warm front. The cold polar high over the Great Lakes has strengthened 8 mb while moving slowly eastward.

The 850 mb chart (Fig. 15b) features a jet streak from northern Louisiana into Tennessee with speeds up to 60 kt. A smaller wind maximum is located over southeastern Texas. These jet maxima advect warm, moist air northward over a broad region of the Mississippi Valley ahead of the advanc-
storms over the midwest and gulf coast states during the day of 11 April. Details of these storms are given by Alberty et al. (1979). Unfortunately, the special AVE-SESAME data period ended on 1200 GMT 11 April.

5. Summary

The outbreak of severe convection in the Red River Valley region of Texas and Oklahoma can be related to the development and space-time phasing of key hydro- and thermodynamic mechanisms. The features creating this severe storm scenario include:
FIG. 15. Same as Fig. 2 except for 1200 GMT 11 April.

1) propagation of a weak upper tropospheric short wave trough from New Mexico into the Texas panhandle;
2) eastward propagation of a jet maximum, which was rotating around a major trough located to the west of the AVE–SESAME region;
3) development of a strong wind maximum over Oklahoma and Kansas during the period 1800–2100 GMT and an associated rapid increase in upper-level divergence;
4) development of a small-scale pressure perturbation in the southern Texas panhandle;
5) creation of a LLJ over northeastern Texas, best defined at 850 mb;
6) development of low-level convergence ahead of and to the west of the LLJ, due to interaction of its primarily southerly momentum with westerly momentum in western Texas;
7) phasing of upper-level divergence and low-level convergence, which led to rapid changes in upward vertical motion over the Red River Valley between 1800 and 0000 GMT.

These processes, interacting in a highly nonlinear mode and phasing properly in space and time, decreased the stability over the Red River Valley. This instability then was released, as upper-level divergence and lower-level convergence created a strong region of upward vertical motion.

The resurgence of severe convective activity over southwestern Texas between 0000 and 0300 GMT 11 April contains some features similar to those noted above, yet they were more subtle and harder to resolve. This storm period was characterized by:

1) strong upward vertical motion over southwestern Texas, most pronounced in the lower levels;
2) appearance of a weaker low-level wind maximum having poorer continuity in space and time than the primary LLJ associated with the first storm area;
3) development of a local region of strong pressure falls whose pattern was lost after only one hour.

Thus, once again, over relatively small space–time scales, a secondary zone of severe convection arose. Certainly the differences between these two areas of severe weather need further study.

Perhaps the most important conclusion of the analysis is that there is a wealth of information in this, the first major three-hourly meso–α scale data collection experiment. These fields demonstrate how quickly the magnitudes of significant meteorological parameters can change over reduced time and space domains. More detailed studies of this case, the other AVE–SESAME periods, and future similar experiments, such as the VAS satellite demonstration, will shed considerable light on the sophisticated and complex nature of the severe storm environment.

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