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AN INVESTIGATION OF FORCING MECHANISMS DURING A SURPRISE TORNADIC THUNDERSTORM

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An Investigation of Forcing Mechanisms During a Surprise Tornadic Thunderstorm

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Abstract

On June 2, 1989 a tornado formed in the Missouri bootheel near the Arkansas border at a time and place where no severe weather was expected. The occurrence of the event was a surprise due to the existence of environmental conditions typically considered unfavorable for thunderstorm rotation. These included a vertical wind profile lacking both the speed and directional changes with height found conducive to mesocyclone formation.

Thunderstorms were triggered in a convectively unstable air mass by convergence along a weak surface front with further lifting provided by lower level differential heating with respect to surrounding areas. Remote sensing of the thunderstorm during its tornadic phase strongly suggest it was a non-supercell type. Thus, the tornado may have formed when the storm updraft converged and stretched positive relative vorticity which pre-existed near the intersection of the front and a weak surface trough.

1. Introduction

During the afternoon and early evening of June 2, 1989, severe thunderstorms developed over extreme eastern Arkansas and west Tennessee (Fig. 1). At 2015 UTC (all times Coordinated Universal Standard or Zulu) a storm near Blytheville Air Force Base (BYH) produced a tornado which was videotaped by a nearby resident and photographed by Air Force personnel. This tornado was on the ground about seven minutes but moved through an open field where it fortunately did no damage. About four hours later state police observed two small tornadoes near Bradford, Arkansas (70 miles northeast of LIT) which damaged some barns and blew down trees. In addition, thunderstorm straight line winds damaged two grain bins near Shearerville, Arkansas, about 10 miles west of Memphis (MEM), Tennessee while 3/4 inch hail was produced by storms just north of the city.

These storms formed in an environment in many ways considered unsuitable for severe or tornadic thunderstorms. Figure 2 shows the National Severe Storms Forecast Center's (NSSFC) 24 hour severe weather outlook issued just three hours before the Blytheville tornado. At 1900 UTC, NSSFC forecasted strongest potential for severe weather to be in western Oklahoma with a slight chance of severe convection as far east as extreme northwest Arkansas.

There are important reasons why eastern Arkansas and west Tennessee were not considered to have a risk of severe thunderstorms. Such storms have long been associated with a conditionally unstable air mass forced dynamically or mechanically upward. For example, Miller (1974) stressed that 500 mb positive vorticity advection (PVA) and its attendant upward vertical motion as the most important element in forcing an air parcel to its lifting condensation level. Palmein and Newton (1969) and later Holton (1979) explained how PVA near the level of non-divergence implied strong divergence near or just below the tropopause which, through mass continuity, forces low level convergence and upward vertical motion. Beebe and Bates (1955) as well as McNulty (1978) correlated 200 to 300 mb divergence with severe thunderstorm occurrence.

More recently, Maddox and Doswell (1982) demonstrated that thunderstorms could also produce tornadoes despite weak or even unfavorable middle and upper tropospheric dynamics. They found that upward vertical motion associated with lower tropospheric warm advection may prove adequate in itself to trigger severe thunderstorms.

The concept of Q-vectors is now being applied as a tool to predict regions of upward vertical velocity and accompanying thunderstorm genesis. Briefly, Q-vectors represent the ageostrophic wind resulting from frontogenetic forcing. An atmospheric layer where Q-vectors converge is one where the air theoretically rises in response to increases in the horizontal temperature gradient. In previous studies, Q-vector convergence at 700 and 500 mb correlated with thunderstorm development provided the air mass being lifted was unstable (Barnes, 1987).

As discussed in later sections of this paper, neither these nor other factors believed necessary for tornadic thunderstorms were present around the area of interest on this day. Thus there were no weather watches issued over the appropriate areas before severe weather occurred. The question remains as to why tornadoes formed on this day and if they may have been more accurately forecast.

This paper investigates these questions through a synoptic and mesoscale analyses of the Blytheville tornado based on conventional and non-conventional data sources. In particular it will be shown in greater detail why upper-level features may have dissuaded forecasters from alerting themselves to severe weather. Subsequent sections will analyze the vertical structure of the air mass to determine the convective potential and then show how this potential was released by forcing mechanisms located near or at the surface. A discussion is presented concerning tornadogenesis near Blytheville based on all available data including photographic records. The final section deals with how such tornadoes may be forecast in the future.

2. Data and Analyses Procedures

Surface temperature, wind, dewpoint and pressure data were obtained from NWS offices and from Federal Aviation Administration Flight Service Stations. In order to increase the number of pressure observations, this study uses altimeter settings since these are more commonly reported than are standard sea level pressures.

Upper air data was derived from standard NWS rawinsondes launched at 1200 UTC, June 2, and 0000 UTC, June 3, 1989. Soundings were plotted using special graphics programs run on the National Weather Service AFOS computer system. Certain lower and middle tropospheric kinematic and dynamic fields were evaluated and plotted by several applications programs used by the NWS forecast office at Memphis including the Upper Air/Quasi-Geostrophic Diagnostics Program (Foster, 1988). All programs are similar in that they use the Barnes objective analyses technique (Barnes, 1973) to interpolate data over a grid based on information provided at individual surface and upper air weather stations. By using finite differencing methods, fields such as Q-vector convergence, are evaluated for each point.

GOES infrared and visible satellite images, available every half hour, were also examined for this study. In addition, precipitation reflectivity values were obtained from the 10 cm non-coherent Weather Service Radar 74-C at Memphis which closely monitored the thunderstorms on this day. Both radar and satellite augmented surface data in locating boundaries induced by evaporative cooling. Satellite data greatly assisted in subjectively comparing the amount of radiational heating certain areas received based on relative cloud coverage.

3. Upper Tropospheric Analyses

Figure 3 shows the 1200 UTC analysis of 850 mb. Low pressure covered the Northern Plains and Great Lakes states while high pressure was along the coast of the Gulf of Mexico. This configuration produced a warm and humid west to southwest flow into the lower Mississippi valley at this level.

There was little else at 850 mbs favoring deep convection. Figure 4 shows very weak cold advection at 850 mb over the Tennessee-Arkansas border indicative of a lack of upward vertical motion just above the boundary layer. A diffuse front may have extended between central Illinois and western Kentucky but based on the 850 wind velocities, it was unlikely that the cooler air mass over Illinois would push south at this elevation. Further analyses (not shown) indicated little moisture convergence in the area where the severe thunderstorms later occurred. Wind speeds through the region were unimpressive, ranging around 10 to 15 miles an hour. Miller (1972) considered lower tropospheric wind speeds under 20 miles an hour as being unfavorable for severe thunderstorms.

There was some evidence of a weak short wave through north central Arkansas as the wind displayed horizontal cyclonic shear between southwest Missouri and west Kentucky. This feature may have been a wind perturbation or the remnants of a wake depression resulting from earlier convection. Height (or pressure) fields don't support the existence of an 850 mb trough in this location and as seen below, there is little evidence it was contributing to upward motion. There was no evidence of a short wave over northwest Tennessee 12 hours later indicating the perturbation may have damped out before reaching the Mississippi river.

The 700 mb environment was similar to 850 mb in that there was little support for deep convection (Fig. 5). There was neutral temperature advection and the air mass was moist with dewpoint depressions generally 5 degrees C or less around BYH. Note that the 700 mb temperature and wind fields indicated an almost barotropic atmosphere. Thus, frontogenetic forcing did not exist at this time and location. Figures 6 and 7 show Q-vectors exhibiting weak divergence through the region of interest suggesting that vertical motion, if any, was downward.

At 500 mb (Fig. 8) a primarily zonal flow was established through the middle and lower Mississippi valley due to the combination of low pressure over the northern United states and high pressure covering the Gulf coast. Thermal advection appears weak with temperature and wind fields again indicative of a quasi-barotropic environment over the south central United States (or Mid South) in the middle troposphere.

An examination of the 500 mb winds and moisture in conjunction with satellite imagery (Fig. 9) suggested a weak trough axis along the Mississippi River valley from southwest Tennessee to south central Louisiana. The air mass was moist through the upper troposphere ahead of this trough with extensive cloud cover and embedded deep convection (see section 4) through west Tennessee and northern Mississippi. In contrast, west of the trough, where one normally expects subsidence, the 500 mb air mass was considerably dryer with dewpoint depressions at or above 30 degrees C from central Arkansas to east Texas. This dryer air clearly was advecting into the Blytheville area.

Further support that the air subsided over eastern Arkansas comes from the 1200 UTC 500 mb wind-vorticity analyses (Figure 10). Combining the interpolated wind vectors and absolute vorticity contours shows weak negative vorticity advection over the region where the tornado occurred less than eight hours later. The analyses at 0000 UTC, 12 hours later (not shown) indicated neutral vorticity advection meaning that any upward dynamic forcing was unlikely during the early afternoon.

As implied in the introduction, if there is NVA or downward vertical motion at 500 mb, there must be convergence in the upper troposphere in order to comply with mass continuity requirements. To further explore this the 300 mb winds were examined (Fig. 11). At 300 mb, a weak trough axis appeared just upwind of the lower Mississippi valley from northeast Arkansas to southern Louisiana.

What is significant is that just ahead of the trough axis was velocity convergence at 300 mb over extreme eastern Arkansas with winds diverging over middle Tennessee and northeast Mississippi (Fig. 12). Convergence at 200 mb (not shown) also extended along the Arkansas-Tennessee border though it was somewhat weaker. Thus, the upper tropospheric kinematics further supported the notion of a subsiding flow aloft over the region which would later experience severe convection.

This case exemplifies that the vertical motion of an air parcel can be forced downward just to the east of an upper tropospheric trough. Petterson (1956) and Shapiro (1982) explain conceptually and mathematically the circumstances in which this can happen. In contrast, the classical or conventional model predicts rising motion over the eastern or exit region of an upper tropospheric trough.

Thus, there are numerous dynamic and kinematic factors throughout the troposphere which would be expected to inhibit thunderstorm development and especially tornadoes on this day over the Mid-South. It is therefore not surprising that little activity was predicted.

4. Vertical Analyses of the Regional Air Mass

A NWS rawinsonde was released at Paducah Kentucky (Fig. 13) or about 100 miles (170 km) from BYH at 1200. There was little temperature advection between 850 and 200 mb along the Tennessee-Arkansas border region with little moisture advection near the surface. Thus from a convective forecasting perspective, the thermodynamic profile obtained from the 1200 UTC balloon launch should closely represent the air mass in which a tornado later formed. However, the lowest 6500 feet (2000 meters) of the sounding in Figure 13 also contains a temperature plot based on 1900 UTC surface observations taken at BYH. In this manner changes in the boundary layer from diurnal heating were taken into account.

Paducah's rawinsonde shows parameters existed which favored at least moderate thunderstorms. The surface based lifted index, which was -5 at 1200 UTC further decreases to -9 by 1900 UTC due to surface heating, clearly indicating substantial instability. There was also no significant stable or inversion layer through the tropopause which means an air parcel required little lifting to reach the level of free convection.

While all thunderstorm updrafts need buoyant energy, empirical and numerical modelling studies (Weisman and Klemp, 1984) agree that tornadic thunderstorms usually form where the wind speed increases and wind direction veers with height. An updraft established in such an environment interacts with the winds through the lower and middle troposphere to produce mid-level cyclonic vorticity through the tilting of horizontal vortex tubes produced by such a vertical shear. Klemp and Rotunno (1983) explain how this process of vertical vorticity generation plays a crucial role in both thunderstorm rotation and updraft intensification.

In accordance with this concept, the bulk Richardson number has been used to determine how different combination of shears and buoyancies affect the type and severity of thunderstorms. This number is defined as:

$$R = \frac{B}{\frac{1}{2}U^2}$$

where B is the buoyancy (measured in joules/kg) and is equal to:

$$g \int \frac{\theta_z - \bar{\theta}_z}{\theta_z} \, dz$$

where θ_z is the potential temperature of an air parcel undergoing moist adiabatic ascent while $\bar{\theta}_z$ is the potential temperature of the undisturbed environment. B is therefore the sum of the temperature excess an updraft parcel has with respect to the environment and is proportional to the "positive area" on a skew-T diagram.

U is a measure of the mean vector wind shear. It is calculated by taking the difference between the mean wind speed over the lowest 6 km and the average wind between speed between the surface and 500 m above the ground. As discussed by Weisman and Klemp, U can also be interpreted as the net inflow of air into the updraft and can be considered as proportional to the updraft kinetic energy.

From the Paducah sounding we found R had a value of 75. Modelling results, as well as observational studies of past convective events (Weisman and Klemp, 1984), show non-severe multicell or short lived single cell storms predominate for values of R greater than 50. The range of R for most supercell or tornadic storms lies between 15 and 35.

This result can be explained by referring to the 1200 UTC Paducah sounding. The value of B was calculated to be near 2400 j/kg which is equivalent to a maximum updraft speed of 70 m/sec or about 35 miles an hour. Entrainment, water loading and friction may reduce this by up to 50 percent but such an updraft should still attain a speed large enough to generate a thunderstorm of at least moderate intensity. Empirical and modelling studies show that supercell thunderstorms or mesocyclones can and do form with buoyancy values around that observed near Blytheville on this day.

The R value exceeds that for the supercell category due to the weak vertical shear of the wind speed within the air mass. For example, the wind at 850 mb was from 270 at 15 kts and increases to only 25 kts from 250 degrees at 500 mb. Wind speeds near the surface or boundary layer were only around 5 kts at the time storms began. While vigorous updrafts could form within the air mass, they would get little dynamic support through interaction with the horizontal winds between the lower and middle layers. Thus, the evidence implies the BYH tornado may have formed from a non-supercell thunderstorm.

5. Surface Analyses and Antecedent Weather Conditions

At 1200 UTC synoptic scale surface weather features were weak over the middle and lower Mississippi valley and surrounding areas (Fig. 14). A high pressure center over the Florida panhandle created a weak southerly flow of warm humid air into the Mid-South. Both temperature and dewpoint were in the upper 60s to lower 70s (degrees F) through west Tennessee, east Arkansas and north Mississippi with winds only around 5 kts. Wind and pressure fields also showed a diffuse front extending from northeast Kentucky through extreme northwest Tennessee westward to northwest Arkansas.

Several factors showed that the front had little strength. First the winds both north and south of the front were only around 5 kts with the isobaric pattern across the frontal zone revealing a very weak trough. Second, the frontal zone near west Tennessee and east Arkansas was barely detectable at either 850 or 700 mb. Referring back to Figure 4, it is seen that north of the front, the 850 flow was advecting warmer air into western Illinois, otherwise the air mass was homogenous throughout the region. From this, one can conclude the front was not only weak and shallow but possibly in the process of dissipating. Nevertheless, despite the low wind speeds, directional components were northerly on the cool side of the front and southerly to its south. The frontal zone was therefore characterized by weak convergence and upward forcing near the boundary layer.

The weather was quite active over southwest Tennessee and northern Mississippi at 1200 UTC. The poorly defined mid-level short wave (see section 2) triggered thunderstorms with very heavy rainfall over and both east and south of Memphis (MEM). These storms were moving east at 15 miles an hour. Conversely, little significant weather approached the Blytheville area at 1200 UTC. High relative humidities associated with radiational cooling resulted in extensive fog over northwest Tennessee, eastern Arkansas and southern Missouri but all existing precipitation was moving away from the Mississippi valley.

The surface weather pattern became a bit more complex by 1500 UTC as shown in Figure 15. The isobaric configuration exhibited a weak trough through southern Illinois into north central Tennessee and central Arkansas. Based on the pressure pattern plus the wind and dewpoint discontinuities, the front was placed from south central Kentucky to northeast Arkansas with high pressure to the north over western Missouri. Wind changes indicated the front may have moved slightly northward near the Missouri bootheel since 1200 UTC. The situation was further complicated by the convective area which had moved into middle Tennessee and northeast Mississippi. By 1500 UTC, overcast skies and a rain cooled air mass covered much of middle Tennessee, northern Alabama and northeast Mississippi as indicated by the squall line symbol in Figure 15. The convective outflow, together with the front, confined the unmodified tropical air mass in a narrow area from northwest Tennessee to southwest Arkansas with cooler air to the northwest and southeast.

The relative sparseness of surface observing stations precluded a precise location of the cold front at 1800 UTC (Fig 16). Based on the temperature, dewpoint and altimeter data it was approximately from northwest Kentucky to somewhere in the Missouri bootheel east to northwest Arkansas. Temperatures north of the front were generally from the mid 70s to lower 80s with dewpoints in the lower to middle 60s. Meanwhile thunderstorms mixed with light rain were over the eastern half of Tennessee while scattered convection extended along an west-east line through northern Mississippi (Figure 17).

Temperatures varied from the mid 60s to near 80 within the area of rain cooled air while dewpoints were around 65 to 70. In west Tennessee and southwest Arkansas, the absence of both precipitation and a dense low cloud cover allowed the tropical air over the region to heat diabatically. By 1800 UTC, temperatures were in the middle 80s while dewpoints remained in the lower 70s. Thus, a narrow region of warm humid unstable air continued covering the Tennessee-Arkansas border area while cooler air remained over adjacent regions.

A persistent feature since 1500 UTC was a surface trough which was just west of the Mississippi river. Since the dynamics aloft (ie., upper tropospheric convergence and negative vorticity advection) favored surface pressure rises in this region, the pressure falls which accompany the trough can be attributed to differential diabatic heating at the boundary layer in the vicinity of the front (see McGinley, 1986). This concept is further supported by the trough axis almost coinciding with the axis of maximum temperature rises. Near and along this trough winds exhibited cyclonic curvature as well as weak convergence.

Finally Figure 18 depicts the 1900 UTC surface situation just over an hour prior to tornado formation. Jonesboro's (JBR) dewpoint dropped 5 degrees from the previous hour as its wind became northwesterly indicating the front had recently moved south of the station. The trough axis now intersected the front through BYH as pressures continued to fall near the Mississippi valley. Winds around this frontal-trough intersection again exhibited very distinct cyclonic relative vorticity with northwest winds at JBR giving way to a southwest flow at MEM and a southeast wind at Jackson, Tennessee (MKL). Winds at BYH remained calm.

The satellite picture near this time (Figure 19) showed low clouds associated with scattered convection continuing over middle Tennessee. Meanwhile, convection redeveloped over northern Mississippi during the previous hour. The position of an associated outflow boundary was estimated to extend from just west of Nashville (BNA) through northeast Mississippi south-westward to near the Arkansas border. Mainly middle and high level thin clouds covered skies over west Tennessee and eastern Arkansas between the outflow boundary and the front. Thus, the BYH vicinity remained within a narrow corridor of unmodified tropical air with clouds and rainfall keeping temperatures cooler to the east and south while slightly cooler Canadian air lies to the north and northwest. Furthermore, the surface trough which extended through BYH is again in the proximity of the surface thermal ridge axis. Wind directions suggested a mesolow center existed somewhere along a line connecting BYH and MEM at 1900 UTC.

6. Remote Sensing Analyses of the Blytheville Thunderstorm and its Tornado

Satellite images of the Mid-South region misled forecasters into not anticipating some kind of severe weather. The 1830 UTC picture in Figure 19 displayed only isolated convective cells of very small size near BYH. The remainder of east Arkansas and west Tennessee remained precipitation free. Main interest was to the south where thunderstorms increased in size and intensity.

One hour later, radar detected two small thunderstorm echoes north and northeast of BYH which strengthened rapidly. Tops at this time were over 40,000 feet while reflectivity values were about 55 dbz, correlating to a rainfall rate of at least four inches per hour. Despite the heavy precipitation implicit with these cells, there was little radar evidence that either storm contained a mesocyclone, or displayed supercell structure. Specifically, horizontal and vertical scans of the storms revealed neither a weak echo region nor hook. Such signatures usually (though not always) signify that a storm is cyclonically rotating and therefore conducive to tornado production (Lemon, 1977). Non-coherent radar (i.e., non-Doppler) in most instances detect such echo patterns within the 70 mile range which is the distance between the radar site at Memphis and Blytheville. In contrast, in their extensive study Wakimoto and Wilson (1989, hereafter referred to as WW) found hook echoes accompanying non-supercell tornadic storms are almost undetectable at distances over 20 miles due to their relatively small sizes.

Satellite images gave further credence to this idea. Figure 20 is an infrared-enhanced image of the BYH thunderstorm less than 15 minutes prior to tornadogenesis. At this time, the cell and its anvil were rather inconspicuous due to its relatively small size. In previous satellite investigations of thunderstorms (Adler and Fenn, 1979; Fujita, 1981), tornadic supercells usually produced a thick anvil extending to areas on the order of 10,000 square miles. In addition, areal divergences of such anvils can be large with values measured as high as 10^{-3} sec^{-1}.

The anvil of the BYH thunderstorms had an estimated area of under 200 square miles with little expansion prior to and during tornado formation. Indeed, the minuscule size of the anvil made it impossible to detect even a V-notch signature (Fujita,1981). More significant growth took place only after the tornado dissipated.

At 2015 UTC, Air Force observers at BLY issued an Urgent Special observation reporting a tornado just north of the base near the border of the Missouri bootheel. Almost simultaneously, a private citizen began videotaping the event from the town of Steele, Missouri.

In Figure 21, the tornado is comprised of a wall of cyclonically rotating dust beneath the dark base of its parent cumulonimbus cloud. The segment of the tornado contacting the ground had little or no visible connection to the funnel aloft throughout its lifetime. This characteristic is similar to non-supercell tornadoes studied extensively by WW. In contrast, supercell tornadoes almost always visibly extend from ground to thunderstorm cloud base. A second feature was that unlike a mesocyclone, the thunderstorm at BYH did not possess a wall cloud with a downdraft-induced clear slot wrapping cyclonically around it.

Finally, the camera visually recorded no lightning with the storm while one hears only an occasional rumble of thunder over audio portions of the tape. In contrast, mesocyclones are quite active electrically with frequent lightning (and therefore, thunder) in most examples (Rust et.al, 1981). Therefore, from the above discussion, the evidence is strong, if not conclusive, that the Blytheville tornado formed within a non-supercell thunderstorm that was in its development stage. The actual strength of the tornado in terms of the F-scale can not be determined as it had nothing within its path to damage.

7. Discussion of Forcing Mechanisms For the Tornadic Thunderstorm

It has already been shown that a moist convectively unstable air mass covered the region of interest during thunderstorm development. Concurrently, numerous kinematic and dynamic factors were present which would have forced weak downward motion between the 850 and 200 mbs. Obviously, mechanisms near or at the surface must have counteracted the forcing above and lifted the air mass to its level of free convection.

The most apparent of these lifting mechanisms was the weak surface front moving into northeast Arkansas from the northwest. That this feature forced the boundary layer upward was best illustrated in the convergence measurements around the area. Figure 22 shows a convergence maximum in the BYH vicinity as southwest winds east of the station shift to northwesterly immediately to the west. The resultant uplift was likely to be shallow but may have been adequate to lift an air parcel to the lifting condensation level which in this case was below 850 mb.

A second element to consider was the differential surface heating experienced along the Tennessee-Arkansas border and its connection to the surface trough. For example, with mainly a high thin cloud cover and no rainfall, BYH warmed from 72 to 87 degrees between 1200 and 1900 UTC. In the same period, the temperature at BNA in middle Tennessee increased from only 71 to 73 as overcast skies and evaporative cooling from a passing thunderstorm inhibited diurnal warming. Thus, the temperature difference between these two stations increases from 1 to 14 degrees over seven hours. Corresponding to this were the pressure tendencies during the same time period. From 1200 to 1900 UTC, pressures fell .06 of an inch at BYH with no net pressure change at BNA. As suggested earlier, the resulting pressure trough appears to enhance the local convergence and relative vorticity, especially near its point of intersection with the front.

From another perspective, when such differential heating occurs, the density and pressure differences associated with a strengthening temperature gradient drive a solenoidal circulation where the warmer air is ultimately forced upward. The best known examples of this type of circulation are the sea breeze and mountain-valley wind. However, Purdom (1973) has demonstrated that variations of the diurnal warming in cloud covered versus cloud free areas cause similar atmospheric responses.

A rate of increase in the circulation between pressure surfaces P_0 and P_1 is expressed by the equation:

$$\frac{dC}{dt} = R \ln\left(\frac{P_0}{P_1}\right) \quad \bar{T}_w - \bar{T}_c$$

where $\bar{T}_w$ and $\bar{T}_c$ are the mean temperatures (deg. C) of the warm and cool air masses respectively. For this study, a crude estimate can be made of the 1900 UTC solenoid between BYH and BNA within the 1000 and 850 mb pressure levels. Surface data is available from the hourly observations while the 850 mb height and temperature data are based on a temporal and spatial interpolation of the June 2nd, 1200 UTC and June 3rd, 0000 UTC regional rawinsondes. The resultant simplified cross-section is presented in Figure 23. In the diagram, T_w and T_c are 22 and 16 degrees C, respectively. This gives a rate of circulation increase of about 280 m^2/s^2 with the warm air branch of the flow rising over BLY or along the axis of maximum temperatures. In reality, surface winds between BYH and BNA had a weak easterly component with westerly wind components near 850 mb. Thus, a weak direct circulation formed between middle Tennessee and areas to the west.

One last contributor to thunderstorm development was that the air mass warmed near its temperature of free convection. The 87 degrees at BYH at 1900 UTC lowers the surface based lifted index to -9 within an environment which lacked a significant inversion or stable layer aloft. In fact, one could argue surface heating alone may have triggered the thunderstorm. The most we can conclude is the combination of frontal convergence, and strong differential diurnal heating of an unstable tropical air mass both contributed in generating a tornadic thunderstorm near BYH despite unfavorable dynamics in the upper atmosphere.

8. Possible Factors Contributing to Tornadogenesis

Tornado formation within the given environment becomes less difficult to understand when one accepts the premise that its parent thunderstorm was a non-supercell. In their comprehensive study WW as well as Brady and Szoke (1989) found the conditions necessary for such tornadoes include a moderately unstable air mass plus a surface boundary providing both convergence and comparatively high values of positive relative vorticity. The convergence can then act to trigger convective updrafts which in turn, amplify the pre-existing vorticity below to tornadic intensities. Figure 24, taken from WW illustrates this process.

It is hypothesized that this mechanism was largely responsible for the BYH tornado. The strongest evidence was that the thunderstorm was located near or along the cold front-trough intersection. This was similar to the WW conditions of a boundary intersection with both convergence and significant cyclonic vorticity as shown in Figure 25. To further understand this process we consider vorticity increases through the convergence term of the vorticity equation:

$$\frac{d\rho}{dt} = -(\rho+f)\nabla\cdot\mathbf{V}$$

where ρ is the relative horizontal vorticity of an enclosed area of air, f is its absolute vorticity and $\nabla\cdot\mathbf{V}$ is the horizontal convergence occurring within the region. From the continuity equation:

$$-(\nabla\cdot\mathbf{V}) = \frac{dW}{dz}$$

where w is the vertical velocity and z the height of the column of air being considered. In the case of an area beneath a single thunderstorm, w can be the upward motion of an updraft. For the BYH thunderstorm, an updraft speed was estimated at about 35 m sec^{-1} while the distance from the ground to clouds base was 3500 feet or about 1.2 km. Since vorticity values for tornadoes are of the order of 1 sec^{-1}, then it would take a thunderstorm over BLY only about 15 minutes to spin up the surface vorticity to tornadic intensities.

Of course this is a very crude estimate and oversimplification of the overall dynamics of convective storm rotation. Vorticity generation by tilting and solenoidal affects were ignored although modelling studies suggest they can play an important, if not primary, role in mesocyclogenesis. But as Rotunno and Klemp (1982) and others point out, vorticity generation in thunderstorms via tilting is highly dependent on relatively strong wind speeds through the troposphere with directional veering with height. As indicated in section 4, wind velocities in the lower and middle troposphere on this occasion were not conducive to mesocyclone formation around BYH and the storm itself was very likely a non-supercell.

Solenoidal contributions to convective vorticity intensification are much more difficult to consider and are almost impossible to predict prior to storm formation. It is dependent on rain-cooled air creating a localized baroclinic zone on the forward flank of the thunderstorm with the updraft intensifying the resultant circulation by both tilting and stretching. Since rain was already falling with the BYH thunderstorm during tornado formation, solenoidal affects may have contributed to the spinup process. Without a much higher data sampling as can be supplied by Doppler radar however, the actual importance of solenoidal vorticity generation can only be speculative.

9. The Blytheville Tornadic Thunderstorm as a Forecasting Problem

Although non-supercell tornadoes are usually weak, they have reached intensities of F4 (Wakimoto, 1983) which means they are capable of taking lives and demolishing homes. Thus, it is important to accurately predict these phenomena.

One problem is the synoptic or meso-alpha scale environment where non-supercell tornadoes can be generated is common and widespread over the United States during the warm season. Such an environment is weakly baroclinic with a convectively unstable air mass and relatively weak vertical wind shear. In the vast majority of cases however, tornadoes do not form under these conditions while the majority of those that do are short lived and cause minimal damage. Thus, non-supercell tornadoes often form in an environment which in most cases does not produce tornadoes. NSSFC could not realistically issue watches for such events without having an unacceptably high false alarm rate.

The thunderstorm forecasting aspect of this event is less of a dilemma. While it is true the upper troposphere had aspects weakly unfavorable for convection, the region did possess an unstable air mass with an approaching cold front at the surface. Differential heating of clear versus cloud covered regions has long been recognized as a subtle but effective thunderstorm trigger. Thus, it is realistic to expect forecasters to anticipate at least scattered thunderstorms for the area which, in fact, is what local WSFO offices did.

But this study still brings up questions concerning the forecasting of convection within an area of opposing circulations. For example, with how much certainty can a forecaster predict if and when dynamics aloft will suppress thunderstorms despite boundary layer convergence? Stensrud and Maddox (1988) studied a case where thunderstorms decayed at a time and place forecasters expected them to intensify. In their particular example, subsidence aloft inhibited thunderstorm formation despite the presence of a moist unstable air mass and strong low level convergence. Similarly, it was not totally obvious that frontal and solenoidal lifting near BYH would overcome downward forcing aloft. And with the available information, there was little reason to mention tornadoes or even severe thunderstorms.

Remote sensing using Doppler radar may resolve these problems. Concerning thunderstorm development, atmospheric profilers will provide hourly kinematic fields, including the vertical velocity profile with height. In this manner, forecasters will have data concerning the relative depth and strength of opposing circulations and at intervals greater than the 12 hours now available.

Tornado prediction is expected to improve with the arrival of NEXRAD or Next Generation Weather Radar. In the study by WW, Doppler radar detected clear air vortices or closed circulations along convergence lines before any precipitation began falling or thunderstorms formed. These vortices are usually 2 km (3.6 miles) in diameter or less and probably arise from horizontal shear instabilities. Tornadoes form when developing thunderstorm updrafts coincide in time and place with these circulations and consequently amplify the ambient vorticity by convergence.

Once NEXRAD becomes available to the NWS forecast and warning offices, weather forecasters can examine wind fields in greater detail along such convergence boundaries as cold fronts or trough lines where these shear instability vortices are present. If they exist and are within the path of approaching thunderstorms, the forecaster may be alerted to possible tornadogenesis in a situation where it is not normally expected using existing techniques. This especially includes locations where NSSFC has not issued a watch box due to unfavorable larger scale conditions.

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References

Adler,R.F., and D.D.Fenn, 1979: Thunderstorm intensity as determined from satellite data. *J. Appl. Meteor.*, **18**, 502-517.

Barnes,S.L., 1973: Mesoscale objective map analyses using weighted time series observations. *NOAA Tech. Memo. ERL NSSL-62*, Norman, Ok., 60 pp.

Barnes,S.L., 1987: Analyses of quasi-geostrophic forcing during the AIMCS project. Volume I: Discussion. *NOAA Tech Memo ERL ESG-27, Vol I.*, 31 pp.

Beebe,R.G. and F.C.Bates, 1955: A mechanism for assisting in the release of convective instability. *Mon. Wea. Rev.*, **83**, 1-10.

Brady,R.H. and E.J.Szoke, 1989: A case study of nonmesocyclone tornado development in northeast Colorado: Similarities to waterspout formation. *Mon. Wea. Rev.*, **117**, 843-856.

Foster,M.P., 1988: Upper air analyses and quasi-geostrophic diagnostics for personal computers. NOAA, NWS Southern Region Scientific Services Division, unpublished report.

Fujita,T.T., 1981: Mesoscale aspects of convective storms. *Proceedings, IAMAP Symposium: Nowcasting: Mesoscale Observations and Short Range Prediction*, Hamburg, European Space Agency, 3-10.

Klemp,J.B. and R. Rotunno, 1983: A study of the tornadic region within a supercell thunderstorm. *J. Atmos. Sci.*, **35**, 1070-1098.

Lemon,L.R., 1977: New severe thunderstorm radar identification technique and warning criteria: A preliminary report. *NOAA Tech. Memo. NWS NSSFC-1*, 60 pp.

Maddox,R.A., and C.A.Doswell III, 1982: An examination of jet stream configurations, 500 mb vorticity advection, and low level thermal advection patterns during extended periods of intense convection. *Mon. Wea. Rev.*, **110**, 184-197.

McGinley,J., 1986: Nowcasting mesoscale phenomena. *Mesoscale Meteorology and Forecasting*, Amer. Meteor. Soc., Boston Mass., pp. 657-688.

McNulty,R.P., 1978: On upper tropospheric kinematics and severe weather occurrence. *Mon. Wea. Rev.*, **83**, 1-10.

Miller,R.C., 1975: Notes on analyses and severe storm forecasting procedures of the Air Force Global Weather Central. *Air Weather Service Tech. Rep. 200* (rev.), Scott AFB, Ill., 94 pp.

Petterson,S., 1956: *Weather Analyses and Forecasting*, **Vol. I**, McGraw Hill, New York, Toronto, London, 428 pp.

Purdom,J.F.W., 1973: Satellite imagery and the mesoscale convective forecast problem, *Preprints, Eighth Conference on Severe Local Storms*, Denver, Co., Amer. Meteor. Soc., Boston, Mass., pp 244- 251.

Rotunno,R. and J.B.Klemp, 1982: The influence of shear induced pressure gradient on thunderstorm motion. *Mon. Wea. Rev.*, **110**, 136-151.

Rust,W.D., W.L.Taylor,D.R.MacGorman, and R.T.Arnold, 1981: Research on electrical properties of severe thunderstorms in the Great Plains. *Bull. Amer. Meteor. Soc.*, **62**, 1286-1293.

Shapiro,M.A., 1982: *Mesoscale Weather Systems of the Central United States*. CIRES, Univ. of Colo, NOAA, Boulder Co., 78 pp.

Stensrud,D.J., and R.A.Maddox, 1988: Opposing mesoscale circulations: A case study. *Weather and Forecasting*, **3**, 189-204.

Wakimoto,R.M., 1983: The West Bend Wisconsin tornado of 4 April, 1981: A problem in operational meteorology. *J. Climate Appl. Meteor.*, **22**, 181-189.

Wakimoto,R.M. and J.W.Wilson, 1989: Non-supercell tornadoes. *Mon. Wea. Rev.*, **117**, 1113-1140.

Weisman,M.L., and J.B.Klemp, 1984: The structure and classification of numerically simulated convective storms in a directionally varying wind shear. *Mon. Wea. Rev.*, **112**, 2479-2498.

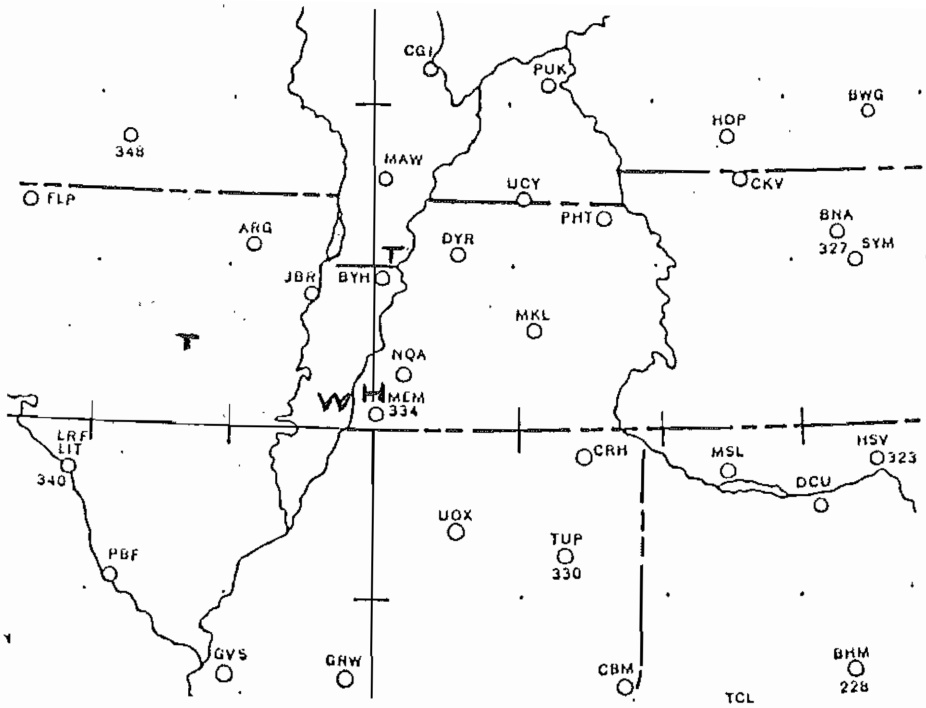


Figure 1. Map of the Mid South showing location of severe weather events on June 2, 1989. Tornadoes, large hail and wind damage denoted by T, H, and W, respectively.

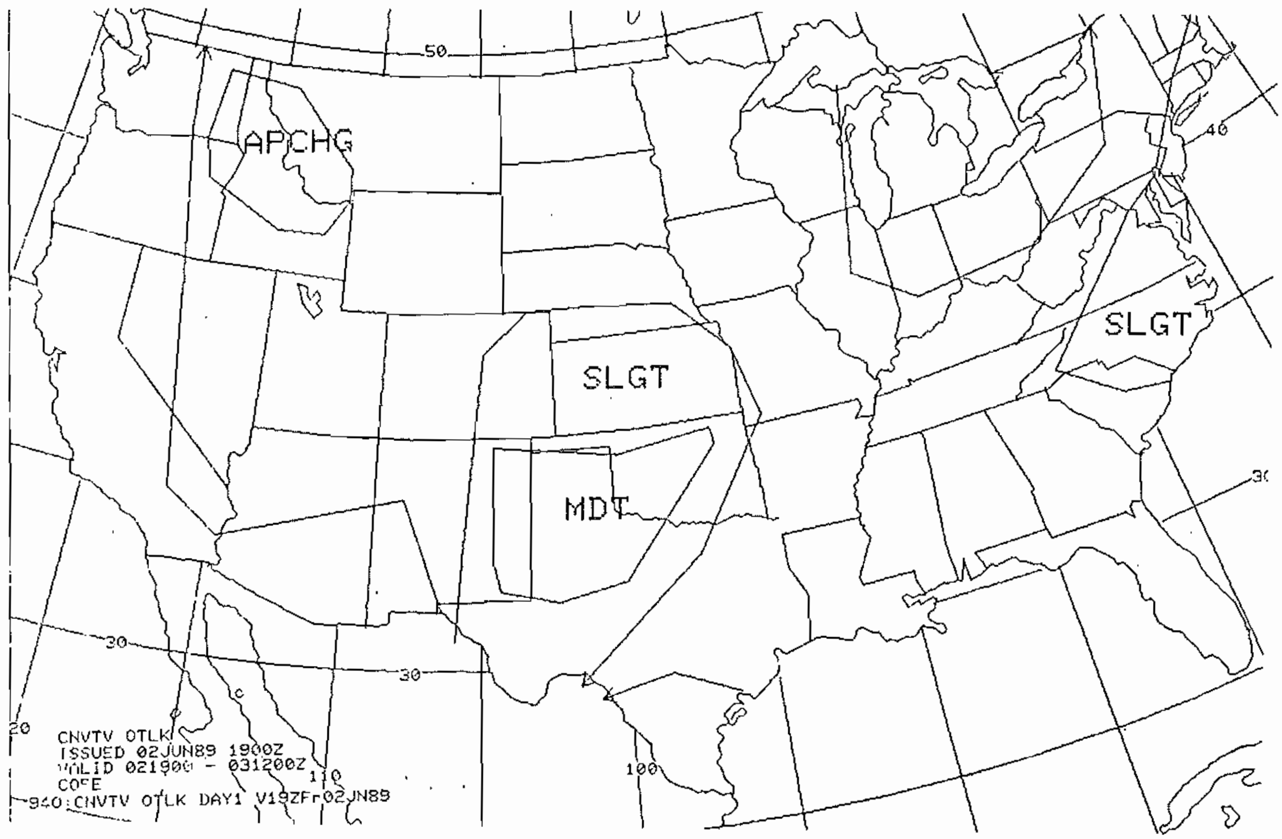


Figure 2. National Severe Storm Forecast Center convective outlook issued at 1900Z June 2, 1989.

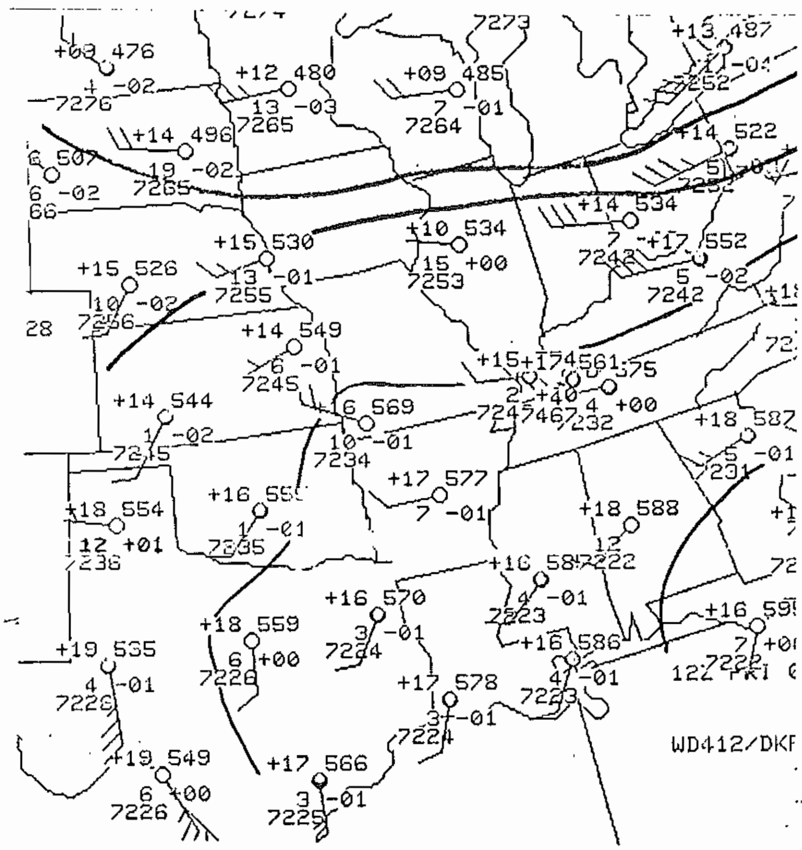


Figure 3. 850 mb regional plot for 1200Z June 2, 1989.

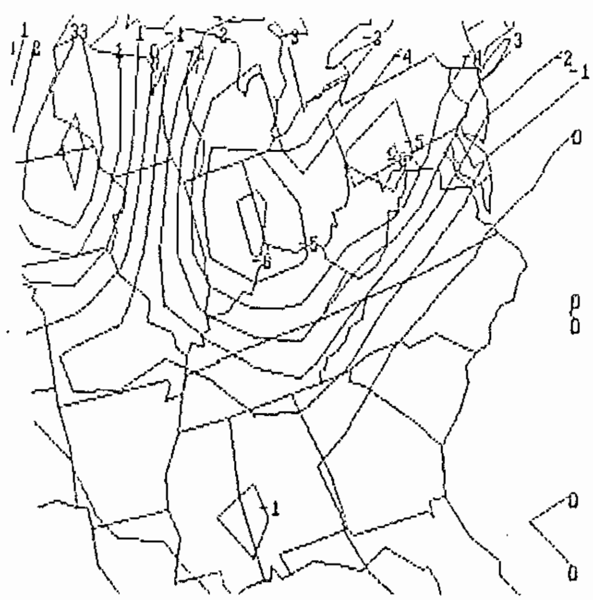


Figure 4. 850 mb temperature advection for 1200Z June 2, 1989.

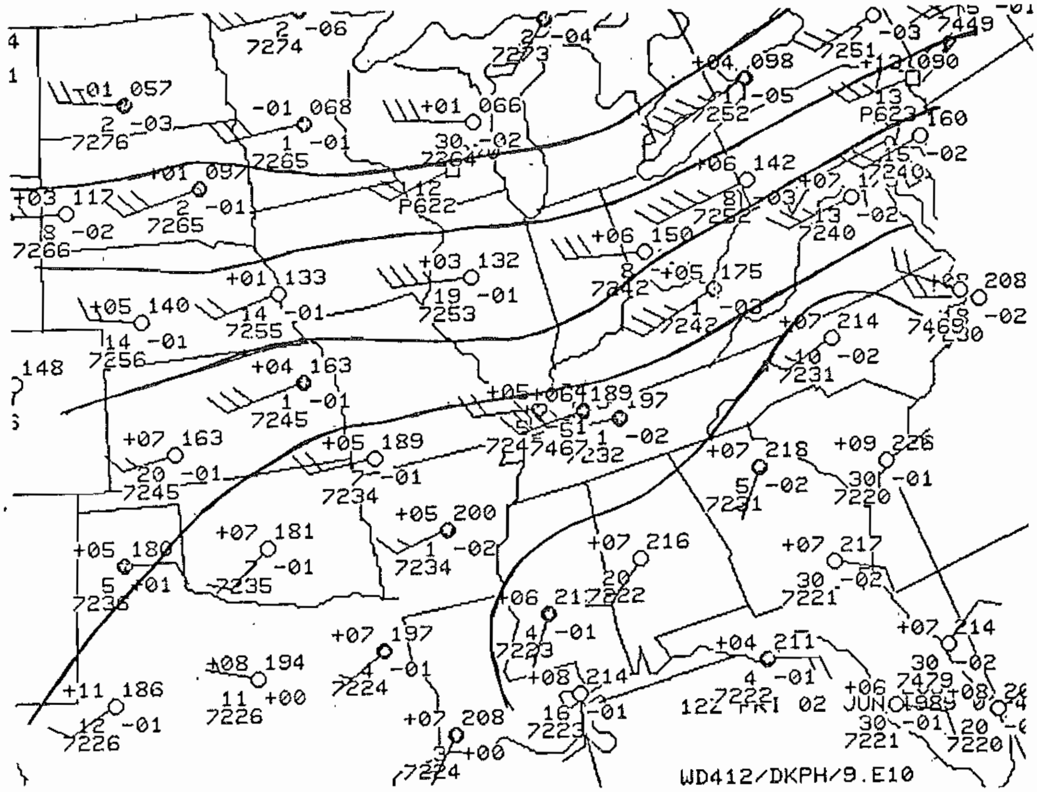


Figure 5. 700 mb regional plot for 1200Z June 2, 1989.

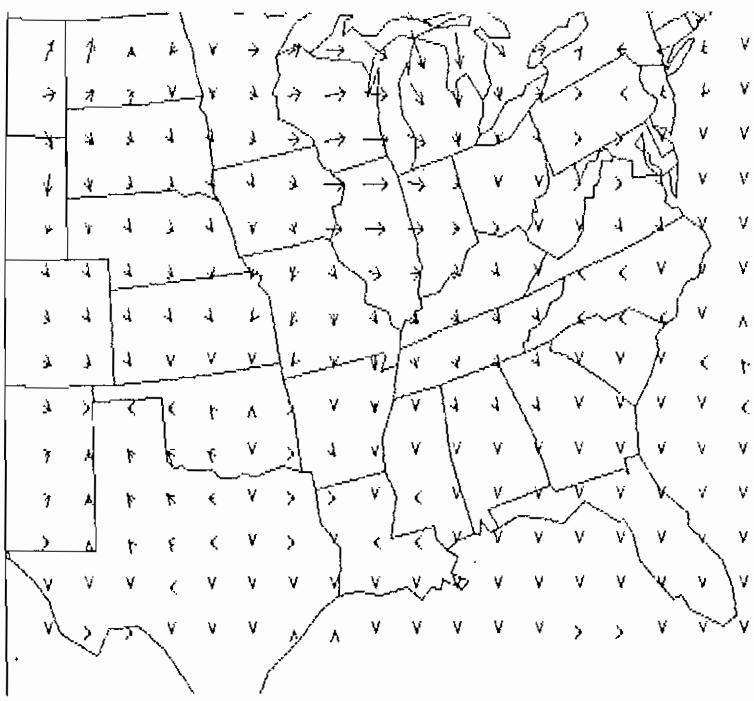


Figure 6. 700 mb Q-vectors for 1200Z June 2, 1989.

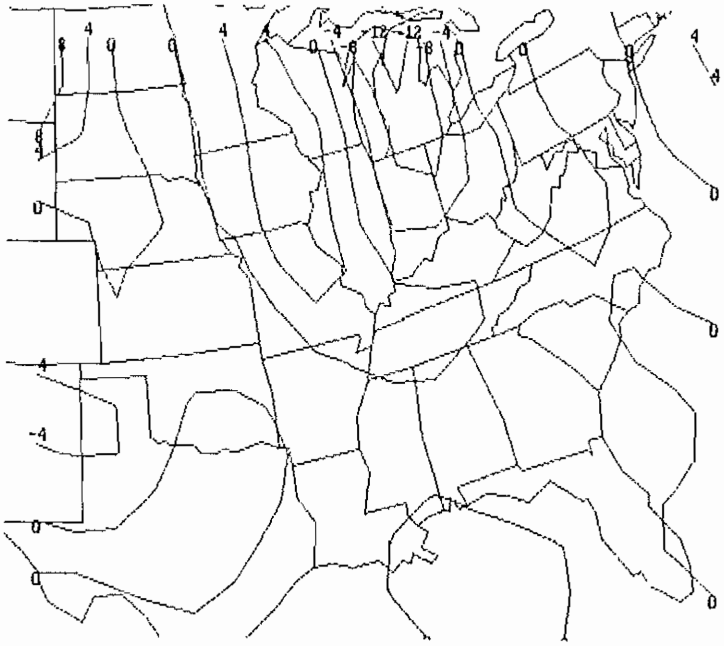


Figure 7. 700 mb Q-vector divergence.

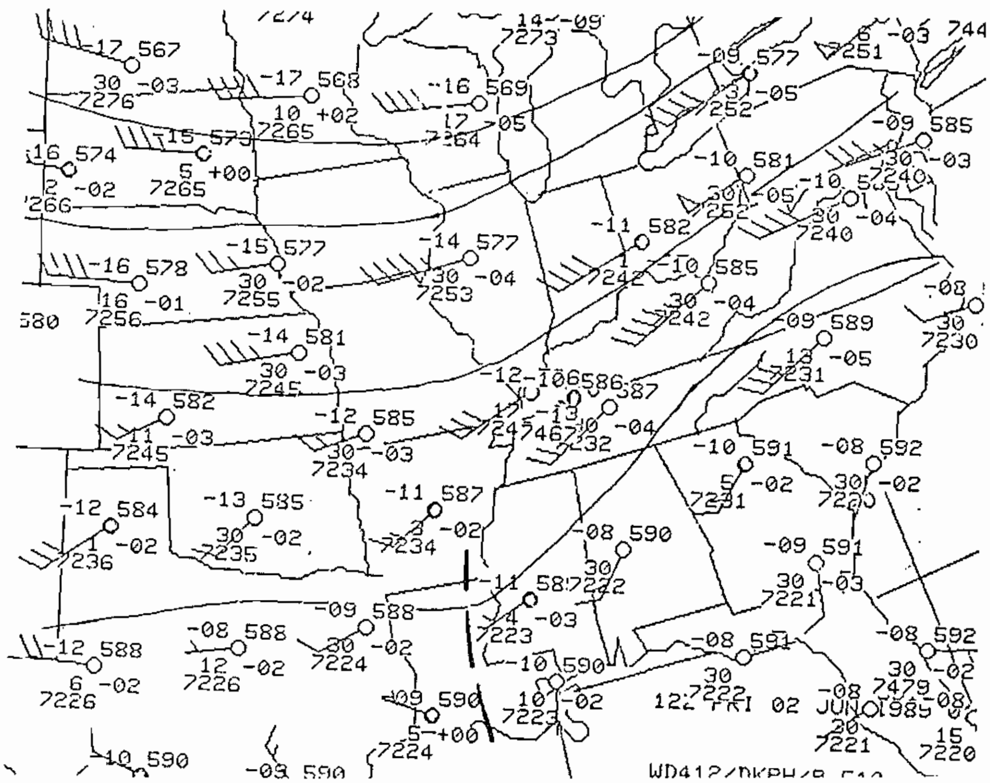


Figure 8. 500 mb regional plot for 1200Z June 2, 1989.

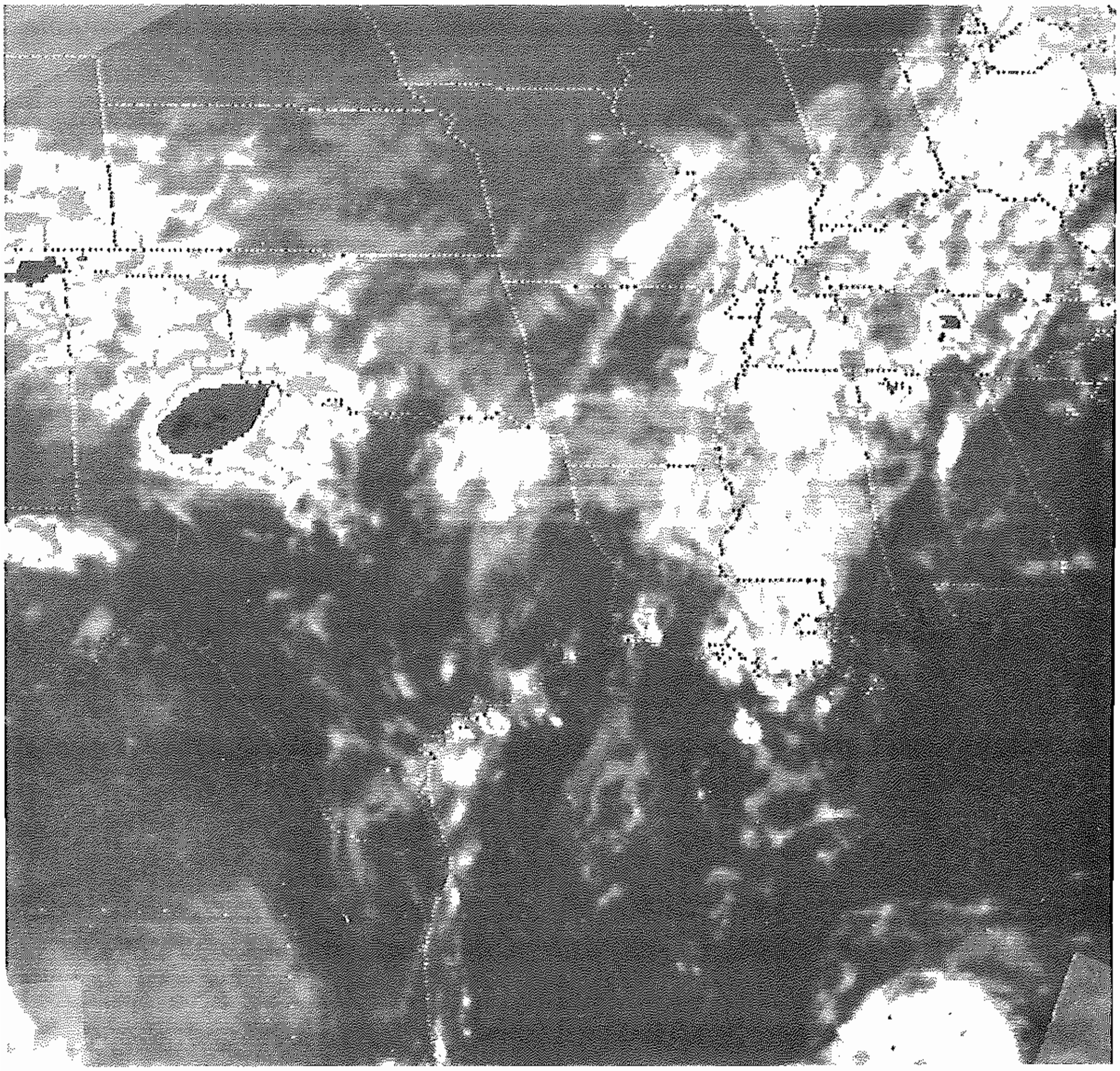


Figure 9. Infrared satellite image for 1200Z June 2, 1989.

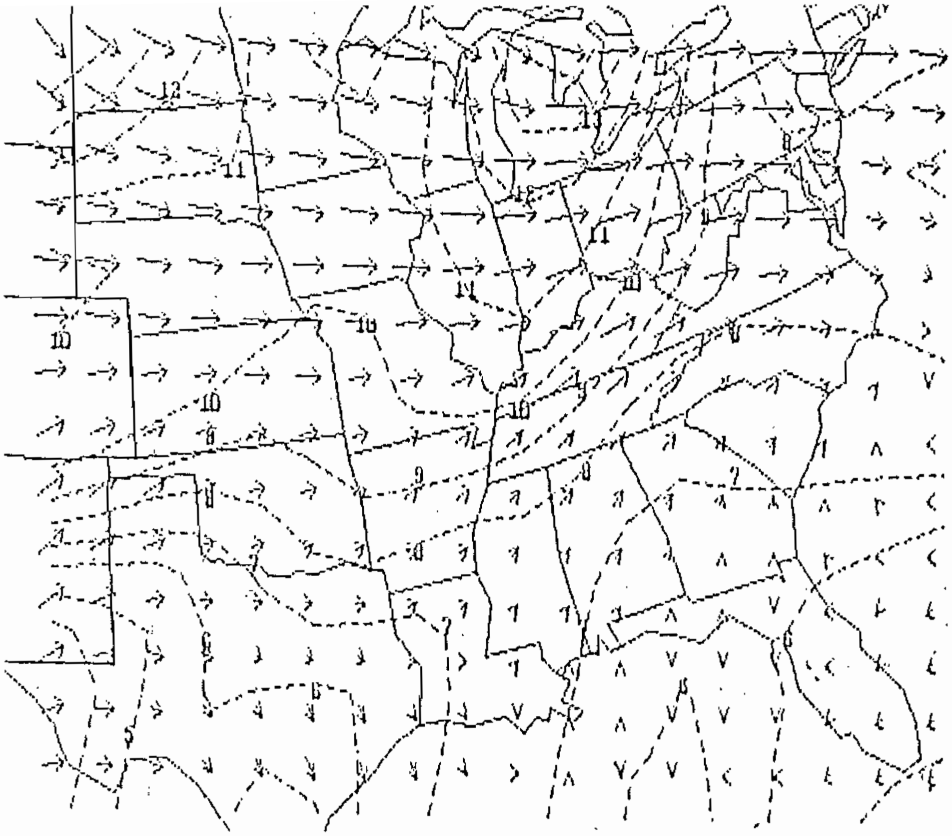


Figure 10. Plot of 500 mb vorticity and wind vectors from 12Z June 2.

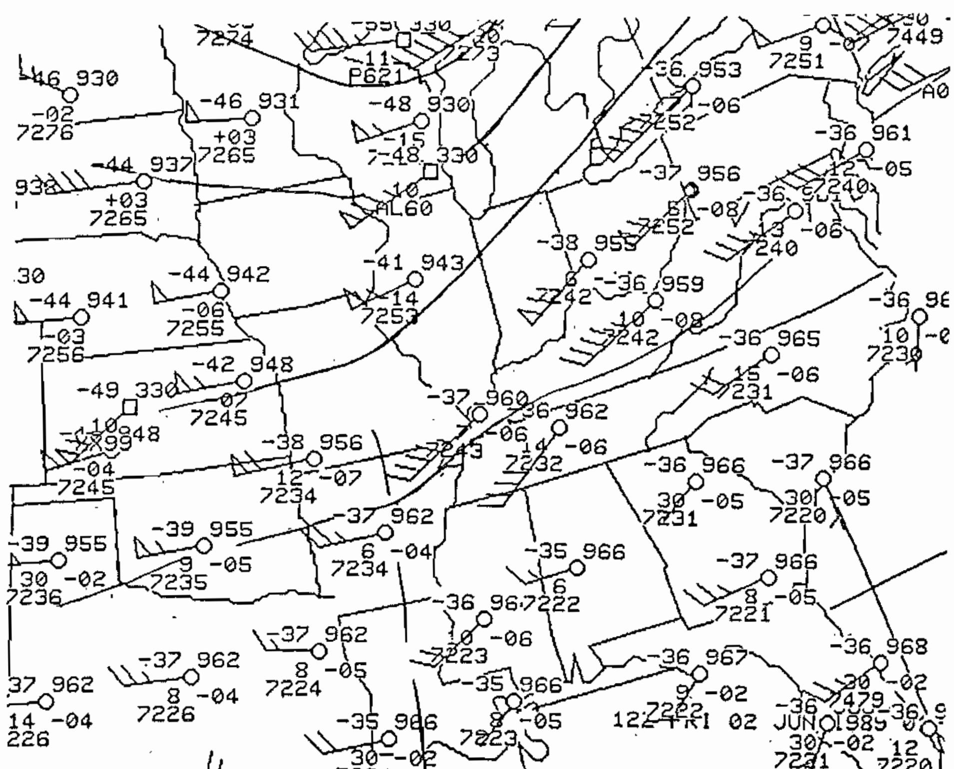


Figure 11. 300 mb plot for 1200Z June 2, 1989.

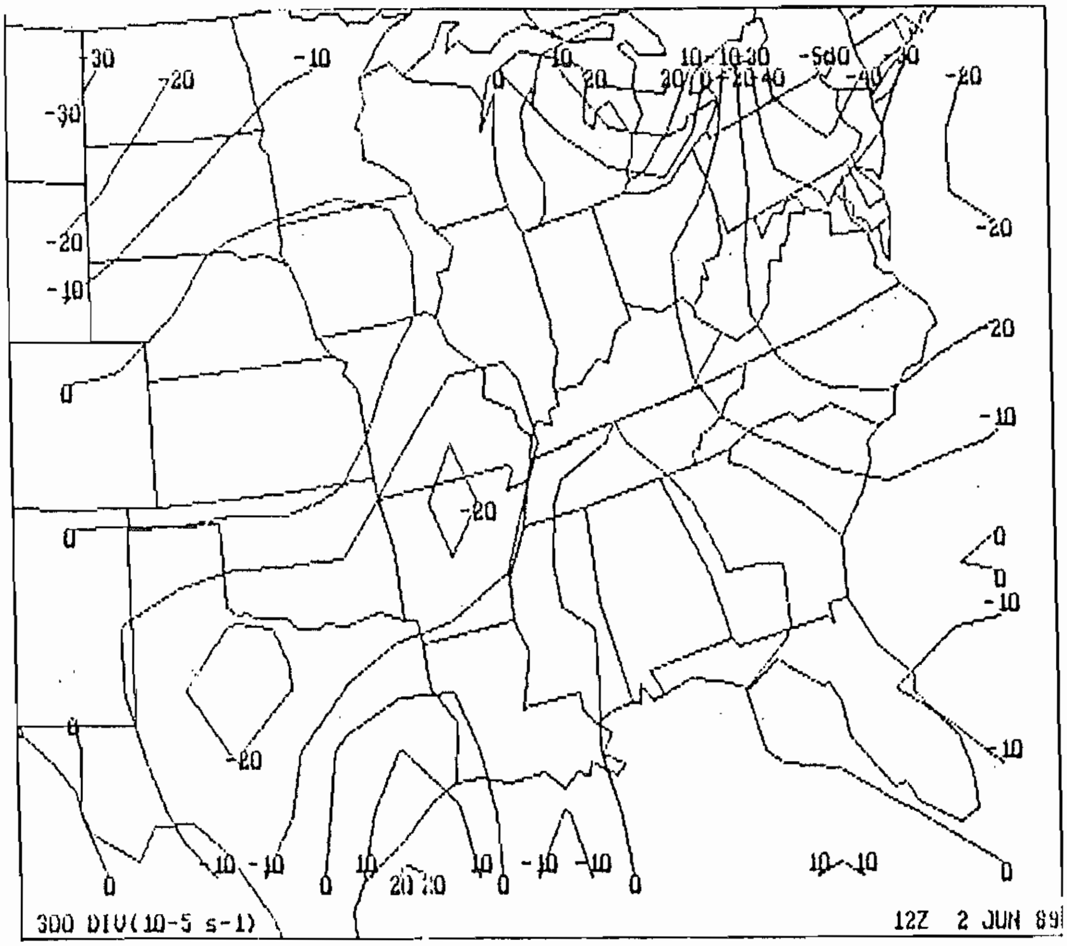


Figure 12. 300 mb divergence. Units are $x10^{-5}$ s^{-1}.

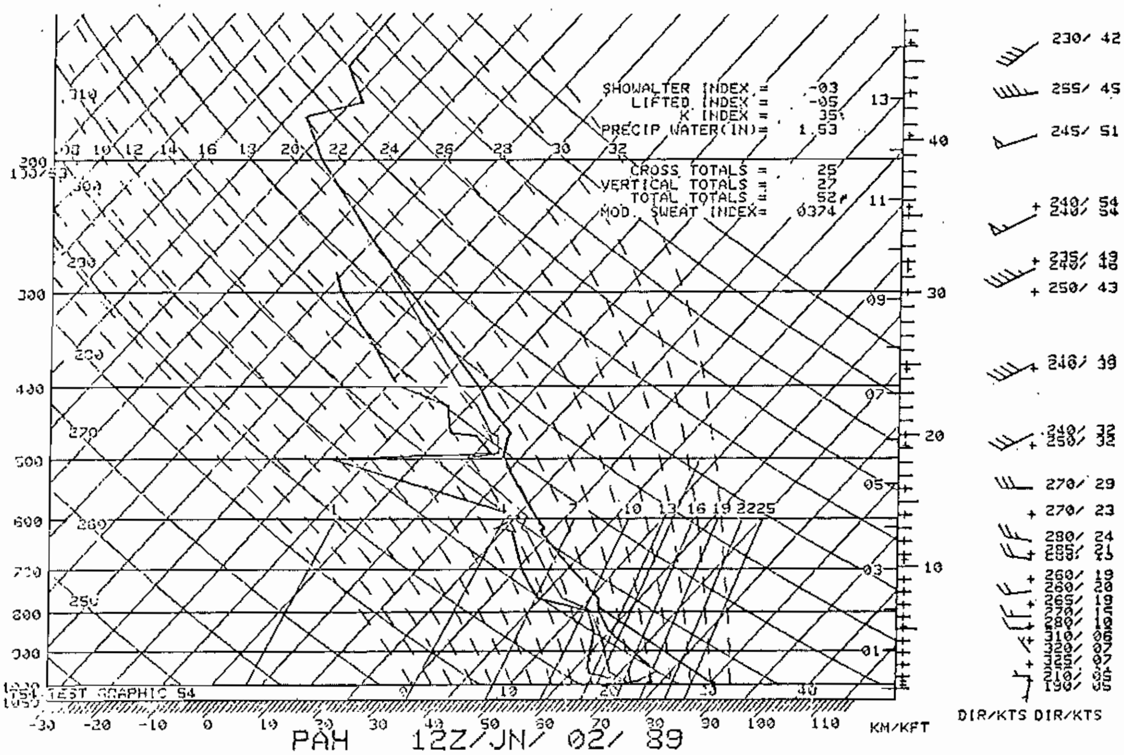


Figure 13. 1200Z June 2, 1989 rawinsonde plot for Paducah, KY. Temperature and moisture are also plotted based on 1900Z surface observations taken at Blytheville, AR.

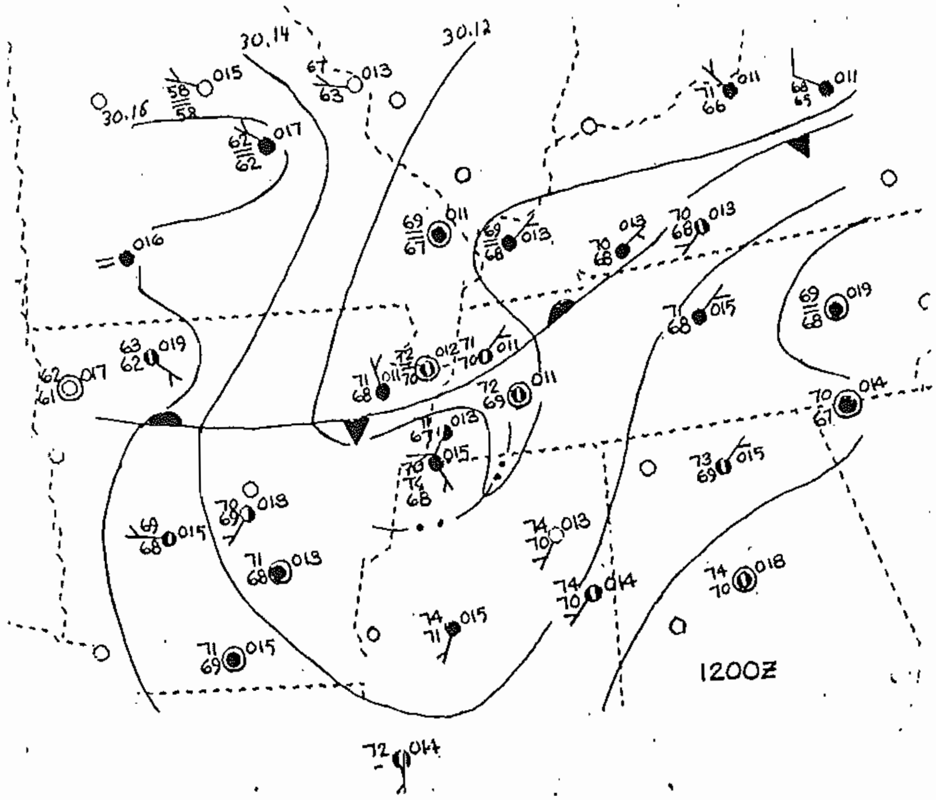


Figure 14. Regional surface plot for 1200Z June 2, 1989. Contours represent altimeter settings.

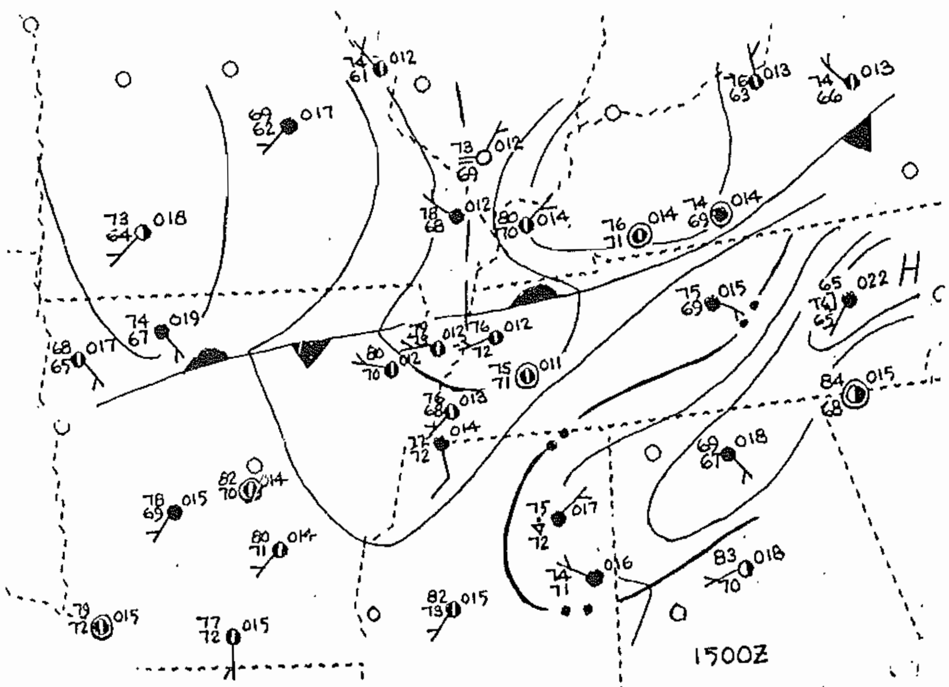


Figure 15. 1500Z surface analysis.

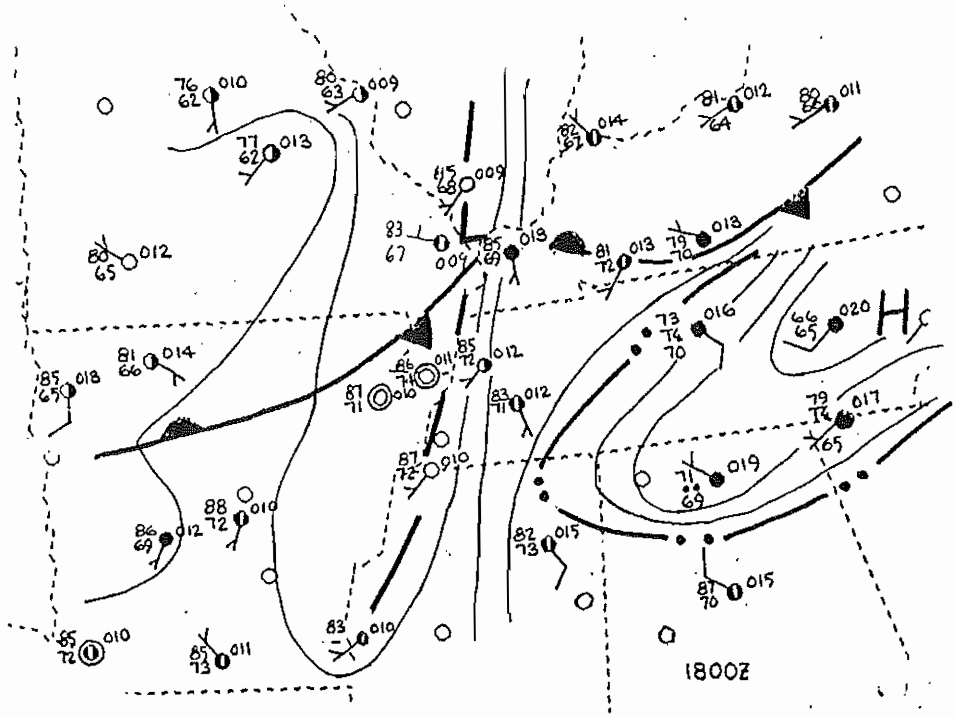


Figure 16. 1800Z surface analysis.

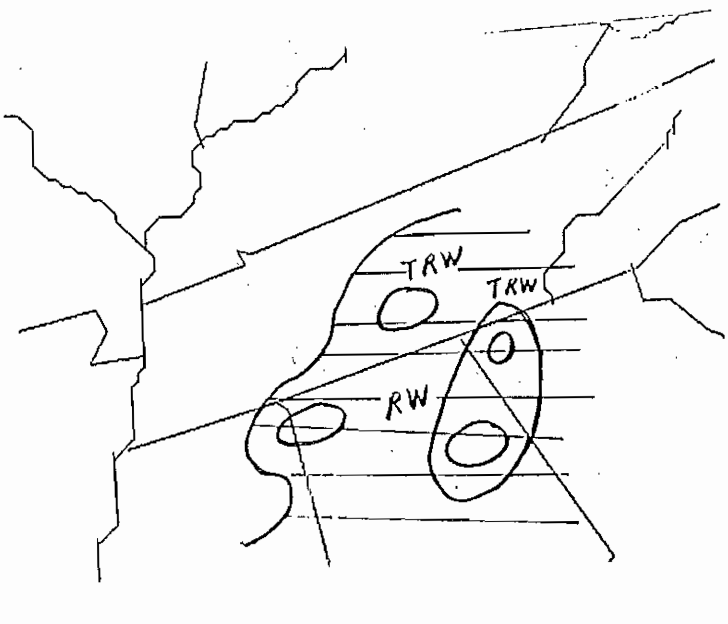


Figure 17. NWS radar summary for 1735Z.

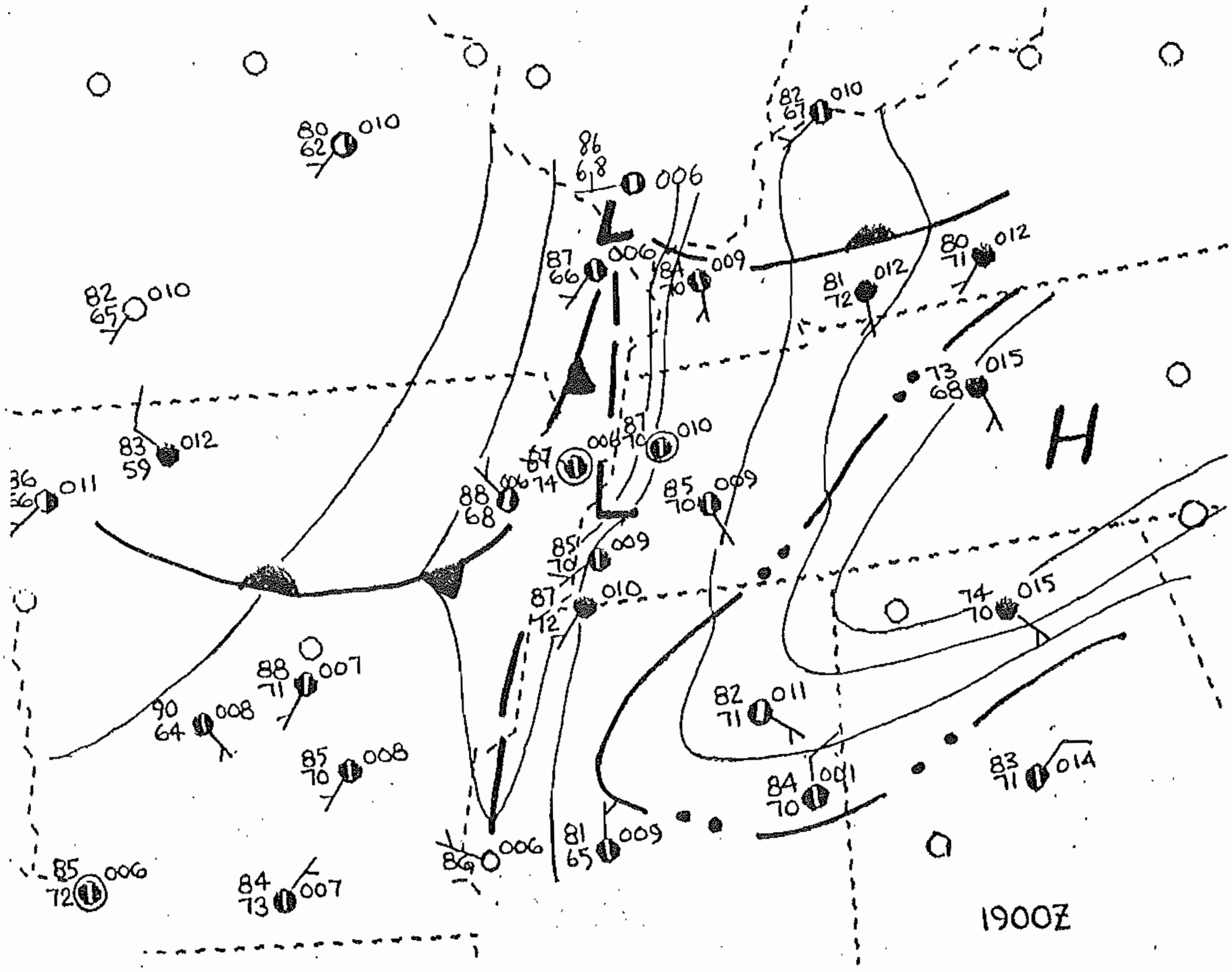


Figure 18. 1900Z surface analyses.

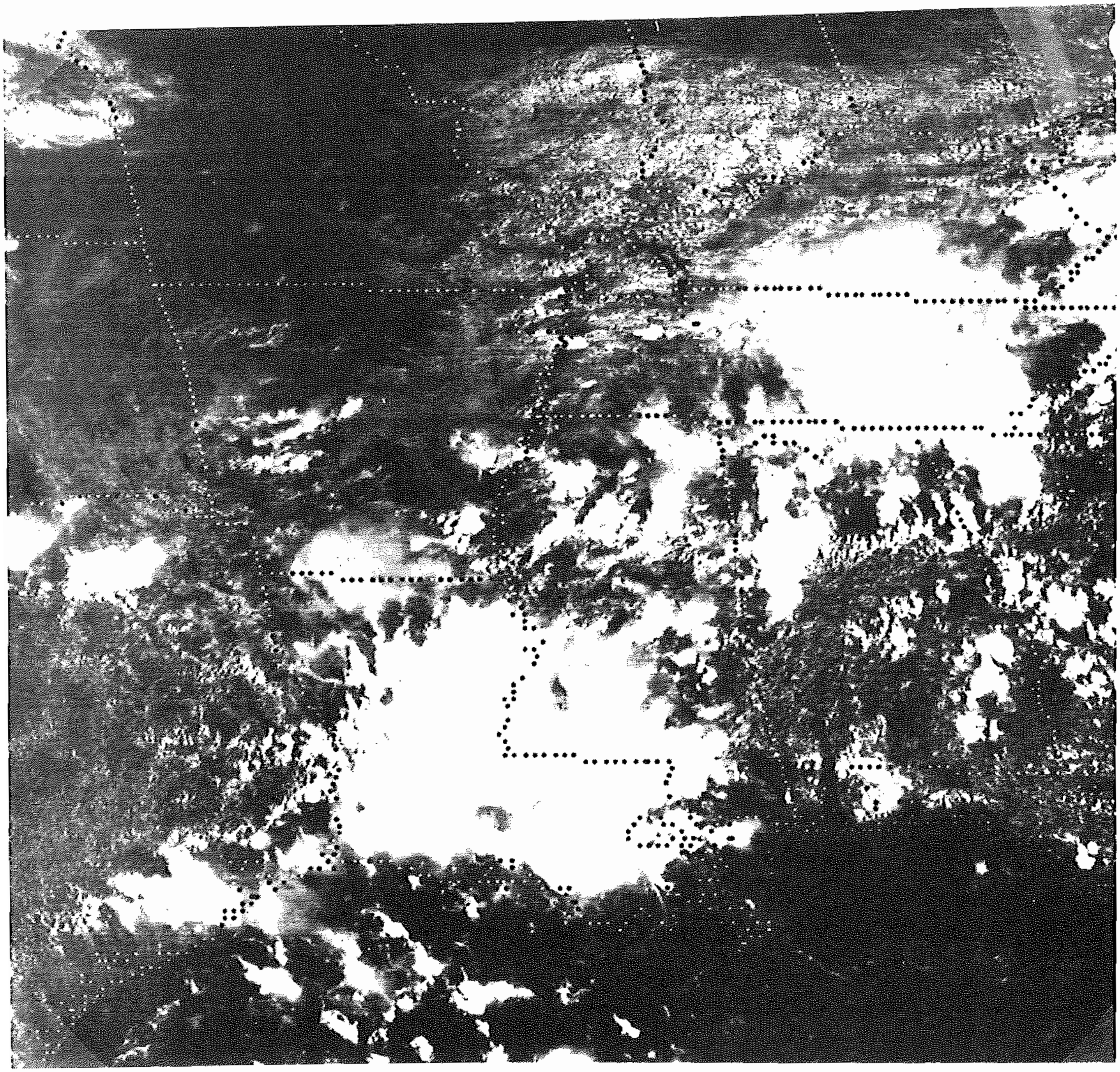


Figure 19. 1830Z infrared satellite image.

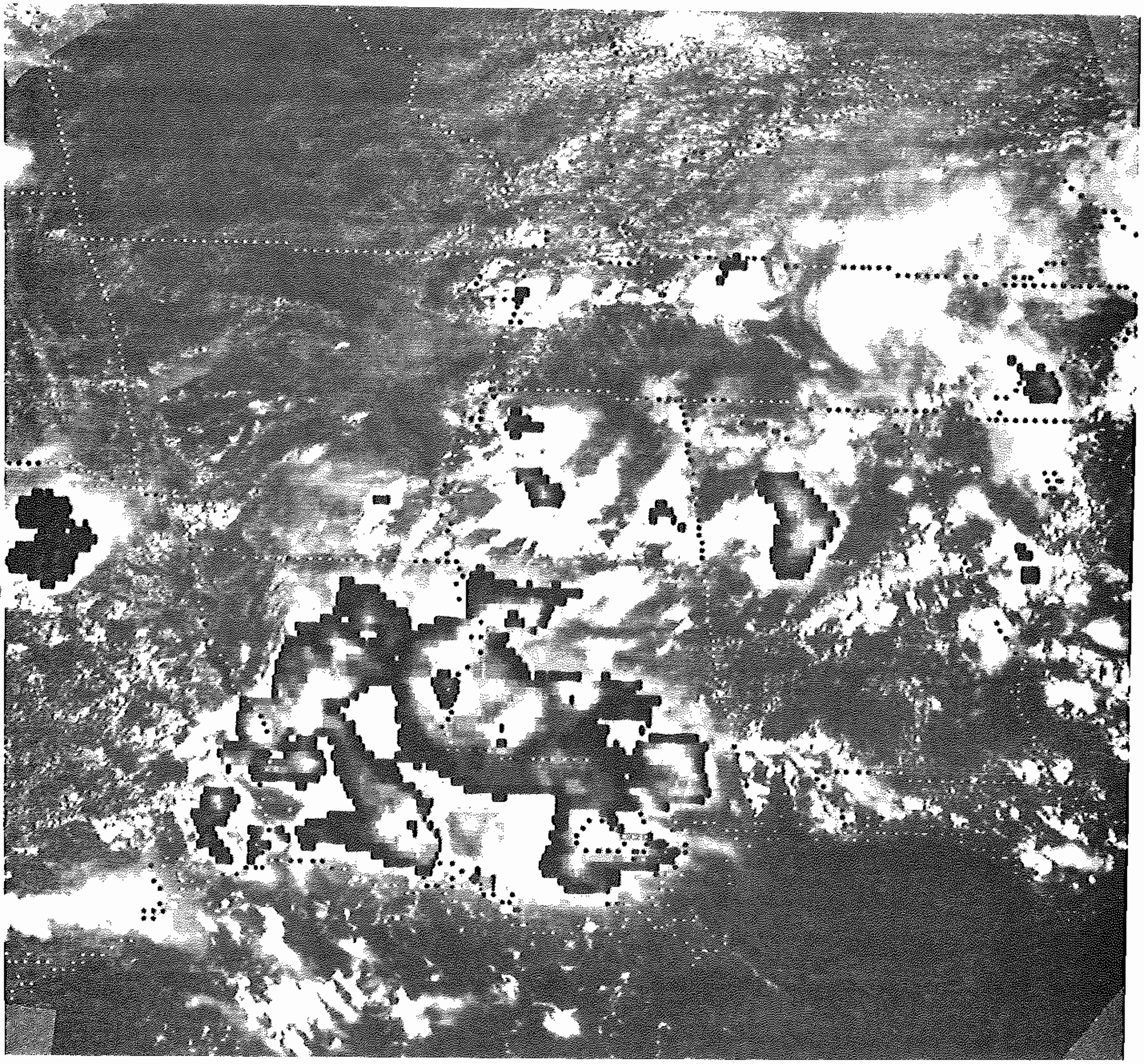


Figure 20. Infrared enhanced satellite image for 2000Z.

Figure 21. Photograph of tornado moving through an open field.

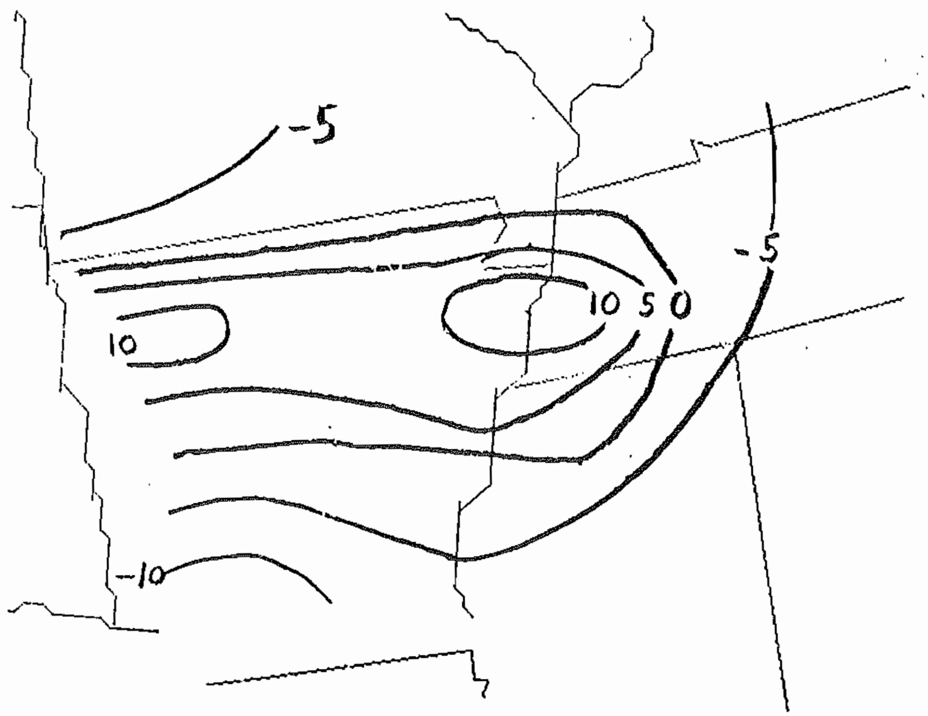


Figure 22. Surface convergence at 1900Z. Units are x10^{-6} s^{-1}.

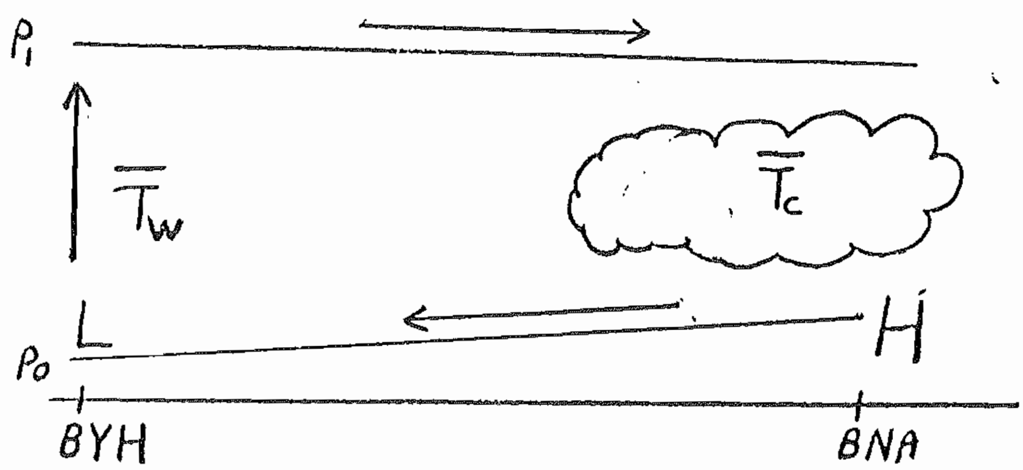
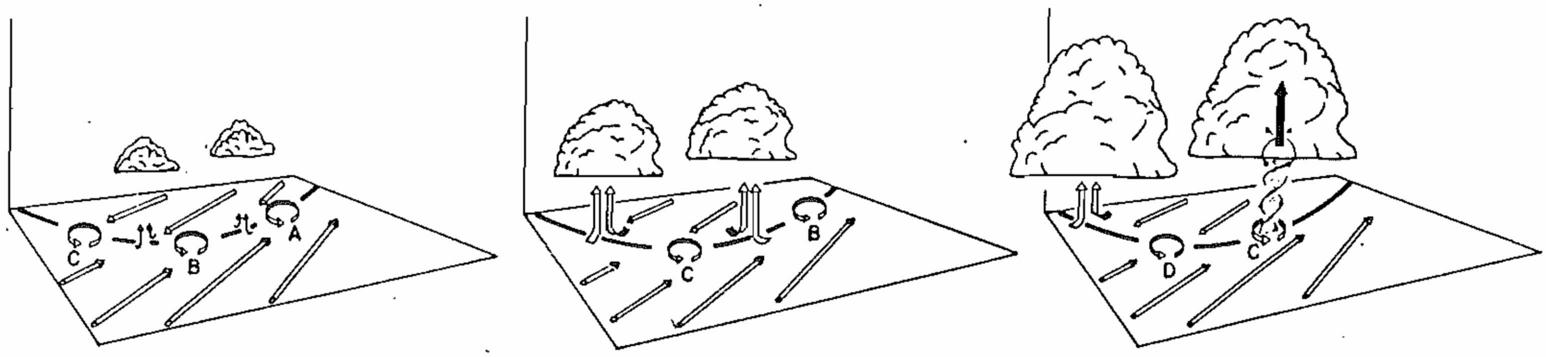


Figure 23. Schematic of circulation caused by differential heating between a rain-cooled air mass over BNA and relatively cloud-free air at BYH.



Schematic model of the life cycle of the non-supercell tornado. The black line is the radar detectable convergence boundary. Low-level vortices are labeled with letters.

Figure 24. From Wakimoto and Wilson (1989).

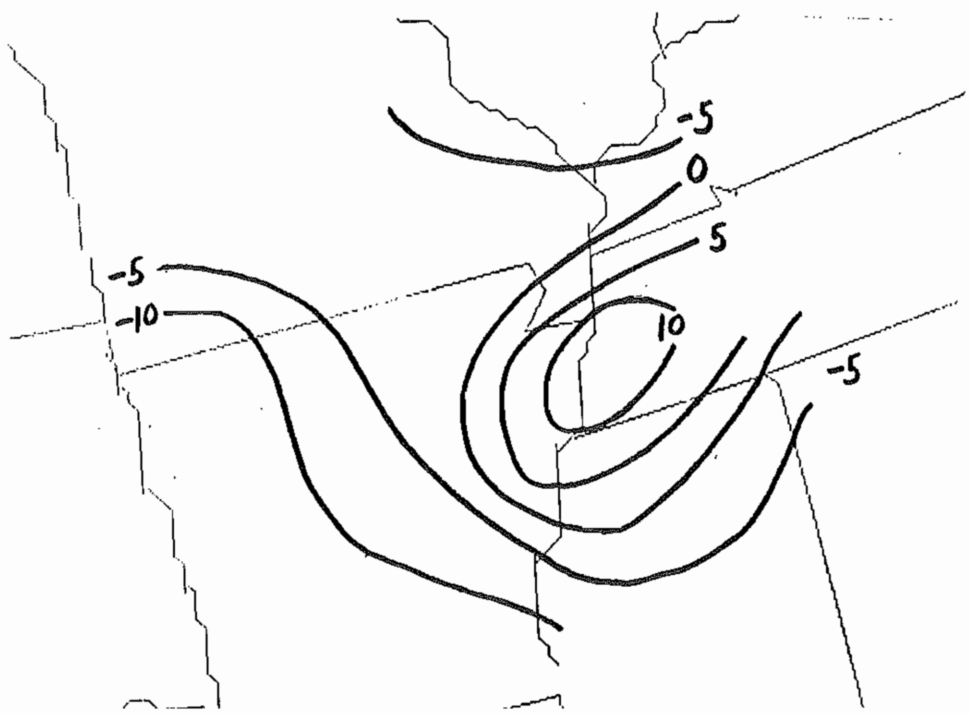


Figure 25. Surface relative vorticity measured at 1900Z. Units are $x10^{-6}$ s^{-1}.