Multiple Mescoscale Interactions and Their Effect on Tornadogenesis Prior to and During the November 6, 2005 Evansville, Indiana Killer Tornado

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Abstract

During the late evening hours of November 5, 2005, forecasters were preparing for synoptic environment conducive for linear storm modes with an attendant threat of damaging wind gusts to effect Western Kentucky and Southern Indiana. The situation did not materialize in this manner. Shear profiles produced storm structures that became quais-linear while a jet streak entered the region and enhanced updraft strength beyond what was expected. The underestimated updraft strength was also dependent upon CAPE in the lowest levels of the atmosphere, a variable shown to be of great importance during cool season, highly dynamic tornadic episodes. Lastly, the interactions of gravity waves prior to and during tornadogenesis enhanced mesocyclone vorticity, producing supercellular structures, and culminated as the final ingredient to produce the deadly Evansville F-3 tornado.

Introduction

The early morning of November 6, 2005 at 1:39 local time, a strong F-3 tornado touched down outside of Evansville, Indiana and began a 41-mile track through northwestern Kentucky and Southern Indiana As it passed through the south side of Evansville it unfortunately caused 23 fatalities. The severe setup was poorly forecast but a reanalysis of the event indicates strong evidence for tornadic potential.

Earlier in the evening, forecasters were preparing for a linear storm mode event due to largely unidirectional shear and a low CAPE environment. As the evening progressed, synoptic forcings increased upper level divergence in the region of interest while low-level instability increased. During the storm's life cycle, evidence suggests that numerous gravity waves directly interacted with the updraft of the storm, increasing the vorticity of the mesocyclone and furthering the transition to supercellular convective structure as well as the subsequent tornadogenesis.

It is evident that the setup and environment lead to robust updrafts and quasi-linear storm structures and that the transition to a supercellular storm structure was due to a changing shear profile due to synoptic interactions as well as the direct interaction of numerous gravity waves with the storm's updraft, enhancing it's vorticity and thus strengthening the storm.

Data

The research presented is complemented by data from numerous sources. Upper air and surface data was compiled and plotted by Weather Unisys. Sounding data was collected from the University of Wyoming sounding data archive. Radar images are courtesy of the National Climatic Data Center archives and numerous research papers are cited throughout the paper and provided background information on highly dynamic, low instability environments as well as gravity wave radar signatures and gravity wave interactions with pre-existing storms.

Synoptic Environment Overview

At 00Z on November 6, a well-defined upper level trough was situated over the north central United States with the base of the trough over the Kansas and Oklahoma border. 300 mb jet flow over the region of Arkansas, Missouri, Oklahoma and Illinois was on the order of 70 knots with weak speed gradients. The effects of curvature in the geostrophic flow as well as slight diffluence over Arkansas and Missouri provided for some upper level ageostrophic divergence, enhancing vertical motion in this region.

At the surface, a low-pressure center was noted near St. Louis with a cold front dragging southwestward into Arkansas, Oklahoma, and Northern Texas. Also noted was an attendant warm front extending northward to the Illinois and Wisconsin border placing the Ohio River Valley in the warm sector of

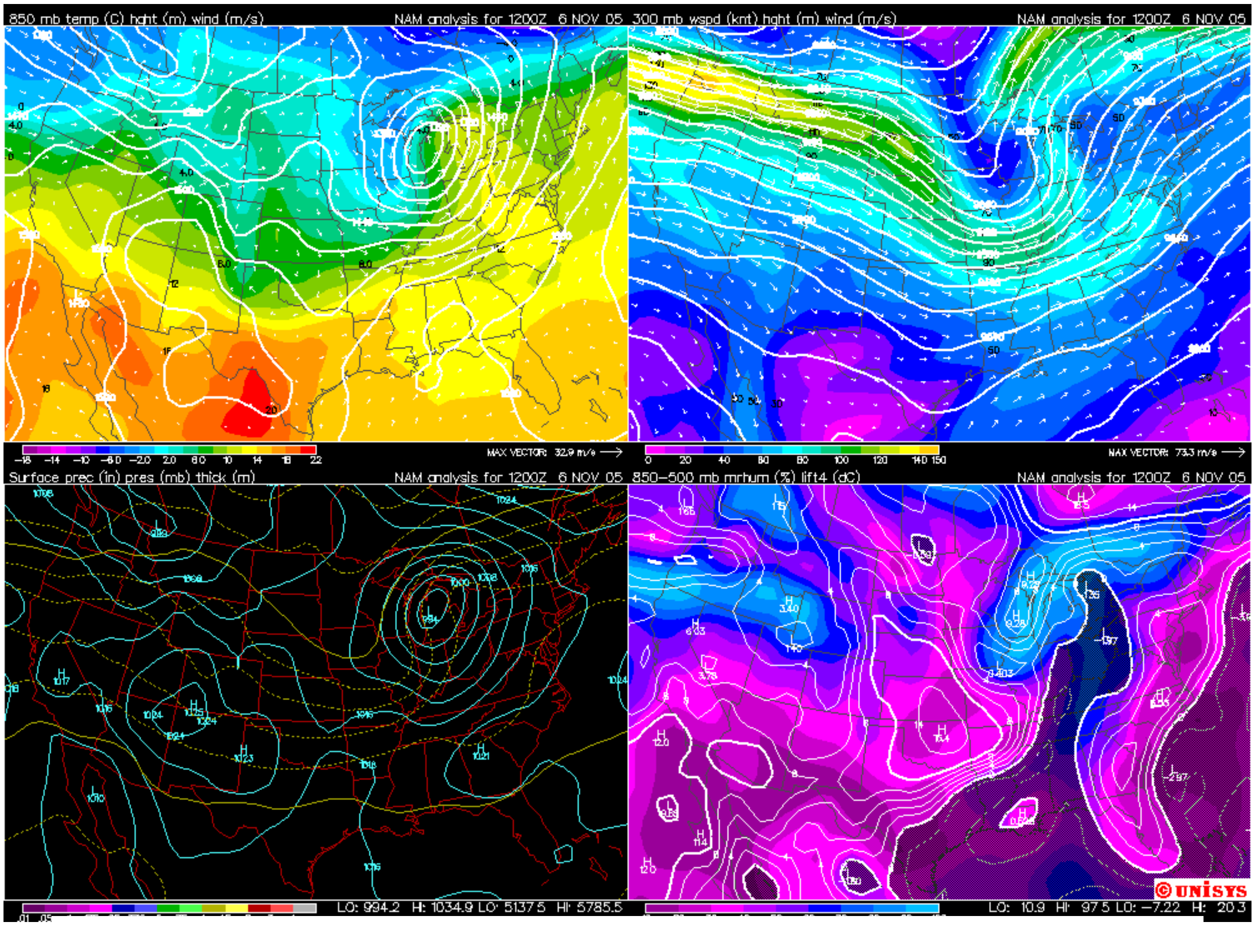


Figure 1: From top left to bottom right: 850 mb analysis, 300 mb analysis, surface analysis, low level moisture analysis, all valid at 12Z on November 6th, 2005. Note the 300 mb negatively tilted trough as well as the Jet Streak located in Missouri and Southern Illinois.

the surface cyclone. The combination of these factors produced a line of strong to severe convection ongoing at this time from Southern Missouri into much of Arkansas.

At 12Z on the 6th, a few hours past the event time, the upper level trough had strengthened, becoming more negatively tilted (Figure 1). The jet rounding the base of the trough had strengthened as well, placing maximum wind speeds in the 90-100 knot range. The speed gradient also increased, thus increasing the ageostrophic divergence experienced in the left exit region of the jet. By 12Z, the left exit region had moved past Evansville, Indiana but by tracking the progression of the trough from the 00Z analysis, it is noted that the left exit region of the jet streak was located to provide its maximum upper level ageostrophic divergence to the region of Western Kentucky and Southern Indiana between 06Z and 09Z, precisely during the event. This increase in upper level divergence thus enhanced upward vertical motion in the region, allowing for stronger and more robust updrafts. The ageostrophic divergence created by the jet streak is in addition to the ageostrophic divergence in place due to the strengthened curvature effect of the trough also directly over the region.

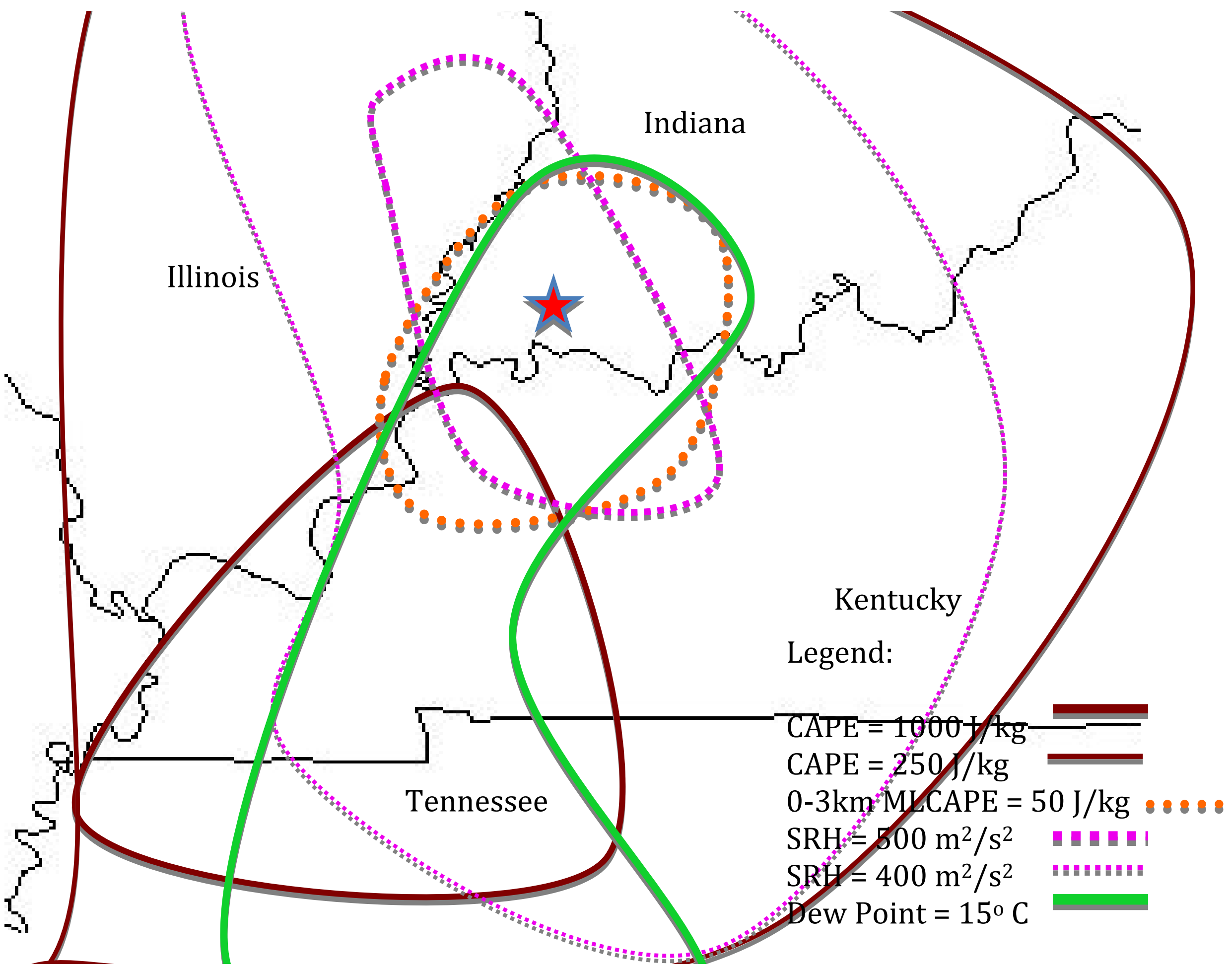
The surface low, by 12Z, had propagated north to the Canadian border, pushing the warm front into Canada as well (Figure 1). The surface cold front was located very near the Illinois and Indiana border. This cold front still served as the focus for the convection though it should be noted that the convection was well ahead of the surface cold front.

Mesoscale Environment Analysis

Low CAPE, High Shear Environments

The Evansville tornado was produced in a low CAPE, high shear environment with total CAPE of 835 J/kg and Storm Relative Helicity of 523 m^2/s^2 per 0700 RUC sounding reanalysis at the time of tornadogenesis coupled with observed storm motion, and 0-3 km MLCAPE of 60 J/kg (Davies, 2007). When these environments are present, it can often be difficult to ascertain the tornadic potential of the environment. A

Figure 2: Figure 2 is a Mesoscale environment analysis of Southern Illinois, Southern Indiana, and Western Kentucky at 0700 UTC, just before tornadogenesis. Note the maximization of relevant parameters in the region surrounding Evansville, noted by the star. It should be noted that the Level of Free Convection was around 1500 m agl near Evansville at this same time.



statistical compilation study by Jonathon Davies in 2007 helped to define some of the necessary parameters for these events.

When distinguishing between non-tornadic, tornadic, and significant tornadic events in low CAPE, high shear environments, three variables seem to stand out in terms of importance: Storm Relative Helicity, Level of Free Convection, and 0-3 km MLCAPE (Davies, 2007). While total sounding MLCAPE does show an increasing trend such that the likelihood of tornadogenesis as well as likelihood of stronger tornadoes does increase with increasing MLCAPE, an analysis of 0-3 km MLCAPE shows a stark contrast between tornadic and non-tornadic thunderstorms in these environments. It appears statistically significant that 0-3 km MLCAPE values greater than 60 J/kg are an indication of higher tornadic potential in these environments (Davies, 2007). Level of Free Convection shows a linear trend such that lower levels of free convection are found with higher likelihoods of tornadic activity in these environments (Davies, 2007). Lastly, Storm Relative Helicity shows strong statistical significance. In low CAPE environments, likelihood of significant tornado events jumps dramatically with SRH values exceeding 200 m^2/s^2 (Davies, 2007).

At the time of the tornado event, the atmosphere was conducive for significant tornadogenesis based on the parameters described above. Figure 2 illustrates the local, mesoscale environment near the time of the tornado with respect to the discussed parameters.

Figure 3 is a RUC sounding of the atmosphere at Evansville at 0700 UTC on the 6th.

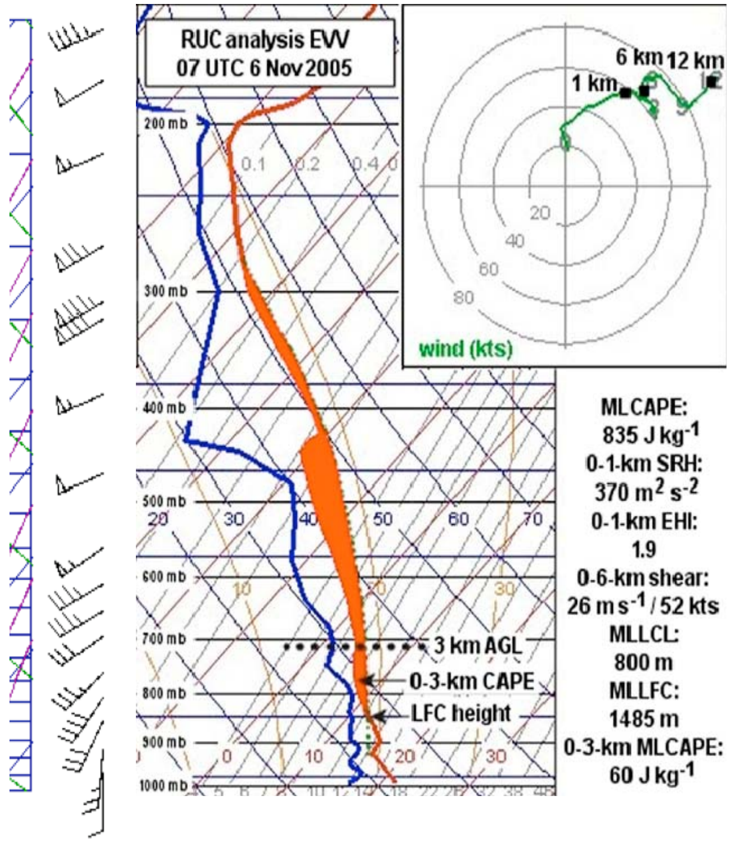


Figure 3: RUC sounding for Evansville at 0700 UTC Nov. 6th. Important parameters are indicated. The wind profile is strongly veering and low-level shear is strong. Image produced by meteorologist Jonathon Davies

Evolving Shear Environment

By 00 UTC on the 6th, regional wind profiles (not shown) indicated largely unidirectional shear from the southwest except for the surface, where winds were southerly and only around 5 knots. Speed shear was well defined and hodographs were nearly linear. This shear profile, coupled with low CAPE and uniform and linear forcing suggested the dominant storm mode would be linear. As early as 02 UTC, however, the shear profile began to change.

As evident in Figure 3, surface winds increased and the lowest 3 km began to strongly veer by 0700 UTC. The strong shift in shear profile was due to the strengthening surface low. Figure 1 shows a 984 mb surface low in southwestern Michigan, deeper than the 992 mb surface low noted 12 hours previous (not shown). In response to the pressure falls, ageostrophic winds near the surface increased and provided a southerly component to the winds in the lowest 3 km of the atmosphere (Figure 3). At the same time, a weak Low Level Jet was noted across Mississippi, Alabama and into Tennessee, feeding into the region including western Kentucky and Southern Indiana. This further enhanced the veering profile of the winds.

The low level jet also played a second important role. While temperatures in the region had remained nearly constant during the evening, moisture from the Gulf of Mexico was advected northward by the Low Level Jet just ahead of the approaching cold front. Dew points that had been around 11 degrees Celsius in Southern Indiana around 00 UTC jumped to around 16 degrees Celsius by 0700 UTC. The increase in low-level moisture lowered the liquid condensation level and in this atmospheric profile, lowered the level of free convection, thus increasing the CAPE in the lowest levels despite a nearly constant temperature profile.

Lastly, the presence of a mid to upper level jet streak in the region around the time of the storm helped to change the shear environment and make the environment more conducive for right moving supercell thunderstorms. Prior to the presence of the jet streak, winds above 500 mb were unidirectional out of the southwest and showed little speed shear. As the jet streak approached, winds above 500 mb veered with time to become more westerly and speed shear increased as the wind maxima was seen just above 300 mb (Figure 3). This response created a more strongly veering wind profile and added curvature to the hodograph, enhancing environmental helicity and thus making the environment more conducive for supercellular structures as opposed to the linear structures previously developing (Figure 4). This work has been previously documented, both by

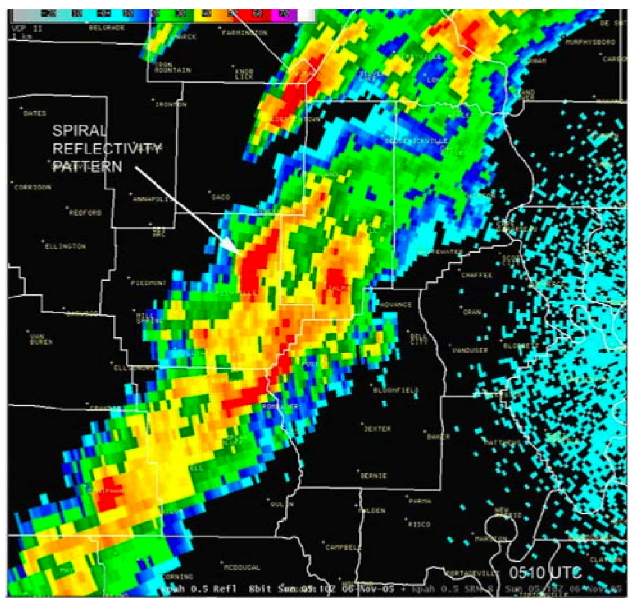


Figure 4: Base Reflectivity image from 0510 UTC of the storm that will produce the Evansville tornado. At this time, the storm is in the transition stage from linear to supercellular convective mode primarily in response to the modified wind profile become more strongly veered. The spiral pattern is evident in the reflectivity. The radar site, WFO Paducah, is on the far right of the image.

Burgess and Curran in 1985 and by

Glass and Britt in 2001, both hypothesizing and showing that existing storm structures can change as environmental shear structures change with time along the storm's path.

The storm structure shown in Figure 4 is a hybridization of linear convective modes and supercellular convective modes and is actually classified as a transitional variation of the high precipitation supercell family (Spoden, 2006). It is at this time (0510 UTC) that the storm shows the first sign of rotation with the presence of a mesovortex embedded in the western flank of the spiral structure (Figure 5). Maximum rotational velocities reached 12 m/s and the rotation spanned a depth of 14 km with a very broad circulation diameter of 11 km (Spoden, 2006). While this rotation is weak, it is indicative of a storm structural change being induced by the changing wind shear structure. Research done by Pryzbilinski and Schmocker in 2001 indicates that spiral patterned reflectivities in highly sheared, transitionally sheared environments have a higher likelihood of tornadic activity. The evidence thus far and the knowledge of future storm structure confirm this work.

Gravity Wave Interactions

Gravity wave interactions with the atmosphere have been well studied with respect to convective initiation and enhancement. Initiation effects have been studied by Uccellini in 1975 and Corfidi in 1998 while gravity wave production by convection was studied as long ago as 1945 by Brunk. It has only been within the past decade, however, that gravity wave interactions with pre-existing updrafts with at least marginal vorticity have been studied. Before discussing the direct interactions of gravity waves in the Evansville case, a brief synopsis of gravity wave dynamics is necessary.

Gravity waves may be excited when a parcel of air is perturbed in the vertical within an area of static stability (Coleman, 2008). Lidzen and Tung showed in 1976 that while gravity waves require static stability to form, they also require an atmospheric layer through which they may duct in order to propagate their energy forward instead of having the energy simply leak vertically into the atmosphere. The same study showed that lower

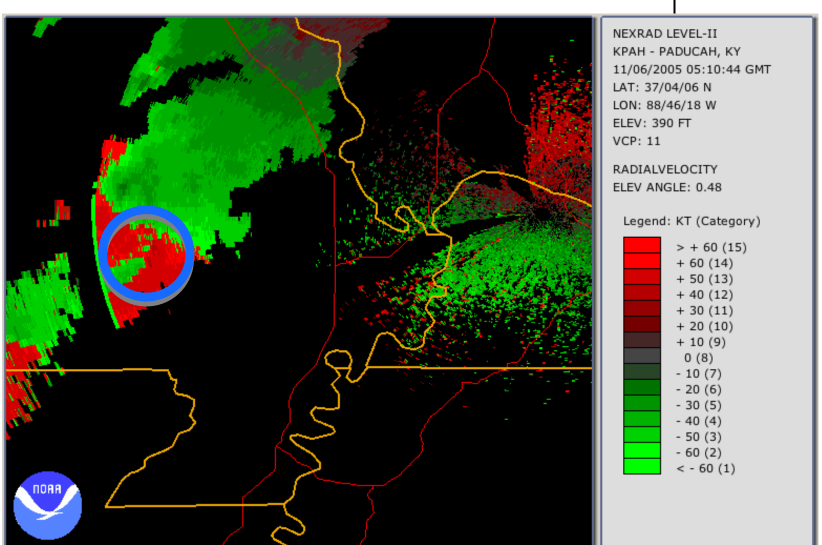


Figure 5: Storm relative velocity from 0510 UTC seen by WFO Paducah WSR-88D. This image is at the same time as figure 4 and shows the first detection of a mesovortex within the storm structure as it transitions in response to a changing shear environment. The mesovortex is circled.

atmospheric gravity waves can be ducted by near surface stable layers provided the stable layer meets three criterion:

1. the layer must be deep enough to accommodate at least ¼ of the vertical wavelength of the wave produced
2. the stable layer must contain no critical level
3. the stable layer must be topped by a conditionally unstable layer with a Richardson number less than .25

isentropic surface, is shown in Figure 6. The arrows represent wind and vertical motion perturbations created by the wave.

As a gravity wave interacts with a pre-existing mesocyclone, it affects the vorticity in three distinct ways, as described by the dynamical vorticity equation:

1. Stretching of pre-existing vorticity by horizontal convergence
2. Tilting of horizontal vorticity into the vertical
3. Solenoidal effects

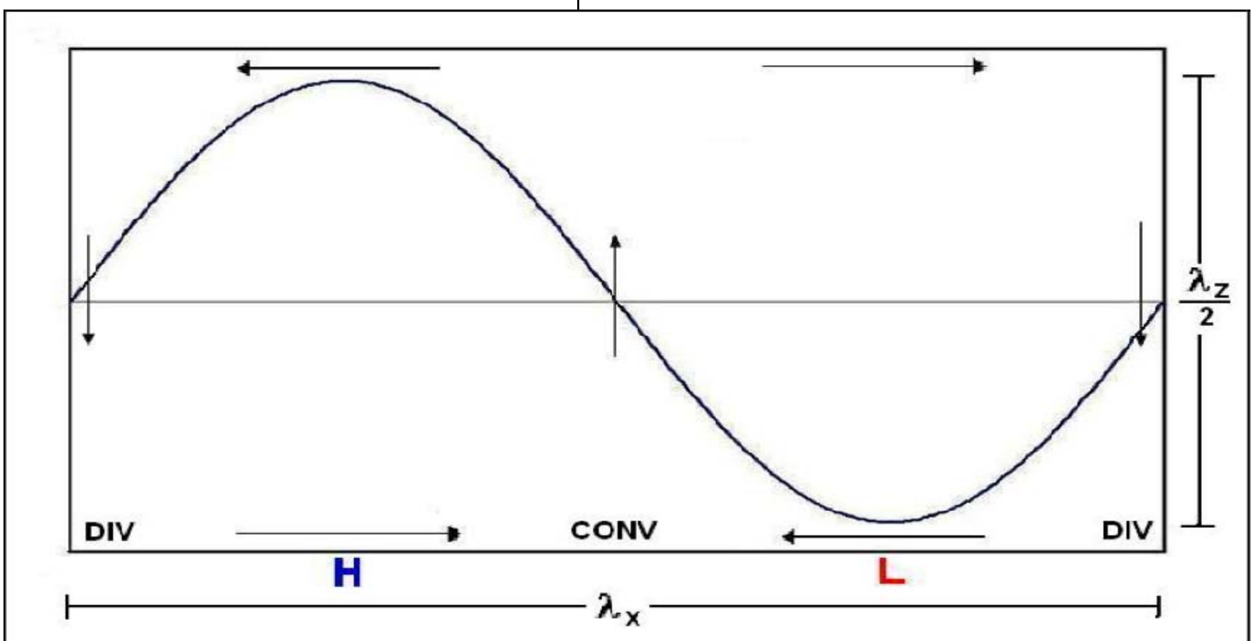


Figure 6: A conceptual model of a gravity wave moving to the right represented by the perturbation of an isentropic surface. The arrows represent wind and vertical motion perturbations while areas of convergence and divergence are noted. This model is adapted from Eom 1975, Bosart and Sanders 1986, and Cram et.al. 1992.

Should the atmosphere meet these criteria and should some mechanism produce a gravity wave, it will duct outward until the energy is dissipated or allowed to leak into the vertical. A conceptual model of a simple gravity wave, expressed as a perturbation of an

For mesoscale length scales, solenoidal effects can be neglected (Coleman, 2008).

Gravity Wave Convergence

Gravity wave convergence is maximized in the model (Figure 6) at 90 degrees ahead of the wave ridge (Coleman, 2008). At this portion, the horizontal wind perturbations are perpendicular to the wave front and thus perpendicular to the wave motion. Because of this, the parcel of air directly interacting with this portion of the wave is stretched. Should this air parcel, or those directly surrounding it, have pre-existing vorticity, this vorticity can be stretched. By the vorticity equation, any positive stretching of an air parcel with positive vorticity increases the positive vorticity in that air parcel (Coleman, 2008). It also stands to reason that the higher the amplitude of the wave and the slower the wave's forward propagation relative to the air parcel in question, the greater the stretching effect on that parcel and the greater potential increase in vorticity (Coleman 2008, Eom 1975). Mathematical and numerical studies show that the stretching of vorticity may, at least temporarily, double the vorticity of a mesocyclone (Coleman 2008).

Gravity Wave Induced Shear Changes

The second effect, tilting, also plays a role in increasing the vorticity of the mesocyclone. During passage of the gravity wave, observational studies completed using WSR-88D VAD wind profilers show strong vertical shear increases (Coleman 2008). The passage creates backing of the winds in the lowest 2,000 ft while veering the winds above 9,000 ft (Coleman 2008). This effectively lengthens the local environmental hodograph, and creates a more strongly veering atmospheric wind profile, which increases local storm relative helicity, an atmospheric parameter well shown to promote increases in mesocyclone vorticity.

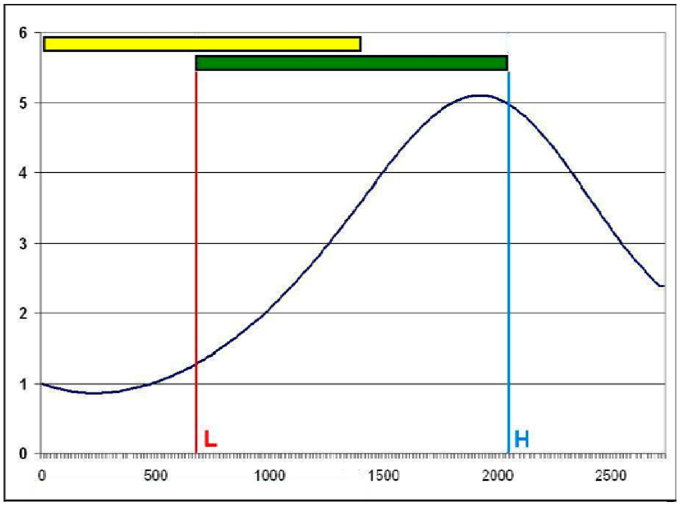


Figure 7 is a numerical simulation of mesocyclone vorticity versus time during one complete gravity wave passage. The L and H represent the wave trough and ridge passages respectively. The yellow bar shows time of constructive tilting and the green bar shows time of constructive stretching. This model was produced by Thomas Coleman and Kevin Knupp, 2008

Figure 7 shows a numerical simulation of mesocyclone vorticity during one complete passage of a gravity wave. The vorticity increases to a maximum of nearly 5 times its original value before decreasing on the backside of the wave. Of interesting note is the final vorticity value, which is twice the original vorticity. This implies that the vorticity tilting and stretching is not a reversible process and that the mesocyclone is strengthened even after the gravity wave has finished interacting with the mesocyclone.

Evansville Regional Gravity Wave Environment

The environment surrounding Evansville around the time of the tornado was supportive of gravity wave propagation and thus gravity wave interaction with pre-existing storm structures. First, the environment meets the three criterions for gravity wave ducting:

1. The layer is deep enough to allow for ¼ of the vertical wavelength.
2. There is no critical level within the stable ducting layer. This is because there is no wind speed equal to the phase speed of the waves produced in this atmospheric environment. With no critical layer, the waves cannot be absorbed and can thus be ducted in the horizontal.
3. There exists a conditionally stable layer above the ducting layer with a Richardson number of $0.09 < 0.25$ thus preventing the layer above from absorbing the gravity wave's energy.

The stable layer through which the waves are able to duct lies between 750 m above ground level and 1,125 m above ground level (Figure 3). Through numerical research by Coleman and Knupp (2008) and observational analysis by Sanders and Bosart (1985) it has been shown that the highest likelihood of radar detectable precipitation associated with a traveling gravity wave would be near or just ahead of the wave ridge. Observational analyses confirmed this and proved radar's usefulness in tracking gravity wave propagation. This method of radar tracking is very effective at identifying gravity wave interactions with our target storm prior to and during tornadogenesis. Gravity wave interactions are also strongest when there is pre-existing storm level vorticity. Environmental shear changes toward becoming more veering have already been shown to have had an effect on storm structure and attendant vorticity (Figures 3, 4, and 5).

Storm - Gravity Wave Interactions

In the hour and a half prior to tornadogenesis, gravity waves can be clearly seen on radar propagating toward and through the supercell thunderstorm that eventually produces the Evansville tornado. Figure 8 shows the progression of storm structure through time as it approaches Evansville and clearly shows the progression of the gravity waves in the vicinity.

The first reflectivity image is valid at 0627 UTC. Just over one hour after Figure 4 is valid, the storm shows a reflectivity pattern that suggests a complete transformation to classical supercellular structure. The southeast flank of the storm exhibits a hook echo, indicative of a strong, rotating updraft. By 0600 UTC, area wind profilers indicate the transition to a strongly veering vertical wind profile is complete and is thus a valid reason for why the storm structure transformation has taken place. A small, curving bow just south of the hook echo is indicative of a strong rear flank downdraft, further identifying the storm as having made the transition from a quasi-linear convective storm mode to a supercellular storm mode. To the west of the hook echo, a light reflectivity patch is noted extending

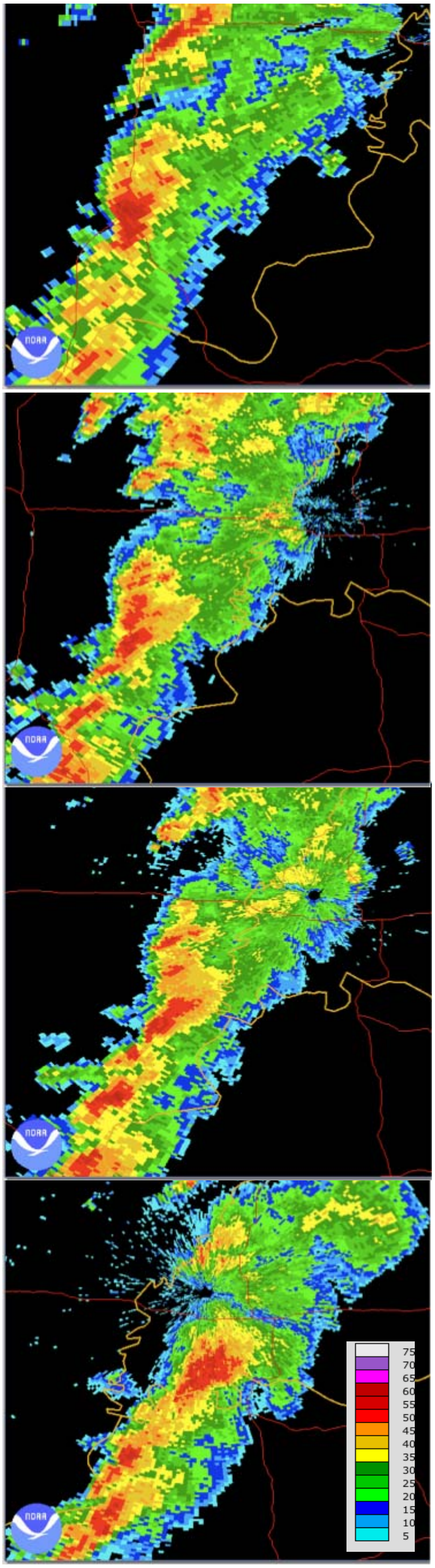


Figure 8, left: To the left is a series of base reflectivity radar captures from the KVWX radar site north of Evansville, Indiana. From top to bottom the time stamps are 0627, 0653, 0707, and 0739. The images clearly show gravity wave propagation and lead up to tornadogenesis at 0739

outward from the main precipitation shield. This reflectivity tag is the first indication of gravity waves interacting with the storm environment. While animated radar loops of the storm provide strong visual evidence that this is the first indication of a gravity wave, another method can be used to show that this is indeed the case. In the top image, the radar beam height above ground level is approximately 1,050 meters at the distance the reflectivity tag is noted. This falls into the stable ducting layer defined earlier and shown in Figure 3.

The next reflectivity image down, valid at 0653 UTC, shows the reflectivity tag passing through the hook echo. The hook echo is the location of the updraft of the storm and thus is the reflectivity signature identifying the location of the mesocyclone. From base reflectivity, the storm structure looks unchanged by the gravity wave interaction. Figure 9, however, indicates strengthening due to the passage of the gravity wave. The first image of Figure 9 is the storm relative velocity of the same geographical area as Figure 8 and is valid at 0653. The second image is the same area only seven minutes later at 0700, a few minutes after the gravity wave interacts with the mesocyclone. Prior to the gravity wave passage, gate-to-gate rotational shear is broad and is

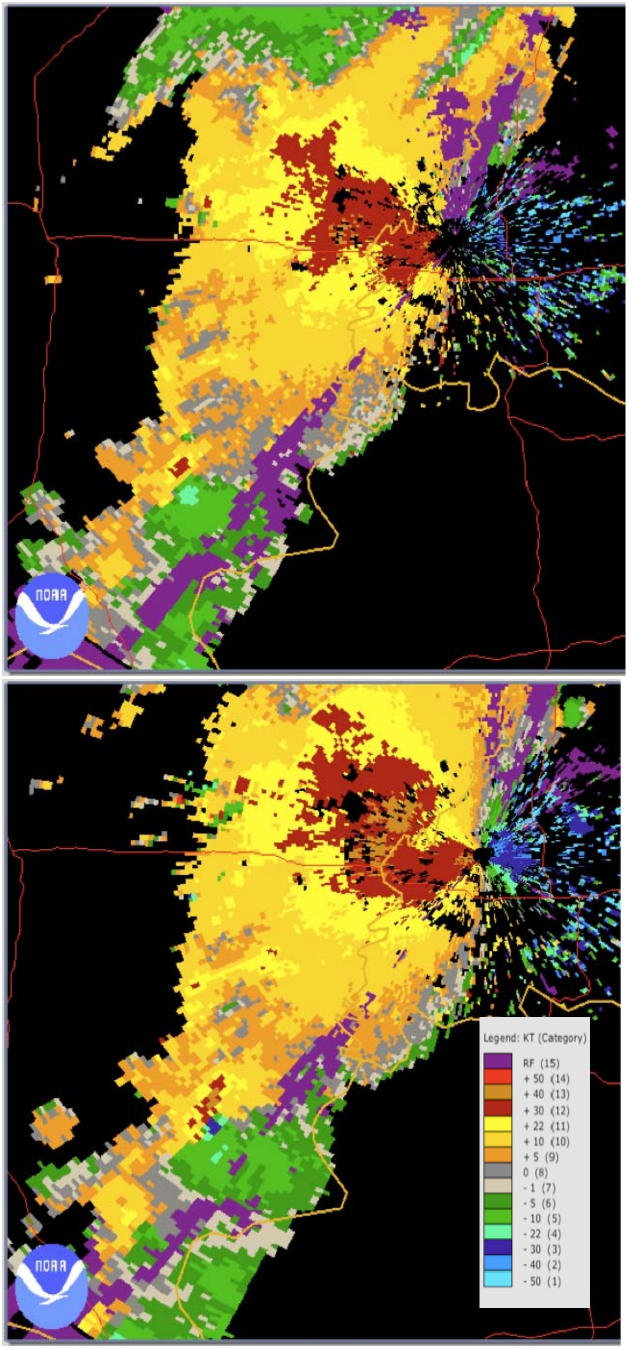


Figure 9, left: This figure shows storm relative velocity radar captures from the same geographical area as defined in Figure 8. The radar site, KVWX is located in the upper right of each image. The first image is valid at 0653 UTC and the second image is valid at 0700 UTC. The legend on the bottom right is valid for both images. This time sequence shows vorticity increase with the passage of a gravity wave.

at maximum 52 knots. After passage of the gravity wave, rotational gate-to-gate shear tightens up and increases to at least 60 knots (Figure 9). This tightening of the circulation and strengthening of the shear is indicative of a stretched vorticity tube and follows exactly as the gravity wave model suggests occurs during gravity wave interactions with mesocyclones.

The third image on Figure 8 is valid at 0707 UTC. In this image, a supercellular structure is still evident as are two reflectivity tags indicating the presence of two gravity waves. The first gravity wave has passed the hook echo and thus the storm's updraft. The effects of this passage are detailed in Figure 9. The second gravity is producing a much stronger reflectivity signature, maximum of 35 dbz, and is well southwest of the main storm.

The fourth image in Figure 8 is valid at 0739 UTC. This is the time of tornadogenesis. The image shows that the reflectivity tag from the previous image has caught up to the hook echo and thus the updraft of the supercell. A third gravity wave is also evident well southwest of the storm. The series of images that make up Figure 8 show a progression of the gravity waves that is faster than the progression of the storm itself. This is to be expected as it has already been defined that the ducting layer contains no critical level and thus no wind speeds matching the phase speed of the waves. This ensures that the storm motion will be less than that of the gravity wave propagation, allowing the waves to travel through the storm's updraft. Figure 10 is the same as Figure

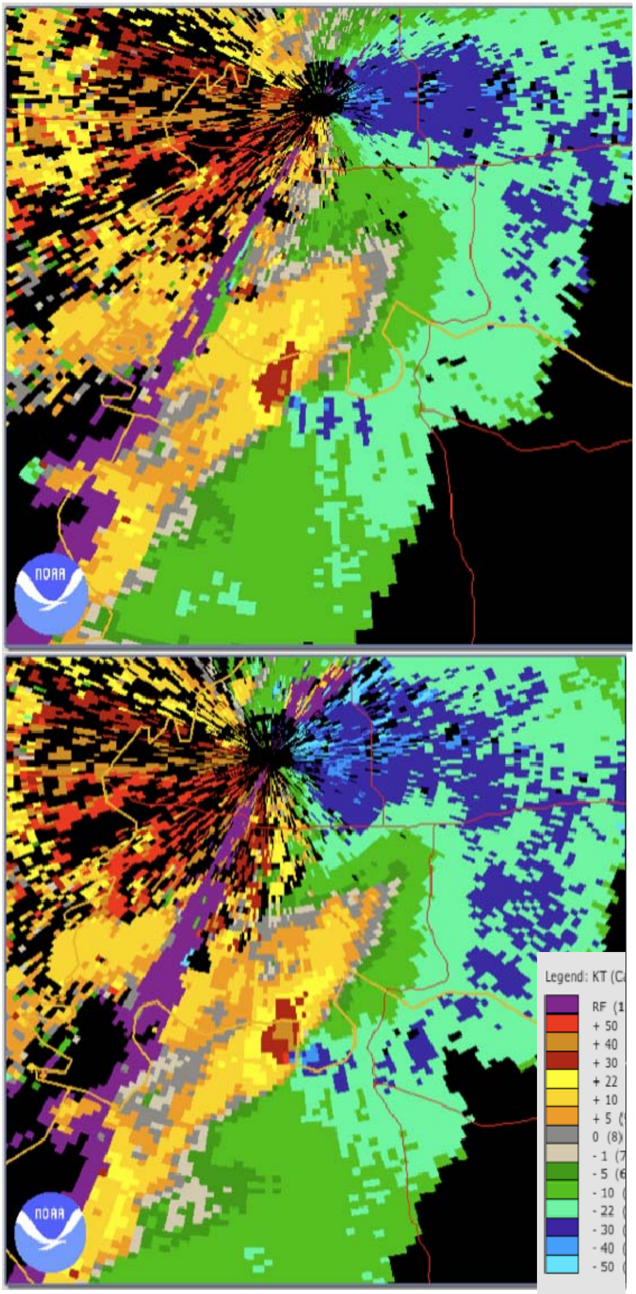


Figure 10: Same geographic region as Figures 8 and 9. Storm relative velocity is shown with the legend in the bottom right being valid for both images. The top image is valid at 0739 UTC and is the time of tornadogenesis and passage of the second gravity wave. The bottom image is valid 0745 and shows 100 knots of rotational gate-to-gate shear.

9 but valid at 0739 and 0745. The top image shows the supercell's circulation right as tornadogenesis occurs and the gravity wave is passing through the mesocyclone. At this time, rotational gate-to-gate shear is near 75 knots. Six minutes later, at 0745, the second image shows a tighter and stronger mesocyclone with rotational gate-to-gate shear approaching 100 knots (Figure 10). At 0745, the tornado is entering the south side of Evansville, Indiana and is at its strongest surface wind speed.

Of additional note is that tornadogenesis did not take place after the first interaction with a gravity wave. Coleman and Knupp's research indicates that tornadogenesis created or enhanced by gravity wave interactions with mesocyclones usually does not occur until the tertiary or later gravity wave interaction (2008). While this particular case saw tornadogenesis after the secondary interaction, the basic principles of Coleman and Knupp's research appear to hold true. A majority of the research was done on high CAPE, high shear environments which may explain the slight discrepancy in this case.

Post Event Information

After producing the F-3 tornado in Evansville, the supercell quickly moved to the northeast and out of the favorable region for continued supercell storm structures (Figure 2). The individual storm produced no additional reports of severe weather of any kind and by 0930 had lost all supercellular characteristics and merged into a squall line that continued northeastward into Ohio and Lower Michigan. The northern half of the squall line did produce numerous wind damage reports, as forecasters had expected for the entire evening, across Central Indiana, Southern Michigan, and Northwestern Ohio. Along with the Evansville tornado, a second F-3 tornado did occur in the region in Crittendon County, Kentucky at nearly the same time as the Evansville tornado. This supercell, south of the Evansville supercell, was able to remain in a more favorable supercell environment much longer and continued to produce wind damage and sporadic large hail for the next several hours. The two F-3 tornado reports were, however, the only tornadoes to touch down in the region from either supercell.

Summary

During the early morning hours of November 6, 2005, an F-3 tornado touched down in Evansville, Indiana and killed 23 people. The event was not well forecast but a reanalysis of the event shows that the evidence for tornadic potential was present. Studying cases like this is important to improve forecaster awareness and help fulfill the mission of the National Weather Service to protect life and property. The situation occurred as follows:

During the late afternoon and early evening of November 5, 2005, forecasters were expecting an overnight threat of damaging wind from a squall line of thunderstorms that formed in Missouri and Arkansas earlier in the afternoon. Vertical wind shear over Western Kentucky and Southern Indiana was nearly unidirectional but had decent speed shear. As the night progressed, the vertical wind profile changed in response to ageostrophic forcings at the surface, the increase in the low level jet, and the arrival of a mid to upper level jet streak, all of which combined to produce a strongly veering wind profile over the region (Figure 3).

The jet streak also provided enhanced upper level ageostrophic divergence, allowing for stronger updrafts than were expected. At the surface, CAPE remained small, less than 800 J/kg in most locations. The low level jet, however, provided an increased low-level transport of moisture from the Gulf of Mexico. This increased surface moisture lowered the liquid condensation level and the level of free convection across the region, increasing total CAPE but most importantly 0-3 km CAPE. Research by Jonathon Davies stresses the importance of low-level CAPE in low total CAPE but highly sheared environments. As storms moved toward Southern Indiana, they took advantage of the changing vertical wind shear and began to transition from quasi-linear to classical supercells.

At the same time, the atmospheric profile in place was conducive for gravity wave ducting. Strong convection to the south of the region produced gravity waves that were easily ducted northward and into the supercell's path. As the gravity waves interacted with the mesocyclones, the mesocyclone vorticity increased and after two direct interactions, tornadogenesis occurred.

Understanding this severe weather setup is vitally important for future forecasting success. The even occurred in the middle of the night when many were sleeping. A lack of proper situational awareness prior to the event meant that many in the path of the storm went to bed without knowledge of any potential hazards overnight. Due to these factors, many of those killed never had any warning to seek shelter before being subjected to the full impact of the tornado. Increased situational awareness can prevent future episodes of this occurring.

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