Convective Initiation Within a Warm Sector Cloud Band

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Abstract

A case study is presented of convection that formed within a warm sector cloud band. The air mass in which the cloud band resided was the maritime tropical warm sector of a well-developed extratropical cyclone. Morning forecasting efforts anticipated convective development to the east of the cloud band where the atmosphere was marginally unstable, or west of the cloud band in somewhat less stable air which also featured a dryline-like feature as well as an approaching kata-type cold front. Initial fields from the Rapid Update Cycle reveal the region of convective initiation to be convectively unstable, with ample moisture and moisture advection in the lower troposphere, both in the presence of significant frontogenesis.

1.Introduction

Portions of central Missouri, including the city of Columbia, MO (COU), experienced a brief episode of convective precipitation on the afternoon of 19 April 2000. Radar and satellite imagery indicate that a narrow line of thunderstorms formed near 2000 UTC on the day of the event, moved through COU around 2100 UTC, and then into eastern Missouri by 2200

UTC. This event is worthy of examination because the thunderstorm development occurred in a region that had been cloudy throughout the day and was sandwiched between two regions of abundant solar heating. Furthermore, an examination of the Storm Prediction Center's preliminary severe weather reports of the day (not shown) indicates that there were reports of large hail from central Missouri.

The impetus for this study was the debate on the morning of 19 April 2000 over whether to field storm chase teams, and if so, to send them east toward a region of insolation and high convective available potential energies (CAPEs)/low convective inhibitions (CINs), or west toward the region of better dynamics that was blanketed by clouds. With this effort, we hope to understand better the dynamics of convective onset of that afternoon. The present study approaches the time of convective initiation from three perspectives. First, the traditional analysis of plotted surface data leads the examination of the environment. Secondly, output from the Rapid Update Cycle (RUC) helps us to reveal the three-dimensional structure of the atmosphere at the time of convective initiation. Finally, Geostationary Operational Environmental Satellite (GOES) imagery (Fig. 1a) as well as GOES-derived soundings help us to understand the stability profiles and tendencies at, and prior to, the start of deep moist convection.

2. Methodology

Observed surface data, RUC initial fields, and GOES satellite imagery and soundings at or very near the time of convective development form the basis of our analysis. With surface data, a subjective analysis was completed to elucidate the strength of thermal and moisture fields as well as to locate and assess troughs and frontal boundaries.

RUC initial fields from 1200 UTC to 2300 UTC on 19 April 2000 were analyzed in order to find the dynamic forcing for the brief episode of convection. Both plan view and cross section analyses were employed to express kinematic and other quantities. Smith et al. (2000) and Schwartz et al. (2000) have shown that the RUC shows significant skill in resolving dynamic parameters such as divergence, CAPE, moisture advection, and wind fields. Furthermore, the RUC is the ideal model for convective case studies, as it is updated hourly and has a 40 km grid spacing.

Lastly, both infrared and visible satellite imagery from GOES-8 are used for the analysis of this event. The infrared imagery has a 4 km resolution while the visible images from the UNIDATA educational floater possess 1 km resolution. The floater images, which were centered over Missouri and Iowa for the time period of interest, revealed cumulonimbus tops, wave clouds, and especially, an area of clearing near the region of, and just prior to, convection onset. GOES-8 also has a sounding instrument on board that samples 19 channels; each channel senses a different layer of the atmosphere, which can be compiled into a vertical profile of the temperature and moisture content in the atmosphere (Holt 1998). From this vertical information, various parameters can be generated that pertain to the site-specific sounding. Examples of such parameters are precipitable water, ground surface temperatures, and several stability indices. Some of the stability values, like CAPE and CIN, are calculated based not upon a surface parcel, but on the level possessing the highest equivalent potential temperature (θ_e, most potential buoyancy) among the lowest three levels sounded. The soundings are displayed on a skew-*T* log *p* diagram along with a first guess profile derived for each sounding location from the Aviation (AVN) numerical forecast model. As the satellite sounder instrument scans each 30 km x 30 km area box, they are divided into nine 10 km x 10 km fields of view. If the algorithms that determine cloudiness deem that four of the nine areas are clear, then the values are averaged for that area and a profile is produced. If less than four fields-of-view are found to be clear, then no sounding is produced, although other cloud products can be computed (Holt 1998). (As of 12 September 2000, GOES soundings were run in a single field-of-view mode. Still, we emphasize that the soundings presented here were collected during use of the nine field-of-view mode.)

3.Case Analysis - 19 April 2000

a.Surface Analysis

A mesoanalysis of Midwest surface features at 2100 UTC 19 April 2000 (Fig. 1b) reveals a complex weather pattern with several boundaries of concern. A cold front associated with a low pressure center over South Dakota trails through central Nebraska and southwestward to northwestern Kansas. A warm front is also evident, oriented from northwest to southeast, through central Iowa and into extreme northeast Missouri; mid-Missouri is ensconced in the warm sector of the cyclone.

Upon closer examination of the surface mesoanalysis (Fig. 1b), the presence of two additional boundaries becomes apparent. First, evidence of a wind shift line is seen in central Kansas. As indicated by the surface plot presented here and by satellite imagery from the hour prior (presented shortly), no appreciable cloud cover is associated with this feature. Secondly, a dryline type boundary is also apparent, stretching from central Iowa southward into northwest Missouri and southeast Kansas. The 2100 UTC isodrosotherm analysis indicates that this moisture gradient is strongest in northwestern Missouri.

The strong moisture boundary appears to be of great importance to the weather across the affected area. A region of cloudiness (shown explicitly later) existed at 1800 UTC along and to the east of the strong dew point gradient at 2100 UTC. Convection initiated (Fig. 2) just ahead of this boundary in Missouri between 1900 UTC and 2000 UTC. COU first reported a thunderstorm during the 2000 UTC hour. From a forecasting perspective, convective initiation in this area may have seemed unlikely beforehand since this same locale had been under broken to overcast sky conditions for the roughly six hours prior to 2000 UTC. Indeed, this cloud band reduced temperatures beneath the band as indicated on the mesoanalysis (Fig. 1b). Still, the presence of a noticeably strong moisture gradient (especially over northwestern Missouri, which was closer to the dynamic synoptic-scale system) indicates that this is the area in need of monitoring for convective development. The westernmost edge of the cloud band is sharp and well defined. The sharp cloud edge is in good spatial agreement with the rapid decrease in dew point temperatures at the surface.

Four major boundaries have been located in the Midwest by means of surface mesoanalysis. A confluent wind shift area in Kansas seems to be of little import to significant sensible weather. The analyzed cold and warm fronts are associated with large areas of cloud cover, but minimal precipitation. The most important and influential surface feature in relation to convection and cloud cover over Missouri is the zone of very strong moisture gradient where dew point temperatures vary from the 30s in northwest Missouri to near 65^{o}F in the central section of the state.

b.Rapid Update Cycle output

At 2000 UTC, a narrow band of thunderstorms was developing over west central Missouri, approximately 50 miles west of COU (Fig. 2). A strong southerly flow near the surface had pushed 60°F dew points across all of Missouri, and as far north as central Iowa. Significant moisture convergence (3 to $6*10^{-7}$ s^{-1}) was indicated at 950 mb (Fig. 3).

A broad 1000 mb low was indicated over eastern Nebraska and northeastern Kansas, while closed 850, 700, 500 and 300 mb cyclonic circulations were vertically stacked over north central Nebraska (not shown). A 110 knot jet streak (Fig. 4) extended from northwestern Kansas into central Nebraska, placing west central Missouri in the right-exit region, although weak divergence (~$1*10^{-5}$ s^{-1}) is diagnosed. Plan view analysis shows a θ_e ridge extending from Texas into southeastern Iowa at 850 mb, while high θ_e values were pushing into southwestern Missouri at 700 (Fig. 5a) and 500 mb (Fig. 5b).

Cross-section analysis at this time is more compelling. Figure 6 shows a deep layer of convective instability over Missouri. Relative humidity values of greater than 80% are located from near COU and eastward from near 950 to 750 mb, thus resolving the cloud band of interest quite well. A sharp gradient of relative humidity is evident vertically and to the west of COU. Figure 7 shows advection of lower mixing ratios of 10 to $16*10^{-8}$ g kg^{-1} s^{-1} near 800 mb and just west of COU. This correlates very well with the strongest frontogenesis (near 800 mb) and strongest vertical motion (Fig. 8). Thus, frontogenetical forcing in the presence of convective instability combined with the thermodynamic impact of the advection of dry air at 800 mb over a moistening layer near the surface provided the forcing for vertical motion at the time of convective initiation. While upper tropospheric divergence was weak, the advection of high θ_e air into Missouri in the lower troposphere suggests that synoptic-scale forcing in the form of isentropic uplift played at least some role in initiation. However, it is unlikely that convection would have been initiated within the cloud band without the presence of frontogenesis on the mesoscale level.

c.GOES imagery

At 1415 UTC 19 April 2000 low clouds cover northern and western Missouri and southeastern Kansas (Fig. 9). As in Fig. 1b a few hours later, clear areas include most of Nebraska, southwestern Iowa, extreme northwestern Missouri and east central Kansas, west of Emporia and Topeka. On the eastern side of the cloud band, clear skies can be found over most of southeast Missouri. By 1615 UTC 19 April 2000 (Fig. 10), cumulus elements begin developing on the west side of the low cloud band as it treks eastward.

Just prior to convection initiation at 1915 UTC 19 April 2000 (Fig. 11), there appear to be more diffuse low reflectivity clouds over the cumulus field in a region south and east of the Kansas City area. The area shows up clearly on the MB-curve-enhanced IR image as colder and therefore higher cloud tops (Fig. 12). A few of the cumulus elements with cold cloud tops along the Missouri/Kansas border have wispy tops, indicating the early stages of convection and vertical development. Perhaps the most interesting aspect of this satellite image is a thin, linear break in the clouds, oriented northeast to southwest, very close to Whiteman Air Force Base (KSZL). The band is approximately 110 km long but very narrow, estimated to be 2 to 3 km wide via satellite grid spacing. This would become a key feature for the developing convection.

Deep convection initiates between 1915 and 2015 UTC, evidenced by a line of cumulonimbus tops just east of Whiteman Air Force Base oriented northeast-to-southwest and well-aligned with the narrow band of clearing noted in the 1915 UTC IR and floater images. These vertically developed storms are oriented parallel to and within the eastern and western bounds of the original cloud band first noted at 1215 UTC. There are four distinct elements discernible via the enhanced IR image in the developing squall line at 2015 UTC (Fig. 13).

d.GOES sounding profiles

1) Jefferson City, Missouri

The soundings analyzed span the period from 1200 UTC to 1800 UTC. Table 1 shows how calculated soundings parameters changed at Jefferson City, Missouri, over the course of the six hours leading up to the convection. At 1200 UTC (Fig. 14a), the GOES sounding shows dew points below 850mb to be fairly constant around 12ºC, and a nearly constant temperature around 15ºC to above 800 mb. Despite the highest K index out of any of the soundings analyzed, there is no level at which the low level lifted parcel would become positively buoyant. The Lifted Index is the highest for any value analyzed for this time and location, with a +1 indicating stable conditions.

By 1500 UTC (Fig. 14b), surface heating has raised the surface temperature to 24ºC and surface dew points are 16ºC.Note also that the sounding is to a point where CAPE and CIN were now calculable (779 J kg^{-1} and 469 J kg^{-1}, respectively). The K Index has decreased to 21, a value not strongly indicative of convective support at that time, but the Lifted Index becomes negative, indicating instability within the atmosphere.

At 1800 UTC (Fig. 14c), there is strong enough surface heating to create a small area of positive buoyancy at the surface, though the algorithm to calculate CAPE (3 J kg^{-1}) and CIN (0 J kg^{-1}) only account for the lowest two positive and negative energy areas (even if there are more significant features aloft that are not captured). In this case, as will be seen for several of the Kansas City soundings, the CAPE area has increased and CIN decreased, but the calculated numbers to the right of the sounding do not reflect the changes. The main difference in CAPE and CIN now versus the 1500 UTC sounding (Fig. 14b) is the increase in dew points from the low teens to upper teens below 850 mb. The Lifted Index drops to -5, indicating very unstable conditions, and the K Index increases to above 20.

2) Kansas City, Missouri

Soundings for Kansas City, MO are analyzed from 1200 UTC to 1900 UTC (Table 2), with the 1600 UTC sounding missing due to cloud cover or another obscuration. At 1200 UTC, the surface temperature is near 20ºC and drops fairly steadily to 10ºC at 700 mb (Fig. 15a). Dew points begin near 18ºC at the surface, and differ substantially from the 1200 UTC Jefferson City sounding, indicating the presence of much drier air in western Missouri below 700 mb. The K Index of 11 does not suggest much convective support (due to dry mid level air), but the Lifted Index suggests some atmospheric instability because of its negative value.

By 1500 UTC (Fig. 15b), the Kansas City sounding has roughly doubled its CAPE (2342 J kg^{-1}), and quartered the CIN (71 J kg^{-1}) from 3 hours prior. The Lifted Index has also dropped to -5, but this stability index does not account for the marked decrease in dew points between 700 and 950 mb over the three hour period. There is marked difference between dew point profiles of the AVN 'guess' and the GOES derived product, which verifies the statement from Gordon, et al (1998), that dew point profiles, not temperature, differ greatly between model and satellite derived soundings. From 950 mb to 550 mb, there is a 5ºC dew point spread between the more moist GOES sounding and drier AVN nearer the surface. However, good agreement is found above 550 mb in dew points.

At 1700 UTC (Fig. 15c), CAPE has nearly doubled again, but this time there is no negative buoyancy layer over which to stop a lifted parcel's ascent. The surface temperature has increased 5ºC in two hours, and the K Index now trends upward, the Showalter index tends toward negative values, and the Lifted Index reaches its most negative value (-8) seen for this case. The dew point difference has spread throughout a deeper layer, from the surface to about 325 mb, indicating the GOES sounding shows a more moist profile than the AVN.

By 1900 UTC (Fig. 15d), the surface appears to have reached its convective temperature of 28ºC, where parcel ascent will begin based solely on thermodynamics in the absence of mechanical lifting. The K Index rises, but nowhere near the values reached at Jefferson City, and the Showalter Index, Total Totals Index, and Lifted Index begin a trend toward increased stability and less convective support.

4.Discussion

The work of Johns and Doswell (1992) guided this analysis. As such, three key ingredients were sought to achieve moist deep convection. First, a moist layer of sufficient depth in the low or mid-troposphere is required. GOES soundings demonstrate that Kansas City did not have a sufficient moist layer, whereas the Jefferson City area possessed a sufficient moist layer up to 850 mb at all times. However, the surface analysis from the time of the event revealed a moisture boundary just east of the Kansas City area. Indeed, both radar and satellite analyses show the location of convective initiation to be about one half way between Kansas City, and Jefferson City, Missouri. Secondly, a lapse rate steep enough to allow for a substantial 'positive area' is needed. The GOES soundings for Kansas City during 14Z-23Z, exhibited lapse rates of 6º-7ºC km^{-1} from 850-500mb.The Jefferson City sounding had a lapse rate (for the same time period) of 7ºC decreasing to 6ºC. Moreover, the RUC initial fields clearly demonstrate the deep layer of convective instability over mid-Missouri just east of the intense relative humidity gradient. Also, satellite imagery (1 km) strongly suggest that a narrow line of clearing within the cloud band was sufficient to allow solar heating to destabilize the atmosphere by 1900 UTC over western Missouri. Third and finally, sufficient lifting of a parcel from the moist layer to the parcel's LFC is required to initiate deep moist convection. From the RUC output we know that the region of convective initiation was also experiencing vertical motions of -2 to -4 $\mu b\ s^{-1}$ in the lower to mid-troposphere at the time convection began.

To conclude, convection on this day did not initiate on either edge of the cloud band, but instead near the middle of it. This occurred in the presence of frontogenetical forcing and a clearing in the cloud band that permitted local differential heating. Chase teams were not dispatched prior to the arrival of convection in the Columbia, Missouri, area due to low forecast confidence. The lack of tornadic activity in Missouri proved the decision not to chase a fortunate one.

Authors

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