J 3.3 SOME INFERENCES ON THE VISUAL CLOUD AND THE SUPERCELL RADAR ECHO RELATIONSHIP

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1. INTRODUCTION

Beginning with Browning and Donaldson (1963) and many others to follow, the supercell radar structure has been well established. In parallel for the last 30 years supercell visual observations have been made through both amateur and professional scientific field photographs and movies/videos. Much has been learned and continues to be learned through both of these differing observation sets. Moreover, both platforms are continually being improved, for example by the introduction of the phased array Doppler radar (for research purposes) and the visual technology via digital photography. But surprisingly these two complimentary data sets have only rarely been combined to elucidate interrelationships and improve our understanding of storms. Here we attempt to begin this process. We begin by reviewing the radar detection of non-supercell storm structure and relate that to the visual structure of these storms. We then briefly discuss the supercell model and relate it to the storm dynamics. These dynamics are then related to visual cloud interpretation principals and these principals to cloud structure and radar interpretation. The result is that we attempt to interrelate and compare the radar – visual cloud observations pointing out the radar counterpart to visual storm structures and vice versa. Features we emphasize include the Weak Echo Region, Bounded Weak Echo Region, hook echo, the storm summit, and to an extent other updraft and downdraft related cloud and echo structures.

2. NON-SUPERCELL STORMS

As is the case with radar rendition of all weather, the detection and recognition of radar features is very much a function of the radar itself (here we assume an S-band radar having a 1^{o} beam) and the range to the target. Moreover, when using radar we must scan the storms using a full volume scanning routine (When characterizing human beings we don't simply look at the feet but we scan the entire person).

With a storm nearby (less than ~ 80 km), when scanning with radar antenna elevations of a few degrees (~ 3^{o} or less), the echo core depicts the precipitation cascade or downdraft region. As observed visually this is typically seen falling immediately adjacent to the somewhat sloped cumulonimbus (CB) tower marking the principal storm or cell updraft. It is an area that appears most often as a "slate-grey", featureless region extending from the cloud to the ground.

Using the same modest radar antenna elevations but with a storm at ~ 200 km in range, the beam slices through the storm from ~ 5 km to ~ 10 km AGL. Here the echo core is now characterized substantially or completely by updraft and is located substantially within the CB tower itself. This is also true if the radar samples the nearby storm but with intermediate elevation angles.

If we now sample the longer-range storm with the intermediate antenna elevations we sample the storm within the anvil region up to the cloud summit. This region is dominated by divergence with the echo core or cores characterized by regions of stronger divergence and diminished updraft.

3. SUPERCELLS

Again we begin with a nearby supercellular storm and a low-level scan. These storms are often rather elliptical with a "notch" or concavity on the updraft storm-flank bordered by a strong reflectivity gradient. This concavity or "inflow notch" is open toward the direction from which the storm-relative inflow approaches and accelerates into the storm (see Fig. 1 from Browning [1964]). The inflow notch is the inflow portion of the low-level mesocyclone velocity signature associated with supercell storms. It is here within this inflow notch that Donaldson et al. (1965) found, with a

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soon-to-be tornadic supercell, a bell shaped CB with a rain-free cloud base (RFB). This is the location of the intense updraft as is characteristic of supercells. This CB tower is often noteworthy as well due to its very white (in sunlight) and "hard" cumuliform edges. These edges can also often be seen to rise very rapidly. The "wall cloud" marks the surface roots of the updraft. The wall cloud is most often a quasi-circular abrupt lowering of the RFB. Here, rain cooled and moistened surface flow has originated from the immediately adjacent precipitation region and is drawn upward by an upward directed vertical perturbation pressure gradient force. The wall cloud often has an animated appearance with cyclonically striated and twisting ascent. At times scud clouds will form along the edges or beneath the wall cloud and will rise rapidly into the base. While there is no known radar signature for the wall cloud it is wholly contained beneath and attached to the CB RFB. As the storm evolves it is not uncommon for often thin precipitation curtains to descend and rotate about a portion of the wall cloud.

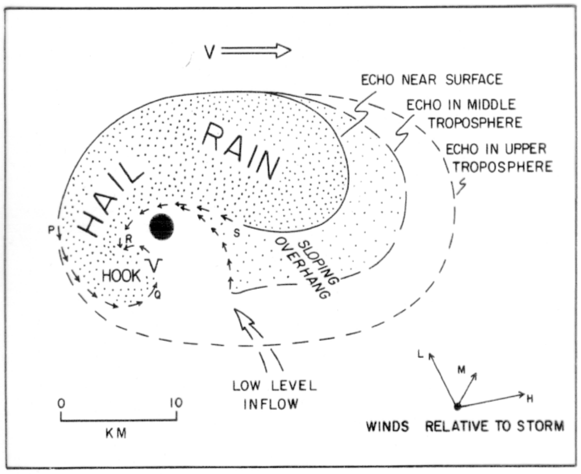

Figure 1 ***Schematic diagram showing horizontal sections at three levels through the radar echo (~ 30 dBZ) for a supercell storm. The three vectors L, M, and H represent storm relative environmental winds in low, medium, and high levels of the troposphere. Note the low-level inflow.***

As range to the storm increases or the radar antenna elevation increases the storm is sampled at a higher altitude. What was before an open concavity is now a radar-detected, quasi-circular, or elongated "donut hole". While this donut may be filled by weak to moderate echo within mid-levels it is encircled by significantly higher reflectivity echo, commonly 55 dBZ to 65 dBZ. This weak echo hole called a "Bounded Weak Echo Region" (BWER) marks the location of the intense, central, updraft core. The BWER itself is a conical shaped region in three dimensions that penetrates into the heart of the storm aloft and is capped above by a high reflectivity echo core and further by the storm summit above. But what is the visual counterpart to this BWER?

In order to more effectively explain this feature we will first consider the radar detected "Weak Echo Region" or WER. Recall that the CB anvil is the reflection of the divergent outflow created when the updraft encounters either an equilibrium level or the tropopuase. Here the rising column of air encounters what may be envisioned as a flat plate, which deflects the upward flow in all directions creating a divergence source (see Fig. 2, a modified Fig. 1). Essentially coincident with this source is a radar echo reflectivity core.

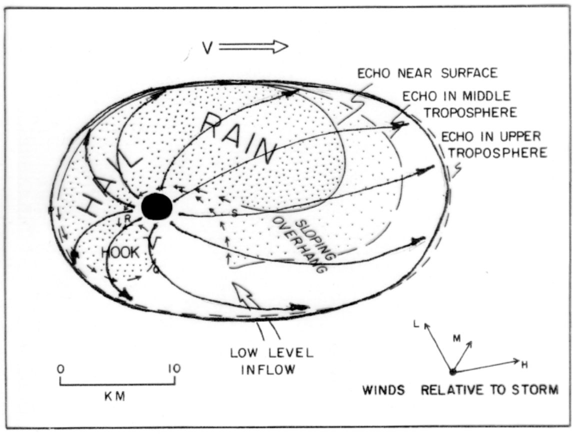

Figure 2. ***Same as Fig. A except with divergent outflow at updraft summit interacting with high level environmental flow.***

This divergent flow is extremely strong, in some cases averaging a 150 ms^{-1} velocity change across the storm summit. Large quantities of radar detectable precipitation are transported with this flow outward to the edges of the upper tropospheric echo canopy illustrated in Fig. 2. The edges of this upper tropospheric canopy of precipitation are also the edges of the anvil. But this anvil is somewhat different from that associated with non-severe storms in that it is often characterized by thick cumuliform cloud owing to the intensity of the divergent outflow and its interaction with the environmental flow. This cumuliform, thick, upshear lip first mentioned by Fujita and Arnold, [1963) is now often called "knuckles" by storm chasers. Additionally, anvil level convection can occur and generate some additional precipitation in the anvil.

Note that after reaching the edges of the high-level canopy, the anvil edges, the advected and anvil-generated precipitation begins its descent towards the earth's surface. However, as it descends from the base of the anvil it is swept back northward (in the Fig. 1 and 2 case) by the environmental winds. It is this descending precipitation that creates first the upper tropospheric echo, then the middle tropospheric echo, and finally the echo near the surface in Figs 1 and 2. This "overhanging" canopy of precipitation is called the radar "echo overhang". The region beneath it is known as the WER. Visually the echo overhang can commonly be seen beneath the anvil as virga or an amorphous grey and featureless region that masks the cloud behind it.

It has been shown that storms in a moderately or strongly sheared environment having a WER with displaced (toward the updraft flank) echo top are typically severe. Thus, this three dimensional radar echo structure is used as severe thunderstorm warning criteria. Interestingly, this same three-dimensional storm structure can be identified visually as indicated above and can serve as a visual aid in identifying severe storms.

We are now ready to return to our question concerning the visual manifestation of the BWER. With the knowledge that the BWER marks the high-speed updraft core, we know it is contained within the CB tower. Further, Browning (1964) and others to follow have concluded that developing precipitation in the updraft skirts surrounding the BWER are unable to penetrate into the unmixed updraft core. The cloud droplets within that core do not grow to radar detectable sizes until carried well aloft in the updraft. Additionally, the descending precipitation from the upshear echo overhang is swept toward and around the CB tower (but does not penetrate far into it) further defining the BWER within. Thus, the BWER is entirely contained within the CB tower and penetrates upward within the overhang to near the storm summit where a highly reflective echo core caps the feature.

Note that the base of the echo overhang does not descend far into the echo inflow indentation or notch because it is here that the horizontal low-level inflow jet caries these particles much more rapidly horizontally than they descend due to their small fall speeds. Thus, this precipitation is carried into the edges of the updraft and CB where it will again ascend. By the time these melted and sublimated droplets reach low levels near the CB base they are so small and few as to be invisible to the human eye. The largest hail falls from the intense echo surrounding the BWER reaching the surface within the strong reflectivity gradient surrounding the inflow notch and further inward toward the precipitation cascade and reflectivity core. The heaviest rain falls from the forward and left portions of the storm.

In addition to the extensive WER and BWER another feature of the supercell storm seen in Fig 1 is the hook echo. Studies of hook echoes have revealed that they are typically characterized by downdrafts and light to moderate rain sometimes mixed with hail that descended from the anvil base. Note that this region of the echo overhang has descended more rapidly than the surrounding echo overhang reaching the surface further south. It appears that the hook echo precipitation streamer descends within a downdraft bringing that precipitation to the surface more rapidly than precipitation outside the downdraft. This is also the region of the "clear slot". The clear slot is an elongated region where the cloud base has given away to clearing and sunlight (during daylight hours). (The hook echo and clear slot mark to storm-relative outbound portion of the mesocyclone velocity signature). Thus, the edge of the CB just ahead of the hook and clear slot is actually "eaten" away by a strong downdraft and is a location where descending cloud material can sometimes be seen resembling a "water fall". This strong downdraft is within and part of the "Rear Flank Downdraft" and sometimes the "Occlusion downdraft". With time the clear slot (and hook echo) can be seen to progress cyclonically around the center of the mesocyclonic circulation as that circulation occludes.

If a tornado is to be produced it will often be initially located where the "V" is shown in Figure 1. With persistence of the tornado it will often migrate toward the interior edge of the wrapping hook or toward the bulbous portion of the hook. This places the tornado just in advance of or on the edge of the clear slot. Rapidly ascending scud cloud and cloud material will often be seen ahead and/or north of the advancing tornado while descending cloud will be seen on the trailing edge and/or south of the tornado. With time the clear slot will move cyclonically as described above until it nearly encircles the tornado leading to the tornado demise with the occlusion.

When the supercell is located at longer ranges from the radar, the beam will pass through the storm in mid-levels even with small antenna elevation. This will most often prevent the BWER from being detected owing to the much broader radar beam and poor spatial resolution. Instead, only the lessened overhang and WER can be detected. Moreover, the hook echo is usually not detectable because it is a low-level feature. If it is detectable at all in some form it is no longer "hooked" and it will often take the form of a blunt "pendent" echo or knob without curvature.

Whereas the mesocyclone is only partially encompassed in echo near the storm base, aloft where it is radar sampled at longer ranges from the radar it will be found completely engulfed by precipitation. Storms whose mesocyclones are encompassed by precipitation near the earths surface are often called HP supercells. Note that a "classic" supercell detected near the radar will often have an HP appearance at longer ranges. In this case, storm type can be confused due to range from the radar. This also suggests that the HP can be detected with confidence only when the storm is at moderate to small ranges from the radar.

3. CONCLUSIONS

Here we have only just begun to attempt to combine visual and radar data. But there is considerable potential with the advent of the digital video and photography when combined with digital Doppler radar data. We encourage the radar community to join forces with the storm "intercept" or storm chase community and to collect visual and radar data simultaneously and in coordination. Further, the precise surface locations of the photography must be carefully established along with the range to the visual features. With these complimentary data sets carefully combined the potential for insights into increased understanding is great. Moreover, the synthesis of these data with other varied data sets such as atmospheric electricity, mobile mesonet, Doppler radar's on wheels, conventional surface and upper air observations, manned and unmanned aircraft, and satellite will give us far greater understanding. These are some of the challenges for future research.

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