

A Satellite Perspective of the June 15, 1988 Tornado Outbreak in Denver, Colorado

by

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1.0 INTRODUCTION

On June 15, 1988, a series of unusually strong tornadoes occurred in Denver, Colorado, USA. While F0 - F1 "landspouts" (Brady and Szoke, 1988) are not unusual on the high plains of the United States, the 15 June tornadoes were more significant, producing F2 - F3 type damage at many points in Denver. Even so, the 15 June tornadoes were not the classical supercell variety. As pointed out by Roberts and Wilson (1988), Doppler radar showed no rotation within the storms prior to their intensification. In this case, the thunderstorm updrafts appear to have stretched surface vortices which had developed along a gust front in advance of the storms. The updraft intensification and vortex stretching seem to have occurred immediately following the collision of two outflow boundaries, both of which were associated with prior thunderstorm activity.

This paper examines what additional insight satellite data provide toward the understanding of the events of 15 June, and whether or not these data contain forecast information valuable in the short-range forecast sense. Briefly, our results find an important mesoscale chain of events -- seen clearly by satellite -- which led directly to the Denver tornadoes. This sequence of events was visible on satellite imagery nearly four hours before the actual outflow intersection in Denver, although the first two hours of this development did not provide specific short-range forecast clues. The information available from satellite in this case provides a deeper understanding of the evolving situation which could have helped focus the short-range forecast in several key areas. Among these were: 1) an outflow boundary that crossed the Denver area early and triggered a new storm on a large elevated terrain feature to the south; 2) new outflow produced by this storm which moved back toward Denver to become one of the two key ingredients of the outbreak; and, 3) an approaching shortwave trough that was masked to radars on the plains by the front range of the Rocky Mountains.

The final discussion in this paper is directed toward exploring how satellite and Doppler radar might best be used together -- satellite's role being to bring the short range forecaster and radar operator to a more highly alerted status, with radar then being responsible for the short term warning function.

2.0 DATA SOURCES

Satellite data for this study were from the Geostationary Operational Environmental Satellites (GOES), and included both GOES-East (located over the equator at 75W longitude), and GOES-West (located over the equator at 135W longitude). Also available for the study were observations from 22 mesonetwork sites operated by PROFS (Program for Regional Observing and Forecast systems) in northeastern Colorado (CO), and reflectivity and velocity information from two S-

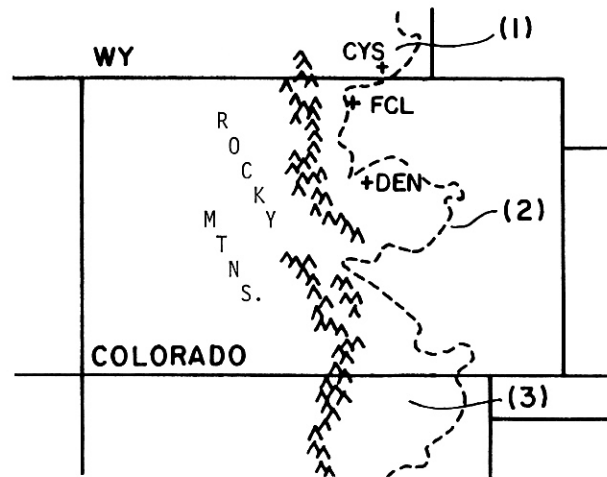


Figure 1. Map of Colorado and surrounding areas showing geographical features referred to in text. The line of carats through central CO is the so-called "front range" of the Rocky Mountains. Dashed line indicates 5000 ft. terrain height contour. Features 1, 2 and 3 are the Cheyenne Ridge, the Palmer Lake Divide, and the Raton Mesa, respectively. DEN is Denver, FCL is Fort Collins, and CYS is Cheyenne, Wyoming.

band Doppler radars. The radars were Lincoln Laboratory's FL2, situated about 15km southeast of Denver's Stapleton Airport, DEN, and NCAR's CP2, located about 45km northwest of FL2.

3.0 CONVECTIVE EVOLUTION

3.1 Colorado Topography and Weather

Most of the weather that occurs in northeast Colorado is strongly influenced by the sloping terrain of the high plains which characterizes the eastern part of the state, and by the Rocky Mountains which characterize the west (Figure 1). The peaks and valleys of the Rockies tend to disguise and distort synoptic systems as they traverse western CO. To the east, upslope flow plays a significant role in both stratiform and convective precipitation events. The gentle, east-west ridges in eastern CO also play an important role in establishing mesoscale controls on local weather. For example, under southerly low-level flow, the Palmer Lake Divide (feature 2, Figure 1) can induce a mesoscale convergence zone which stretches from DEN north-north-eastward approximately 60 nm. The convergence and vorticity associated with this zone (called the Denver Convergence-Vorticity Zone, or DCVZ) can be a favored location for severe weather along the CO front range (Szoke and Brady, 1989).

3.2 The June 15th Outbreak

On June 15, 1988, boundary layer flow was generally south-southeasterly behind a surface front which had passed through the state earlier. A region of surface high pressure was situated to the northeast of the state. Flow aloft was relatively weak as an upper tropospheric ridge pushed into the southwestern United States. Winds veered and increased from south-southeast at 10 kts near the surface, to westerly at about 25 kts at 400 mb. The morning Denver RAOB (Figure 2) showed the airmass in central CO to be quite unstable. With a forecast temperature and dewpoint of 80F and 48F, respectively, (which is what actually occurred) the afternoon

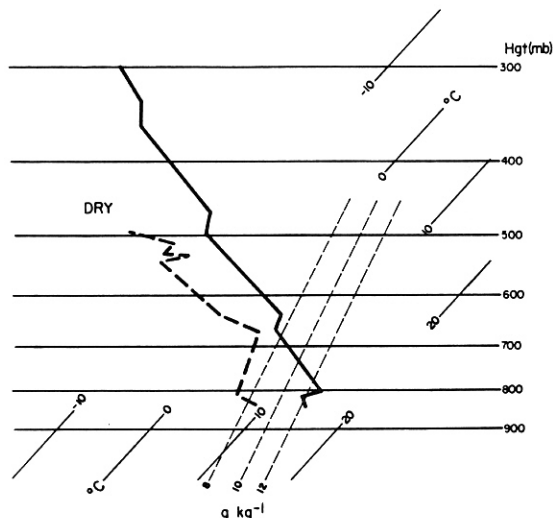


Figure 2. Denver morning (1200 UT) RAOB data from June 15, 1988. Shown are conventional temperature and dewpoint plots displayed on a Skew T-log P diagram.

Lifted Index would be -7.0. Had the expected afternoon temperature of 70 °F occurred, the LI would have been -4, and strong forcing would have been required to overcome a stable region found between 600 and 700 mb.

Convective activity began forming along the front range around midday, and by 1900 UT a thunderstorm was moving south-southeastward from the foothills, toward Denver (storm 'O' in Figure 3). By 2000 UT, that storm had nearly dissipated, but its cold air outflow had spread across a large portion of the populated region to the east of the front range, and into the city of Denver. This rain-cooled, stable area is clearly seen in visible GOES imagery (Figure 4). An analysis of potential temperature at 2000 UT, using PROFS mesonetwork data (Figure 5), also clearly shows the outflow area. The analysis indicates that the newly created airmass is measurably heavier than that of the surrounding environment, even though the storm itself has nearly disappeared. The existence of this outflow boundary was also confirmed by close inspection of FL-2 radar reflectivity data (not shown). It is interesting to note that the DCVZ -- which had triggered small cells earlier (segment A-B, Figure 3) -- was "undercut" by this outflow, and the activity along it dissipated as the outflow passed. This because, the time this outflow interacted with DCVZ, surface temperatures were about 72 - 75 °F and vertical forcing of about 6-8 m/s would have been required to overcome the mid-level stability (Figure 2).

The visible satellite images shown in Figures 4, 6, and 7 show the sequence of events which followed. By 2030 UT, the outflow boundary had passed through the Denver metro

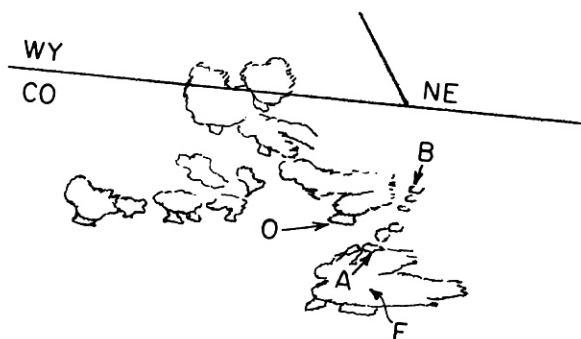


Figure 3. GOES-West VIS image from 1916 UT on June 15, 1988. Thunderstorms are forming in the Rockies, and one storm in northeast CO (storm 'O') has moved off the front range toward the Denver metroplex. Segment A-B is a line of small cells which have developed along the Denver Convergency/Vorticity Zone (DCVZ). Larger storms have also formed to the south, along the Palmer Lake Divide (indicated by letter 'F').

area, and was moving upslope across the northern half of the Palmer Lake Divide. There, equivalent potential temperature values were the highest in the region (about 340K as opposed to 337-338K, elsewhere), and by 2100 UT the boundary triggered new thunderstorm activity, 'N' in Figure 7. Sequential satellite imagery in animated form (loops) clearly show the rain-cooled stable air traveling south-eastward through the region with new convective activity forming on its leading edge.

Events over the next hour were complex. Notice in Figure 4 the large thunderstorm anvil that was associated with a very large thunderstorm complex located about 75 km south of the Denver area, along the ridgeline of the Palmer Lake Divide. It had appeared in real-time that the storm "N" (Figure 7) might have been the result of triggering by outflow from this storm. However, as noted above, closer inspection of satellite imagery shows this storm to be the result of triggering by outflow from storm "O" in Figure 2.

Storm "N" grew quickly, and by 2120 UT it produced a new outflow boundary which travelled northward from the Palmer Lake Divide toward the Denver metro area. Since the earlier outflow had led to a clearing of the skies over the Denver area, strong solar insolation had re-heated that area rapidly (see Figure 8). The average changes in temperature/Theta between 2000 UT and 2130 UT for each of the regions illustrated in Figure 8 were: -6F/-3.5K for region labeled "II" and +1F/+0.0K for the region entirely outside the outflow affect areas. At the same time, the Temperature/Theta change within the old outflow area, EXCLUSIVE of Regions

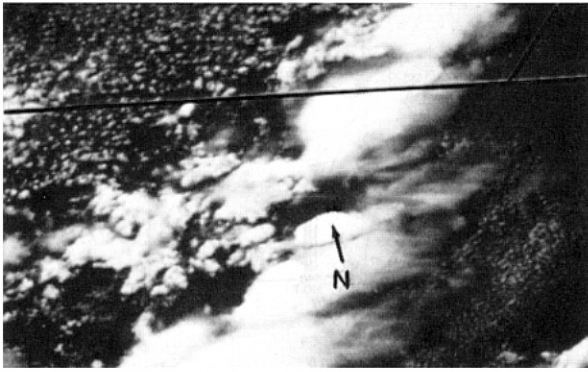


Figure 7. GOES-East VIS image from 2100 UT on June 15, 1988. Storm designated by letter 'N' is new activity referred to in text.

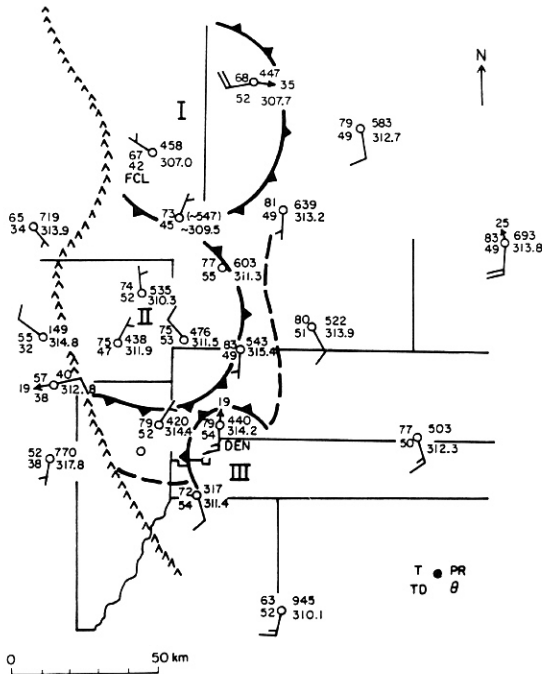


Figure 8. PROFS mesonetwork data for 2130 UT on June 15, 1988. Station model as indicated, and variables as in Figure 3. Region 'I' is area of new, and extremely cold, outflow. Region 'II' is new outflow that is not quite so cold. Region 'III' is an area of new outflow associated with storm moving back toward DEN from the Palmer Lake Divide (see text). Dashed line represents first outflow, which passed through the region some one and a half hours earlier.

The purpose of this paper has been to illustrate how satellite data can be used together to effectively unravel a complex, mesoscale weather situation as convective activity develops. From this discussion it should be clear that short-range forecasters and radar operators untrained in, or disconnected from, other sources of data can be severely handicapped in their ability to properly diagnose developing weather patterns. This, in turn, can hamper their ability to produce timely and effective warnings. A basic knowledge of mesoscale dynamics, and a data set with which such knowledge can be applied, is an essential ingredient for short-range warning capabilities being expected of future Weather Service forecast offices.

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