LIGHTNING RELATIVE TO PRECIPITATION AND TORNADOES IN A SUPERCELL STORM

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OVERVIEW OF STORM

During the 1998 spring field program in central Oklahoma, data were acquired from a 10-cm polarimetric radar operated by the National Severe Storms Laboratory and from the lightning mapping array operated by New Mexico Institute of Mining and Technology. On June 13, a supercell storm was positioned well for data collection by both the lightning mapping array and the polarimetric radar for roughly one hour, during which it produced tornadoes and large hail. Our paper will focus on data from this period.

Cloud flash rates exceeded 100 per minute throughout the analysis period. As shown in Figure 1, cloud-to-ground flash rates were typically #2 per minute, but tended to be larger during the two F-2 tornadoes, the maximum rate being 8 per minute. Approximately 90% of all cloud-to-ground flashes that occurred during the analysis period were the anomalous flashes that lower positive charge to ground (positive ground flashes), instead of the usual negative charge (negative ground flashes). Also, many of the cloud flashes that occurred in the upper part of the storm during this period appeared to discharge negative charge above positive charge, a polarity inverted from what is normally observed. Shortly after the storm moved beyond the range of three-dimensional lightning mapping data (after the period shown here), it weakened and dissipated. As the storm weakened, its dominant ground flash polarity changed, so most subsequent ground flashes were negative.

LIGHTNING RELATIVE TO PRECIPITATION

Figure 1 shows that trends in the number of VHF radiation sources from lightning at 8–10 km MSL were similar to trends for the mass of graupel near and within the mixed phase region of the storm. Laboratory studies (e.g., Takahashi 1978, Saunders et al. 1991) and an increasing body of storm observations (e.g., Dye et al. 1986, Bringi et al. 1997) have suggested that storm electrification is caused by noninductive charge exchange during rebounding collisions of cloud ice with actively riming graupel. The relationship between graupel mass and number of VHF sources shown here provides further support to the hypothesis that the noninductive graupel-ice mechanism is responsible for much of storm electrification.

The relative minimum in both VHF lightning radiation source rates and graupel mass between 0055 and 0100 UT overlapped and followed a period in which the mass of hail increased at middle levels (see, for example, large hail mass in Fig. 2). It appears likely that the mass of hail grew at the expense of the mass of graupel during this period. Furthermore, the decrease in VHF source rates at middle levels shortly after 0050 UT corresponded to an increase in the mass of wet hail at temperatures colder than freezing. This increase suggests that updrafts became strong enough to cause wet growth of precipitating ice in some regions. Wet growth would contribute little or nothing to electrification by the noninductive graupel-ice mechanism, because when colliding ice particles become wet, rebounding tends to cease.

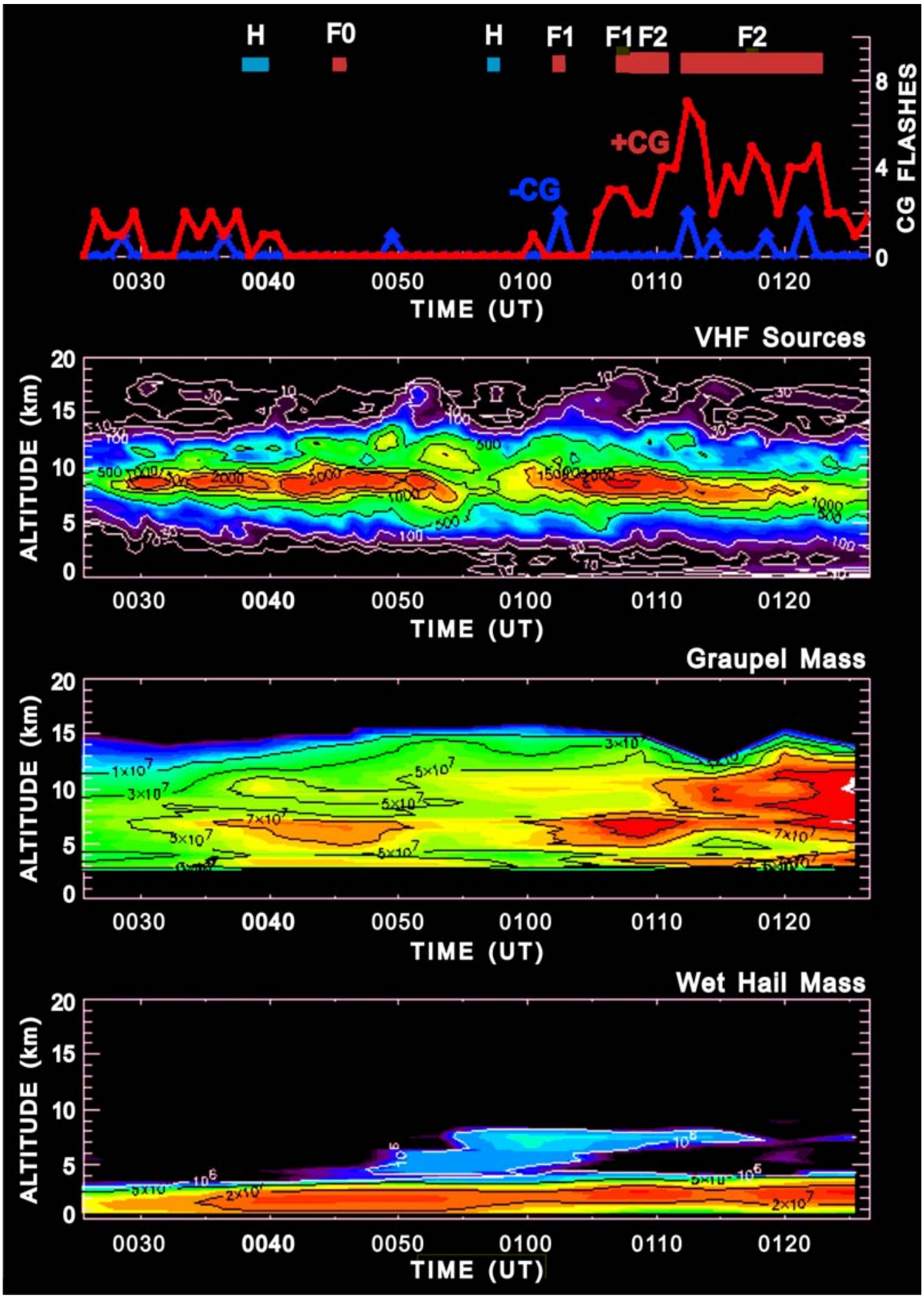

Figure 1. *(Top) Time-series plot of cloud-to-ground lightning flash rates (min^{-1}) from the U.S. National Lightning Detection Network with time-height plots of (second) VHF sources from the lightning mapping array, (third) graupel mass (kg), and (bottom) wet hail mass (kg). Precipitation mass was inferred from the polarimetric radar. Time-height data were analyzed in 0.5-km layers, so units are per 0.5-km layer. The time of each large hail report is indicated by an H at the top of the plot. The time of each tornado is indicated by a bar labeled with its F-scale damage rating.*

LIGHTNING RELATIVE TO UPDRAFTS AND SEVERE WEATHER

Some information about updrafts may be inferred from the vertical development of lightning activity (Fig. 1). Between 0040 and 0115 UT, over-shooting turrets of lightning activity appeared at roughly 10-minute intervals. The increase in height with time of each

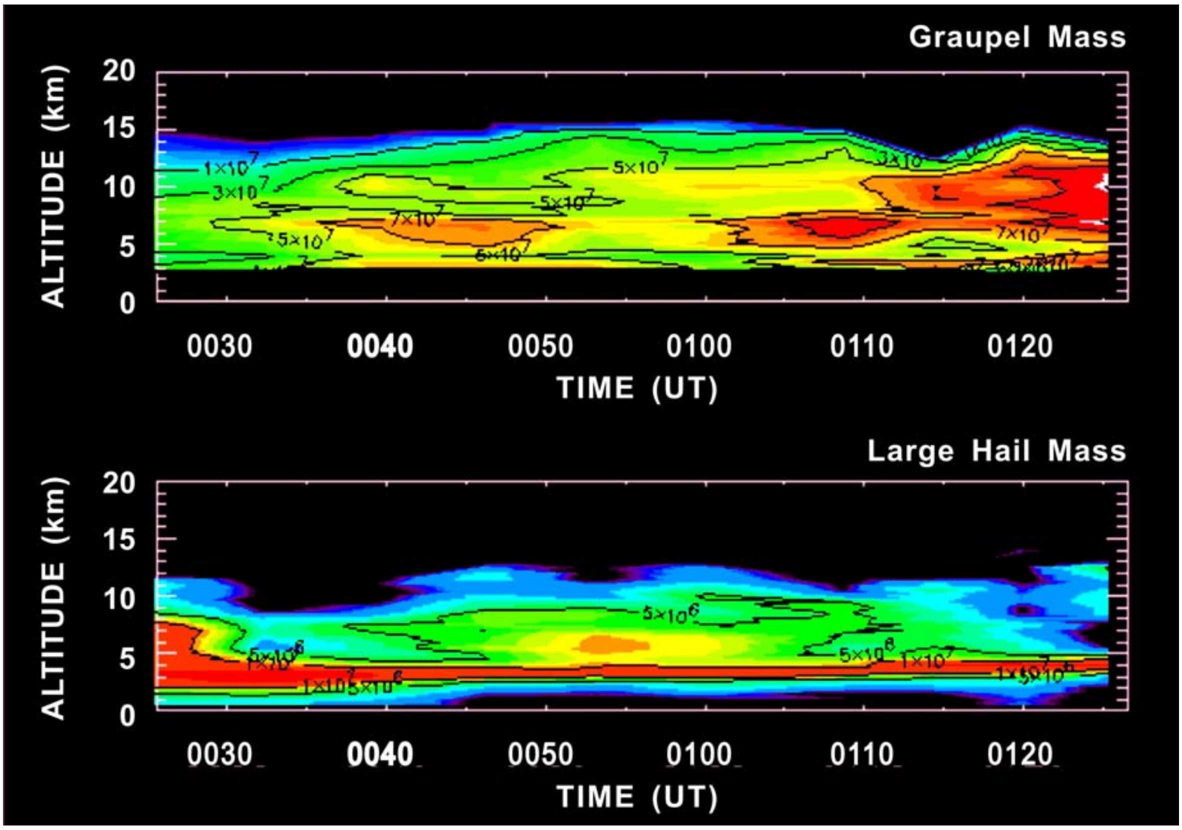

Figure 2. *Time-height plots of (top) mass of graupel and (bottom) mass of hailstones having a diameter $1.9 cm. Data were analyzed in 0.5-km layers; units for precipitation are kilograms per 0.5 km.*

turret is suggestive of a rising surge in the updraft. For some of the turrets, it is possible to extrapolate downward in space and backward in time to periods of increasing VHF sources at lower altitudes. The beginning of the highest-reaching and most sustained turret (note the increasing number of VHF sources at $14 km MSL beginning at roughly 0100 UT) appears to correspond to the earlier rapid increase in mass of wet hail at middle levels (Fig. 1). The number of VHF sources at 8–10 km MSL had a relative minimum just after 0055 UT, but soon began increasing and reached its maximum value for the entire analysis period at 0105–0109 UT.

It appears from these data that this extremely strong updraft surge led to wet growth of graupel and hail beginning at roughly 0055 UT. Initially, wet accretion would tend to convert graupel to hail. This and the increased collection efficiency would reduce electrification due to rebounding collisions with riming graupel. However, graupel mass (and lightning activity) soon began increasing again, probably a result of increases in both the size and number concentration of riming graupel in the strong, sustained updraft surge.

A combination of the above microphysical and kinematic inferences may provide some insight into the cause of the larger positive cloud-to-ground flash rates between 0105 and 0125 UT in Figure 1. Though it appears that the large updraft surge led to wet growth in at least some regions, we hypothesize that, in other regions of the updraft, graupel was not in wet growth, though the liquid water content was larger than usual. Essentially all modern laboratory studies of noninductive charging (e.g., Takahashi et al. 1978, Saunders et al. 1991) indicate that actively riming graupel gains positive charge, instead of what appears to be the more usual negative charge, during rebounding collisions with cloud ice when the liquid water content is unusually large (but not large enough to cause wet growth). If such a reversal were sustained enough, it would cause a corresponding reversal of at least part of the charge distribution of the storm itself. Such a reversal would replace the negative charge normally tapped by cloud-to-ground flashes with positive charge.

Our hypothesis, therefore, is that the strong updraft surge on June 13 eventually led to an increase in cloud-to-ground flash rates, but that unusually large liquid water contents in the mixed phase region led to a reversal in the polarity of the charge distribution. This reversal, in turn, caused an increase in flashes that lowered positive charge to ground, instead of the usual negative charge. Note that Rust and MacGorman (2002) presented evidence that the polarity of the charge distribution is inverted from normal in some storms that produce positive cloud-to-ground lightning. This hypothesis may explain some, but probably not all, occurrences of positive cloud-to-ground lightning.

Trends in lightning activity and tornado occurrence were consistent with the hypothesis that increases in lightning activity due to large updraft surges tend to lead severe weather occurrence. However, increases in flash rates were neither as prominent nor as clearly associated with severe weather as those reported for Florida severe storms by other investigators (e.g., Williams et al. 1999), possibly because flash rates were very large throughout most of the period of the Oklahoma City storm. In this storm, the rate of VHF emissions tended to increase at middle levels of the storm prior to tornadoes. Furthermore, tornadoes tended to occur during or shortly after the updraft surges inferred from lightning turrets. In particular, the two most violent tornadoes began during the latter stages of, or just after, what appeared to be the dissipation of the largest, most sustained updraft surge.

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