8.4 THE SCIENTIFIC BASIS FOR A RADAR-BASED LIGHTNING LAUNCH COMMIT CRITERION FOR ANVIL CLOUDS

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1. INTRODUCTION

Triggered lightning poses a threat to the launch of space vehicles at the NASA Kennedy Space Center (KSC) and other launch sites. The Airborne Field Mill Project II (ABFM II) was conducted during June 2000 and May/June 2001 near KSC to investigate the magnitude and duration of the electric fields inside thunderstorm anvils, and how these fields and their lifetimes were related to the cloud microphysics and radar reflectivity. The overall motivation for this work was to develop improved and physically-based Lightning Launch Commit Criteria (LLCC) that would be safe but less restrictive than the current LLCC. The airborne measurements were made using the University of North Dakota Citation II jet aircraft in conjunction with simultaneous radar coverage from the Patrick Air Force Base WSR74C (5 cm) radar and the Melbourne NEXRAD WSR88D (10 cm) radar. Measurements of total lightning (IC and CG) were made using the KSC Lightning Detection and Ranging (LDAR) and the Cloud to Ground Lightning Sensing systems.

The airborne 3-dimensional vector electric fields were measured over a range from <0.1 to >100 kV/m using a set of 6 low noise field mills as described in Bateman et al., 2005 and calibrated using the techniques of Mach and Koshak, 2003. Microphysical observations on the aircraft were made with the Particle Measuring Systems FSSP, 1D-C, 2D-C and the Stratton Park Engineering Corp. Cloud Particle Imager and High Volume Particle Spectrometer (HVPS), thus spanning particle sizes from a few microns to about five centimeters, i.e. frozen cloud droplets to very large aggregates. A Rosemont icing detector showed no evidence of supercooled water in any anvils investigated. Thus, the non-inductive charge separation process is unlikely to be active in these anvils.

2. EXAMPLE OF ONE ANVIL PASS ON JUNE 13, 2000

Fig. 1 shows measurements made on June 13, 2000 for a 7 minute period (~50 km of flight track). The Citation investigated this anvil for over 3 hours, first with lightning present and then for 2 hours after the last lightning. This pass at 11 km altitude, –40 C, was east to west across the anvil while lightning was occurring in the storm core 25 to 40 km to the south. The maximum reflectivity encountered during this pass was15 – 20 dBZ from 2107 to 2108:30. The measurements of Fig. 1 are representative of the ABFM II anvils. Most penetrations were primarily at altitudes of 7 to 11 km (roughly -15 to –45 C). The concentrations in all size ranges increase gradually as the aircraft moves into higher reflectivity, but as in Fig. 1 larger increases usually occur for particles in the sizes up to about 500 μm than for particles >1 mm size. In regions with strong electric fields slightly downwind of storm cores there is a surprising degree of consistency in particle size distributions from storm to storm. The concentrations from 2108:00 to 2108:30 in Fig. 1 are typical of those observed in other thick anvils near the storm core with electric fields >20 kV/m.

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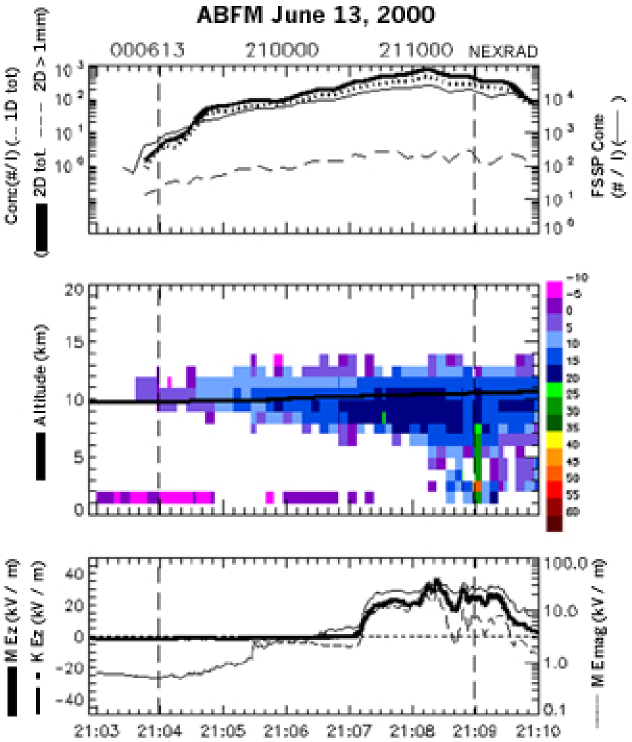

Figure 1.

Top Panel: Time history of Particle concentrations measured by the following instruments:

PMS FSSP (1 to 48 μm), light, solid line = total conc. on right scale;

PMS 2D-C (30 μm to ~3 mm), bold line = total conc., dashed line = conc. >1 mm on left scale;

PMS 1D-C (15 to 960 μm), dotted line = total conc. on left scale.

Middle panel: Radar reflectivity curtain above and below the aircraft from NEXRAD radar at Melborne FL, bold line = aircraft altitude.

Bottom panel: Vertical component of the electric field, Ez, bold line on left on a linear scale, and the resultant vector field, Emag, light line on right on a log scale.

The electric field measurements show more variability and increase much more abruptly than the relatively smooth increase in particle concentrations as the aircraft traverses the anvil. In this and other anvils we found that when the reflectivity near the aircraft was less than 5 to 10 dBZ the magnitude of the 3-dimensional electric fields were less than 3 kV/m, a value that poses little threat of triggering lightning. We also found that the increase in electric field was usually very abrupt as illustrated in Fig. 1.

3. ABFM II ANVIL DATA SET

In order to examine the nature of the measurements from all anvil cases a data set was produced based on all times when the Citation was flying in anvil. To be considered as “In-Anvil” the aircraft had to have been flying in a region in which the anvil had a definite base. Regions in which radar reflectivity appeared to be reaching the ground were excluded from the In-Anvil classification. Thirty second averages of the aircraft measurements were used in this data set. The data set included different calculated reflectivity parameters nearest in time and space to the location of the aircraft. At the nominal flight speed of 100 to 120 m/s, 30 s of aircraft data corresponds to 3 to 3.6 km of flight path. This data set was filtered to remove periods when the 74C radar reflectivity was attenuated by either a wet radome or intervening precipitation or when the aircraft was flying in the cone of silence above the radar.

4. ELECTRIC FIELD VERSUS PARTICLE CONCENTRATION

Using this entire anvil data set to examine the relationship between electric field and particle concentration we obtain the results shown in Fig. 2. It is immediately obvious that there is a “knee” in this plot at an electric field of roughly 1 kV/m. This “knee” demonstrates that the abrupt increase in electric field seen in Fig. 1 at ~ 2107 is characteristic of the entire anvil data set. Fig. 2 plots the total concentration from the 2D-C probe which measures particles in the size range ~ 0.1 to ~2 mm. Plots using several different particle size ranges all exhibited this knee, even for the largest particles, i.e. those most responsible for the radar reflectivity.

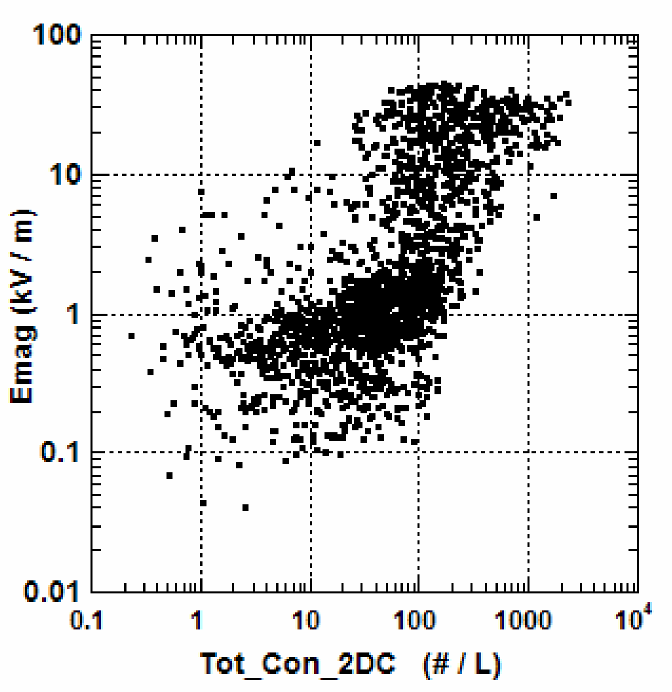

Figure 2.
Scatter plot of electric field magnitude (Emag) versus the total concentration of particles measured by the 2D-C probe for the entire ABFM II data set.

5. ELECTRIC FIELD VERSUS REFLECTIVITY FOR ABFM II ANVILS

Fig. 3 presents the relationship between electric field and 4 different reflectivity parameters. Because electrification primarily occurs in the mixed phase zone containing both ice and supercooled water, we limited these averages to altitudes above the freezing level, ~5 km MSL in Florida during the summer. The lower right plot shows the average reflectivity in a cube with 3 km sides centered on the aircraft position. For average cube reflectivity < 5 dBZ there are few points with electric field >3 kV/m, but there is considerable scatter of points in the plot. Examining a reflectivity variable averaged over a larger volume has the advantage that if substantial charge exists nearby, but not at the aircraft position, the variable would include nearby regions of higher reflectivity and perhaps give warning of nearby charge. The upper left plot shows the average calculated reflectivity within the volume extending from the altitude of the 0C isotherm to the top of the cloud over an 11 x11 km area extending horizontally 5 km in the N, S, W and E directions from the 1 km grid point containing the aircraft position. The lower left plot is similar except the volume average is calculated over a horizontal area of 21x21 km. These 2 parameters show very similar results. The lower left quadrant of both of the plots show that for an average reflectivity of <5 dBZ the observed electric field was <3 kV/m.

A shortcoming of the volume averages is that averaging the reflectivity within a box or column throws away potentially important information on the depth of the anvil. A thin anvil can have the same average reflectivity as a much deeper anvil, but deeper anvils are more likely to contain charge than shallower anvils. The upper right plot of Fig. 3 shows the 11x11 Volume Averaged Height Integrated Radar Reflectivity (VAHIRR). This was calculated by multiplying the 11x11 average reflectivity in dBZ by the average thickness of the anvil over the 11x11 km area. The 11x11VAHIRR plot shows a trend of an increase in reflectivity values with increases in Emag >3 kV/m unlike the 1x1 average reflectivity and also a larger dynamic range.

A statistical analysis of extreme values for the 11x11 km VAHIRR ≤ 10 dBZ km, (equivalent to an average of 10 dBZ in a 1 km thick anvil, or 5 dBZ in a 2 km thick anvil) showed that the probability of having an electric field larger than 3 kV/m. was less than 1 in 10,000. Dye et al., 2004 discuss these and other reflectivity parameters in more detail.

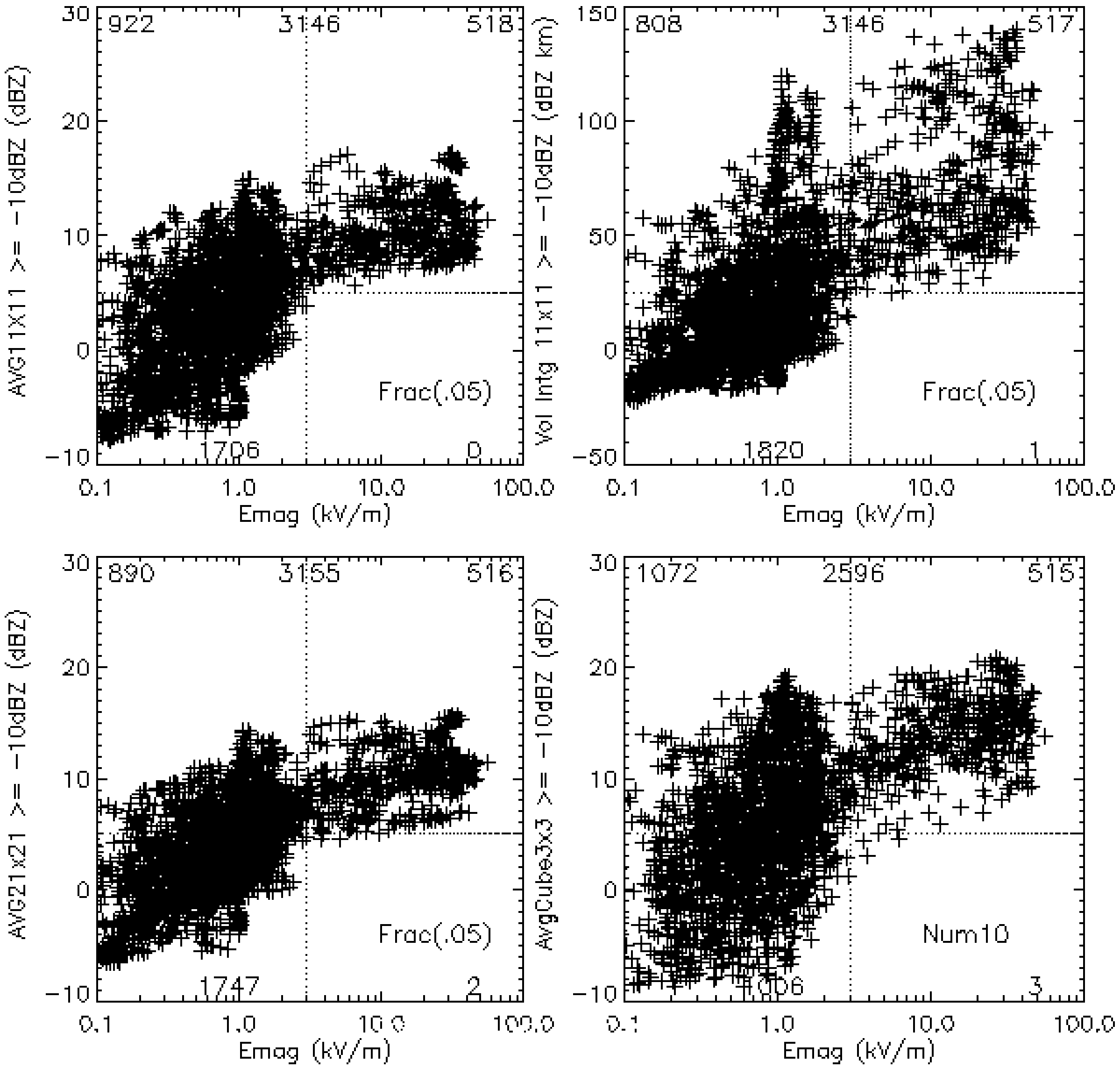

Figure 3. Electric field magnitude (Emag) versus average reflectivity for 4 separate reflectivity parameters (See Text). Data points for which the aircraft was within 20km of reflectivity >35 dBZ or within ±20 km of lightning within the last 5 min are not included.

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