ELECTRICAL DECAY ESTIMATES IN ANVIL CLOUDS

Report No. 2 of 2 under Contract No. CC-90233B

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Introduction

This is the second and final report under a contract to develop a simple model of the decay of pre-existing electrification in anvil clouds. This project was undertaken to aid NASA and the USAF in determining when such clouds do not constitute a triggered-lightning hazard for either an outgoing launch vehicle or a landing Space Shuttle. Rather than repeating the introduction and model description from the previous report [Willett, 2001], this brief final report will assume that material as understood and will simply call attention to the changes that have been made since that time. The present configuration of the model, including the improvements mentioned below, is fully described by Willett et al. [2003], included as part of this report by attachment. Additional results of the application of the present model to the ABFM dataset are described by Dye et al. [2002, 2003]. Further conclusions -- in particular, an attempt to validate the model against observations -- will be forthcoming under a follow-on contract.

Theoretical Model

The main theoretical work during this contract interval has been an investigation of the extent to which the essential aspect of this model -- linear decay of the electric-field intensity in the "high-field limit" -- might be generalized beyond the strict horizontal homogeneity with infinitesimally thin charge layers and uniform microphysics for which it was developed by Willett [2001]. As described by Willett et al. [2003], it has been found that the model can also be applied to the other familiar, one-dimensional geometries (cylindrical and spherical symmetry) and that the initial charge-density distribution in each of these three, one-dimensional cases can depend arbitrarily on the single, independent, spatial variable as long as the electric field magnitude everywhere within the cloud remains large enough. (In fact, the cloud microphysics can also depend on that same independent variable, but this introduces the undesirable complexity that the electrical decay time varies across the cloud.) In all of these circumstances the field decays linearly with time at the *same* rate as that derived in the first report!

The definition of the high-field limit -- $\gamma \gg 1$ -- that was specified for a monodisperse cloud by Willett [2001] has been generalized as follows. A "transition field," E_γ, is defined as that field intensity for which the total small-ion loss rate due to electrically driven attachment to the cloud particles (integrated over the observed size distribution) equals that due to diffusive attachment. Further, the constant current density in this limit is defined as

$$J_0 \equiv 2eq/(A_e N) \quad (1)$$

where the denominator is to be taken as an integral over the size distribution. Both E_γ and J_0 depend only on cloud microphysics and are independent of geometry. The generalized result is then

$$E_p(p,t) = E_{p0}(p) - J_0 t/\varepsilon_0, \quad E_p(p,t) >> E_\gamma \quad (2)$$

where $E_p(p,t)$ is the only non-zero component of field intensity in a particular symmetry, p is the independent spatial variable (z, R, or r, respectively, in horizontal, cylindrical, or spherical symmetry) and $E_{p0}(p)$ is the corresponding initial field distribution.

Unfortunately, this result cannot be generalized much further. To see this, notice that superposition does not apply to these simple, one-dimensional solutions because of the non-linear behavior of the cloud medium in the high-field limit: Although the conduction-current density is in the same direction as the electric field, its magnitude is saturated. [In vector notation, $\boldsymbol{J}(\boldsymbol{r},t) = J_0\boldsymbol{E}(\boldsymbol{r},t)/|\boldsymbol{E}(\boldsymbol{r},t)|$, which is not a linear function of $\boldsymbol{E}$.] Therefore, the model can only be applied to situations in which the initial charge distribution can be reasonably approximated as one-dimensional.

Based on the consensus that ventilation, although it does increase the diffusive loss of small ions to the larger particles, does not change the general conclusion that electrical-attachment loss dominates at high fields [*e.g.*, *Pruppacher and Klett*, 1978, Section 17.3.3], this issue has not been investigated further. Neither have I attempted to account for the actual shapes of the cloud particles; I have simply assumed them all to be spherical, relying on the previous conclusion that this is the most conservative assumption.

Anvil Results from the ABFM Campaign

The ABFM Team has identified 19 flights (excluding that of 25 June 2000, during which the aircraft was forced to fly below the anvil because of a loss of cabin pressure), 7 from June, 2000, and 12 from May and June, 2001, during which the aircraft made anvil penetrations [Jim Dye, ABFM Workshop, November, 2002]. For each of these flights, electrical decay times and other data have been computed at least from the time of the first anvil penetration through the time of the last such penetration. These results are tabulated in the attached 19 ASCII files, each named for the included time interval and date, and constitute the main deliverable under this contract. (These files have also been forwarded to NCAR for partial inclusion in the updated "merged" files of significant ABFM data.)

The format of the attached text files is, first, a row of column headings and then one row of data for each 30 s time interval having valid size spectra [Jim Dye and Bill Hall, personal communication, March, 2003]. In each row the columns are separated by TAB characters and are given in the following order: time/date (HHMMSS-HHMMSS DD MMM YYYY, HHMMSS-HHMMSS D MMMM YYYY, or HHMMSS-HHMMSS DD MMMM YYYY), z (flight altitude, m), T (K), q (pairs/m^3/s), total number of particles (cm^{-3}), number of particles larger than 0.96 mm (cm^{-3}), E_Y (V/m), τ_D (s), and τ_E (s). (Recall that τ_D is the exponential time scale for field decay in the low-field limit. The parameter of most interest here, τ_E, is defined as the time required for the field to decay from 50 kV/m to zero, assuming the high-field limit. Thus, the corresponding linear decay from any other initial field can readily be computed as $E(t) = E_0 - [50000 \text{ V/m}]t/\tau_E$.)

Altitude and temperature for our 30 s time intervals are averages of the included 10 s values that are tabulated in the "merged" files on the NCAR ABFM web site. The ionization rate at flight altitude is interpolated from the formula

$$q(z) = 5.7\text{X}10^6 \text{ Exp}[z/(6.06\text{X}10^3)] \quad (3)$$

which is an adequate fit to the subtropical data of *Hake et al.* [1973, Figure 19] over the altitude range of interest. Data from the HVPS instrument have been ignored in June, 2000, during which they were judged to be unreliable [Jim Dye, personal communication, March 2003], but valid HVPS data have been required throughout May and June, 2001. (It is a simple matter to re-analyze selected intervals from 2000, including HVPS data, if they are validated in the future.) Rows that would correspond to time intervals with invalid size spectra have been omitted entirely. Here, the spectra are taken to be invalid (1) if the error flag, "-9.99000E+02", occurs anywhere in the spectra that are actually used (FSSP, 2-DC, and, for year 2001 only, HVPS), (2) if, during year 2001, the HVPS reported zeros in all bins, or (3) if the 2-DC instrument reported zeros in all bins.

Discussion

A Microsoft Excel 2000 file has been attached to this report that is essentially a filtered concatenation of the ASCII files described above. According to a list of time intervals that correspond to actual or probable anvil penetrations, which was provided by Sharon Lewis [personal communication, April, 2003], non-anvil intervals have been deleted from this Excel file. The remaining values of E_Y, τ_D, and τ_E have been plotted against one another, data from each flight day being represented by a different symbol/color (except that the rather few points from 7 June 2000 and from 5 June 2001 have been omitted to reduce confusion).

Evidently τ_D and τ_E are roughly linearly related during most flight days. This result lends support to Jim Dye's earlier observation [ABFM Workshop, Melbourne, FL, November, 2002] that the particle-size spectra tend to have similar shapes throughout Florida anvils. It is easy to see from the formulae for the limiting cases [Willett et al., 2003] that τ_D is proportional to the first moment of the size distribution (integrated particle diameter), whereas τ_E is proportional to the second moment (effectively, to integrated area). The linear relationships on the plot of τ_D versus τ_E therefore imply that these two moments tend to be proportional within a given day. It is also evident from the other plots in the attached Excel file that E_Y is relatively independent of the other two parameters. Since the ratio, $\tau_D/\tau_E = E_Y/E_0$, is proportional to the ratio of the first to the second moment of the size distribution, this independence again suggests a proportionality between integrated diameter and integrated area.

Nevertheless, the apparent proportionality constant clearly varies from day to day, as indicated by the grouping of points from different days into obvious visual features on all three plots. I do not yet have a physical interpretation for the implied change in shape of the size distribution from day to day.

Acknowledgments

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List of *Additional* Symbols

$\mathbf{E}(\mathbf{r},t)$	Vector electric-field intensity
$E_p(p,t)$	Time- and space-dependent electric-field intensity in a one-dimensional cloud of a particular symmetry
$E_{p0}(p)$	Initial electric-field distribution inside that cloud
E_Y	Transition field intensity at which the integrated, electrically driven and diffusive loss rates of small ions are equal
$\mathbf{J}(\mathbf{r},t)$	Vector current density
J_o	Constant, uniform magnitude of conduction-current density in the high-field limit
p	The single, independent, spatial variable in the a particular symmetry
$\mathbf{r}$	Generalized vector position
z	Flight altitude

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