16B.4 THE ROLE OF ELEVATED CLOUD BASE HEIGHT IN THE INVERTED ELECTRICAL POLARITY OF SEVERE STORMS

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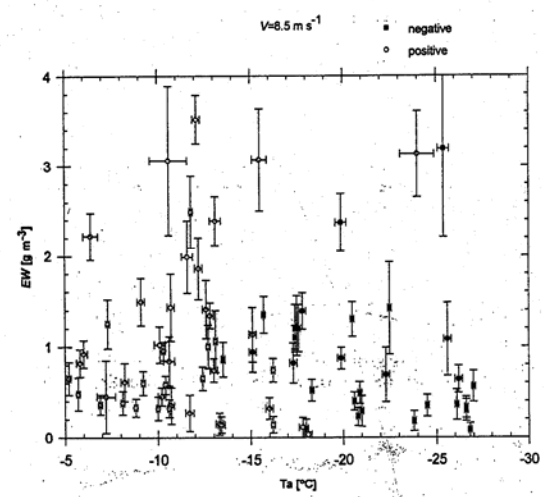
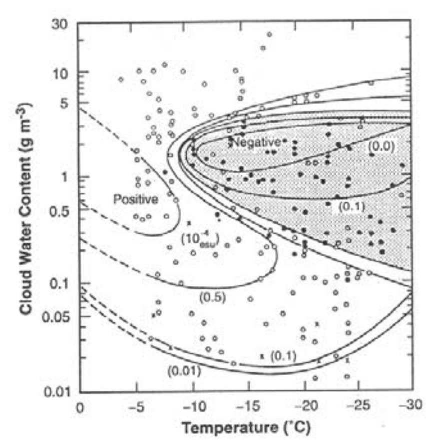
1. INTRODUCTION

The great majority of thunderstorms worldwide possess gross electrical structures approximated by positive dipoles - with positive charge aloft and negative charge in midlevel of the cloud. These ordinary thunderclouds produce a predominance of negative cloud-to-ground lightning (Rakov and Uman, 2003). Recent studies provide good evidence for an exceptional class of storms that exhibit a main dipole with inverted polarity (Krehbiel et al, 2000; Rust and MacGorman, 2002; Lang et al, 2004). These exceptional storms documented in the recent STEPS (Severe Thunderstorm Electrification and Precipitation Experiment) produce a majority of ground flashes with positive polarity. These findings serve to link inverted polarity storms with numerous earlier studies in which the ground flash observations were the only electrical observations (Curran and Rust, 1992; Branick and Doswell, 1992; Seimon, 1993; Stolzenberg, 1994; MacGorman and Burgess, 1994; Knapp, 1994), and clustered positive ground flash activity was observed. The present study is concerned with the physical origins of the inverted polarity storms.

2. A MICROPHYSICAL BASIS

The widely accepted explanation for the electrification of thunderstorms rests on the selective charging of large ice particles (graupel and hail) by collisions with smaller ice particles (ice crystals and small graupel), and their vertical separation by differential motion under gravity. The molecular scale details remain elusive, but numerous laboratory simulations (Takahashi, 1978; Saunders et al, 1991; Pereyra et al, 2000) all show important roles for in situ temperature and cloud water content. All laboratory results are in agreement in showing negative charging of the large ice particles at intermediate values (0.5-2 gm/m^3) of supercooled water content. Most importantly for the present study, Figure 1 shows that the lab studies agree that in high (>2 gm/m3) water contents, the large ice particles charge positively for all values of cloud temperature. This is the situation favorable to storms with inverted electrical polarity. This empirical explanation for inverted polarity clouds was suggested by Williams et al (1991), and remains the basis for the mechanism here. The remainder of this study is concerned with conditions of cloud development favoring the formation of large values of cloud water content in the mixed phase region.





Figures 1a, 1b, 1c: Laboratory results in the diagram of temperature (^{0}C) and cloud water content. Included are results from 1a) Pereyra et al (2000) 1b) Takahashi (1978); and,

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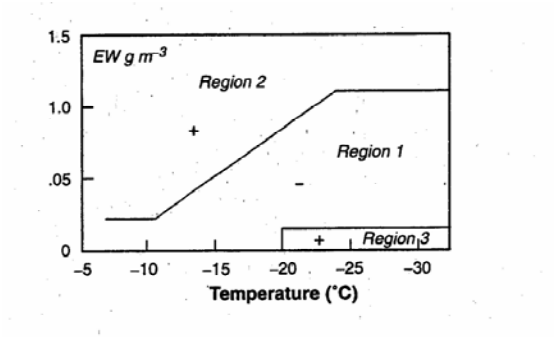


Figure 1c: Laboratory results in the diagram of temperature (^{0}C) and cloud water content. Included are results from 1c) Saunders et al (1991).

3. THE ROLE OF CLOUD BASE HEIGHT

The adiabatic cloud water content is an upper bound on the liquid water content in moist convection, and the achievement of such values will guarantee the positive charging of the large ice particles according to the laboratory studies in Figure 1 (Williams et al, 1991). Adiabatic values are most likely to be achieved when (1) dilution by mixing is suppressed, and (2) when loss of cloud water by precipitation is suppressed. Both these conditions are favored by higher cloud base heights, as illustrated in Figures 2 and 3. Figure 2 illustrates the tendency for updraft width to increase with cloud base height, following evidence in Williams and Stanfill (2002). Broader updrafts are less likely to be diluted by mixing with their environment. Figure 3 illustrates the tendency for suppressed warm rain coalescence (Rosenfeld and Woodley, 2003) with a higher cloud base, thereby allowing more cloud water to access the mixed phase region. Adiabatic cloud water contents are reduced somewhat as cloud base increases (Ludlam, 1950), but this effect is probably dwarfed by the precipitation effect shown in Figure 3. Severe storms in the LP (Low Precipitation) supercell category are most likely to show inverted polarity, and these storms by their very name are low in the production of rainfall.

Previously compiled evidence for a role for cloud base height in enhancing the flash rates of tropical continental thunderstorms (Williams et al, 2004) is reproduced in Figure 4. The flash rates were recorded with the Lightning Imaging Sensor on the NASA TRMM (Tropical Rainfall Measuring Mission) satellite and the cloud base heights were determined from the measured dew point depressions at surface stations close to these thunderstorms. Despite considerable scatter in the results, the mean flash rates increase quasi-exponentially by an order of magnitude from storms with cloud base heights typical of maritime conditions (CBH = 500 m) to strong continental conditions (CBH = 3000 m).

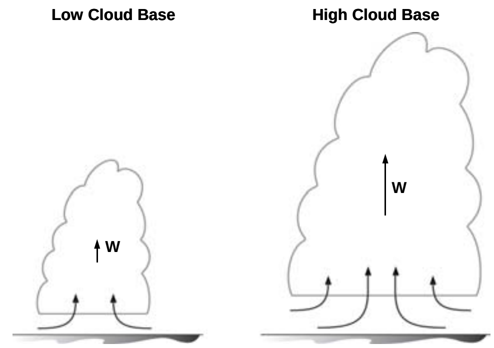


Figure 2: Illustration of effect of cloud base height on updraft structure and cloud water content

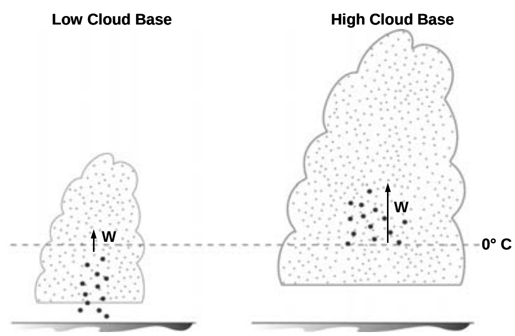


Figure 3: Illustration of effect of cloud base height on depletion of cloud water by coalescence of cloud droplets.

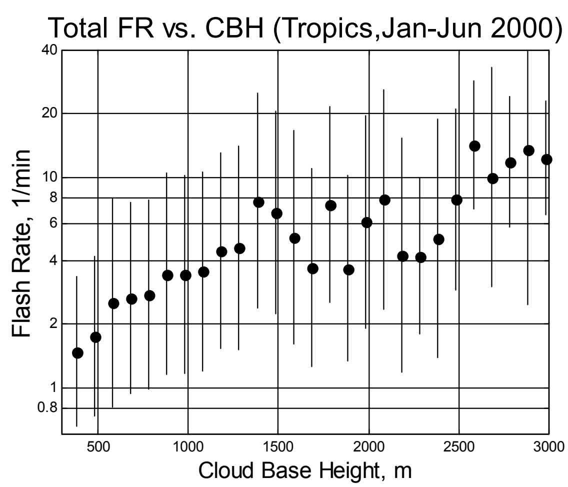


Figure 4: Lightning flash rate versus cloud base height for 700 tropical continental thunderstorms

4. GEOGRAPHICAL EVIDENCE

Numerous observations now available (Curran and Rust, 1992; Branick and Doswell, 1992; Seimon, 1993; Stolzenburg, 1994; Knapp, 1994; MacGorman and Burgess, 1994; Krehbiel et al, 2000; Rust and MacGorman, 1994; Carey et al 2003; Lang et al, 2004) show that clouds with inverted polarity occur preferentially in the western Great Plains and in the lee of the Rocky Mountains. The STEPS domain in 2000 in eastern Colorado is a subset of this larger region. Locations of storms studied by Stolzenburg (1994) and MacGorman and Burgess (1994) are included in Figure 5a. Also shown are locations for LP super cells compiled by storm chase teams (E. Rasmussen, personal communication, 1999). LP storms are again most likely to show clustered positive ground flash activity. Storms with this characteristic are notably absent in Florida and Alabama, sites of extensive recent investigations of severe storms with the NASA LISDAD (Lightning Imaging Sensor Demonstration and Display) (Williams et al, 1999; Goodman, 2003) field experiments. How do these storm preferential locations in Figure 5a fit in with the hypothesized role for cloud base height?

Figure 5b shows the climatology of noontime cloud base height for July, based on surface station thermodynamic observations of temperature and dew point temperature from Albright (1939). The cloud base height is seen to increase from the 1000 m level on the East/Gulf Coasts to 1500 m in the Mississippi valley, to 2000 m in the Great Plains, to 2500 m at the eastern edge of the Rocky Mountains. The cloud base height is therefore notably higher in the north-south swath where storms with inverted polarity are most common.

Given the evidence that inverted polarity storms are also often severe (Rust and MacGorman, 1994; Krehbiel et al, 2000; Rust and MacGorman, 2002; Lang et al, 2004), instability for updraft production is also an important issue. In the tropical atmosphere, the wet bulb potential temperature (θ_w) forming the right hand boundary of the positive area on a tephigram has been shown to be a good proxy for Convective Available Potential Energy (CAPE) (Williams and Renno, 1993). The climatology for θ_w over the CONUS for noontime in July is shown in Figure 5c, also based on surface station data in Albright (1939). The characteristic ridge of high θ_w air in the lee of the Rockies coincides with the region in which inverted polarity storms are most common. A comparison of the climatologies in Figures 5b and 5c shows that the corridor of inverted polarity storms is characterized simultaneously by large instability and high cloud base height. The cloud base height increases farther west, but the instability declines. Thunderstorms in Denver, Colorado and Albuquerque, New Mexico are generally non-severe and have normal electrical polarity (Moore and Vonnegut, 1977; Wilson et al, 1992).

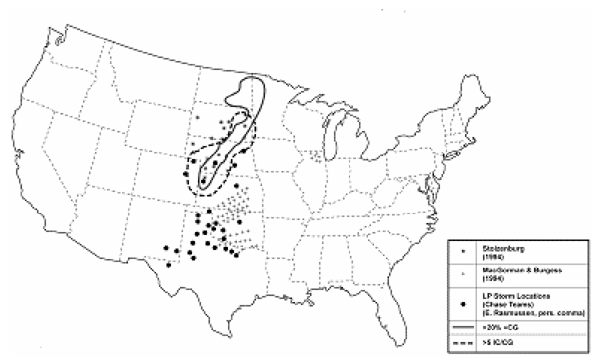
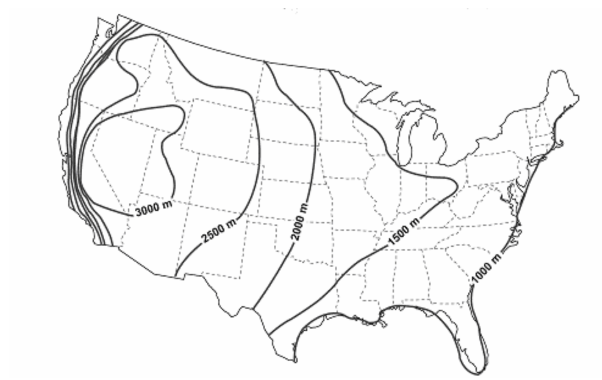
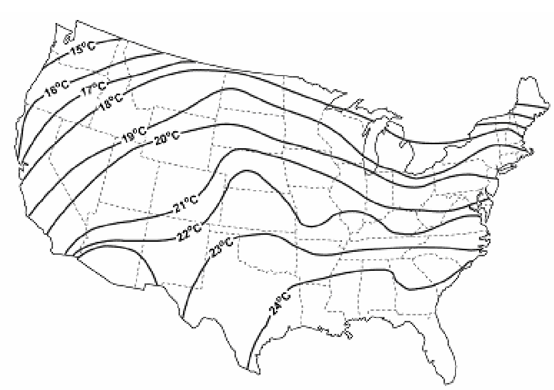


Figure 5a) Locations of storms with clustered positive ground flashes (Stolzenberg, 1994; Rust and MacGorman, 1994), locations of LP supercells (E. Rasmussen, pers. Comm,.,1999), locations of enhanced intracloud to cloud-to-ground lightning (Boccippio et al, 2001), and locations of enhanced percentage of positive polarity ground flashes (Zajac and Rutledge, 2000).



5b) The climatology of cloud base height at noontime in July.



5c) The climatology of wet bulb potential temperature at noontime in July.

Clustered positive ground flash activity has been documented for severe storms that cross the ridge in θ_w (Smith et al, 2000), evident in Figure 5c in the western Great Plains. This study does not afford an explanation however for why some storms begin with a predominance of positive ground flashes when they are west of the θ_w ridge. It is likely in such a situation that their cloud bases are quite high, consistent with scenarios illustrated in Figures 2 and 3.

5. STORMS WITH LARGE HAIL

Severe storms with clustered positive ground flashes (Curran and Rust, 1992; Branick and Doswell, 1992; Seimon, 1993; Burgess and MacGorman, 1994; Knapp, 1994), and with more extensive documentation of inverted cloud polarity (Rust and MacGorman, 2002; Lang et al, 2004), are often accompanied by large hail. Climatologies on large hail (Doswell and Bosart, 2001; Polsten, 1996) also show predominant activity in the north-south corridor in the lee of the Rocky Mountains. The presence of large hail is however, no guarantee for inverted polarity storms, and in fact the majority of large hail is accompanied by an abundance of negative cloud-to-ground lightning. Growth of large hail is dependent on both strong updraft and abundant cloud water (Knight and Knight, 2001; Williams, 2001), and elevated cloud base heights are not systematically associated with large hail (Fawbush and Miller, 1953). Two types of hailstorm producing large hail have been identified in Polsten (1996), with the minority (Type B) associated with the dry line environment in which cloud base heights are expected to be higher than normal. Published results (Curran and Rust, 1992; Branick and Doswell, 1992; Smith et al, 2000; Gilmore and Wicker, 2002; Lang et al, 2004) already suggest that Type B hailstorms are more likely to exhibit an inverted electrical polarity.

6. AEROSOL EFFECTS?

Lyons et al (1998) and Murray et al (2000) have documented substantial enhancements in positive ground flash activity associated with the ingestion of smoke by storms. One possible interpretation follows Figure 3 and is based on smaller cloud droplets, suppressed coalescence and more cloud water availability to the mixed phase region. A second interpretation, and one more in keeping with the general theme of this paper, is a thermodynamic one. The season studied by Lyons et al (1998) was hotter and drier than normal (Smith et al, 2003) in a similar north-south corridor to the one highlighted in Figure 5c. These dual temperature trends will both serve to elevate the cloud base and invite scenarios illustrated in Figures 2 and 3. Further studies of in situ microphysics are needed to distinguish aerosol and thermodynamic effects.

7. CONCLUSIONS

A substantial body of evidence supports the idea that elevated cloud base heights are conducive to storms with inverted polarity of the main cloud dipole. The evidence includes the results of laboratory simulations, the geographical distribution of 'anomalous' storms compared with a climatology of cloud base height, and some direct comparisons of LCL and predominant ground flash polarity presented at this Conference (Carey and Buffalo, 2004).

8. ACKNOWLEDGEMENTS

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