Atmospheric Research 135–136 (2014) 274–284

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Continuous variability in thunderstorm primary electrification and an evaluation of inverted-polarity terminology

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ARTICLE INFO

Article history:
Received 16 February 2012
Received in revised form 18 September 2012
Accepted 5 October 2012

Keywords:
atmospheric electricity
lightning
thunderstorm
inverted polarity
electrification

ABSTRACT

Several field campaigns since the year 2000 have focused on anomalously electrified or "inverted polarity" thunderstorms. This study synthesizes these recent results, and considers how variability in the non-inductive relative-growth rate electrification mechanism might clarifying the meaning of "inverted polarity". Instead of falling into two polarity classes, electrification and charge structure in strong updrafts vary continuously, as expected if depletion of supercooled water is a primary control on electrification. Two- or three-dimensional storm flows or other electrification mechanisms are required to combine one or more of these electrification regimes into "inverted" or otherwise complicated local charge sequences. Cloud flashes that result from these local charge sequences should be termed "positive" and "negative" instead of "normal" and "inverted" because cloud flashes of either polarity can occur at any altitude in thunderstorms.

1. Notions of storm polarity

Is the notion of inverted-polarity meaningful in explaining observations of electricity in thunderstorms? Of particular concern is what physical observable is inverted. This paper proposes a distinction between properties (such as charge structure, electrification, and flashes, as well as storms as a whole) that vary continuously and those that can be bifurcated meaningfully into two polarity classes.

1.1. Electrification and Charge Structure

The primary driver of thunderstorm electrification is thought to be non-inductive (NI) rebounding charging between ice hydrometeors in the presence of supercooled water (Saunders et al., 2006; Emersic and Saunders, 2010). It is thought that the relative growth rate (RGR, Baker et al., 1987) of the two ice hydrometeors from the vapor phase controls the sign of charging. The relative growth rate effect is enhanced as supercooled water is collected. The NI-RGR mechanism can readily explain the production of a prototypical "normal-polarity" tripolar charge structure (Simpson and Scrase, 1937; Simpson and Robinson, 1941; Williams et al., 1989), but is also effective at producing charge structures that have been more recently referred to as "inverted-polarity" (Marshall et al., 1995; Rust and MacGorman, 2002; Rust et al., 2005; Wiens et al., 2005; Kuhlman et al., 2006; MacGorman et al., 2005; Tessendorf et al., 2007; Carey and Buffalo, 2007; Weiss et al., 2008; Tessendorf, 2009; Bruning et al., 2010).

In the normal-polarity model, precipitation carries negative charge in the midlevels of the storm and positive in lower parts of the storm. Non-precipitating cloud ice carries positive charge in the upper parts of the storm, and negative charge in the midlevels of the storm. The negative regions typically combine into a large net negative charge region midway through the depth of the storm. A tripolar structure fits with observations that most storms lower negative charge in ground strikes. While observations have clearly shown that this model in isolation is inadequate to explain all features of in-situ measurements of the electric field in storms (Rust and Marshall, 1996; Stolzenburg et al., 1998), it is usually

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http://dx.doi.org/10.1016/j.atmosres.2012.10.009

possible to find at least vestigial evidence of the electrification mechanism in the form of a tripolar-like charge sequence.

The most likely place in which to find evidence of tripolar-like structures is in 1-dimensional storms with strong cylindrical symmetry, where precipitation trajectories most closely follow the classic updraft-downdraft model of (Byers and Braham, 1949). Even in storms with more complicated flow regimes, it is usually possible to identify a region where the boundary layer thermodynamic state is most efficiently processed through the storm, i.e., the "updraft core." This region maps well on to Stolzenburg et al. (1998)'s updraft profiles, where the NI-RGR mechanism is strongly implicated in producing the lower three charges in their conceptual model.

In a review of the inverted-polarity studies cited above, Tessendorf (2009) defined inverted-polarity storms as those exhibiting, at least somewhere within the storm, a tripolar structure that was inverted from the normal sequence. In updraft regions, an inverted (from the two uppermost charges in the tripolar sequence) dipole was often observed, with the lower negative charge of an inverted tripole absent or reduced. If these storms produced ground strikes the majority were observed to be of positive polarity. This study seeks to clarify how it is that such charge sequences can become inverted from the normal-polarity tripolar sequence given our current understanding of the NI-RGR electrification mechanism.

We do not intend a complete characterization of thunderstorm charge structures in this study. Instead, our focus is primarily on the NI-RGR electrification mechanism and evidence of its operation in production of charge structures within the updraft core, in a sequence of charge that some might consider tripolar (e.g., (Rust and MacGorman, 2002; Rust et al., 2005; Carey and Buffalo, 2007). The relative depletion rate of cloud water has been linked to inverted polarity hypotheses (Williams et al., 2005), and the choice to focus on the updraft core also allows us to assume that the relative growth rate effect is dominated by supercooled liquid collection, and not lesser effects that might operate in clouds at ice supersaturation in the absence of cloud liquid water (e.g., Mitzeva et al., 2006).

We restrict our analysis of the electrification in inverted polarity storms to a single electrification mechanism and the tripolar charge structure that it can explain, because tripolar language tied to the NI mechanism still dominates wider understanding of thunderstorm charge structure and the language used to describe it — consider its continued appearance in introductory (Ackerman and Knox, 2007; Aguado and Burt, 2010) and advanced (Williams, 2001) meteorology and storm electricity (Tessendorf, 2009) texts. By pointing out some problems with the normal/inverted dichotomy (which implicitly references the tripole), this paper acknowledges problems with the way a tripolar baseline is used, and contributes to the ongoing search for a simple framework that accounts for observed charge structures and links them in a clear way to one or more electrification mechanisms.

The primary evidence discussed in this study comes from recent results from the Severe Thunderstorm Electrification and Precipitation Study (STEPS, Lang et al., 2004), the Thunderstorm Electrification and Lightning Experiment (TELEX, MacGorman et al., 2008), Carey et al. (2005) and Albrecht et al. (2011). These studies have shown that storms that produce predominantly positive ground strikes have shallower warm cloud depth and more vigorous updrafts that enhance positive charging to graupel (Williams et al., 2005). Charge inferred from in-situ electric field and lightning mapping measurements from the STEPS and TELEX campaigns also confirm that some form of inverted-polarity electrical structure is present in at least some part of the storms that produce predominantly positive ground strikes. In these structures, the first two net regions above the ground are inverted from those of the normal tripole. Based on energetic arguments, the above authors have argued that the enhanced positive charging to graupel leads to an enhancement of the positive charge region that is the source of charge lowered in positive ground strikes.

Recent studies also suggest that a 2D or 3D storm flow is a minimum requirement for producing the locally inverted structures necessary for positive ground strikes. This is because, as we show below, the electrification mechanism always produces a normal-polarity-like structure with positive charge lowest. Put another way, the basic non-inductive graupel-ice electrification mechanism does not produce a lower negative charge region in a 1D storm flow where positive charging to graupel is enhanced, and so the interplay between regions of simultaneously enhanced and less enhanced positive charging rates to graupel are important.

1.2. Flashes

1.2.1. Cloud flashes

Normal- / inverted-polarity terminology has also been used to describe cloud flash polarity. Historically, cloud flashes were thought to be between the upper positive and midlevel negative charge regions in the normal-polarity tripole, (these regions are the positive dipole in the simplest charge models, e.g., Wilson, 1916, 1925), and as such were referred to as normal-polarity cloud flashes. The lower positive charge center in the normal tripole was thought to be weaker, with flashes between it and the main negative charge center preferentially coming to ground. Low-level flashes that did not come to ground would therefore have a vertical dipole orientation that is inverted from upper level cloud flashes in the normal tripole.

In storms with enhanced positive charging to graupel and associated elevated tripole, inverted flashes become increasingly common, though they remain tethered to the lower negative dipole formed in the NI charging process. Mansell et al. (2010) argued that the relative amounts of charge in the tripole can vary significantly, leading to top-heavy or bottom heavy tripole structures in normal-polarity storms. VHF lightning mapping array data show that bottom-heavy tripole structures often produce low-level inverted-polarity flashes in a negative dipole. The terms normal and inverted, while helpful shorthand for describing polarity, only indicate "normality" relative to the previous paradigm of cloud flash understanding.

It seems that a new characterization of the relative frequency of normal and inverted-polarity cloud flashes is necessary to declare normality of either polarity of cloud flash. Likewise, the presence of cloud flashes between a negative dipole is not necessarily evidence of an inverted-polarity storm.