Precipitation Ice and Lightning: From Global to Cell Scales

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Abstract

Theory predicts a close relationship between precipitation ice mass and lightning flash rates. *To what degree and over what scales (global, regional, cell scale) are theoretical relationships between ice and lightning, with attendant assumptions, verified in observational data?* Herein we review recent global observations of lightning and ice water path using results from the Tropical Rainfall Measurement Mission (TRMM) satellite Lightning Imaging Sensor (LIS), and extend these results to both regional and individual thunderstorm scales.

1. Introduction

The basis for relating precipitation ice water content to lightning flash rate revolves around the generally accepted mechanism for charge generation in active thunderstorms, non-inductive charging (NIC). In NIC, particle-scale charge separation occurs between precipitation-sized ice particles such as graupel and smaller, more numerous ice crystals in a mixed-phase environment. The mixed-phase environment is supported by vigorous updrafts in deep cumulonimbus clouds. Cloud-scale separation of charge into familiar multi-polar (e.g., dipolar, tripolar etc.) charge structures ensues via combinations of particle advection due to the draft structure and gravitational settling. In turn, the evolving cloud charge structure creates electric fields large enough to initiate electrical breakdown between the charge centers and associated lightning.

One key to this process is the "generator" precipitation current in the ice phase (here we focus on *precipitation* because it is the easiest to observe; e.g., with radar). While it is only one part of the ice-ice collision pair and potential charging current (e.g., Blyth et al., 2001), it is well known that precipitation ice (P_{ice}) in the mixed-phase region is critical to the initiation and maintenance of active thunderstorm lightning activity (witness the typical dearth of oceanic lightning but copious small ice development in maritime cumulonimbus clouds; Nesbitt et al., 2000; Petersen and Rutledge, 2001; Christian et al., 2003). Importantly in deep convection the P_{ice} mass is also implicitly related to cloud updraft strength in the mixed-phase region via its dependence on the supply of condensate. Indeed, one could also make the argument that P_{ice} is implicitly related to smaller cloud-ice concentrations in the mixed-phase region via ice particle multiplication processes (however, the column of cloud-ice and associated generation processes are difficult to observe), and may serve as an indirect tracer for primary ice nucleation via its tie to updraft magnitude and condensate supply. Hence a given observation of P_{ice} mass contains a great deal of information content relative to lightning production.

On global climate scales the ability to deduce P_{ice} mass components from lightning observations has potential application in studies of the global tropospheric water and radiation budgets; i.e., fallout and melting of ice to produce liquid precipitation vs. temporary upper tropospheric transport and/or storage of water in the form of ice crystals which later sublimate. On more regional to cell scales, the ability to functionally map observable quantities like P_{ice} mass (derived from say, radar) to model prognostics like graupel and hail mixing ratios, could provide the means to link observed lightning activity to forecast lightning activity, or visa versa, provide the means to use lightning data to nudge model convective parameterizations and associated water/heating budgets. Within the aforementioned physically-based background, this study will address the correlation between P_{ice} mass and lightning flash rate from global to cell scales.

2. Methodology

2.1 Global lightning and ice water comparisons

To compare *global* lightning activity to global ice water contents, data from the TRMM LIS and Precipitation Radar (PR) were combined for the pre TRMM-boost (prior to August 2001) northern and southern hemisphere

warm seasons (1998-2000, June-August; December-February, respectively). A detailed methodology is discussed in Petersen et al., (2005, 2006), but can be summarized as follows: Three years (1998-2000) of LIS and TRMM 2A25 algorithm PR radar reflectivity (Z) data were analyzed. LIS flash densities (FD) were gridded to $0.5^{\circ} \times 0.5^{\circ}$ grid boxes (flashes/km²/month). For the PR data, within in each grid square columns containing reflectivity-pixels (horizontal resolution 4.3 km, 250 m vertical) identified as both "rain-certain" and "convective" were processed for each orbit to provide ice water path (IWP, kg m⁻²) by vertically integrating ice water contents (IWCs) in each pixel column from an altitude of -10 °C to echo top (18 dBZ in the case of TRMM PR), and then finding the area-average IWP for each 0.5° x 0.5° LIS FD grid square. Based on numerous observational studies -10°C was chosen as the temperature threshold below which significant NIC processes were expected to be most active. The resultant IWP and LIS FD were compared in scatter plots using both ensembles of instantaneously-viewed IWPs and FDs for each 0.5° x 0.5° grid square and time integrated warm-season grid square means. The results for the ensemble and time-integrated techniques were virtually identical.

2.2 Regional lightning and ice water comparison

To compare *regional* lightning FD and ice mass, seven years of cloud-to-ground (CG) lightning flash data and archived KHGX (League City, Texas; Houston) VCP-11 radar reflectivity data (1997-2003) were analyzed for warm season (June – August; JJA) daylight hours (0900 – 1859 CDT; cf. Gauthier, 2006). Each of the radar volumes were interpolated onto a 150 x 150 x 20 (x, y, z) Cartesian grid with horizontal (x,y) and vertical (z) grid resolutions being 2 km and 1 km, respectively. To minimize erroneous data-pairs resulting from missing, and/or poorly sampled data, the radar analysis was only performed for pixels at a range in excess of 15 km from the KHGX radar (i.e., outside of the "cone of silence") and within 150 km of the radar. Estimations of the total precipitation ice mass (M_{ice}; kg)) in each volume were then made by applying a Z-M relationship used by Carey and Rutledge (2000) and Petersen and Rutledge (2001) to all valid 4 km³ pixels located between z = 7 and 11 km (climatologically the -10°C to -40° C region of the troposphere). Coincident CG data (i.e., flashes occurring from the beginning of one volume scan to the beginning of the next) detected by the NLDN were gridded to match the horizontal dimensions of the Cartesian radar grid, with FDs calculated in flashes km⁻² hour⁻¹. Flashes with positive peak currents <10 kA were not included (Cummins et al., 1998). In this fashion we were able to correlate radar derived values of Mice with ground strike locations, and flash densities (FDs), observed by the NLDN. The subsequent pixel data were compared over the regional sampling domain as discussed in the TRMM methodology above.

2.3 Cell-scale lightning and ice water comparison

The first approach taken to compare cell-scale M_{ice} to total lightning flash counts (FC), involved the use of case studies analyzed from field campaigns conducted in several regions of the U.S. (Deierling et al., 2005; Deierling, 2006). These regions include the High Plains of northeast Colorado, western Kansas and the northeast Alabama region. Each study made use of dual-polarimetric radar data from respective field campaigns to a) first identify hydrometeor types (precipitation ice in particular); b) subjectively identify cell boundaries; c) map gridded cells of radar-identified graupel and hail in each discrete cell to their associated Z; d) use an appropriate Z-M to compute IWCs for temperatures < -5°C; and e) multiply IWC by radar-determined precipitation ice volume to compute total ice mass M_{ice} (kg). Total lightning data from each field campaign (interferometer data from STERAO; Defer et al., 2001), VHF Lightning Mapping Array (LMA) data from STEPS (Wiens et al., 2005) and northeastern Alabama (Goodman et al., 2005) and for each individual case study at each sample volume time and for each cell were subsetted into "flashes" for comparison to the radar-derived M_{ice} . A single scatter plot was then constructed using all *cell* M_{ice} and lightning FC data points for all radar volume times.

A second more automated approach to comparing gross cell M_{ice} statistics to lightning utilized an automated radar storm cell identification and tracking algorithm (cf. Gauthier, 2006) to perform a *Lagrangian* analysis, comparing storm total IWPs in the Houston KHGX dataset with storm *CG flash counts* (FCs) on a cell-by-cell basis (hence forth referred to as the CT method). Here, we set the minimum storm size area and tracking

altitude for identifying radar reflectivity cells as 12 km^2 (3 pixels) at an altitude of 2 km, with a threshold reflectivity value of 30 dBZ. Cell totals of FC and M_{ice} were then computed for each pixel comprising the cell. Note this approach did not account for cell vertical tilt, nor did it account for flashes coming to ground in regions of reflectivity less than 30 dBZ. Applied to each volume within our radar dataset, the algorithm yielded a total of 676,153 cells for comparison allowing us to test (extend) the global results of Petersen et al. 2005 on (to) much smaller scales (at least in terms of total vs. CG lightning trends).

3. Results

On global scales Petersen et al. (2005) demonstrated a strong correlation between LIS FD and radar-derived IWP. When the IWP-FD relationship was partitioned between oceanic, land, and coastal regimes a leastsquares linear fit between FD and IWP retained a strong correlation (> 0.9), exhibiting little variation between regimes (Fig. 1). Importantly, the associated analysis necessarily relied on a large number of TRMM LIS/PR orbital "snapshots", which were subsequently filtered in time and space. However, the hypothesis driving the TRMM global IWP-FD analysis was based on the assumed validity of NIC theory and attendant physics, which act over much smaller, and more continuous, temporal and spatial scales. This leads us to pose the question: To what degree the observational results can be meaningfully extended to smaller scales.

First, consider the regional comparison (using continuous data as opposed to discontinuous TRMM orbit data) of CG lightning flash density from the Houston, Texas area (Sec. 2.2) shown in Figure 2. Here we illustrate the relationship between binned ice mass (Mice) and FD values for the pixels sampled in 46,479 radar volumes over seven summer seasons within 150 km of the KHGX radar. As in the case of the global result, the relationship between M_{ice} and FD is exceptionally strong (R > 0.97). Further, while not shown in Fig. 2, this relationship is also invariant if data points are partitioned between storms occurring over land and the Gulf of Mexico. Figure 2 clearly suggests that the relationship between Mice and FD holds on a regional basis, with the caveat that we have only examined the Houston region of the U.S. Gulf Coast and we have only used the CG lightning component. Can we observe anything similar on the scale of individual thunderstorms (cell scales)?



Figure 1. TRMM-LIS lightning flash density vs. IWP for land (red), ocean(blue) and coastal (green) grid squares. $+/-1\sigma$ error bars in IWP are shown for each flash density bin, as are least-squares trend lines and associated equations for each regime.



Figure 2. Average M_{ice} (ordinate) occurring in each lighting FD bin (abscissa) for ensemble of KHGX radar volume samples. The first bin interval is associated with non-lightning events, with remaining variable sized bin intervals each encompassing roughly 5-10% of the remaining data pairs; data points are plotted relative to the interval mid-point, horizontal bars represent bin widths, vertical error bars associated with $\pm 1\sigma$ for each data point

An 11-storm cell scale comparison of M_{ice} and cell FC for each storm and individual radar volume sample times within each storm (cf. Deierling, 2006) is presented in Fig. 3. Note that the M_{ice} and lightning are well correlated for total lightning flash rates exceeding ~1 per minute (R > 0.9). Near this flash rate threshold it is physically difficult to attribute a given cell M_{ice} with a lightning flash rate (and it is also probable that the measurement noise exerts a stronger influence). The small sample of storms presented in Fig. 3 precludes the drawing of any strong conclusion regarding the invariance of the relationship between M_{ice} and FC for the different storm types (e.g., high plains vs. sub-tropical). However, qualitatively the scatter plot does at least suggest similarity between the FC- M_{ice} relationships of the respective storm types. This is especially true for the larger flash rate cases, a result at least qualitatively consistent with Petersen et al. (2005) in terms of FC- M_{ice} regime invariance.

The problem of storm sample size (statistically) can be mitigated through use of the automated cell tracking "brute force" technique discussed in Sec. 2.3. Here we find that for thunderstorms in the vicinity of Houston, Texas, a very strong correlation exists between M_{ice} and CG flash count (R > 0.8) over a very large storm sample of storm cells (Fig. 4). Collectively, Figs. 3-4 strongly suggest that the relationship between precipitation ice mass and lightning is relatively robust for scales approaching that of individual thunderstorms, and for cell flash rates that rise above a lower threshold of O[1-10 fl/minute].

4. Conclusion

A combination of space borne (TRMM-LIS) and groundbased lightning and radar observations have demonstrated that the relationship between precipitation ice mass and lightning flash activity is robust over scales ranging from global to that of individual thunderstorms. Topics of ongoing research involve assessing the degree to which these relationships can be used to better quantify the role of ice in tropospheric water budgets, and the development of methods by which similar relationships could be applied in numerical forecast models. Finally, it should be noted that without the suite of TRMM instruments, including TRMM-LIS, evaluating/documenting global tropical ice mass–lightning relationships would have been impossible.

5. References:

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Cell Flash Rate vs. Precip. Ice Mass: KS., CO., AL



Figure 3. Cell total flash rate vs. precipitation ice mass for radar volume times in Kansas/Colorado storms (**black**) and N. Alabama storms (**red**). Each points represents a single radar volume time from the total of 11 thunderstorm cases studied.



Figure 4. Cell CG flash count vs. cell ice mass for 676,14: individual cells tracked near the KHGX radar.