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TRMM OBSERVATIONS OF THE BASIC RELATIONSHIP BETWEEN ICE WATER CONTENT AND LIGHTNING

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1. INTRODUCTION

Precipitation based charging theory and laboratory studies predict a strong correlation between lightning flash rate and the presence of significant precipitation-sized ice particles in deep convection. These ice particles are the result of robust mixed-phase processes driven by vigorous updrafts. Indeed, simple scaling arguments based on continuous collection theory and an assumed direct proportionality between charge generation rate and lightning flash rate, predict a relationship between lightning flash rate and precipitation ice water content (IWC) that is approximately linear (e.g., Petersen and Rutledge, 2001). Importantly, the scaling approximation and laboratory results are independent of ambient meteorological convective regime (e.g., land vs. ocean regimes). That is to say, the underlying physics of precipitation based charging and its relationship to lightning flash rate (e.g., Blythe et al., 2001) should be universal, no matter where a cloud occurs. In clouds of any environment, either the requisite physics for charge generation and lightning exist or they do not.

While the assumed “universality” of the cloud physics-charging-lightning chain is somewhat simplistic, it does give us a framework to test some simple hypotheses as they relate to ice. For example, consider the TRMM Lightning Imaging Sensor (LIS) data presented in Fig. 1. If the relationship between precipitation ice mass and charging theory is universal, we would hypothesize based on Fig. 1 that the spatial patterns observed in a map of ice mass should be very similar to that of the lightning pattern of Fig. 1. For example, there should be large decreases in precipitation ice mass as one moves from continent to ocean or from Central Africa to the Amazon. Would we hypothesize the same for rainfall?

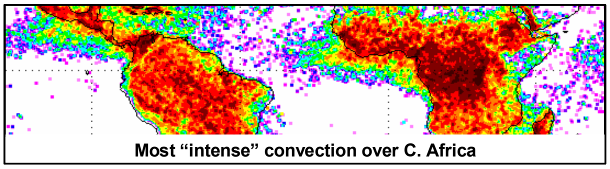

Figure 1. OTD Lightning flash density for DJF (5-year mean). Warm colors = large flash count; cool colors = low flash count (factor of 10-100 less). Adapted from Christian et al., 2003.

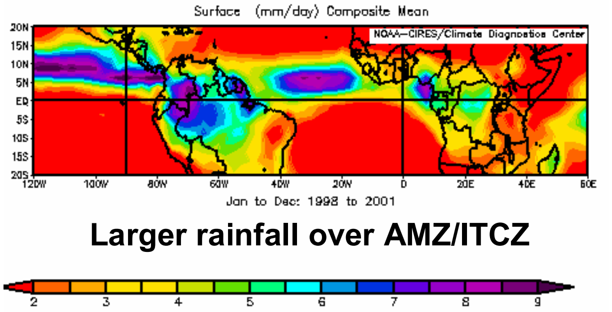

Figure 2. GPCP annual mean rainfall (mm/day) 1998-2001.

In general, observations and common experience suggest that lightning-producing convection tends to generate moderate to large rainfall rates. Therefore, as in the case of ice mass, we might also hypothesize at least some similarity in the maps of rainfall and lightning (e.g., Petersen and Rutledge, 1998). However, Fig. 2 suggests that the *global* pattern similarity is only weak. This is because convective rain processes need not be coupled to robust mixed phase ice processes, and this is especially true in the Tropics. This explains, in part, why large rainfall occurs in deep convection over oceanic regions of the ITCZ in the relative absence of lightning (cf. Christian et al. 2003) and why there is such a rainfall-lightning disparity observed between continental regions of the Amazon (AMZ) and central Africa (Figs. 1-2). Clearly, the chains of causality between the rain process and lightning do not contain enough common links, at least in environments or transient convective regimes where ice processes do not contribute substantially to measured rainfall. Hence with regard to correlating precipitation rates to lightning, we may be more successful if we deal explicitly with the ice phase (e.g., Deierling et al., 2005; this conference).

Subsequently, in this study use space-based lightning and radar observations to address 1) the fundamental correlation between lightning and precipitation ice water path (e.g., integrated amounts of graupel and hail) over the global tropics; and 2) the

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degree to which this relationship varies between ocean and continental convective regimes.

2. DATA AND METHODOLOGY

To address the relationship between ice mass and lightning we have examined three years (1998-2000) of TRMM LIS and Precipitation Radar (PR) data. PR reflectivity pixels were processed for each TRMM orbit to provide ice water paths (IWP; kg/m^2) over the global tropics by vertically integrating ice water contents upward from the altitude of the -10 C level (determined for each pixel using NCEP Reanalysis data) to echo top. Ice water contents were computed for warm seasons in the northern and southern hemisphere. The reflectivity at each PR range gate (4.3 km pixel, 250 m gate spacing) was converted to ice water content using a Z-M relationship based on an exponential size distribution and ice particle density adjusted to precipitation type (convective or stratiform) and reflectivity magnitude. After vertically integrating the ice water contents, pixel-level IWPs were averaged in grid boxes of 0.5° x 0.5°. LIS lightning flash densities (flashes/km^2/day; FD) for pixels observed by the PR were also computed and gridded at the same resolution.

After gridding IWPs, the data were partitioned into land, ocean and coastal regimes; i.e., regimes exhibiting very dissimilar lightning flash density (Fig. 1). For each regime the gridded IWPs at 0.5° resolution were subsequently binned as a function of FD at intervals of 0.01 fl/km^2/day. Once binned, scatter plots and cumulative frequency distributions could be generated of FD vs. IWP. This enabled statistical analysis of the underlying relationship between the two variables and in particular, the potential for using lightning information to directly infer IWP independent of regime. Using the 0.5° grid box samples, scatter plots of IWP were created for both unconditional and conditional samples. Here, the term "unconditional" implies that all grid boxes with detectable IWP were included regardless of lightning activity. "Conditional" implies that data points were only included in the sample if there was lightning activity registered in a given grid box

3. RESULTS

LIS FDs and PR IWPs are plotted in Figs. 3 and 4 respectively. To ensure that the predominant cloud types and physical processes being considered were convective in nature, warm season values are plotted for both hemispheres in the same figure. Additionally, only pixels identified as "convective" by the TRMM 2A-25 algorithms are included in Fig. 4. Comparing Figs. 3-4 a clear correspondence is observed between lightning flash density and ice water path. Even though the FD and IWP values displayed in Figs. 3 and 4 are not scaled to a common reference, the similarity in pattern is striking- especially in regions of topography (e.g., Himalayas, Columbia, Sierra Madre, C. Africa, Madagascar, etc.). One area that does suggest some difference in behavior is observed over sub-tropical South America (30° S). This region is frequented by severe hail storms and it may be that the Z-M relationship used in the IWP calculation is not appropriate. Alternatively, TRMM 2A25 attenuation correction algorithm may not be working properly in areas where storms produce large hail. With the exception of this S. American region, however, it is clear that *globally*, ice mass and lightning are well correlated, and much more so than lightning and rainfall (Fig. 2). A similar relationship has been noted using passive microwave data by Blythe et al. (2001). From a more quantitative perspective, how well are IWP and FD correlated and do the relationships differ if

LIS FD (Fl/km^2/month) JJA, DJF 1998-2000

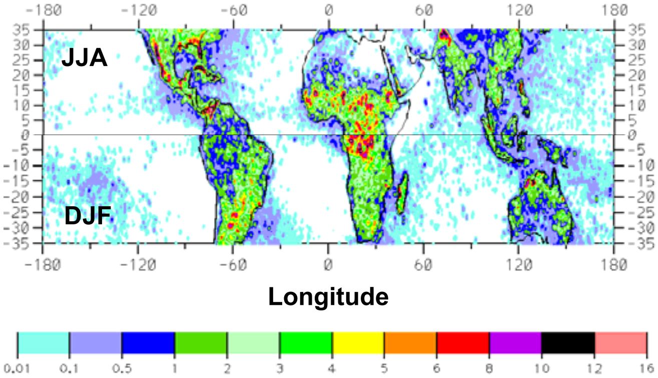
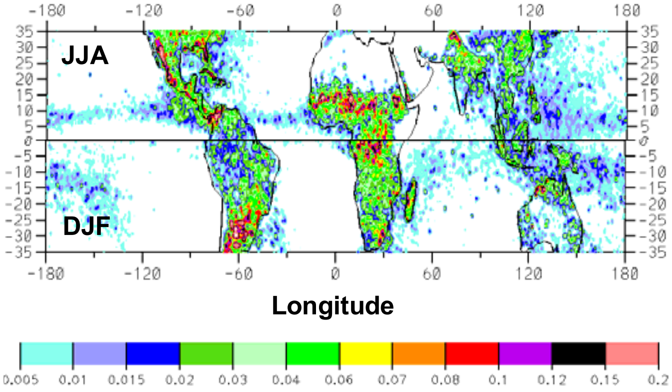


Figure 3. TRMM LIS flash density for JJA (N. Hemisphere) and DJF (S. Hemisphere) 1998-2000.

Figure 4. As in Fig. 3 but ice water path (kg/m^2).

TRMM PR IWP (kg/m^2) JJA, DJF 1998-2000



we compare land, ocean and coastal areas in a global sense?

When IWPs and FDs for all 0.5° grid boxes with IWP > 0 are plotted for each regime, the result is Figure 5 (N Hemisphere summer used as an example; but same result over the whole globe). Fig. 5 suggests that IWP and FD are positively correlated (R=0.7), that the relationship between the variables is similar in going from land, to ocean, to coastal regimes, and that the scatter decreases as the signal (FD) gets stronger. Fig. 5 also suggests that there is a noise floor in the data at somewhere around 0.01-0.02 Fl/km^2/day. That is, at low flash densities, it is still possible to have significant, but lower IWP (this is not unexpected in the tropics).

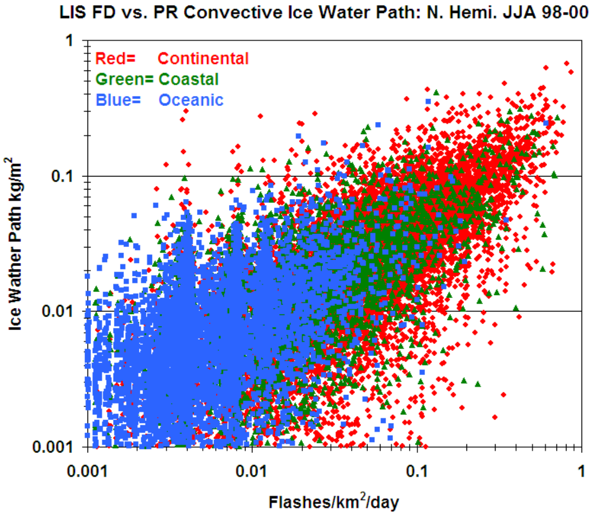


Figure 5. Scatter plot of convective IWP (ordinate) as a function of FD (abscissa). Regimes are indicated by color.

To further assess the degree of uniformity in the relationship between IWP and FD, we eliminated some of the "noise" in Fig. 5 by binning and averaging IWP data points as a function of FD. These results are presented in Fig 6. together with error bars representing the +/- one standard deviation of the IWP in each bin. Note that the FD scale in Fig. 6 is truncated at 0.2 Fl/day/km^2. This is because decreasing sample numbers of PR-diagnosed IWP data points in FD bins larger than 0..2 Fl/day/km^2 did not permit a robust mean IWP to be computed (within a +/- 25% confidence interval). The increasing variance of the IWP distributions with increasing FD is evinced by the increasing width of the error bars with larger FD.

The "universality" of the underlying relationship between ice mass and flash density now becomes clear. Regardless of the regime, the data points lie along the same lines with slopes that vary by less than 20% (at a very high correlation of R=0.98) and the same zero FD intercept of 0.01 kg/m^2 (which intercepts the data points in Fig. 5 at approximately 0.01-0.02 Fl/km^2/day). This supports the hypothesis that the underlying physics of charge generation involving precipitation-sized ice behave consistently, no matter the regime, at least within the limits of detection (for LIS this threshold is about 1 Fl/min.; Boccippio et al. 2000). Indeed, Figs. 5 and 6 further suggest some utility of total lightning data (at least, where lightning occurs) as a constraint in the prediction/retrieval of precipitation ice water content.

It is interesting to note that the median of the coastal and oceanic lightning flash density distributions (as constructed here) fall within the "noise" threshold of the IWP samples. In fact, approximately 75% of the oceanic lightning FD distribution falls in the noise level of IWP. This is also evident when the individual data points are inspected (Fig. 5).

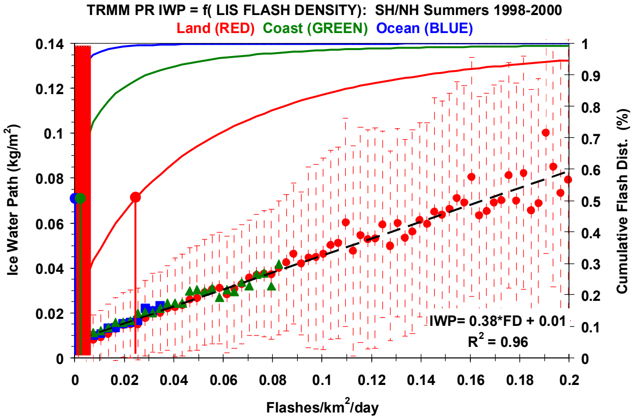


Figure 6. Scatter plot of averaged IWP for each FD bin (colored as indicated) with error bars (+/-1 σ). IWP is plotted on the left ordinate. The cumulative distribution of FD for each regime is indicated on the right ordinate. The median value of each FD distribution is indicated by the colored solid points. The equation for the best fit line through the land data points is indicated in the lower right (relationship for coast and ocean were nearly identical).

The number of oceanic data samples with FDs exceeding ~.06 Fl/km2/day in Fig. 6 is very small. We see a gradual increase in larger FD points within the coastal regime, but neither the ocean nor coastal regimes produce the number of data points observed over land at the moderate to high end of the FD spectrum (as indicated by the relative separation of the median land FD from the ocean and coast regimes).

4. CONCLUSIONS

Herein we used space based lightning (LIS) and radar (PR) observations from the TRMM satellite to examine two problems: 1) the fundamental relationship between precipitation ice mass and lightning flash density; and 2) the degree to which this relationship varies between oceanic, coastal, and land convective regimes. These problems were addressed on a "global" scale to filter out noise in the measurements and sub-climate scale variability. We hypothesized, based on precipitation electrical charging theories, that the relationship between ice water path and lightning flash density should be both robust and "universal"; i.e., exhibit high correlation and be independent of regime.

When gridded ice water paths were binned by flash density and globally averaged for land, ocean and coastal regimes, correlations between the two variables were found to be quite large (R>0.9) for all three regimes. Best-fit lines between flash density and ice water path for all three regimes were nearly identical, exhibiting differences in slope of less than 20% with nearly identical intercepts of ~0.01 kg/m^2 (an apparent lower threshold in IWP for achieving a detectable FD with LIS in a 0.5 x 0.5 Deg. grid cell). The results suggest that 1) when averaged over all tropical ocean, land and coastal regimes there is no discernable difference in the relationship between ice-phase precipitation mass and lightning flash density between ocean, coastal and land regimes (in contrast to rainfall); and 2) to first order, the physical assumptions of precipitation-based charging and mixed phase precipitation development are robust, suggesting that lightning data may be a useful variable for inclusion in combined space borne algorithms developed to retrieve precipitation ice water content (at least over the large scales examined herein).

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