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Small ice crystals and the climatology of lightning

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[1] Vigorous debate still surrounds the cloud electrification process and unexplained regional variations in lightning activity. Here, we show that climatological maxima in lightning activity are associated with small effective diameter D_e of ice crystals near cumulonimbus cloud tops. This relationship, unlike lightning's more well-known relationship with cloud top height, is consistent over land and ocean. Since multiple studies indicate that D_e is reduced by atmospheric aerosol, this relationship strengthens previous suggestions of a role for aerosols as well as dynamics in electrification. Moreover, the angular distribution of backscattered radiance shows that modest ($\sim$10%) D_e decreases reflect large ($\sim 2\times$) increases in the number of small ($<\sim$30 μm) particles N, a finding supported by cloud model simulations. Both relationships provide an important new test of cloud microphysics and/or electrification models. **Citation:** Sherwood, S. C., V. T. J. Phillips, and J. S. Wettlaufer (2006), Small ice crystals and the climatology of lightning, *Geophys. Res. Lett.*, *33*, L05804, doi:10.1029/2005GL025242.

1. Introduction

[2] Though a number of mechanisms may separate charge in thunderstorms under various circumstances [e.g., *MacGorman and Rust*, 1998], it is now widely agreed that strongly electrified storms owe most of their charge separation to "non-inductive" transfer between frozen particles, primarily a suspended graupel and a smaller, ascending cloud ice particle [*Mansell et al.*, 2005]. The microphysical explanation of non-inductive charging remains hotly debated. Charging between unrimed crystals has recently been observed [*Mason and Dash*, 2000] and explained [*Dash and Wettlaufer*, 2003], but laboratory experiments have long suggested that supercooled water is a critical, complicating factor in real storms [*Takahashi*, 1978]. It remains to be determined whether that indicates additional physics, or the same physics operating in a more complicated environment. Inconsistencies between experimental findings imply significant differences in simulated thunderstorm charge distributions [*Scavuzzo et al.*, 1998; *Helsdon et al.*, 2001] but this result is model dependent [*Mansell et al.*, 2005]. *Scavuzzo et al.* [1998] found that charge separation could be dominated either by small (<100 μm) or large (>100 μm) cloud particles depending on the charging parameterization, suggesting that further attention to the behavior of different size ice particles may help test charging theories.

[3] The difficulties in accurately simulating individual storms limit the evaluation of charging models based on case studies. One alternative is to compare predicted and observed trends in typical electrification as key parameters change. For example, idealized calculations based on one popular charging parameterization suggest that electrification should vary with the product of the radar reflectivity (determined by the amount and size of frozen precipitation) and the mass of cloud ice particles in the appropriate temperature range of 0 to −40C [*Baker et al.*, 1995]. Radar studies are consistent with this [*Deierling et al.*, 2005] but do not give information on cloud-sized ice.

[4] The most obvious trends in observed electrification are regional variations in average lightning counts [*Boccippio et al.*, 2000], which far exceed variations in rainfall or storm frequency. In particular, lightning exhibits a striking preference for land. Evidence for an aerosol role has proven elusive [*Smith et al.*, 2003; *Williams et al.*, 2002]; a second possibility is that higher cloud bases promote continental lightning. The best-supported explanation is updraft speed, which case studies indicate must exceed 6–7 m s^{-1} near the freezing level for strong electrification [*Zipser and Lutz*, 1994]. Continental updrafts are significantly stronger than maritime ones, though this difference itself cannot be simply explained [e.g., *Lucas et al.*, 1994; *Sherwood et al.*, 2004]. Unfortunately vertical velocity data are limited to a few field campaigns. Stronger updrafts should generally produce taller storms with colder tops, and taller storms do indeed produce more lightning [*Williams*, 1985], but a single relationship does not hold globally [*Rutledge et al.*, 1992]. Maritime storms are too tall to explain their lack of lightning. Thus, questions still surround lightning's land-ocean contrast and other variations [*Williams and Sátori*, 2004].

2. Climatologies of Ice Diameter and Lightning

[5] Here we compare seasonal climatologies of lightning flash rate, for the period 1999–2003 from the Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) on board the Tropical Rainfall Measuring Mission (TRMM) Satellite [*Christian et al.*, 1992], with those of ice particle effective diameter (D_e) obtained by *Sherwood* [2002a, 2002c] from Advanced Very High Resolution Radiometer (AVHRR) individual pixel radiance data at 3.7 and 11 μm. The latter comprise all observations of deep convective clouds (11 μm brightness temperature T_{11} < 210 K) at tropical latitudes from January 1984 to April 1998. Random sampling of weather becomes small in multi-year averages, revealing climatological variations. These well exceed interannual variations, justifying our comparison of different time periods.

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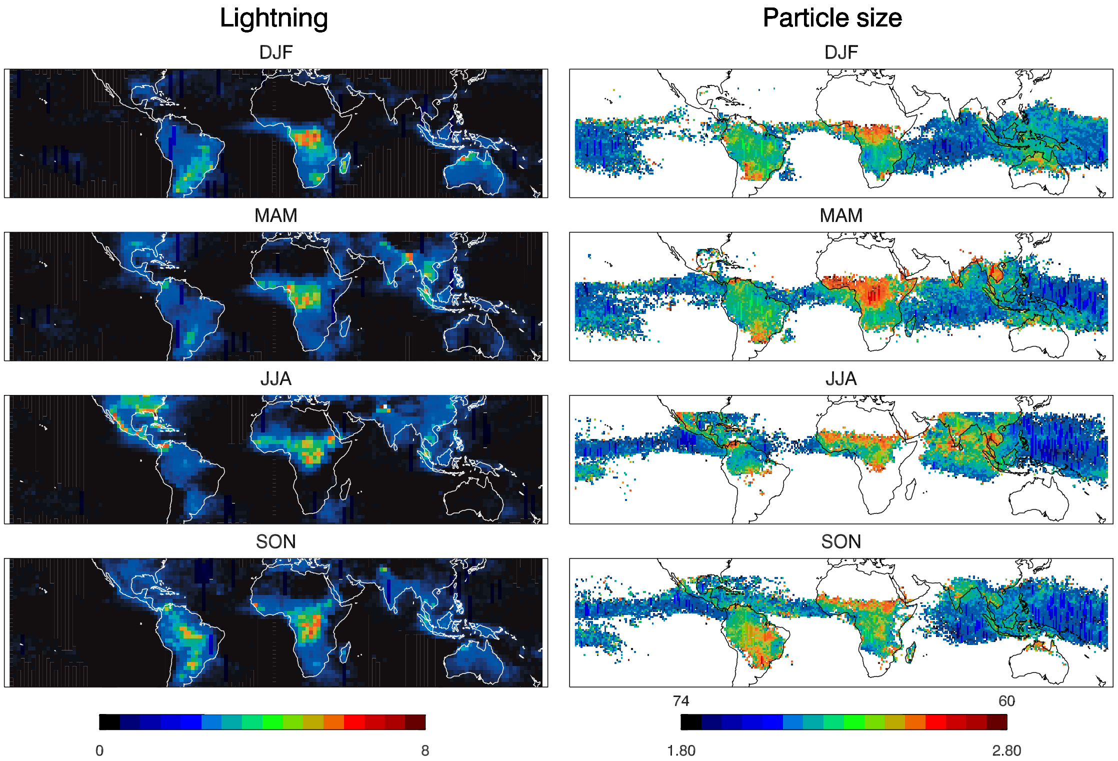

Figure 1. (left) Seasonal mean LIS/OTD combined lightning counts (flashes per km^2 per month). (right) 3.7 μm reflectance (lower scale, %) or D_e (upper scale, μm) among clouds with $T_{11} < 210$ K.

[6] The climatologies (Figure 1) show a noteworthy correspondence, with locations of anomalously small D_e usually producing frequent lightning. Contrast of MAM and SON seasons is particularly useful since their convection distributions are relatively similar. Several highly localized electrification features appear, for example over southern Brazil, northernmost Columbia and the Caribbean, the Sahel and Congo regions of Africa, and southeast Asia during local spring and/or summer—each of which is accompanied by a similarly localized minimum in D_e. These "hot spots" do not differ systematically from other areas in terms of convection frequency or diurnal cycle [*Yang and Slingo*, 2001]. Not all features match, for example in the Congo region where D_e varies but lightning stays fairly constant throughout the year, which could indicate saturation of the charging mechanism [*Dash and Wettlaufer*, 2003].

[7] We used T_{11} to examine storm height patterns (not shown), which superficially resemble D_e with taller storms producing smaller D_e. However, lightning's pattern correlations with D_e and T_{11} were 0.57 and 0.27 respectively—lightning is much better correlated with D_e. The main reason for this is the relatively weak land-ocean contrast in storm height: the mean land-ocean difference in T_{11} was only 35% of the standard deviation over land, compared with 155% for D_e and 132% for LIS. The land-ocean contrasts in D_e and lightning are consistent with a single relationship between the two variables, while the contrasts in storm height and lightning are not.

[8] Another climatological observable related to lightning is graupel. While graupel concentrations are clearly correlated with lightning in a manner similar to D_e and T_{11}, at least one study has found that its land-ocean contrast may

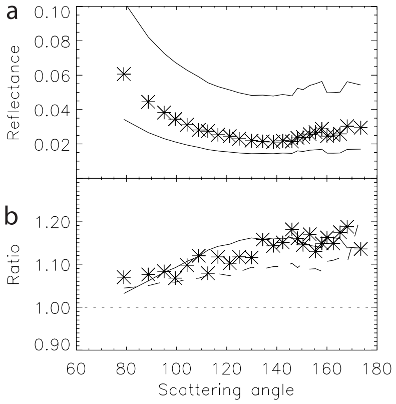

Figure 2. (top) Reflectance as a function of scattering angle, where 180 is scattering back toward the sun. Symbols, observed; upper and lower solid curves, MODIS ice model with D_e = 58 and 101 μm, respectively. (bottom) Symbols, ratio of BDRF for polluted vs. normal observed subsets; solid line, ratio for a mixture of 35% MODIS 20-μm and 65% MODIS 101-μm particles vs. 100% MODIS 58-μm particles; dashed line, ratio for a mixture of 40% hexagonal 19-μm crystals [*Minnis et al.*, 1998] and 60% MODIS 101-μm vs. 100% MODIS 58 μm. The MODIS model assumes mainly bullet rosettes, and lacks scattering features characteristic of hexagonal crystals. Each plotted value is a mean weighted by AVHRR viewing geometry frequency of occurrence.

Table 1. Effective Diameter, and Small Particle Concentrations, of Ice Distributions Simulated 1 km Below Cloud Top by an Explicit Microphysical Model[a]

CCN Factor	D_e, μm	<30 μm, cc^{-1}	<10 μm
3.16	54	83.5	24.4
1.00	71	32.3	4.8
0.32	70	12.1	0.01
0.10	90	2.7	0.01

[a] CCN factor is the coefficient by which the control distribution of CCN, based on observations, was multiplied.

also be inadequate for a single relationship with lightning to hold [*Toracinta et al.*, 2002]. This may depend on the specific graupel proxy used.

3. Interpretation of D_e Variations

[9] Small D_e in electrified, graupel-laden storms may seem contradictory. Since D_e is the mean volume divided by the mean surface area of particles, however, it is dominated by the more numerous cloud particles. It is also sensed above the mixed-phase region of the cloud. We now explore the D_e variations further using the BDRF (bidirectional reflectance function) or angular distribution of observed radiance, which manifests particle properties since multiple scattering at 3.7 μm is only moderate. *Sherwood* [2002a] obtained this BDRF for all cases; we repeated his procedure for a subset of the data including only the seasons and continental regions most polluted with biomass burning aerosol.

[10] Comparison of the all-case BDRF (Figure 2a) to the model calculation used by the Moderate Resolution Imaging Sensor (MODIS) [*Baum et al.*, 2000] reveals good agreement for $D_e \approx 70$ μm. The "polluted" (low-D_e) cases produced more reflectance in all directions, but especially in backscattering directions (Figure 2b). This asymmetry, a hallmark of small particles, can be reproduced by assuming that 35–40% of the scattering in polluted clouds was caused by ~20μm particles—but not by assuming that all the particles shrank by the same percentage. Further, the flattening above 140 is consistent with a greater number of hexagonal particles in the polluted cases (hexagonal ice scatters less near 130 than most other shapes [*Liou*, 2002]), suggesting growth of the small particles by vapor deposition.

[11] The satellite-inferred changes are reproduced in calculations by spectral microphysics model [*Phillips et al.*, 2002, 2005] under varying CCN concentration. This model predicts reductions in D_e of roughly 20% going from extremely few to many CCN (Table 1), consistent with ~10% average reductions observed with biomass burning [*Sherwood*, 2002a]. The simulated number of smallest particles increases markedly, with little change for $D > D_e$. Such a sensitivity of particle number N is corroborated indirectly by the observed covariation of stratospheric water vapor and D_e, whose explanation required more than a doubling of N per 10% drop in D_e [*Sherwood*, 2002b], also quantitatively consistent with Table 1.

4. Implications for Thunderstorm Electrification

[12] Existing models predict that electrification should be proportional to the total mass of cloud ice in the mixed-phase region of the storm, with little size dependence. However, we find that lightning counts appear related to the amount of small ice (<30 μm) that appears at cloud top. Our D_e is unlikely to be directly related to the volume or mass of cloud ice at lower altitudes, though it may be related to the number of those particles, especially if recirculated anvil air is a significant ice source [*Heymsfield et al.*, 2005]. Thus, our results are not explained by arguments such as those of *Baker et al.* [1995].

[13] There are, however, several other plausible candidate explanations. First, strong updrafts can activate aerosols in greater numbers and enhance homogeneous freezing to produce more cloud particles near cloud top, directly contributing to N [*Sherwood*, 2002a; *Melani et al.*, 2003; *Heymsfield et al.*, 2005; E. J. Jensen and A. S. Ackerman, Homogeneous aerosol freezing in the tops of high-altitude tropical cumulonimbus clouds, submitted to Geophysical Research Letters, 2006]. Such updrafts are also well known to favor strong electrification by lofting larger graupel to greater heights, and possibly by increasing supercooled water content [e.g., *Williams and Sátori*, 2004]. Thus the association between N and lightning may simply reflect a common dependence on updraft strength. This hypothesis may be tested in models or through observing vertical velocities in storms, although the latter approach would require much larger amounts of data than are presently available. If this hypothesis holds, then satellite-observed D_e would have potential practical value in improving space-based estimates of severe storm characteristics such as vertical velocity and/or supercooled water content.

[14] Alternatively, model results (*Khain et al.* [2001], *Phillips et al.* [2002], *Ekman et al.* [2004], and those reported here] and observations [*Sherwood*, 2002a] indicate that CCN aerosols can increase N —similar to the "Twomey effect" long noted in shallow clouds—and are responsible for much of its observed seasonal, interannual, and long-term variability in some tropical locations. Thus, our results are consistent with a role for pollution in abetting charge separation as suggested by *Michalon et al.* [1999]. A possible mechanism is aerosol suppression of the warm-rain process [e.g., *Rosenfeld*, 2000], causing liquid water to ascend higher into the cloud and/or increasing ice splinters. Another is aerosol modification of storm dynamics [e.g., *Ekman et al.*, 2004]. Several highly localized springtime maxima in lightning activity and N (in southeast Asia, the Sahel, and South America) coincide with known locations of biomass burning, providing circumstantial evidence that regional variations are partly aerosol-controlled. Other maxima, however, do not. We conclude that aerosols are, at best, a partial contributor to climatological lightning variations, but probably contribute to its land-ocean contrast.

[15] A final factor that could contribute to the lightning-N relationship is that cloud-top N could, through recirculation, affect the small-ice concentration in the mixed-phase region. Since non-inductive charging depends on relative particle growth rates, hence size differences, small particles may separate more charge per unit mass than large ones. Many uncertainties surround this possibility but it bears further investigation.

[16] It will be a long time before comprehensive data on vertical velocities or mixed phase cloud composition are available for storms worldwide. We suggest that, in the

meantime, a key test for thunderstorm models is whether they can simulate the relationships reported here, consistently across continental and maritime environments.

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