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Lightning response to smoke from Amazonian fires

Orit Altaratz,[1] Ilan Koren,[1] Yoav Yair,[2] and Colin Price[3]

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[1] The effect of anthropogenic aerosols on clouds has the potential to be a key component for climate change predictions, yet is one of the least understood. It is possible that high aerosol loading can change the convection intensity and hence the electrical activity of thunderstorm clouds. Focusing on the Amazon dry season, where thousands of man-made forest fires inject smoke into the atmosphere, we studied the aerosol effects on thunderclouds. We used the ground-based World-Wide Lightning Location Network (WWLLN) lightning measurements together with Aqua-MODIS aerosol and cloud data to show evidence for the transition between two opposing effects of aerosols on clouds. The first is the microphysical effect which is manifested in an increase in convective intensity (and electrical activity), followed by the radiative effect that becomes dominant with the increase in aerosol loading leading to a decrease in convective intensity. **Citation:** Altaratz, O., I. Koren, Y. Yair, and C. Price (2010), Lightning response to smoke from Amazonian fires, *Geophys. Res. Lett.*, *37*, L07801, doi:10.1029/2010GL042679.

1. Introduction

[2] The effect of smoke aerosols produced by biomass burning on clouds poses one of the largest uncertainties in the estimation of the anthropogenic effects on climate. Small changes in cloud coverage, reflectance, life-time or height in the atmosphere can be translated into 10's of W/m^2 change in the surface and top of the atmosphere radiative fluxes.

[3] There are two main pathways by which aerosol can change cloud properties: microphysical and radiative [*Kaufman and Koren*, 2006]. Often the end result is a superposition of the two processes [*Koren et al.*, 2008].

[4] The microphysical effect is related to aerosols serving as cloud condensation nuclei (CCN) and cloud ice nuclei (IN). Changes in CCN and IN concentration modify the size distribution of cloud droplets [*Twomey*, 1977] and later-on ice particles and hence affect many internal cloud processes like condensation and evaporation rates, latent heat release and collision coalescence efficiency [*Rosenfeld et al.*, 2008]. Heavy smoke from forest fires in the Amazon has been shown to reduce cloud droplet size and as a result delay the onset of precipitation. Delaying the onset of precipitation allows for the invigoration of the clouds, causing stronger updrafts, large hail, and a greater likelihood for intense convection [*Andreae et al.*, 2004]. Cloud simulations [*Khain et al.*, 2005; *van den Heever et al.*, 2006] have also shown that pollution aerosols in moist unstable atmosphere can induce clouds to develop stronger updrafts and downdrafts, grow taller and trigger secondary storm development.

[5] The radiative pathway of aerosols affecting cloud properties is a consequence of the absorption [*Hansen et al.*, 1997] and scattering of solar radiation by aerosol particles. The absorbing aerosols heat the surrounding atmospheric layer (reducing the relative humidity) while cooling the surface. This process stabilizes the temperature profile below the aerosol layer and reduces the surface moisture fluxes, leading to a reduction of the cloudiness [*Koren et al.*, 2004, *Feingold et al.*, 2005, *Davidi et al.*, 2009].

[6] The superposition of these two effects (microphysical and radiative) creates a smooth transition from low aerosol concentrations (measured here as aerosol optical depth, AOD) dominating the sharp trend in enhanced cloud formation due to the microphysical effect into the semi-linear cloud suppression due to aerosol radiative effects for higher AOD values [*Koren et al.*, 2008].

[7] Strong correlations are known to exist between continental cloud vertical development and lightning activity [*Price and Rind*, 1992; *Yoshida et al.*, 2009]. Deep convective clouds that exhibit strong updrafts [*Deierling and Petersen*, 2008], with large mixed-phase region and enhanced graupel and ice mass fluxes [*Deierling et al.*, 2008], have been shown to be correlated with stronger electrical activity. All of these factors are essential for the non-inductive charging process that is generally believed to generate most of the thunderstorm electrification [*Takahashi*, 1978; *Saunders et al.*, 1991].

[8] Previous studies of smoke effects on thunderstorms electrical activity have shown higher rates of positive cloud to ground flashes with high peak currents, in the presence of smoke for forest fires in Central America that influenced storms over the central plains of the United States [*Lyons et al.*, 1998; *Murray et al.*, 2000], for smoke in the Amazon region [*Fernandes et al.*, 2006] and for a pyro-CB formed over fires in Canada [*Rosenfeld et al.*, 2007]. Additional studies of the storms in the southern Great Plains after the 1998 Mexican fires showed that this region was unusually dry and hot during the period of increased percentage of positive flashes [*Smith et al.*, 2003]. They compared the lightning characteristics of thunderstorms in the northwestern US after the fires of 2000 with those storms in the Great Plains after the 1998 fires and found that the 2000 fires were not accompanied by significant lightning anomalies. Using a 1.5-dimensional numerical cloud model they showed that the increased positive cloud to ground flashes fraction was not sensitive to changes in the CCN size distribution, but decreased significantly (to the climatic average) when the humidity was increased. They concluded

[1]Department of Environmental Sciences, Weizmann Institute, Rehovot, Israel.
[2]Department of Life and Natural Sciences, Open University, Ra'anana, Israel.
[3]Department of Geophysics and Planetary Science, Tel Aviv University, Ramat Aviv, Israel.

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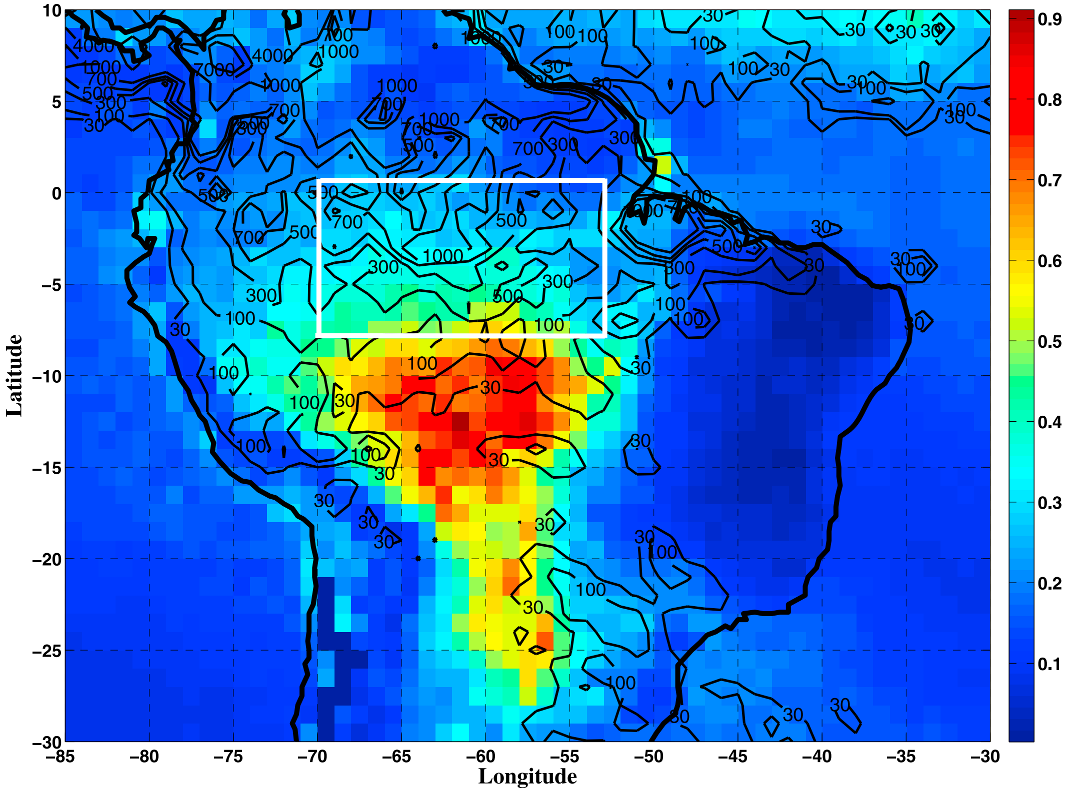

Figure 1. Mean aerosol optical depth at 550 nm (AOD) from the Aqua MODIS Level 3 aerosol product calculated for Jun–Aug 2007. The superimposed contours are the total lightning strokes counts for this period. The region of interest is marked on the figure by the white rectangle.

that the anomalies in positive lightning in May 1998 may have been partly caused by the exceptionally dry weather. *Williams et al.* [2002] who studied cloud electrification in the Amazon showed evidence for weaker than average clouds electrification for extreme polluted conditions in the early pre-monsoon period (October). They explained that the clouds in those conditions lack sufficient ice for charging processes in the mixed phase region at T > −20° (the most important part for charge separation; see extensive review by *Saunders* [2008]). The electrically active vertical zone is shifted to higher altitudes, reducing the charging rate, the electric field build-up and eventually the number of flashes.

[9] Biomass burning in the Amazon Basin [*Setzer and Pereira*, 1991] either from deforestation or from agricultural practices generates a smoke pall of variable density across millions of square kilometers, during the dry season between June and September. Half of the moisture for the cloud formation and precipitation in the Amazon is water vapor evaporated locally through plant evapotranspiration [*Salati*, 1987; *Xue et al.* 2006]. Hence, changing the moisture transport from the surface to the free atmosphere can change cloudiness significantly.

[10] In this study we examine the relationship between the thunderclouds structure (cloud top height and cloud fraction) and their electrical activity, and the effect of the released smoke on thunderstorm intensity, for the Amazon region during four dry (biomass burning) seasons (June–August of 2006–2009).

2. Data and Analysis

[11] We used the Very Low Frequency (VLF) global ground-based World-Wide Lightning Location Network (WWLLN) measurements of high peak current lightning strokes (see http://wwlln.net) [*Lay et al.*, 2007]. The network is based on the time of group arrival method for calculating the time and location of lightning strokes, detected by at least 5 out of its globally distributed sensors. The WWLLN has grown from 25 sensors in 2005 to 40 in 2009. The location accuracy and efficiency of the WWLLN change for different regions around the globe. *Rodger et al.* [2006] found a detection efficiency of ~4–6% of all strokes with peak current greater than ~30 kA for the Amazon region. These results indicate that the system is biased toward detecting the strongest lightning strokes. There is also a difference in the detection efficiency of the system for different years due to addition of new sensors as the network expands.

[12] Cloud and aerosol properties were taken from the measurements of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the afternoon (1:30 pm local time) sun-synchronous Aqua satellite [*Platnick et al.*, 2003; *Levy et al.*, 2007]. These data (1:30pm) are the best representation of the noon and afternoon convective activity.

[13] Our study area over the Amazon basin was bounded between latitudes 8°S–1°N and longitudes 70°W–53°W (see the rectangle in Figure 1) where stable subsidence driven meteorological conditions exist during the dry season [*Koren et al.*, 2004]. It is the transition region between the heavy smoke fires to the south, and the high convective activity to the north of this region. The mean AOD for the dry season

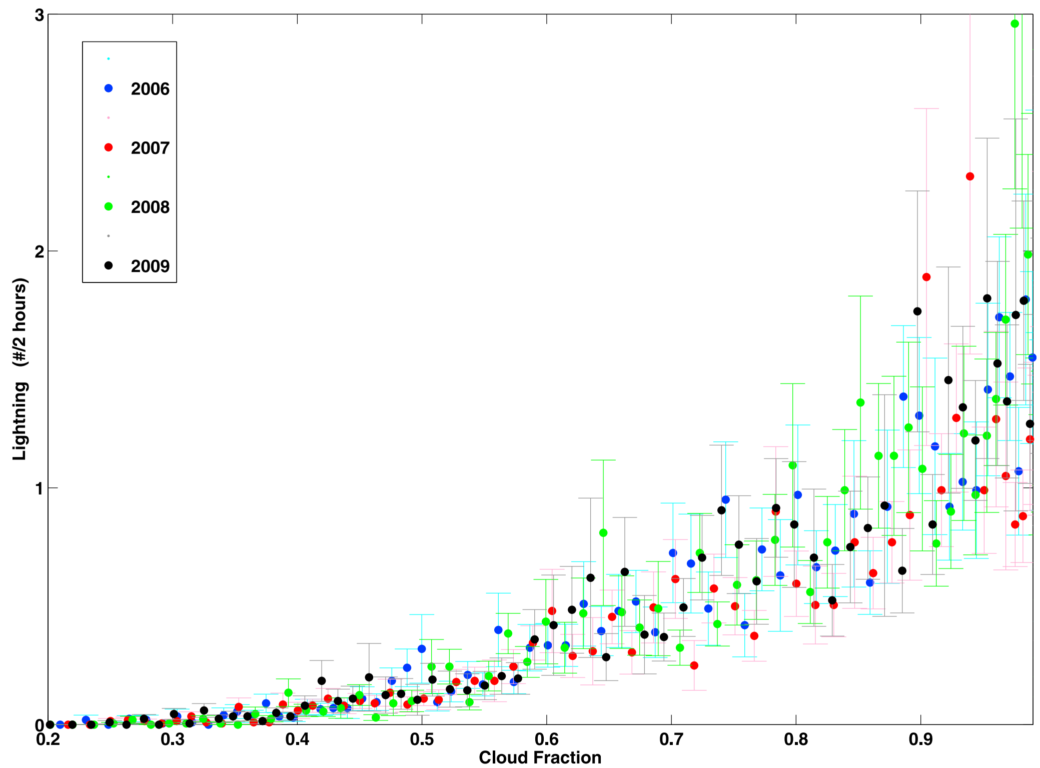

Figure 2. Relationship between number of lightning strokes between 12:30–14:30 local time (#/2 hours) and Cloud Fraction. 2006 data are marked in blue, 2007 in red, 2008 in green and 2009 in black.

months of 2007 (Jun–Aug) and the total lightning strokes count is presented in Figure 1.

[14] The measured data of cloud fraction (Cf), cloud top pressure (P) and AOD (at 550 nm) values were averaged into a 1-degree grid (MODIS algorithms, Level 3), that includes information on clouds and the surrounding aerosols (unless the grid box is completely overcast). The lightning data were collected into two datasets for two different time windows: two hours between 12:30–14:30 (local time), and ten hours between 12:00–22:00 (local time). The two different time windows were chosen based on the life time of the correlated parameters. A cloud system lifetime is around two hours, so the 13:30 local-time remotely-sensed clouds dimensions were chosen as a good measure for the properties of the clouds that generated the electrical activity during the shorter time window. Regarding aerosol loading, we assumed that the atmospheric aerosol loading changes more slowly than cloud system and the 13:30 local-time remotely-sensed AOD is a good measure for the afternoon and early evening conditions, during longer time of electrical activity.

[15] The datasets were gridded into 1-degree boxes. The lightning data were first sorted as a function of Cf, P or AOD and then every 200 points with similar Cf, P or AOD's were averaged to create the presented scatter plots (Figures 2–4). An estimation of the error was calculated from the standard deviation of each bin divided by the square root of the number of data points in the bin.

3. Results and Discussion

[16] First we examined the interdependence of thunderclouds dimensions, measured as cloud coverage (fraction) and cloud top pressure and electrical activity (number of lightning between 12:30–14:30 local time). Since a cloud system lifetime is around two hours, the 13:30 local-time remotely-sensed cloud dimensions were chosen as a good measure for the properties of the clouds that generated the electrical activity during that time. The results show (Figures 2 and 3) that clouds with higher tops or larger coverage produce more high peak current strokes (the WWLLN detects only strokes with peak current higher than ~30 kA). Despite the use of only a small fraction of the total flashes numbers and the big variance in the dataset the observed trend is similar for the 4 years of data. The more invigorated the cloud is, the higher the capability to produce high peak current strokes. This supports previous studies [*Ushio et al.*, 2001] that examined the relationship between cloud height and lightning activity by using data from the Tropical Rainfall Measuring Mission (TRMM) satellite. They found that flash rate increases as a power law with storm height. *Williams* [2001] also showed that high electrical activity must be associated with the presence of mixed-phase-hydrometeors together in the same region, and it requires the cloud to have deep vertical development. The cloud must extend to the −40°C isotherm and must contain an intense core updraft.

[17] Next the effect of the smoke on thundercloud electrical activity was investigated. The number of lightning strokes detected by the WWLLN was used as a measure for the clouds' convective intensity (based on the previous results shown in Figures 2 and 3). Since the atmospheric aerosol loading changes slowly, the 13:30 local-time remotely-sensed AOD was chosen as a good measure for the afternoon and early evening conditions, when the main lightning activity takes place [*Williams et al.*, 2002]. The

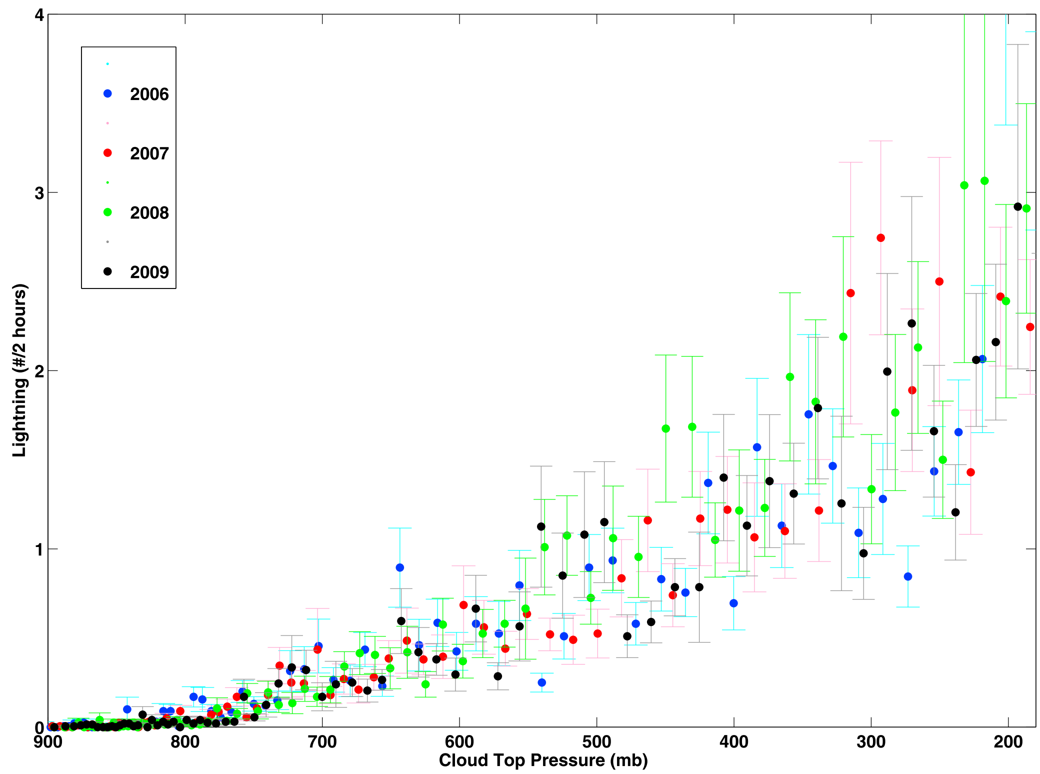

Figure 3. Relationship between number of lightning strokes between 12:30–14:30 local time (#/2 hours) and Cloud Top Pressure (mb). 2006 data are marked in blue, 2007 in red, 2008 in green and 2009 in black.

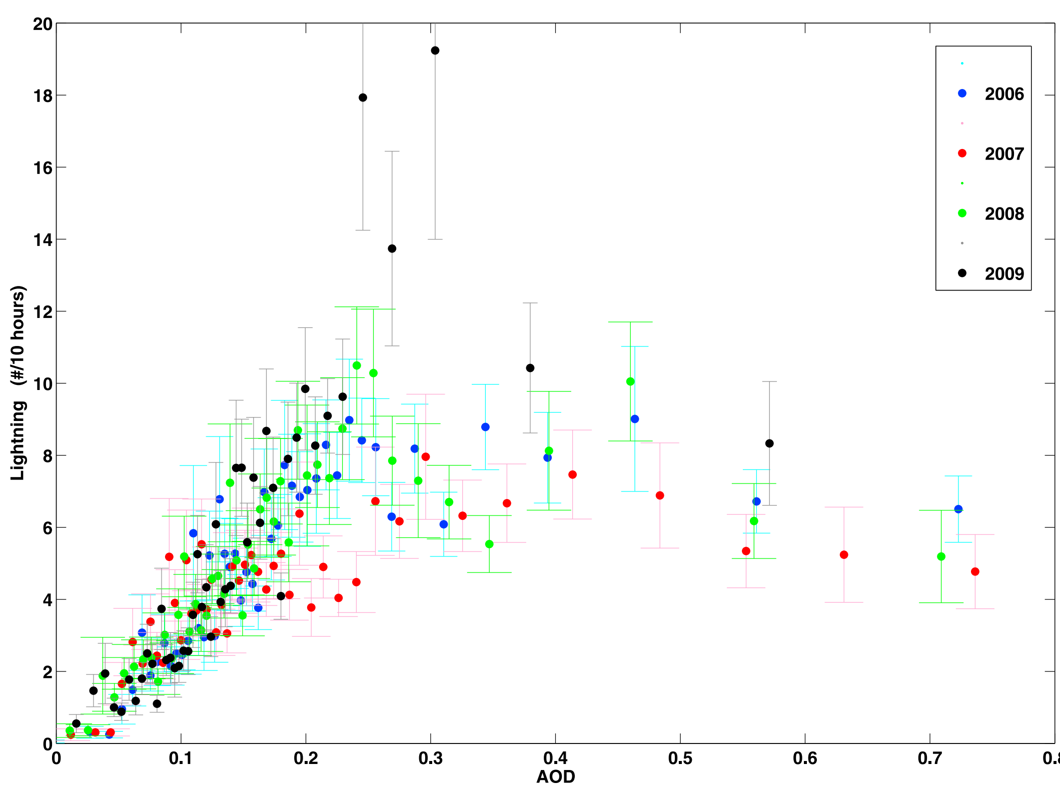

Figure 4. Relationship between number of lightning strokes between 12–22 local time (#/10 hours) and AOD. 2006 data are marked in blue, 2007 in red, 2008 in green and 2009 in black.

correlation between lightning number (between 12–22 local time) and measured AOD shows that there is a clear "boomerang trend" (Figure 4) similar to what was found by *Koren et al.* [2008]. The peak of the 2009 curve is higher, probably due to better detection efficiency of the system in this year (additional sensors). The trend is robust and consistent for all the years. For low values of AOD, the number of measured lightning strokes increases with increasing AOD, while for higher values of AOD the trend reverses and as the AOD increases the number of observed strokes decreases. The tipping point at AOD~0.25 is similar to what was found by *Koren et al.* [2008] for cloud fraction and cloud top pressure as a function of AOD. Since the WWLLN detects only the strokes with high peak currents, trends in the number of measured strokes can reflect changes in the total lightning amount or changes in the strokes power distribution. Either way this measure reflects the capability of the convective clouds to generate strong electric fields and lightning.

4. Summary

[18] The ground-based WWLLN lightning measurements together with Aqua-MODIS aerosol and cloud data were used to investigate relationships between cloud dimensions and their electrical activity and to study the complex effect of smoke aerosols on thunderclouds. The results show that there is a consistent trend between cloud dimensions and their electrical activity. Bigger clouds with higher cloud coverage or deeper vertical dimension produce more lightning strokes. Despite the detection of only a small fraction of the total flashes numbers and the big variance in the dataset the observed trends are similar for the 4 years of data. The number of produced lightning is a direct measure for the convective intensity of the cloud. Examination of the relation between aerosol loading and electrical activity showed that for low aerosol loading the increase in CCN concentration produces invigoration of the clouds and their electrical activity, while for higher values of aerosol loading the absorption effect takes over. The lower atmosphere becomes more stable and the surface fluxes are suppressed, inhibiting deep convective clouds and diminishing their potential for electrical activity.

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References

Andreae, M. O., D. Rosenfeld, P. Artaxo, A. A. Costa, G. P. Frank, K. M. Longo, and M. A. F. Silva-Dias (2004), Smoking rain clouds over the Amazon, *Science*, *303*, 1337–1342, doi:10.1126/science.1092779.

Davidi, A., I. Koren, and L. Remer (2009), Direct measurements of the effect of biomass burning over the Amazon on the atmospheric temperature profile, *Atmos. Chem. Phys.*, *9*, 8211–8221.

Deierling, W., and W. A. Petersen (2008), Total lightning activity as an indicator of updraft characteristics, *J. Geophys. Res.*, *113*, D16210, doi:10.1029/2007JD009598.

Deierling, W., W. Petersen, J. Latham, S. Ellis, and H. Christian (2008), The relationship between lightning activity and ice fluxes in thunderstorms, *J. Geophys. Res.*, *113*, D15210, doi:10.1029/2007JD009700.

Feingold, G., H. Jiang, and J. Y. Harrington (2005), On smoke suppression of clouds in Amazonia, *Geophys. Res. Lett.*, *32*, L02804, doi:10.1029/2004GL021369.

Fernandes, W. A., I. R. C. A. Pinto, O. Pinto Jr., K. M. Longo, and S. R. Freitas (2006), New findings about the influence of smoke from fires on the cloud-to-ground lightning characteristics in the Amazon region, *Geophys. Res. Lett.*, *33*, L20810, doi:10.1029/2006GL027744.

Hansen, J., M. Sato, and R. Ruedy (1997), Radiative forcing and climate response, *J. Geophys. Res.*, *102*, 6831–6834.

Kaufman, Y., and I. Koren (2006), Smoke and pollution aerosol effect on cloud cover, *Science*, *313*, 655–658, doi:10.1126/science.1126232.

Khain, A., D. Rosenfeld, and A. Pokrovsky (2005), Aerosol impact on the dynamics and microphysics of convective clouds, *Q. J. R. Meteorol. Soc.*, *131*, 2639–2663, doi:10.1256/qj.04.62.

Koren, I., Y. J. Kaufman, L. A. Remer, and J. V. Martins (2004), Measurement of the effect of Amazon smoke on inhibition of cloud formation, *Science*, *303*, 1342–1345, doi:10.1126/science.1089424.

Koren, I., J. V. Martins, L. A. Remer, and H. Afargan (2008), Smoke invigoration versus inhibition of clouds over the Amazon, *Science*, *321*, 946–949, doi:10.1126/science.1159185.

Lay, E. H., A. R. Jacobson, R. H. Holzworth, C. J. Rodger, and R. L. Dowden (2007), Local time variation in land/ocean lightning flash density as measured by the World Wide Lightning Location Network, *J. Geophys. Res.*, *112*, D13111, doi:10.1029/2006JD007944.

Levy, R. C., L. A. Remer, S. Mattoo, E. F. Vermote, and Y. J. Kaufman (2007), Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance, *J. Geophys. Res.*, *112*, D13211, doi:10.1029/2006JD007811.

Lyons, W. A., T. E. Nelson, E. R. Williams, J. A. Cramer, and T. R. Turner (1998), Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke from fires, *Science*, *282*(5386), 77, doi:10.1126/science.282.5386.77.

Murray, N. D., R. E. Orville, and G. R. Huffines (2000), Effect of pollution from Central American fires on cloud-to-ground lightning in May 1998, *Geophys. Res. Lett.*, *27*(15), 2249–2252, doi:10.1029/2000GL011656.

Platnick, S., M. D. King, S. A. Ackerman, W. P. Menzel, B. A. Baum, J. C. Riedi, and R. A. Frey (2003), The MODIS cloud products: Algorithms and examples from Terra, *IEEE Trans. Geosci. Remote Sens.*, *41*, 459–473, doi:10.1109/TGRS.2002.808301.

Price, C., and D. Rind (1992), A simple lightning parameterization for calculating global lightning distributions, *J. Geophys. Res.*, *97*, 9919–9933, doi:10.1029/92JD00719.

Rodger, C. J., S. Werner, J. B. Brundell, E. H. Lay, N. R. Thomson, R. H. Holzworth, and R. L. Dowden (2006), Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study, *Ann. Geophys.*, *24*, 3197–3214.

Rosenfeld, D., M. Fromm, J. Trentmann, G. Luderer, M. O. Andreae, and R. Servranckx (2007), The Chisholm firestorm: Observed microstructure, precipitation and lightning activity of a pyro-Cb, *Atmos. Chem. Phys.*, *6*, 9877–9906.

Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. O. Andreae (2008), Flood or drought: How do aerosols affect precipitation?, *Science*, *321*, 1309–1313, doi:10.1126/science.1160606.

Salati, E. (1987), The forest and the hydrological cycle, in *The Geophysiology of Amazonia*, edited by R. E. Dickinson, pp. 273–296, Wiley, New York.

Saunders, C. P. R. (2008), Charge separation mechanisms in clouds, *Space Sci. Rev.*, *137*, 335–353, doi:10.1007/s11214-008-9345-0.

Saunders, C. P. R., W. D. Keith, and R. P. Mitzeva (1991), The effect of liquid water on thunderstorm charging, *J. Geophys. Res.*, *96*, 11,007–11,017, doi:10.1029/91JD00970.

Setzer, A. W., and M. C. Pereira (1991), Operational detection of fires in Brazil with NOAA/AVHRR, paper presented at 24th International Symposium on Remote Sensing of the Environment, Environ. Res. Inst. of Mich., Rio de Janeiro, Brazil.

Smith, A. J., M. Baker, and J. A. Weinman (2003), Do forest fires affect lightning? *Q. J. R. Meteorol. Soc.*, *129*(593), 2651–2670, doi:10.1256/qj.02.175.

Takahashi, T. (1978), Riming electrification as a charge generation mechanism in thunderstorms, *J. Atmos. Sci.*, *35*, 1536–1548, doi:10.1175/1520-0469(1978)035<1536:REAACG>2.0.CO;2.

Twomey, S. (1977), Influence of pollution on the short-wave albedo of clouds, *J. Atmos. Sci.*, *34*, 1149–1152, doi:10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2.

Ushio, T., S. J. Heckman, D. J. Boccippio, H. J. Christian, and Z.-I. Kawasaki (2001), A survey of thunderstorm flash rates compared to cloud top height using TRMM satellite data, *J. Geophys. Res.*, *106*, 24,089–24,095, doi:10.1029/2001JD900233.

van den Heever, S. C., G. G. Carrio, W. R. Cotton, P. J. DeMott, and A. J. Prenni (2006), Impacts of nucleating aerosol on Florida convection. Part I: Mesoscale Simulations, *J. Atmos. Sci.*, *63*, 1752–1775, doi:10.1175/JAS3713.1.

Williams, E. R. (2001), The electrification of severe storms, in *C.A. Doswell, III*, edited by S. C. Storms, pp. 527–561, Am. Meteorol. Soc., Washington, D. C.
Williams, E., et al. (2002), Contrasting convective regimes over the Amazon: Implications for cloud electrification, *J. Geophys. Res.*, *107* (D20), 8082, doi:10.1029/2001JD000380.
Xue, Y., F. de Sales, W. P. Li, C. R. Mechoso, C. A. Nobre, and H. M. Juang (2006), Role of land surface processes in South American Monsoon development, *J. Clim.*, *19*, 741–762, doi:10.1175/JCLI3667.1.
Yoshida, S., T. Morimoto, T. Ushio, and Z. Kawasaki (2009), A fifth-power relationship for lightning activity from Tropical Rainfall Measuring Mission satellite observations, *J. Geophys. Res.*, *114*, D09104, doi:10.1029/2008JD010370.

O. Altaratz and I. Koren, Department of Environmental Sciences, Weizmann Institute, Rehovot 76100, Israel. (orit.altaratz@weizmann.ac.il)
C. Price, Department of Geophysics and Planetary Science, Tel Aviv University, Ramat Aviv 69978, Israel.
Y. Yair, Department of Life and Natural Sciences, Open University, Ra'anana 43107, Israel.