Do aerosols affect lightning?: A global study of a relation between aerosol optical depth and cloud to ground lightning

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ABSTRACT: The effects of aerosol particles on precipitation have been studied for several decades and it was shown that aerosols can either increase or decrease precipitation, depending on local thermodynamical, dynamical and microphysical conditions. The effect of aerosol particles on the electrification of storms and lightning production is less known; however, since precipitation and lightning in deep convective clouds are generated by the same physical processes, it can be expected that aerosol particles would also influence lightning. Recent local analyses of several regions of the earth indicate that the aerosol optical depth (AOD) is positively correlated with lightning density. Here, we explore this relationship globally for the four seasons of the year 2012. We use AOD data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite. Cloud to ground lightning events (those with the strongest peak currents) were recorded by the World Wide Lightning Location Network (WWLLN); the flashes were summed between 12:00 and 18:00 local time. The relation between lightning and AOD was studied separately for several ranges of the convective available potential energy (CAPE) and the vertical velocity in pressure coordinates (ω). The CAPE and ω values were provided by NCEP Climate Forecast System.

We show that over most of the continents the increase in AOD is related to an increase in lightning density for all the seasons. There are some large regions of the planet (Amazonian forest, southern Africa, Mexico, USA, northern Australia, Europe) where this correlation is evident. For these regions up to 500% more lightning flashes were registered on moderately polluted days compared to clean days. Also some coastal oceanic regions exhibit high correlations between both variables. The data over the oceanic regions located far away from the coastlines are scarce and no clear relationship between AOD and lightning is observed.

A possible reason for the observed correlation between AOD and lightning densities could be meteorological conditions that can influence both variables in a similar way (such as instability conditions). However, the analysis of the correlation between lightning and AOD for different CAPE and ω ranges indicates that, independently of instability conditions, there are more lightning flashes registered on polluted days than on clean days. These results point toward a positive influence of aerosol loading on lightning production for moderately polluted atmosphere.

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INTRODUCTION

Charge separation in clouds occurs during collisions between graupel and ice particles in the presence of supercooled droplets (Takahashi et al. 1978; Jayaratne and Saunders 1983; Saunders 2008). The complete set of parameters that determine charge amount and sign after each collision is unknown; the laboratory experiments show that temperature, cloud water content and droplet size distribution can influence the magnitude of the separated charge (Saunders 2008; Avila et al. 1999). The dispersion of results produced by different laboratory studies on cloud electrification shows that this process could be affected by a large number of parameters.

As the lightning flashes are the direct consequence of the electric field build-up during collisions of cloud hydrometeors; it can be expected that microphysical properties of these hydrometeors would affect the resulting electrical activity. For example, an increase in the number of colliding particles or a change in their size distribution would lead to a different number of collisions, different amount of separated charge and due to that to a different electric field. The main changing mechanism involves ice crystals and graupel, therefore, a correlation between ice amount and lightning can be expected. Petersen et al. (2005) showed that such a correlation exists on a global level. Also, models of lightning production that are based on ice content show a good agreement between simulations and observations (Yair et al. 2010).

Cloud droplets and ice particles formation depends on the amount of aerosol particles and their properties, as they serve as cloud condensation nuclei and ice nuclei (one exception is homogenous ice nucleation which occurs in the temperatures below -40°C). Relations between clouds, precipitation and aerosol particles have been studied for decades and it was shown that, for certain conditions, aerosols can influence clouds and precipitation (Rosenfeld et al. 2008; Koren et al. 2012). The magnitude of this influence however, is still an open question.

The same physical processes generate precipitation and lightning in deep convective clouds and recent local studies indicate that lightning is correlated with aerosol optical depth (Altaratz et al. 2010; Yuan et al. 2011). In this study we explore this relation on a global level.

METHODOLOGY

The relationship between lightning and AOD is studied globally for the year 2012. We use AOD data registered by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite at about 13:30, local time. Two AOD regimes were defined: a moderately polluted regime with AOD between 0.2 and 0.4 and a clean regime with AOD less than 0.14. The AOD regimes were determined in order to obtain a similar average number of lightning data in a mean grid square within each regime.

Cloud to ground lightning events (those with the strongest peak currents) were recorded by the World Wide Lightning Location Network; the flashes were summed between 12:00 pm and 18:00 (local time), which is a time range that includes the time of over-flight of the Aqua satellite.

In order to separate microphysical and meteorological effects, the relations between lightning, AOD, CAPE and vertical velocity in pressure coordinates (ω) were studied. The CAPE and ω data were provided by NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly products. For each longitude, CAPE and ω value within the time range between 12:00 pm and 18:00 was used. Since no clear global relation was observed either between lightning and CAPE, or between lightning and omega, the relationships were evaluated for selected regions of the globe and some detailed additional results for the

Amazon rainforest are shown here. The AOD regimes were redefined in order to have a similar number of data points in each regime for this specific location.

RESULTS AND DISCUSSION

First, global results for the whole year 2012 are discussed; then, global results for each season of the year 2012 are shown, and finally the results for the Amazon rainforest calculated for the period between September and November are addressed.

The difference between average lightning registered on polluted and clean days was calculated for the whole planet on a grid with the resolution of 3x3 degrees. Figure 1 presents the results for the grid squares where lightning was registered on a minimum of 10 days, between 12:00 and 18:00 of local time, for each AOD regime. White grid squares have insufficient data points for the calculation.

Note that 78% of all grid squares with valid data present more lightning registered on moderately polluted days than on clean days. Very large areas of South, Central and North America, Southern Africa, Europe, Indonesia and Northern Australia show positive difference between lightning recorded on polluted and clean days. Oceanic coastal regions (e.g. Eastern Pacific, Western Atlantic, Gulf of Mexico) also show a positive correlation between lightning and AOD; however, such a correlation is not observed for oceanic regions located away from the coastlines.

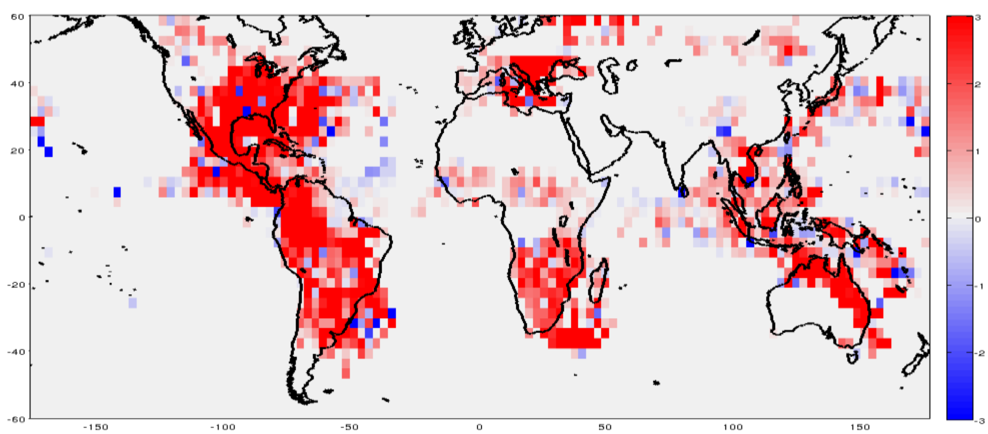

Fig.1. Difference between lightning observed on polluted (0.2<AOD<0.4) days and clean (0<AOD<0.14) days [flashes/deg^2/hr]. Lightning flashes, registered by the WWLLN, were summed between 12:00 and 18:00 (local time). AOD data were registered by MODIS on Aqua satellite at about 13:30pm (local time).

Figure 2 presents the average change (in percentage) between lightning amount registered on polluted and clean days (100% * Lightning $_{polluted}$ / Lightning $_{clean}$), calculated for each grid square separately. There is a very significant increase of lightning counts for moderately polluted days, as compared to clean days. For large regions in the Americas, Europe and Australia the change reaches 500%. Also over oceanic coastal regions, lightning registered on polluted days is several times greater than on clean days.

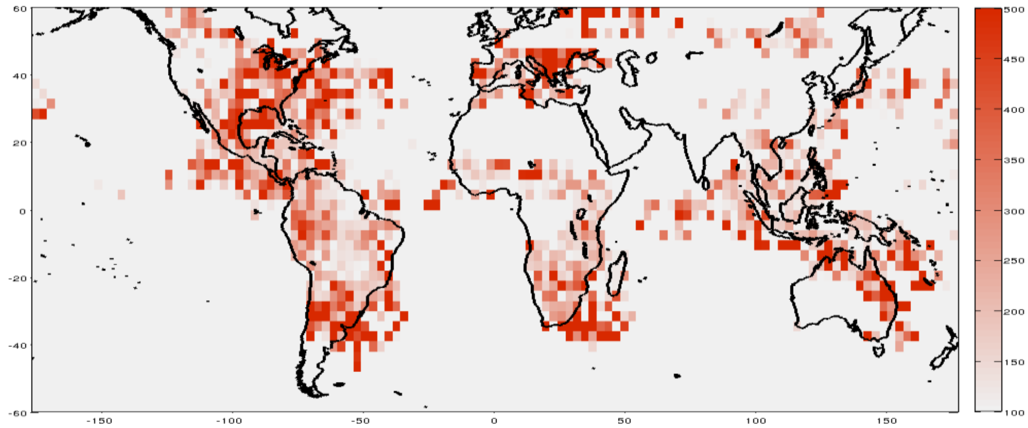

Fig. 2. Percentage of lightning observed on polluted (0.2<AOD<0.4) days with respect to clean days (0<AOD<0.14). MODIS and WWLLN data processed as in Fig. 1.

Figure 3 shows the histogram of the differences between flash densities registered on polluted and clean days over the Tropics (latitudes: 23°S to 23°N). Positive difference is observed for 77% of grid squares. Negative difference corresponds basically to oceanic regions located far away from coastlines, as shown in Figure 1.

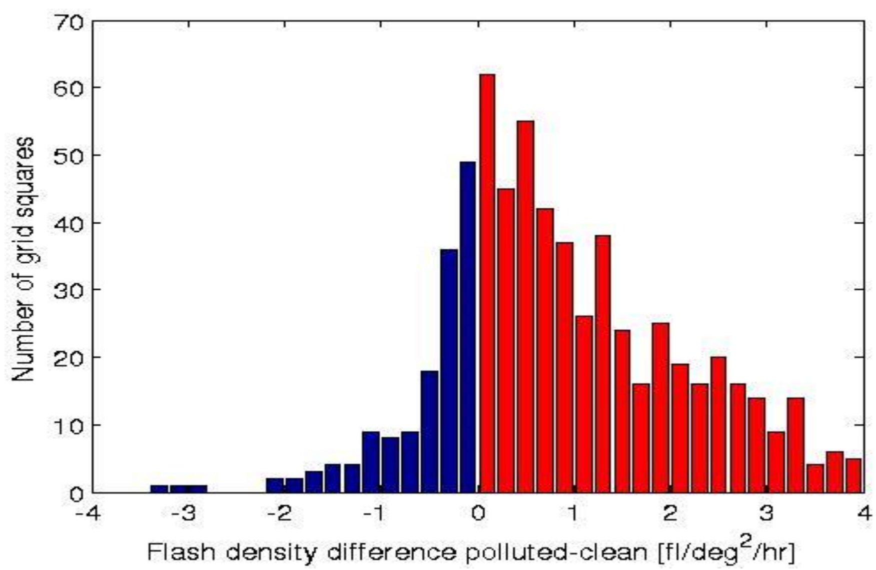

Fig. 3. Histogram of the difference between flash densities registered on clean and polluted days for the Tropics.

Figure 4 shows the differences in lightning density that were measured on polluted and clean days separately for the four seasons of 2012. Independently of the meteorological conditions that are typical for each season (in the northern and southern hemispheres), in general more lightning flashes are registered in moderately polluted atmosphere than in clean air.

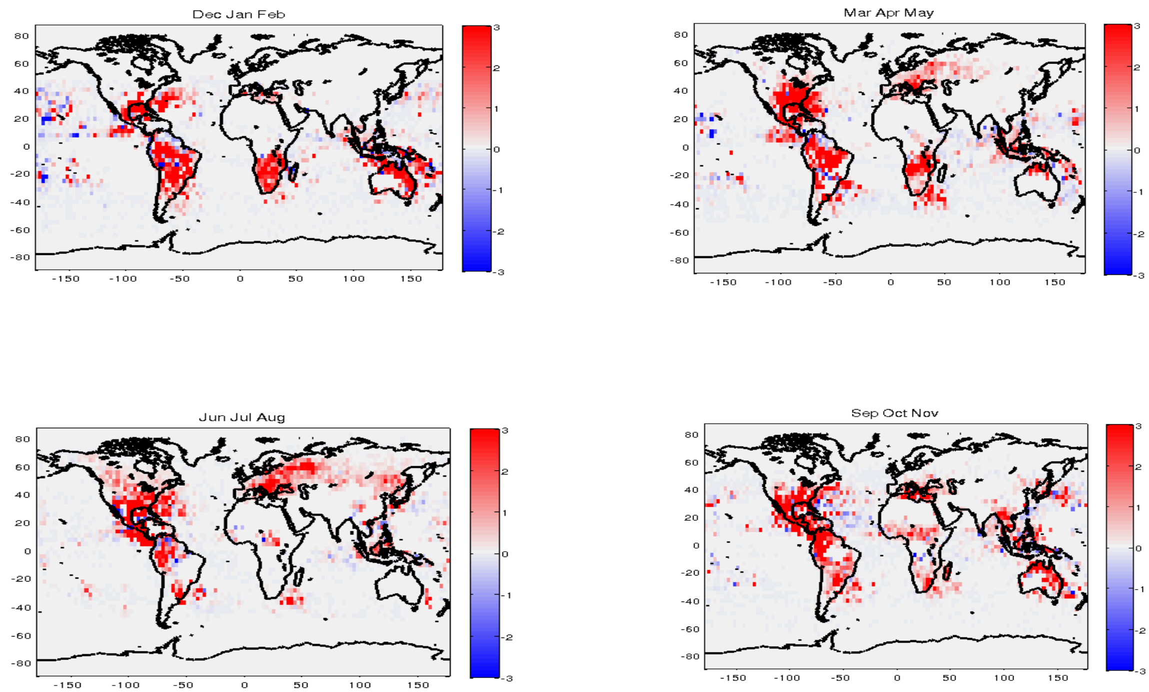

Fig. 4. Difference between lightning observed on polluted (0.2<AOD<0.4) and clean (0<AOD<0.14) days for the four seasons of 2012 [flashes/deg^2/hr]. MODIS and WWLLN data processed as in Fig. 1.

The above results clearly show that there is a correlation between lightning density and AOD for most of the continental regions of the earth. This correlation indicates that lightning production could be influenced by a change in aerosol particles loading. However another possible explanation is that the meteorological (instability) conditions increase both AOD and lightning density. In order to check this hypothesis and to separate these two effects (microphysics and meteorology) the relation between AOD and lightning was explored for different ranges of CAPE and vertical velocity (ω). The calculations were done with finer resolution (1x1 degree) for several oceanic and continental regions. AOD regimes were redefined for each specific region in order to obtain a similar number of lightning data in each AOD category. Over the oceans, no relation between lightning and CAPE was found; over the continental regions the two variables are slightly correlated. Koren et al. (2012) observed that precipitation is strongly correlated with vertical velocity (ω) at 400 hPa. We also analyze the correlation between lightning and ω_{400hPa}; the two variables seem to be correlated for oceans and continents but the magnitude of the correlation depends on the specific local conditions.

Figure 5 presents the relation between lightning density, AOD and CAPE for one of the regions studied: Amazon rainforest during the period from September to November (the transition season before the rains are established, when the biomass burning takes place). Mean flash density was calculated for polluted and clean atmosphere for CAPE ranges between 0 and 4000 J/kg, at intervals of 500 J/kg. Flash density increases with CAPE, but it is always higher for polluted air than for clean one, with the exception of the lowest CAPE conditions. High standard deviations reflect the uncertainties of AOD and lightning measurements and CAPE calculations, but also are related to the complexity of the lightning phenomenon, which is a function of many meteorological parameters.

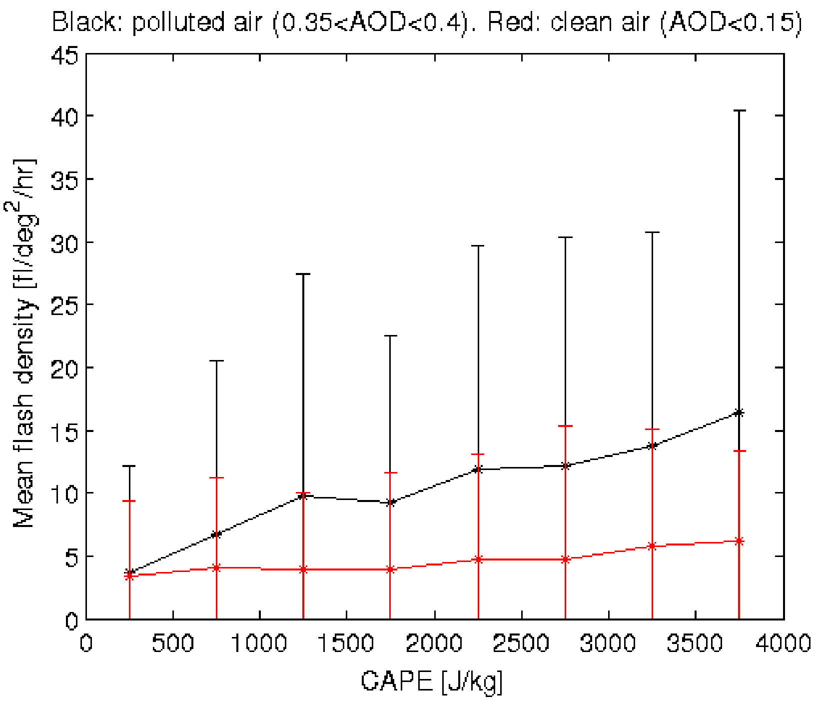

Fig. 5. Relation between lightning density and CAPE for polluted (black) and clean (red) atmosphere for Amazon forest.

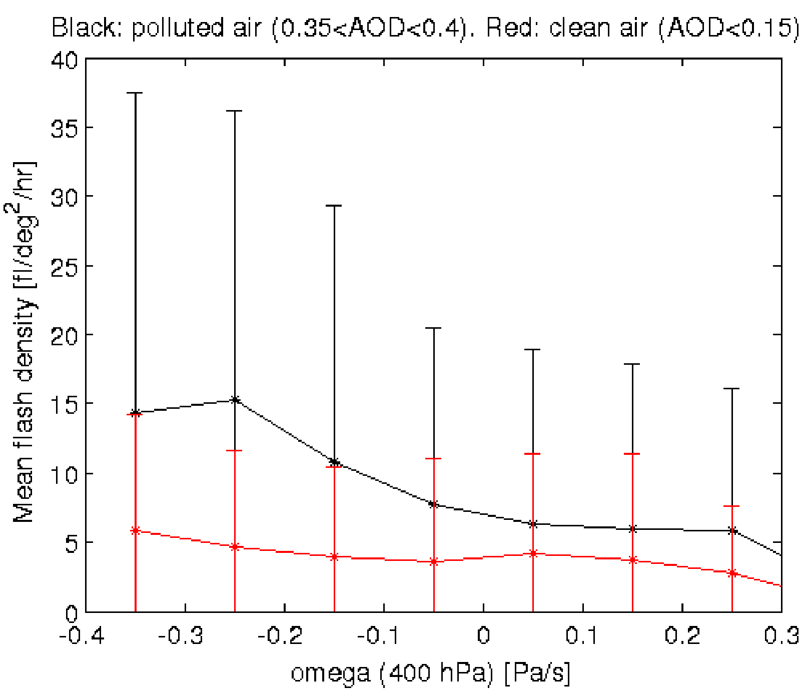

Fig. 6. Relation between lightning density and ω_{400hPa} for polluted (black) and clean (red) atmosphere for Amazon forest.

Figure 6 presents the relation between lightning density, AOD and ω_{400hPa} for the Amazon rainforest during the period from September to November. Mean flash density was calculated for polluted and clean conditions and for ω_{400hPa} ranges between -0.4 Pa/s and 0.3 Pa/s at intervals of 0.1 Pa/s. Negative ω values indicate net upward air motion. Lower negative values usually lead to deeper clouds, whereas positive ω values correspond to subsidence and shallower clouds. As expected, the highest flash densities occur for the lowest ω values; however the AOD effect seems to be independent of ω, since higher lightning densities appear in the polluted atmosphere within the whole ω range.

CONCLUSIONS

The results of this study show that lightning is related to the aerosol loading (measured by AOD) for large continental and coastal regions of the earth. Many regions exhibit mean lightning density higher by 500% during moderately polluted days (0.2<AOD<0.4) than during clean days (0<AOD<0.14). A positive correlation between flash density and AOD is observed for all seasons and for a wide range of CAPE and vertical velocity conditions. These results indicate that aerosol particles are among the factors that affect the electrical activity of thunderstorms.

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