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# Lightning activity and aerosols in the Mediterranean region

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ABSTRACT

In the framework of this study, the effect of aerosols on lightning activity has been investigated for the first time over the broader Mediterranean Sea. Atmospheric optical depth data retrieved by MODIS on board Aqua satellite and cloud to ground lightning activity data provided by ZEUS network operated by the National Observatory of Athens were analyzed for a time period spanning from 01/01/2005 up to 31/12/2013. The results indicate the importance of aerosols in lightning modulation. The mean aerosol optical depth (AOD) values of the days with lightning activity were found to be higher than the mean seasonal AOD in 90% of the under study domain. Furthermore, the increasing rate of lightning activity with increasing aerosol loading was found to be more pronounced during summertime and for AOD values up to 0.4. Additionally, the spatial analysis showed that the percentage of days with lightning activity during summertime is increasing with increasing AOD. Finally, time series showed similar temporal behavior between AOD seasonal anomalies and days with lightning activity differences. Both the spatial and temporal analysis showed that lightning activity is correlated to AOD, a characteristic consistent for all seasons.



## 1. Introduction

Lightning activity has received attention globally over the past few decades due to the link with severe incidents. Lightning activity is not only directly but also indirectly associated with livestock and human injuries and deaths. Furthermore, forest fires, electrical, and communication system breakdowns, and damage to human property have impact to people as individuals and to societies as a whole. Environmental interest is also present, as lightning activity is closely related to tropospheric ozone and convective precipitation.

Westcott (1995) was the first to investigate the connection between urban areas and lightning strikes frequency. The analysis of lightning data recorded by the National Lightning Detection Network (NLDN) from 1989 to 1992 for sixteen United States metropolitan cities showed enhancement of lightning activity over and downwind for most urban areas. The concluding suggestion that the spatial change of lightning activity is associated not only with topographic features and meteorological effects but also with anthropogenic emissions raised many questions and led to numerous studies. Westcott's suggestion regarding the effect of anthropogenic emissions on lightning activity was extended by a study performed by Murray et al. (2000), who reported on the influence of natural aerosols on lightning occurrence. The authors noticed that increased concentrations of aerosols advected into the atmosphere during 1998, due to biomass burning in Central America, led to anomalous higher lightning activity over the central United States. The diurnal and seasonal cycle of lightning activity was additionally studied by Orville et al. (2001) by using NLDN data over Houston from 1989 to 2000. Furthermore, mechanisms responsible for the enhanced lightning activity were identified as the unique regional geographical features (coastline), the heat island over Houston, and the increased level of aerosol concentration due to anthropogenic activity, although a separation of the effects was not possible. In order to decouple the aforementioned topographical and meteorological effects from the aerosol effect on lightning, Steiger and Orville (2003) studied the unique case of Southern Louisiana. The results indicated a clear relationship between major pollutant areas and increased lightning activity.

Meanwhile, technological advances and upgrades of lighting detection systems allowed scientific groups originating from different countries to study the spatial and temporal distribution of lightning activity. Holt et al. (2001) studied the strong seasonal, spatial, and temporal trends of lightning activity over Europe and the United Kingdom by utilizing the Arrival Time Difference (ATDnet) lightning detection system. Defer et al. (2005) investigated the lightning activity distribution over the eastern Mediterranean during the cold period of the year focusing on lightning multiplicity and duration while Katsanos et al. (2007) studied the spatial and temporal distribution of lightning in the central and eastern Mediterranean, with emphasis on the relationship

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of lightning activity with precipitation. Soriano et al. (2001), on the contrary, investigated the cloud electrical activity over the Iberian Peninsula for the warm seasons between 1992 and 1994 and highlighted the strong spatial correlation between convective precipitation and cloud to ground lightning activity. Kotroni and Lagouvardos (2008) who investigated the relation of lightning activity with terrain height, slope, and vegetation in the Mediterranean area, found among other results, a positive relationship of lightning activity with elevation during spring and summer and with the elevation slope throughout the year except winter. A study performed by Soriano and Pablo (2002) investigated the urban effect of nine small Spanish towns on lightning activity and reported statistically significant lightning activity enhancement over and downwind of most study areas. Furthermore, positive correlation between both the population number and the anthropogenic emissions with lightning percent change was found.

Consistent with the existing literature were also studies concerning Southern America. Farias et al. (2009), Naccarato et al. (2003), and Pinto et al. (2004) focused on large metropolitan urban areas of Brazil (Sao Paulo, Campinas, Sao Jose, Belo Horizonte) and confirmed the enhancement of lightning strikes density over the urban areas when compared to the suburban and surrounding areas. Similar were the results obtained by Kar et al. (2009) by investigating the effect of increased aerosol concentration on the percentage change of lightning activity over five South Korean metropolitan cities.

During the past decade, satellites dedicated to environmental research gradually allowed measurements of numerous atmospheric quantities, including aerosol concentration, with higher spatial coverage. Altaratz et al. (2010) have investigated the connection between lightning activity and different atmospheric quantities, including among others aerosol optical depth (AOD) values retrieved by the moderate resolution imaging spectroradiometer (MODIS) onboard Aqua satellite, for the dry seasons between 2006 and 2009 and over the central Brazil–Amazon. Daily averaged AOD values and lightning obtained from MODIS–Aqua, MODIS–Terra, and the Tropical Rainfall Measuring Mission satellite were additionally used by Lal and Pawar (2011) and Yuan et al. (2011) in order to investigate the total lightning activity for the time period between 2001 and 2008 over Bangalore and between 2000 and 2008 over the tropical ocean, respectively. The results indicated that lightning enhancement is closely related to aerosol loading. Wang et al. (2011) have investigated the relationship between aerosol and lightning activity, over the Perl River Delta metropolitan region in China for the period between 2000 and 2006. Annual AOD mean values retrieved by MODIS and cloud to ground lightning strikes density over the study region showed similarly geographical distribution with higher values encountered over the Guangdong metropolitan city. More recently, Kucienska et al. (2014) investigated the relation between lightning activity and AOD, for different AOD categories between 60°S and 60°N latitudes. The results indicated an increase in lightning activity with increasing AOD. The correlation was stronger over the Western Atlantic, central Africa, central Europe, and Northeast Asia and the Amazon regions.

Khain et al. (2008) studied the possible effect of aerosols on lightning activity density by combining the Weather Research and Forecasting (WRF) model and the Hebrew University Cloud Model (HUCM) for typical tropical cyclone atmospheric conditions. The results showed that the increasing continental aerosol concentration creates more favorable conditions for lighting activity over the cyclone periphery. Further investigations on aerosols and tropical cyclone interactions (Khain et al., 2010; Rosenfeld et al., 2012) have strengthen the hypothesis that an increase in continental aerosol concentration is related to lightning activity intensification. Furthermore, Mansell and Ziegler (2013) have studied lightning activity with respect to aerosol concentration variations and documented that while lightning activity intensifies with increasing in aerosol concentrations (up to 2000 $cm^{-3}$), further increase in aerosol concentration leads to the decrease of lightning activity. Additionally, Gryspeerdt et al. (2014) studied the relation between the aerosol index retrieved by MODIS–Aqua AOD and the TRMM lightning imaging sensor (LIS) data for the period 2005–2007 and for the geographical region between 30°S and 30°N. The authors documented on the increased lightning rate of high aerosol index population areas compared to low aerosol index population cases, especially over land. Finally, Zhao et al. (2015) used the WRF model in order to study lightning activity fluctuations with respect to polluted and clean aerosol atmosphere cases. Their results, consistent with previous investigations, showed that under similar meteorological backgrounds, increasing in aerosol concentration leads to enhancement of lightning activity.

As reported, several studies based on land and satellite instrumentation have reported the connection between aerosols and lightning activity. However, no such study has been conducted for the broader area of the Mediterranean basin. Over the Mediterranean Sea, a region that is surrounded by the Sahara desert on the south and the highly populated and industrialized Europe on the north, both natural and anthropogenic aerosol coexist. Basart et al. (2009), based on the Aerosol Robotic Network (AERONET) observations for the period between 1994 and 2007, have reported on the aerosol characterization in the Mediterranean region. The study indicated that although the composition of the atmosphere over the Mediterranean region is geographically dependent, the aerosol concentration is mainly characterized by continental, both of natural (biogenic, mineral, biomass burning) and of anthropogenic (urban and industrial fine particles) origin aerosols, superimposed by maritime and coarse African dust particles. On local terms, De Meij et al. (2012) have reported on the trends of $SO_2$, black carbon (BC), $NO_x$, and $NH_3$, which are among the major pollution aerosol type emissions on the central Mediterranean region, for the time period between 2000 and 2010. Additionally, according to Boselli et al. (2012), Saharan dust transport, continental air masses from northeast/northwest and maritime westerly air masses dominate the long distance aerosol transport over the central Mediterranean region. Regarding the strong and extreme aerosol events, Gkikas et al. (2009) have studied the seasonal variation of the columnar light extinction due to aerosols (AOD) at 550 nm over the broader Mediterranean region for the period 2000–2007 based on MODIS–Terra observations. They have reported that strong events are more frequent in the western Mediterranean and during summer, whereas extreme events (AOD up to 5.0), related to Saharan dust outbreaks, are occurring mainly during spring in the central and eastern Mediterranean region. Due to wet deposition, extreme aerosol events were reported to be rare during winter. Furthermore, a south-to-north gradient on decreasing AOD is observed while the distance from the African continent is increasing.

The purpose of the present research is to investigate lightning characteristics with respect to aerosol loading over the broader Mediterranean Sea by utilizing data provided by ZEUS lightning detection system and satellite instrumentation.

## 2. Data and methodology

AOD values at 550 nm were retrieved by the moderate resolution imaging spectroradiometer (MODIS) onboard the afternoon sun-synchronous Aqua satellite, at about 13:30 local time. The high accuracy of MODIS/Aqua AOD values has been established, against ground measurements, globally (Levy et al., 2010). Over sea surfaces, the accuracy of AOD ($\pm 0.03 \pm 0.05$*AOD) is higher than the corresponding over vegetated land ($\pm 0.05 \pm 0.2$*AOD) (Remer et al., 2005). The Aqua/MODIS atmospheric product is provided at different processing levels describing their spatial and temporal resolutions both for aerosols and clouds. The aerosol optical properties, in Level 2 data, are provided at a nominal resolution of 10 km × 10 km (at nadir). The Level 2 measurements, referring to a 5-min interval of the satellite overpass, are summarized to Level 3 data, which are provided at regular latitude/longitude grid with spatial resolution 1° × 1° on a daily basis. In the framework of this study, Aqua's level 3 AOD data were used.