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Lightning in the Mediterranean and its relation with sea-surface temperature

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Abstract
Here we present the analysis of lightning activity over the Mediterranean, based on a 10 year long dataset (2005–2014) provided by the ZEUS long-range lightning detection system. The major hot-spots of lightning activity are identified, with a clear predominance during the warm period of the year over land in the vicinity of the major topographic features of the area. Special emphasis is also given on the discussion of the seasonal distribution of lightning. In addition, we investigate the relationship of lightning with sea-surface temperature, obtained by high-resolution satellite measurements and we conclude that the number of lightning strokes is positively correlated with the sea-surface temperature during autumn when also the maximum lightning activity over the sea is depicted. We suggest that higher sea surface temperature further destabilises the lower tropospheric layers, enhancing thus convection and therefore lightning.

Introduction
Lightning has received a lot of attention in the scientific literature, since it may cause loss of life, forest fire ignition, damages to agriculture, electric power networks, buildings, electronic infrastructure etc. Ashley and Gilson (2009) have reported approximately 5000 deaths due to lightning in the United States during the past 50 years, while Papagiannaki et al (2013) reported 20 deaths from lightning strokes from 2001 up to 2011 in Greece. The Mediterranean Sea consists one of the major centres of electrical activity during the Northern Hemisphere winter (Christian et al 2003). A number of studies discussing the spatiotemporal distribution of lightning in the Mediterranean area (Holt et al 2001, Katsanos et al 2007, Anderson and Klugmann 2014, Cecil et al 2014) showed the predominance of lightning activity over the sea during winter and over the land during spring and summer.

The continuous monitoring of lightning is of paramount importance for the delineation of convective areas within weather systems-ranging from hurricanes (Price et al 2009), frontal and mesoscale convective systems to local thunderstorms-that are associated with severe phenomena (heavy precipitation, hail, strong winds, etc). Nowadays, ground based lightning detection systems are capable of monitoring the lightning activity at great distances, even at global scale, helping thus to construct reliable databases of lightning over a major part of the globe (Lay et al 2007, Anderson and Klugmann 2014). Recently Mezuman et al (2014) used such a global database from the world wide lightning location network to determine the spatial and temporal distribution of global thunderstorm cells. Lightning detectors onboard low-orbiting satellites also allow observation of lightning activity, but nowadays their measurements suffer from low temporal coverage, since each part of the globe is sensed only for a few minutes per day (Cecil et al 2014).

Many studies have been devoted to the study of the relation of lightning with underlying physiographic characteristics (Soriano et al 2005, Kotroni and Lagouvardos 2008, Mazarakis et al 2008, Goswami et al 2010, Galanaki et al 2015) and found the dependence of lightning with orography but most importantly with steep topographic gradients, that favour further uplift of unstable air masses. A number of studies have been also devoted to the investigation of the atmospheric factors controlling lightning activity and many
authors highlighted a high correlation of lightning activity with the convective available potential energy (Mazarakis et al 2008, Ziv et al 2009, Goswami et al 2010, Pawar et al 2012, Galanakis et al 2015).

Although the sea surface temperature (SST) is a crucial parameter implicated in the air-sea interaction and strongly related to instability, little work has been done to investigate the possible relationship of lightning with SST. Among these studies Laing et al (2000) tried to determine if the ENSO cycle influences lightning activity along the Gulf Coast region and found that lightning increases during La Niña summers. Further in another area of the planet, Tinnmaker et al (2008) found that SST over the Arabian Sea and the Bay of Bengal plays a crucial role on the development of thunderstorms and lightning over the adjoining Peninsular India. Indeed the authors reported a correlation coefficient of 0.847 and 0.922 between the lightning flash count over Peninsular India and SST over the Arabian Sea and the Bay of Bengal respectively.

ZEUS is a European-wide lightning detection system that uses very-low frequency electromagnetic sensors on the ground (Kotroni and Lagouvardos 2008, Lagouvardos et al 2009). The network is operational since 2005, monitoring cloud-to-ground lightning activity over the major part of Europe, the Mediterranean Sea and Northern Africa. Based on the 10 year long database of ZEUS (2005–2014) a climatological analysis of the distribution of lightning activity was performed over the Mediterranean with the aim: (a) to provide additional material for comparison to existing climatologies and (b) to compare with previous findings that were based on a smaller sample of data. In addition to the climatology, the relation of lightning activity to underlying sea-surface temperature over the Mediterranean maritime areas is also investigated and discussed.

**Methods**

The 10 year lightning data used in this study are provided by the ZEUS long-range lightning detection network (Kotroni and Lagouvardos 2008). ZEUS receivers record the radio noise (sferics) emitted by lightning strokes in the very-low-frequency (between 7 and 15 kHz). The VLF signal is preamplified at each receiver site and the signal is synchronized to geographic positioning system time. At each receiver site an identification algorithm is executed that detects a probable sferics candidate, excluding weak signals and noise, and is capable of capturing up to 70 sferics per second. Then, the lightning location is retrieved at the central station of the network using the arrival time difference triangulation technique. The arrival time difference values represent positions between two outstations with the same time difference, and their intersection defines a sferic fix. The location error of ZEUS was calculated to be ~6.8 km, while its detection efficiency varies between 25% and 35% (Lagouvardos et al 2009), values that are valid throughout the studied domain which lies within the periphery of sensors location. The system is capable to monitor and delineate correctly the thunderstorm areas although it under-detects the actual number of cloud-to-ground lightning (Lagouvardos et al 2009, Price et al 2011). Real time ZEUS data over Europe and the Mediterranean Sea can be found at http://thunderstorm24.com.

Lightning data for the entire period (initially provided as individual measurements at specific latitude and longitude coordinates, as inferred by the detection algorithm) were gridded for the needs of this study in 0.1° × 0.1° grid boxes (roughly boxes sized 10 × 10 km in the Mediterranean latitudes). It should be noted that the data availability of the ZEUS system is ~95% since out of the 3652 days of the 10 year period only 193 days were missing. Since the fraction of non-available days is ~5% of the total number of days, we consider that this fraction is too small to jeopardize the robustness of our results. As a thunderstorm day with cloud-to-ground lightning activity (shown in figure1(b)) at each grid box of the studied domain was considered a day when lightning is sensed by ZEUS. For each grid box, the total number of lightning days was obtained through summation during the analysed 10 year period.

For the analysis of the SST daily real-time global data were collected by NASA (http://polar.ncep.noaa.gov/sst/ophi/Welcome.html) at 1/12 of degree horizontal resolution (roughly boxes sized 9 × 10 km in the Mediterranean latitudes). The dataset was produced with a two-dimensional variational interpolation analysis of the most recent 24 h buoy and ship data, satellite-retrieved SST data, and SST’s derived from satellite-observed sea-ice coverage. Bias calculation and removal, for satellite retrieved SST, is the technique employed in the 7 day Reynolds–Smith climatological analysis (Reynolds et al 2007). SST data were compared with lightning number for each day of the autumn months and at grid boxes of 0.1° × 0.1°.

**Results**

Figure 1(a) shows the lightning density calculated, in 0.1° × 0.1° grid over a domain bounded from 30°N to 48°N and from 0°E to 33°E, an area within the periphery determined by the location of the six sensors. In order to avoid some occasional noise produced by two sensors in the easternmost and westernmost parts of the Mediterranean basin, a small fraction of the basin was, unfortunately, excluded from the analysis. Moreover, in order to avoid problems that can arise when strokes are grouped into flashes, due to the selection of space and time criteria, as pointed out in Yair et al (2014), the analysis of the results was made on the individual strokes sensed by
ZEUS. The yearly lightning density peaks up to 5 lightning strokes km\(^{-2}\) y\(^{-1}\) over land close to the main topographic features of the area (solid white line in figure 1(a) denotes topographic features higher than 1000 m). Over the sea, the highest density is found over the central part of the basin (the Adriatic and Ionian Seas), with values up to 4–5 lightning strokes km\(^{-2}\) y\(^{-1}\). The areas with the highest lightning stroke density over the maritime areas are spotty and represent mainly individual severe thunderstorms. Of interest is the relatively low lightning stroke density over the Gulf of Lion, over the coastal areas of Egypt and Libya as well as over a major part of the Black Sea. At this point it should be noted that the quantitative reference to lightning density numbers includes an uncertainty which relates to the under detection of the actual number of strokes, an inherent deficiency of long-range lightning detection systems (Virts et al 2013), such as ZEUS. However the lightning density distribution is similar to that presented in

Figure 1. 10 year lightning climatology: (a) stroke density (100×strokes km\(^{-2}\)y\(^{-1}\)), (b) total number of thunderstorm days. The solid white line denotes the 1000 m topography height.
previous studies, as inferred from satellite observations with global coverage (Christian et al. 2003, Cecil et al. 2014).

We now concentrate on the spatial distribution of lightning days over the studied domain. For many applications associated with socio-economic activities (including constructions) and civil protection, this information is also of paramount importance and complementary to that of the lightning density. For that reason, we present in figure 1(b) the total number of lightning days over the 10 year period; in $0.1° \times 0.1°$ grid boxes. The major topographic characteristics of the area are also shown. It should be noted that lightning density maxima (depicted in figure 1(a)) do not always coincide with the maxima of lightning days as the first number shows the intensity of the events and the second their frequency. The main information that figure 1(b) conveys is that the ‘hot-spots’ of lightning days are found over land surfaces close to the main topographic features, a fact that underlines the role of topography and especially of the sloping surfaces in favouring strong ascending motions, in presence of unstable weather conditions, as has been shown in previous studies (Kotroni and Lagouvardos 2008). The largest number of lightning days is evident in the area between Northeastern Italy, Austria and Slovenia, where thunderstorms occur during almost 8% of the days within the analysed period. Hot spots are also evident in Northwestern Italy, close to the Alps, in the continental areas following the main topographic features of the Italian and Greek peninsulas, as well as over the high mountains of the Balkan countries (Carpathian in Romania, Rhodopes and Rila in Bulgaria). Our results compare very well with the thunderstorm days distribution derived from the long-range lightning detection system operated by the UK Meteorological Office (Holt et al. 2001, Anderson and Klugmann 2014). Inspection of the yearly number of lightning days during the 10 year period revealed that 2009 was the most active and 2007 the less active year in terms of observed lightning days (not shown).

Figure 2 presents the percent contribution of each season to the total yearly number of lightning strokes as well as the seasonal stroke density. The winter period is the less active season (figure 2(a)) with a contribution to the yearly number of lightning by less than 10% in the major part of the studied area, except over the warmer Eastern Mediterranean waters where locally the percentage of the total lightning yield reaches 40%–50%. The high percentages that are evident in the eastern part of the basin were also identified by Price and Federmesser (2006) who analysed 5 years of lightning data provided by TRMM satellite. The authors attributed this activity to the positioning of winter jet stream and showed the role of its latitudinal position on the interannual variability of lightning during winter over this area. During spring (figure 2(b)) the lightning activity over the sea is relatively low while it is more important over land, especially over the northern flanks of the African coasts where locally more than 50% of the yearly lightning occurs. This maximum is related to the passage of Sharav cyclones (or Saharan depressions), features that occur mainly during spring, as already analysed in detail by Alpert and Ziv (1989). In addition relatively high percentages (~40%) of the yearly lightning are also evident locally over Turkey.

During summer (figure 2(c)) the striking preponderance of lightning strokes over land is clear over the major part of the studied domain. Indeed over the entire southern European area as well as over the major islands of the central and western Mediterranean (Corsica, Sardinia and Sicily), more that 60% and locally more than 80% of the total annual lightning strokes, is observed. During autumn (figure 2(d)), the picture is inversed compared to summertime as the Mediterranean sea surfaces contribute more than 60% and locally more than 80% of the total yearly lightning strokes, except the easternmost Mediterranean where the percentages are of the order of ~40%. The aforementioned results are in good qualitative agreement with the already available global climatology constructed from satellite data (Christian et al. 2003, Cecil et al. 2014) as well as with the Mediterranean climatology presented in previous studies (Holt et al. 2001, Altaratz et al. 2003, Anderson and Klugmann 2014) but in the present study the analysis is based on both a long period and an improved sampling.

Inspection of the seasonal stroke densities (figures 2(e)–(h)) shows that over the maritime areas stroke densities are low (less than 0.5 strokes km$^{-2}$ y$^{-1}$) during all seasons except autumn when it increases to values reaching 2–3 strokes km$^{-2}$ y$^{-1}$ in the western and central Mediterranean (figure 2(h)). Over land, the stroke densities are lower than 0.5 strokes km$^{-2}$ y$^{-1}$ during winter and autumn and range from 0.5 to 1 strokes km$^{-2}$ y$^{-1}$ during spring (figure 2(f)). During summer over the European land surfaces the stroke densities exceed 1.5 and peak to 5 strokes km$^{-2}$ y$^{-1}$ over ‘hot spots’ also identified in figure 1(a).

This work explores the possible relation of SST with the lightning activity. This task is facilitated by the availability of high resolution SST data from a combination of spaceborne and in situ observations (see methods for details). The combined analysis of SST and lightning is restricted in the period 2006–2014, due to the lack of high-resolution SST data prior to 2006 and for the autumn months, since as shown in figure 2(d), during this period the lightning activity is mainly distributed over the water bodies. An example of the positive correlation between SST and lightning is given in figure 3(a), which presents a monthly longitude-time section (Hovmöller diagram) as an average in the 30°N–48°N latitude band. As an example we select November 2008, which was the most active November in terms of lightning during the analysed period and we use only grid boxes over the sea within
this latitudinal band. The warm waters of the Mediterranean Sea, and especially of the central part, coincide with large number of lightning strokes during the first half of the month. The relatively colder waters of the western part of the basin as well as over the Black Sea, are associated with much lower number of lightning. We identify however, areas with high SST on the eastern part of the basin, that are not associated with...
lightning: this is expected, since high SST is not a sufficient condition for convective development but it requires the presence of certain synoptic conditions that can lead/favour to deep convection. The increased lightning activity with increased SST has been highlighted in the past in the western Mediterranean (De Pablo and Rivas Soriano 2002) and in the maritime area around India (Tinmaker et al 2009). Based on the qualitative demonstration of a positive correlation between high SST and lightning activity, we proceeded with a non-parametric statistical analysis of all grid boxes with lightning with the respective SST for the autumn period of the years 2006–2014. Indeed the available pairs of lightning strokes and SST values (~672 000) have been divided into 30 bins with equal number of pair each. Figure 4 presents the resulting box and whisker plot of the number of lightning as a function of the underlying SST. The interquartile range (25%–75%) as well as the 90th percentile of the number of lightning increase with increasing SST, while the mean number of lightning shows a positive linear correlation with a very high linear correlation coefficient ($r = 0.96$) which is significant at the 99.9% level. The linear trend equation fitted to the mean number of lightning strokes reveals an increase by ~3 of the expected number of strokes for an increase by 2 K of the SST. In order to check on the consistency of the obtained results for the whole autumn season, the same analysis on the available pairs of lightning strokes and SST values has been performed separately for each month. Then when pooling the results for the separate months all together, a similar linear correlation is found with a slightly decreased ($r = 0.90$) but still very high correlation coefficient (not shown).
Thus these results indicate that when convection is present, warmer underlying SST may further increase the production of lightning. The mechanism that lies behind this positive feedback is the change of environmental lapse rate (rate of change of temperature with height). In the presence of high SST, enhanced sensible and latent heat fluxes from the sea surface towards the adjacent air masses increase temperature at the lowest tropospheric levels, inducing thus a steeper environmental lapse rate. This steeper rate, in combination with cool air aloft (a necessary condition for convection to occur) and the presence of moisture from the underlying sea, locally enhances convection and hence lightning activity.

Conclusions

In this study a 10 year long data base of lightning data over most of the Mediterranean and surrounding countries was explored in order to provide a climatological assessment of the spatial and temporal distribution of lightning activity in the area. This study complements existing studies over the area that were produced either by other networks or for much smaller periods.

This work primarily contributes to the improvement of the understanding of the lightning climatology over the Mediterranean. The continuous monitoring of lightning with the ZEUS network during the last 10 years permitted the construction of a robust climate database. The real time and past data discussed herein are made available by the authors in the web address http://thunderstorm24.com.

Additionally, this work explored the relationship between lightning activity and SST and presented evidence of a positive trend in the number of lightning strokes with increasing SST. This finding could be utilised in terms of forecasting the intensity of lightning activity in presence of convection. Further as higher SST values relate with lightning intensification, this finding could be used as an indirect means of estimating the trend of lightning activity in the frame of a warming climate.

It should be noted that since ZEUS is a long-range lightning detection system that suffers, as all similar systems, from underdetection of lightning strokes (Virts et al. 2013, Anderson and Klugmann 2014), improved long-range lightning detection systems would help to better quantify the relation of lightning and SST. It is believed that lightning detectors onboard geostationary satellites (foreseen to be operational at the end of this decade) will further improve this analysis.

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References

Alpert P and Ziv B 1989 The sharav cyclone: observations and some theoretical considerations J. Geophys. Res. 94 18495–514
Altaratz O, Levin Z, Yair Y and Ziv B 2003 Lightning activity over land and sea on the eastern coast of the Mediterranean Mon. Weather. Rev. 131 2060–70
Anderson G and Klugmann D 2014 A European lightning density analysis using 5 years of ATDnet data Nat. Hazards Earth Syst. Sci. 14 815–29
Ashley W S and Gilson C W 2009 A reassessment of US lightning mortality Bull. Am. Meteorol. Soc. 90 1501–18
Cecil D J, Bucheler D and Blakeslee R J 2014 Gridded lightning climatology from TRMM-LIS and OTD: dataset description Atmos. Res. 136 404–14
Christian H J et al 2003 Global frequency and distribution of lightning as observed from space by the optical transient detector J. Geophys. Res. 108 4005
De Pablo F and Rivas Soriano L 2002 Relationship between cloud-to-ground lightning flashes over the Iberian peninsula and sea surface temperature Q. J. R. Meteorol. Soc. 128 173–83
Galanaki V, Vassili K, Konstantinos I and Athanassios A 2015 A ten-year analysis of lightning activity over the Eastern Mediterranean Atmos. Res. 166 213–22
Goswami B R, Mukhopadhyay P, Manzanta R and Goswami B N 2010 Multiscale interaction with topography and extreme rainfall events in the northeast Indian region J. Geophys. Res. 115 D12114
Holt M A, Hardaker P J and McLelland G P 2001 A lightning climatology for Europe and the UK, 1990–1999 Weather 56 290–8
Katsanos D K, Lagouvardos K, Kotroni V and Argirious A A 2007 The relationship of lightning activity with microwave brightness temperatures and spaceborne radar reflectivity profiles in the Central and Eastern Mediterranean J. Appl. Meteorol. Climatol. 46 1901–12
Kotroni V and Lagouvardos K 2008 Lightning occurrence in relation with elevation, terrain slope and vegetation cover in the Mediterranean J. Geophys. Res. 113 D21118
Lagouvardos K, Kotroni V, Beta H D and Schmidt K 2009 A comparison of lightning data provided by ZEUS and LINET networks over Western Europe Nat. Hazards Earth Syst. Sci. 9 1713–7
Laing A, Lajoie M, Reader S and Pfeiffer K 2007 The influence of the El Niño–Southern oscillation on cloud-to-ground lightning activity along the gulf coast: II. Monthly correlations Mon. Weather. Rev. 136 2544–56
Lay E H, Jacobson A R, Holzworth R H, Rodgers C J and Dowden R L 2007 Local time variation in land/ocean lightning flash density as measured by the world wide lightning location network J. Geophys. Res. 112 D13111
Mazarakis N, Kotroni V, Lagouvardos K and Argirious A 2008 Storms and lightning activity in Greece during the warm periods of 2003–06 J. Appl. Meteorol. Climatol. 47 3089–98
Mezuman K, Price C and Galanti E 2014 On the spatial and temporal distribution of thunderstorm cells Environ. Res. Lett. 9 124023
Papagiannaki K, Lagouvardos K and Kotroni V 2013 A database of high-impact weather events in Greece: a descriptive impact analysis for the period 2001–2011 Nat. Hazards Earth Syst. Sci. 13 727–36
Pawar S D, Lal D M and Murugavel P 2012 Lightning characteristics over central India during Indian summer monsoon Atmos. Res. 106 44–9
Price C and Federmesser B 2006 Lightning–rainfall relationships in Mediterranean winter thunderstorms Geophys. Res. Lett. 33 L07813
Price C, Asfur M and Yair Y 2009 Maximum hurricane intensity preceded by increase in lightning frequency Nat. Geosci. 2 329–32
Price C et al 2011 The FLASH project: using lightning data to better understand and predict flash floods Environ. Sci. Policy 14 898–911
Reynolds R W, Smith T M, Liu C, Chelton D B, Casey K S and Schlax M G 2007 Daily high-resolution-blended analyses for sea surface temperature J. Clim. 20 5473–96
Soriano L R, De Pablo F and Tomas C 2005 Ten-year study of cloud-to-ground lightning activity in the Iberian Peninsula J. Atmos. Sol. —Terr. Phys. 67 1632–9
Tinmaker M I R, Kaushar A and Beig G 2009 Relationship between lightning activity over peninsular India and sea surface temperature J. Appl. Meteorol. Climatol. 49 828–35
Virts K, Wallace J M, Hutchins M L and Holzworth R H 2013 Highlights of a new ground-based hourly global lightning climatology Bull. Am. Meteorol. Soc. 94 1381–91
Yair Y, Shalev S, Erlich Z, Agrachov A, Katz E, Saaroni H, Price C and Ziv B 2014 Lightning flash multiplicity in eastern Mediterranean thunderstorms Nat. Hazards Earth Syst. Sci. 14 165–73
Ziv B, Saaroni H, Yair Y, Ganot M, Baharad and Isasarachi D 2009 Atmospheric factors governing winter thunderstorms in the coastal region of the eastern Mediterranean Theor. Appl. Climatol. 95 301–10