Lightning activity in the Mediterranean: quantification of cyclones contribution and relation to their intensity

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Abstract

A 10-year data set of intense Mediterranean cyclones was used for a twofold objective: first to quantify the cyclone’s contribution to lightning occurrence in the region and second to investigate potential connection of lightning with cyclones intensity. For this reason, we used cyclone tracks, lightning observations and reanalysis from the European Centre for Medium Range Weather Forecasts, for the 10-year period of 2005–2014. Results showed that intense cyclones provoke <10% of lightning activity over the Mediterranean Sea, however, in certain areas, cyclone contributions might reach 20–30%. The intense cyclones, which are associated with lightning activity close to their centre, constitute about one third (36%) of the total number of tracked cyclones. Therefore two cyclone groups are identified: those associated with and those without lightning. The first group presents in average 35% more ice and 15% more liquid cloud water content within the upper and lower atmospheric levels, respectively, while is related to approximately three times greater values of convective available potential energy in average. Further analysis shows that the intensities of the cyclones in the two groups present no significant differences, suggesting that deep convection may not be a major mechanism for the occurrence of intense Mediterranean cyclones. Finally, we show that cyclones associated with lightning present the highest lightning activity about 6 h prior to the cyclones maximum intensity.

Keywords: Mediterranean cyclones; deep convection; lightning

1. Introduction

Intense Mediterranean cyclones are linked with environmental risks such as heavy rainfall, windstorms and lightning (Papagiannaki et al., 2013). Especially lightning may inflict fatalities, injuries, fires and economical damage (Mills et al., 2008). Currently, the state-of-the-art lacks of a systematic analysis of the climatology of Mediterranean cyclones associated with lightning.

Lightning observations have been widely used as a proxy for deep convection associated with cold cloud tops and high radar reflectivity. Especially for tropical hurricanes, several studies have shown that strong lightning activity occurred prior to the cyclones maximum intensity. For instance, Price et al. (2009) and Whittaker et al. (2015) showed in a climatological approach that the maximum of lightning impacts occurred approximately 1 day before hurricane winds attain their maximum speed. While numerous studies that investigate the relation between lightning and cyclones are devoted to tropical hurricanes, the relevant literature over the Mediterranean is limited. Recently, Miglietta et al. (2013) studied an ensemble of 14 Medicanes (tropical-like cyclones in the Mediterranean Sea) and their results confirmed that in these systems – as in hurricanes – lightning preceded their stage of maximum intensity. This result comes also in accordance with several past case studies of cyclones in the Mediterranean, especially when considering rapidly intensifying cyclones and Medicanes (e.g. Lagouvardos and Kotroni, 2007; McTaggart-Cowan et al., 2010). On the other hand, Flaounas et al. (2016) used observation data sets and showed that in two case studies of intense Mediterranean cyclones only one of them was associated with deep convection and lightning, despite that both cyclones shared the same duration, same pressure minima and equally attributed heavy rainfall over the western Mediterranean. As follows, the association of Mediterranean cyclones intensity with deep convection and resulting lightning occurrence still remains an open question.

In this study, we have a twofold objective. First, we aim at quantifying the cyclones contribution to the environmental risk of intense lightning activity in the Mediterranean region and second, we investigate in a climatological framework the dependence of Mediterranean cyclones intensity to the presence of lightning.

2. Data and methods

2.1. Lightning and atmospheric data

In order to acquire realistic results, in this study, we analyse atmospheric reanalysis fields and lightning
observations. The atmospheric fields are obtained from the European Centre for Medium Range Weather Forecasting reanalysis of ERA-Interim (ERAI), in a horizontal grid spacing of 0.75° × 0.75° in longitude and latitude (Dee and Uppala, 2009). The lightning observations are provided by the ZEUS long-range lightning detection system, operated by the National Observatory of Athens (Kotroni and Lagouvardos, 2008). ZEUS detects cloud-to-ground lightning strikes with a detection efficiency of the order of 25% and an average location error of the impacts of the order of 7 km (Lagouvardos et al., 2009). It is also noteworthy that ZEUS has a tendency of under-detecting lightning during night-time, without however suffering from missing the detection of thunderstorms within the domain covered by the network that includes the Mediterranean (Lagouvardos et al., 2009).

2.2. Cyclone tracking

To perform cyclone tracking, we used the method developed by Flaounas et al. (2014). This method identifies cyclones as local maxima of relative vorticity at 850 hPa and has been applied to the ERAI reanalysis over the wider Mediterranean region (Figure 1(a)), for the 10-year period of 2005–2014. Only cyclones with a life time of at least 1 day and maximum relative vorticity of $>8 \times 10^{-5} \text{s}^{-1}$ have been retained. These criteria have been shown adequate to distinguish intense cyclones from weak vorticity maxima, abrupt wind stirring or heat-lows (Flaounas et al., 2013). In total, we detected 584 intense cyclones (about 60 cyclones per year).

To associate cyclones with lightning, we attributed to each track point (from genesis to lysis) all impacts that took place within 200 km and within 3 h from its location and time. The radius of 200 km first permits to associate cyclones core intensity with the process of deep convection and second permits to associate lightning activity close to the cyclones centres, where rainfall and convection are expected to be maximum (Flaounas et al., 2015b). This process distinguished two cyclone groups: the first group is composed by 211 cases, where all cyclones are related to lightning at least once during their life time, while the second group presents cyclones with no lightning activity at all and comprises 373 cases.

All tracked cyclones occur over the main cyclogenic regions of the Mediterranean (Figure 1(a) and (b)): over the western Mediterranean, the Ionian and the Aegean Seas (Trigo et al., 1999; Campins et al., 2011). Cyclones in Figure 1(a) and (b) present similar spatial variabilities, however cyclones without lightning tend to present higher rate of occurrence in particular over Northwest Africa, close to Cyprus and the Black Sea. Figure 1(c) shows the seasonal cycle of intense Mediterranean cyclones. In consistency with previous studies (Campins et al., 2011; Flaounas et al., 2013), the intense cyclones frequency of occurrence presents a maximum in autumn and winter (64% of the cases) and a minimum in summer (5% of the cases). It is noteworthy that the cyclones associated with lightning are more frequent in autumn and less frequent in winter, while the opposite is true for the cyclones that are not associated with lightning (Figure 1(c)). A plausible explanation lies to the higher Mediterranean Sea surface temperature in autumn, which increases low-level instability and therefore favours convection (Kotroni and Lagouvardos, 2016).

3. Seasonal cyclones contribution to lightning

Figure 2 shows the seasonal contribution of cyclones to the 10-year total of observed lightning over the
Mediterranean basin. The overall cyclones contribution is higher in winter and autumn when intense cyclogenesis presents its highest rate of occurrence (Figure 1(c)). Given that the most intense cyclones tend to form over the western and central Mediterranean Sea (Figure 1(a)), it comes as no surprise that these marine areas are mainly affected by cyclone-induced lightning, where intense cyclones provoke no >10% of the total lightning activity in winter and autumn. The higher contributions are observed over northwest Africa (between 0°–10°E and 25°–35°N) where cyclones are related to as much as 60% of the total winter and autumn lightning. Secondary maxima of the order of 10–30% are also observed over several cyclogenesis hot-spots, as for instance in the vicinity of the Gulf of Genoa in winter and autumn, over the Ionian Sea in winter and close to North Africa in spring.

In spring and summer, intense Mediterranean cyclones are at their minimum frequency of occurrence (Figure 1(c)), while lightning activity is more frequent over the land (Altaratz et al., 2003; Tuomi and Mäkelä, 2008; Feudale and Manzato, 2014; Ben Ami et al., 2015; Galanaki et al., 2015). Consequently, during these seasons cyclones contribution to lightning is dramatically reduced, except in spring, in the regions over the North African coast and close to the Atlas Mountain. Indeed, this region is previously shown to consist of a cyclogenesis hot-spot (Sharav cyclones; Alpert and Ziv, 1989; Trigo et al., 1999), where cyclones are responsible for uptaking large loads of dust (Flaounas et al., 2015a). Therefore, our results suggest a possible connection between these systems and dust related lightning activity (Proestakis et al., 2016). In summer, cyclones are at their minimum of occurrence (about 6%; Figure 1(a)) contributing thus to lightning in specific areas by no >8% of the seasonal total (Figure 2(d)).

Cyclones contribution to lightning activity over the eastern Mediterranean is shown to be rather weak throughout the year (Figure 2), rarely overpassing 50%. This is due to the fact that we track the most intense cyclones in the region, quantifying thus cyclone contributions to lightning only over the favourable areas of intense cyclogenesis, i.e. mainly over the central and western Mediterranean (Figure 1(a)). Considering lower (or no) vorticity thresholds, the overall cyclone contributions to regional lightning activity increases dramatically. However, such results would lack of a robust interpretation of the role of cyclones in forming thunderstorms in the Mediterranean. Indeed, local vorticity maxima – as tracked by our cyclone tracking method – may not always correspond to cyclonic systems (in the sense of meso-scale wind vortices) but rather to local scale wind circulations such as abrupt wind stirring.

4. Intense cyclone occurrence and lightning activity

Strong lightning activity close to the cyclones centre suggests the development of strong convection. This should be reflected in the composition of clouds, in consistency with the theory of non-inductive thunderstorm electrification. Indeed, lightning activity is related with high cloud ice concentrations (Defer et al., 2005; Petersen et al., 2005; Lagouvardos and Kotroni, 2007), while the magnitude of the transferred charge during the electrification process is expected to be related with adequately high cloud liquid water (Avila
Mediterranean cyclones associated with lightning activity

In Figure 3(a) and (b), we show the composite vertical profiles of cloud ice and cloud liquid concentrations for the two cyclone groups as derived by the ERAI reanalyses, averaged within 200 km from the cyclones centres. According to our cyclone tracking method, the cyclones mature stage is taking place when relative vorticity at 850 hPa is at its maximum (0 h). Therefore composite vertical profiles in Figure 3 are presented as averages of the three time instances of $-6$, 0 and $+6$ h. The cyclones associated with lightning present about 35% more cloud ice (Figure 3(a)) and liquid water (Figure 3(b)) content in the middle atmospheric layers of 500–700 hPa and about 15% more within the lower troposphere (900–700 hPa). It is noteworthy that maximum ice content concentration in Figure 3(a) tends to fall in lower levels from $-6$ h (~600 hPa) to $+6$ h (~700 hPa) due to gravitational fall of ice within the cyclone clouds (Lagouvardos and Kotroni, 2007). Further analysis on the seasonal dependency of the profiles shown in Figure 3(a) and (b) showed that regardless the season, cyclones with lightning activity always present higher ice concentrations by 46% more in autumn and 33% in summer and higher liquid concentrations by 13% in summer and 23% in winter. It is noteworthy that reanalysis is performed in a coarse resolution grid where convection is a subgrid scale process. Consequently, uncertainties may arise into the liquid and ice concentration profiles. However, in this study, we focus on the relative difference between the two cyclones groups. These results are consistent with Flaounas et al. (2016) where radar observations of ice concentration in a cyclone presenting deep convection were compared to the ones of a cyclone where no deep convection and no lightning activity took place. In order to further examine the atmospheric conditions, which lead to lightning occurrence, we calculated the average values of convective available potential energy (CAPE), which is associated with the intensity of updraughts within convection (Crook, 1996). This calculation was performed within the time frame $-24$ to $+24$ h centred at the cyclones maximum intensity (Figure 3(c)). The average CAPE at 0 h for the cyclones producing lightning is of the order of 700 J kg$^{-1}$ in contrast to 200 J kg$^{-1}$ for the cyclones with no lightning. This difference of approximately 500 J kg$^{-1}$ is constantly persistent throughout the cyclones lifetime.

The cloud water content (liquid and ice) in Figure 3(a) tends to decrease in all pressure levels from 0 to $+6$ h. This suggests that convection tends to develop before cyclones reach their maximum intensity. To address this

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**Figure 3.** (a) Vertical profile of ice water content averaged within a radius of 200 km around the cyclone centre. (b) As in (a) but for liquid water content. (c) Composite time series of CAPE centred at the cyclones maximum intensity (0 h corresponds to the cyclones maximum relative vorticity).
issue, we took as a measure of cyclones intensity the maximum relative vorticity at 850 hPa, the maximum 10-m wind speed and the minimum mean sea level pressure (MSLP) within 200 km from each of the track points of each cyclone from the two cyclone groups. Then, the cyclones intensity composite evolution was calculated by averaging cyclones intensity at each time frame with respect to the cyclones mature stage (from -24 to +24 h). Figure 4 shows the composite time series results (time series are normalized with respect to their time average in order to ease comparison). In addition, Figure 4(a) shows the composite time series of lightning occurrences during the cyclones life time. It seems that there is indeed a lag of 6 h between cyclones maximum intensity (0 h) and cyclones maximum lightning occurrence. After -6 h, the cyclone-induced lightning decreases dramatically, reaching its minimum of activity 12 h later, at +6 h. Further analysis shows that for about 80% of the cyclones presenting lightning, their maximum lightning activity takes place from -24 to 0 h (Figure 5) and for about 60% of the cases lightning activity takes place from -12 to 0 h. At 0 h, when cyclones reach their mature stage, the differences between the intensity of the two cyclone groups are rather weak. In fact, a two sampled $t$-test has been performed and showed that maximum intensity averages between the two cyclone groups are not significantly different, regardless the season of cyclones occurrence and regardless if cyclones intensity is measured in MSLP, 10-m wind speed or relative vorticity. Therefore, our results suggest that convection (as inferred from the presence of lightning activity) may play a secondary role in cyclones reaching high intensities.

Figure 4. (a) Composite time series of maximum relative vorticity at 850 hPa, minimum MSLP, maximum 10-m wind speed and number of lightning for cyclones presenting lightning within 200 km from their centres centred at cyclones maximum intensity (0 h), normalized by standard deviation (0 h corresponds to the cyclones maximum relative vorticity). (b) As in (a) but for cyclones that do not present lightning. Time series are normalized with respect to their average.

Figure 5. Frequency histogram of the lag between the time of maximum of lightning and cyclones mature stage, i.e. cyclones time of maximum of relative vorticity.

5. Summary and discussion

In this study, we first quantified the contribution of intense cyclones to lightning over the Mediterranean region. Then, we investigated the relation between cyclones that present lightning and cyclones where lightning was absent. For this reason, we used the ERAI reanalyses and cloud-to-ground lightning data from the ZEUS detection system, as well as a cyclone tracking algorithm, applied to the Mediterranean region from 2005 to 2014. Lightning has been attributed to each cyclone if detected within a radius of 200 km from the cyclone centre. To avoid any uncertainties on the number of observed lightning related to cyclones (e.g. underestimations of night-time impacts), results have been presented in a relative way. Our analysis showed that intense cyclones’ contribution to lightning is higher in autumn and winter contributing to the total of lightning by 5–30% over the Mediterranean Sea, depending...
on the area and season. In certain areas, this percentage was significantly high, especially over North Africa where cyclones contributing to lightning may reach up to 60% of the winter total lightning occurrence. The same analysis has been repeated for a 500 km radius, increasing the overall cyclones contribution to lightning activity in the region. However, this did not affect our results on the main areas where cyclones produce lightning, as presented in Figure 2.

In this study, the intense cyclones that were associated with lightning constitute 36% of the total of 584 tracked cyclones. It was also shown that the cyclones associated with lightning tend to have approximately 35% more cloud ice and 15% more liquid cloud water content in the layer 500–700 hPa and are associated with approximately three times greater values of CAPE. Also, the peak of lightning occurrence was found to precede by 6 h in average the time of cyclones maximum intensity. Both cyclone groups presented similar seasonal cycles and areas of occurrence but most importantly they were shown to present similar intensities, suggesting that deep convection may not consist of a necessary condition for the occurrence of intense cyclogenesis in the Mediterranean.

To investigate the role of deep convection in intense cyclones development, we compared the MSLP deepening rates of cyclones presenting strong lightning activity before reaching their mature stage, to the cyclones that either presented their maximum of lightning activity after their mature stage or to the cyclones that did not present any lightning activity at all. However, no significant differences were found. Fink et al. (2012) showed that convection contribution to MSLP is mainly related through the column integrated virtual temperature. The vertically integrated temperature may however be connected to cyclones intensification through both advection (baroclinic forcing) and deep convection (diabatic forcing). In several case studies of strong extratropical storms, the authors showed that one of the two mechanisms can largely dominate cyclones intensification. In future studies, we will address the question of the (thermo-)dynamics associated with the two cyclone groups intensities in order to delineate the contribution of deep convection and baroclinicity into the formation of intense cyclones in the region.

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References

Altaratz O, Levin Z, Yair And Y, Ziv B. 2003. Lightning activity over land and sea on the eastern coast of the Mediterranean. Monthly Weather Review 131(9): 2060–2070.

Avila EE, Aguirre Varela GG, Caranti GM. 1995. Temperature dependence of static charging in ice growing by riming. Journal of Atmospheric Science 52: 4515–4522.

Ben Ami Y, Altaratz O, Yair Y, Koren I. 2015. Lightning characteristics over the eastern coast of the Mediterranean during different synoptic systems. Natural Hazards and Earth System Sciences 15(11): 2449–2459.

Campins J, Genovés A, Picornell MA, Jansá A. 2011. Climatology of Mediterranean cyclones using the ERA-40 dataset. International Journal of Climatology 31: 1596–1614.

Crok NA. 1996. Sensitivity of moist convection forced by boundary layer processes to low-level thermodynamic fields. Monthly Weather Review 124: 1767–1785.

Dee DP, Uppala S. 2009. Variational bias correction of satellite radiance data in the ERA-Interim reanalysis. Quarterly Journal of the Royal Meteorological Society 135: 1830–1841.

Defer E, Lagouvardos K, Kotroni V. 2005. Lightning activity in eastern Mediterranean region. Journal of Geophysical Research, [Atmospheres] 110: D24210.

Feudale L, Manzato A. 2014. Cloud-to-ground lightning distribution and its relationship with orography and anthropogenic emissions in the Po Valley. Journal of Applied Meteorology and Climatology 53(12): 2651–2670.

Fink AH, Pohle S, Pinto JG, Knippertz P. 2012. Diagnosing the influence of diabatic processes on the explosive deepening of extratropical cyclones. Geophysical Research Letters 39: L07803.

Flaounas E, Dobrinski P, Bastin S. 2013. Dynamical downscaling of IPSL-CM5 CMIP5 historical simulations over the Mediterranean: benefits on the representation of regional surface winds and cyclogenesis. Climate Dynamics 40: 2497–2513.

Flaounas E, Kotroni V, Lagouvardos K, Flaounas I. 2014. CycloTRACK (v1.0) – tracking winter extratropical cyclones based on relative vorticity: sensitivity to data filtering and other relevant parameters. Geoscientific Model Development 7: 1841–1853.

Flaounas E, Kotroni V, Lagouvardos K, Kazadzis S, Gikas A, Hatzianastassiou N. 2015a. Cyclone contribution to dust transport over the Mediterranean region. Atmospheric Science Letters 16: 473–478.

Flaounas E, Raveh-Rubin S, Wernli H, Dobrinski P, Bastin S. 2015b. The dynamical structure of intense Mediterranean cyclones. Climate Dynamics 44: 2411–2427.

Flaounas E, Lagouvardos K, Kotroni V, Claud C, Delanoë J, Flamant C, Madonna E, Wernli H. 2016. Processes leading to heavy precipitation associated with two Mediterranean cyclones observed during the HyMeX SOP1. Quarterly Journal of the Royal Meteorological Society 142: 273–286, doi: 10.1002/qj.2618.

Galani et al. 2011. The relationship with orography and anthropogenic emissions in the Po Valley. Journal of Applied Meteorology and Climatology 53(12): 2651–2670.

Kotroni V, Lagouvardos K. 2008. Lightning occurrence in relation with elevation, terrain slope and vegetation cover over the Mediterranean. Journal of Geophysical Research, [Atmospheres] 113: D21118.

Kotroni V, Lagouvardos K. 2016. Lightning in the Mediterranean and its relation with sea-surface temperature. Environmental Research Letters 11: 034006.

Lagouvardos K, Kotroni V, Lagouvardos K. 2007. TRMM and lightning observations of a low-pressure system over the Eastern Mediterranean. Bulletin of the American Meteorological Society 88(9): 1363–1367.

Lagouvardos K, Kotroni V, Betz HD, Schmidt K. 2009. A comparison of lightning data provided by ZEUS and LINET networks over Western Europe. Natural Hazards and Earth System Sciences 9(5): 1713–1717.

McTaggart-Cowan R, Galerneau TJ Jr, Bosart LF, Millbrandt JA. 2010. Development and tropical transition of an Alpine Lee Cyclone. Part I: case analysis and evaluation of numerical guidance. Monthly Weather Review 138: 2281–2297.

Miglietta M, Liviola S, Malvaldi A, Conte D, Leviizzani V, Price C. 2013. Analysis of tropical-like cyclones over the Mediterranean Sea
through a combined modeling and satellite approach. *Geophysical Research Letters* **40**: 2400–2405.

Mills B, Unrau D, Parkinson C, Jones B, Yessis J, Spring K, Pentelow L. 2008. Assessment of lightning related fatality and injury risk in Canada. *Natural Hazards* **47**(2): 157–183.

Papagiannaki K, Lagouvardos K, Kotroni V. 2013. A database of high impact weather related incidents in Greece: a descriptive impact analysis for the period 2001–2011. *Natural Hazards and Earth System Sciences* **13**: 727–736.

Petersen WA, Christian HJ, Rutledge SA. 2005. TRMM observations of the global relationship between ice water content and lightning. *Geophysical Research Letters* **32**: L14819.

Price C, Asfur M, Yair Y. 2009. Maximum hurricane intensity preceded by increase in lightning frequency. *Nature Geoscience* **2**: 329–332.

Proestakis E, Kazadzis S, Lagouvardos K, Kotroni V, Kazantzidis A. 2016. Lightning activity and aerosols in the Mediterranean region. *Atmospheric Research* **170**: 66–75.

Trigo IF, Trevor DD, Grant RB. 1999. Objective climatology of cyclones in the Mediterranean region. *Journal of Climate* **12**: 1685–1696.

Tuomi T, Mäkelä A. 2008. Thunderstorm climate of Finland 1998–2007. *Geophysics* **44**(12): 6780.

Whittaker I, Douma E, Rodger C, Marshall T. 2015. A quantitative examination of lightning as a predictor of peak winds in tropical cyclones. *Journal of Geophysical Research, [Atmospheres]*** **120**: 3789–3801.

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