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Discussions

Mediterranean depression characteristics related to precipitation occurrence in Crete, Greece

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Abstract

The characteristics of the cyclone tracks and circulation patterns that caused precipitation events of variable intensity for the period 1979–2011 over the island of Crete are presented. The dataset usedfor cyclone identification, is the 0.5 × 0.5, 30 years European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim mean sea-level pressure. Their characteristics are extracted with the aid of Melbourne University algorithm (MS scheme). Daily precipitation data from a dense gauging network over the island of Crete is also used for the classification of the precipitation events in terms of intensity.

Daily precipitation intensity is classified in three severity categories, and the associated cyclones are filtered according to their distance from Crete Island. The atmospheric systems are further investigated both seasonally and annually for their position relative to Crete and morphological characteristics such as intensity and radius.

Generally, it was found that cyclones affecting Crete most frequently approach from northwest and southwest directions and the actual cyclone centers associated with precipitation events are usually located in northwest and southeast positions relative to Crete domain. Precipitation increase is observed in parallel with cyclone pressure decrease as well as cyclone intensity, depth, radius and propagation velocity increase. Specific seasonal characteristics such as lower pressures and cyclone radius can be detected in spring in contrast to winter and autumn precipitation events. The examination of the relation between cyclone characteristics and precipitation occurrence provides improved understanding of the complex hydro-meteorological conditions and therefore valuable hydrologic information related to forecasting potential and management of the resources and the extremes.

1 Introduction

A great number of precipitation events are triggered by cyclonic circulation patterns (Jansa et al., 2001b; Lionello et al., 2006). The extratropical cyclonic circulation patterns are frequently associated with wind, heavy precipitation and changes in temperature (Ulbrich et al., 2003) generating high risk situations such as flash floods and large scale floods with significant impacts on human life and built environment. Particularly in the Mediterranean region, flood events are highly related to specific cyclone pathways (Jansa et al., 2001a). Mediterranean cyclones are responsible for the majority of extreme weather phenomena, effecting the time of occurrence as well as the magnitude of their extreme values (Lionello et al., 2006).

The identification, tracking and evaluation of cyclone characteristics has been subject of many researchers, giving diverse results even when the examined datasets are identical (Neu et al., 2013; Ulbrich et al., 2009). In an effort towards objective analysis, automated systems and algorithms have been developed for the identification and tracking of cyclones as well as the extraction of their characteristics based on spatio-temporal datasets of mean sea-level pressure (MSLP). The state-of-the-art cyclone finding and tracking scheme (MS scheme) developed at the Melbourne University, Australia, has been widely used for the definition of closed and open systems on reanalysis data and has proven to be effective, not only for the generation of an objective climatology, but also for the assessment of individual tracks in an inland sea with complex shoreline topography, such as the Mediterranean. Evaluations of MS scheme has demonstrated its efficiency for both the detection of individual tracks as well as its effectiveness in providing cyclone climatologies (Flocas et al., 2010; Leonard et al., 1999; Simmonds and Murray, 1999). While MS scheme is capable of identifying cyclones in a range of locations with different characteristics, it has previously been employed in the Eastern Mediterranean for the identification and analysis of cyclones (Flocas et al., 2010) and explosive cyclones characteristics (Kouroutzoglou et al., 2011a).

Many studies have thoroughly investigated various characteristics of Mediterranean cyclones including cyclogenesis, temporal variability, location and dynamics. Trigo et al. (1999) performed cyclone detection and tracking using the criterion of geopotential height in order to identify cyclogenesis and cyclolysis regions as well as cyclone characteristics including duration and intensity in the Mediterranean region. His findings include strong cyclogenesis activity in the Gulf of Genoa region, south of the Atlas Mountains and in the Middle East, as well as high frequency and unexpectedly high intensity of spring lows over North Africa. An evaluation of the structure and variability of cyclones affecting eastern Mediterranean region for the 1962–2001 40 year period using MS scheme was performed by Flocas et al. (2010), verifying considerable intermonthly variations for eastern Mediterranean track density. For the same period and with the same scheme, Kouroutzoglou et al. (2011) investigated the characteristics and behavior of Mediterranean explosive cyclones as well as their vertical structure (Kouroutzoglou et al., 2012). Furthermore, Maheras et al. (2001) and Bartholy et al. (2008) identified and analyzed the synoptic scale cyclones that occur in the Mediterranean region for the periods 1958–1997 and 1957–2002 respectively, focusing on the frequency of occurrence, location, genesis and seasonal variations.

Except from the investigation of cyclone parameters and tracks, many studies have investigated the association of cyclones with precipitation. Jansa et al. (2001) investigated the simultaneous occurrence between heavy precipitation and cyclonic centers for western Mediterranean using datasets from relative databases. For the period 1958–2000, Karagiannidis et al. (2009) examined extreme precipitation events in Europe triggered by cyclones, focusing on the characteristics and trends of rain events rather than the features of the causative cyclones. Hawcroft et al. (2012) evaluated the contribution of mid-latitude cyclones to the precipitation of the Northern Hemisphere, showing association of precipitation with cyclones by over 70 % in two different reanalysis datasets. Similarly, Catto et al. (2012) quantified the association of precipitation to the different categories of frontal systems using information of global precipitation and reanalysis data.

The majority of extreme rain events in Mediterranean region are associated with cyclones and rarely develop under different circumstances which can be detected by standard meteorological analysis (Lionello et al., 2006). Investigating the characteristics of the cyclones causing extreme precipitation is of great interest for the Mediterranean area where the relatively small frequency of adverse weather and extreme events creates a false sense of safely that many times results in more damages and severe socio-economic consequences (Lionello et al., 2006). In this extent, Jansa et al. (2001) investigated cyclone-rain relationship considering the extreme cases of precipitation with heavy rain ($> 60\,\mathrm{mm\,day^{-1}}$) and heaviest rain events ($> 100\,\mathrm{mm\,day^{-1}}$) for different Mediterranean regions. Also, Tsanis et al. (2012) performed an analysis of cyclones associated with flood events in means of genesis, tracks and depth of those systems.

The goal of this study is to evaluate the characteristics of the cyclones related to precipitation events of specific accumulations in the island of Crete. Cyclone centers related to rainfall occurrence are identified and analyzed. Furthermore, the relation between the intensity of the precipitation and both local (cyclone position) and quantitative characteristics (pressure, intensity, depth, radius and propagation velocity) of the cyclones is investigated. Here we make the hypothesis that a better understanding of the association of certain atmospheric circulation patterns to rainfall intensities will be helpful for early warning against extreme events that can potentially pose risk to life and property. The analysis presented in this paper is aimed towards a better evaluation of the atmospheric systems characteristics for cyclones suspected to be associated with rain events in the island of Crete.

2 Methodology

The main goal of this research is to reveal statistics on the characteristics of the cyclones causing precipitation of specific intensity intervals. Statistical analysis is performed to the cyclones matched to defined rain categories. The origination, location and characteristics (pressure, intensity, depth, radius and propagation velocity) of those systems are distinguished and examined. The analysis is also extended concerning seasonality (winter, spring, autumn) of the events.

Here we consider that event intensity can be assessed according to the amount of rainfall accumulated at a gauging station over an arbitrary amount of time. Events are classified into three intensity intervals (rain categories) depending on their position with respect to the 50, 95 and 99.5 percentiles of cumulative daily precipitation. The concept of choosing the specific percentiles is the statistical analysis of cyclones associated with precipitation besides the average pattern. The percentiles for every gauging station are estimated after "dry days" exclusion (lower than $1\,\mathrm{mm\,day}^{-1}$). We consider having a rain event occurrence if at least one of the stations has records of rain within the intervals of the rain categories.

The cyclone identification and tracking in this analysis is carried out with the aid of the Melbourne University cyclone finding and tracking scheme (MS scheme) which uses the quasi-Lagrangian perspective (Murray and Simmonds, 1991; Simmonds and Murray, 1999). A special characteristic of the scheme is its ability of defining closed and open systems, with the aid of both pressure and relative vorticity fields (Flocas et al., 2010; Leonard et al., 1999; Ulbrich et al., 2009). This is a great asset of the algorithm because using just the information of local minima can exclude certain type of systems and on the contrary vorticity maxima are not always connected to local pressure minima. The parameters of the cyclone tracks are retrieved from MS scheme and include the cyclone pressure, radius, depth, intensity and propagation velocity.

Radius R is defined as:

$$R^2 = \frac{1}{N}\sum_{i=1}^{N}, r_i^2 \tag{1}$$

where r_i is the distance of the radial line from the cyclone center to the points at which the Laplacian of the pressure is zero (at the edge of a cyclone) and N is the number of the radial lines drawn for every 20° (Lim and Simmonds, 2007; Murray and Simmonds, 1991).

The intensity of the cyclone is given by the Laplacian of the central pressure $\nabla^2 P$ (Lim and Simmonds, 2007; Murray and Simmonds, 1991; Simmonds and Keay, 2000). The depth D of the cyclone is defined as:

$$D = \frac{1}{4} R^2 \nabla^2 P. \tag{2}$$

The depth of the cyclone represents the general influence of the cyclone in terms of intensity and scale as it is proportional of $\nabla^2 P$ and R.

Finally, the propagation velocity of the cyclone is given by:

$$U = \sqrt{U_\mathrm{E}^2 + U_\mathrm{N}^2}, \tag{3}$$

Where U_E is the eastward component of cyclone steering velocity and U_N is the northward component of cyclone steering velocity.

Regarding tracking algorithms, there are inconsistencies within the context of the estimation of the cyclone center and radius (Neu et al., 2013). Detailed distance measures, such as from the cyclone center to the gauging station are can convey insufficient information at poor MSLP dataset grid spacing resolutions. Accordingly, the estimation of exact distances between the cyclone center and each gauging station could lead to the omission of rain events associated with the corresponding cyclone. Motivated by this, a method of spatial matching between cyclone appearance and precipitation events in the area of interest is proposed here. The simple measure of Euclidian distance between the cyclone center and a boundary surrounding the entire area of interest is considered appropriate to overcome uncertainties concerning cyclone exact position and size. In order to restrict the area of interest a rectangle boundary enclosing it is defined. For this approach to be accurate, it is necessary for the area of restriction to have dimensions comparable to the local cyclones' radius.

Another issue of interest is the temporal association of the cyclones to the precipitation events. The temporal synchronization of rain and cyclone recordings leads to a direct matching. However, the recordings of different datasets do not usually have temporal synchronization. In this context, if the rain dataset has time intervals $[T_1, T_2]$ where T_1, T_2 are two consequent rain recordings, the cyclones responsible for event T_2 are those recorded within $[T_1, T_2]$. At this point, it has to be noted that when the exact time of the rain is not available (e.g. daily rain recordings) only an approximate simultaneity between cyclone occurrence and rain can be assumed. Thus, there is a possibility that the cyclone system/s considered as responsible for precipitation events are not actually triggering rain.

Finalizing the procedure, after the cyclones are matched to the defined rain events so as to have the so-called "effecting" cyclones their characteristics are evaluated.

3 Study site

This study is focused on the island of Crete which is located at the southern part of Greece. Crete is the largest island in Greece and one of the largest in Mediterranean with an area of 8265 km^2, mean elevation of 482 m ranging from sea level to approximately 2450 m and average slope 228 $\mathrm{m\,km}^{-1}$. Crete has sub-humid Mediterranean climate characterized by long hot and dry summers and relatively humid and cold winters. As such, most of rainfall occurs in winter and rarely during summer (Koutroulis et al., 2010). Also, the northwestern part of the island receives greater precipitation than the southeastern part (Chartzoulakis and Psarras, 2005; Koutroulis et al., 2010; Vrochidou and Tsanis, 2012). The precipitation in Crete varies between 440 $\mathrm{mm\,year}^{-1}$ for low-land coastal areas and reaches over 2000 $\mathrm{mm\,year}^{-1}$ for mountainous area such as Askifou upland in Chania (Koutroulis and Tsanis, 2010).

In the present study, precipitation characteristics are analyzed based on a dataset of 69 daily gauging stations. Responsible for the compilation and quality of the daily precipitation records is the WRDPC (Water Resources Department of the Prefecture of Crete) service (Koutroulis et al., 2010). Out of the entire dataset, 14 gauges recorded for periods less than 10 years and 49 recorded for more than 30 years. The temporal discontinuity of the rain recordings is of minor importance as the present analysis focuses on the coincidence of cyclonic appearance with precipitation events; in this case there should be at least one gauge station having rain records. Also, approximately 85 % of the gauge stations' records are found to be dry ($< 1\,\mathrm{mm\,day^{-1}}$).

The dataset used in this study for the identification of cyclone tracks involves analysis of MSLP data on a 0.5 × 0.5 regular latitude-longitude grid at a 6 hourly temporal resolution for the period 1979–2011 as derived from the ERA-Interim Reanalysis of ECMWF. The calibration scheme used in this study is equivalent to the one used by (Flocas et al., 2010). Tracks in Mediterranean region have an average lifetime of 28 h when short-lived systems are excluded (Trigo et al., 1999). So, to be consistent with other studies (Bartholy et al., 2008; Flocas et al., 2010; Kouroutzoglou et al., 2011b; Lim and Simmonds, 2007; Murray and Simmonds, 1991; Neu et al., 2013; Simmonds and Murray, 1999) a minimum life span of 24 h is imposed to the tracks included in this analysis. In addition, short lived cyclone systems lasting less than 24 h are not considered important as they provide less precipitation (Bartholy et al., 2008).

The domain of study for the detection and identification of the cyclones includes part of the middle-eastern Mediterranean area and extends between 4–33° E and 32–43° N. The domain of Crete was defined within the domain of 23.4–26.4° E and 34.8–35.7° N. In Fig. 1 the domain of study and Crete boundary are shown. The sectors of analysis are characterized as northwest (NW), north (N), northeast (NE), southwest (SW), south (S), southeast (SE), west (W) and east (E) considering their relative position to Crete domain.

Three types of intensity are defined for daily precipitation in Crete summarized in Table 1. Figure 2 presents the 50, 95 and 99.5 percentiles for all the gauging network of Crete, spatially interpolated with inverse distance weighting (IDW) method. Interpolation is preferred to simple value matching in order to have better visualization of the results.

Accumulated precipitation is recorded at 06:00 UTC at a daily basis for every station while the cyclone tracks are extracted at a temporal resolution of every 6 h at 00:00, 06:00, 12:00, and 18:00 UTC, according to the MSLP dataset. So the tracks considered to be responsible for a specific precipitation event are checked for the date the rainfall was measured at 00:00 and 06:00 UTC and also for the previous day at 18:00, 12:00, and 06:00 UTC in order to include in the analysis every possible cyclone which could have caused the recorded precipitation. This way a day long duration is checked for cyclone appearance for every rain recording.

Characteristic events of flash floods in Crete are those of Giofyros basin for 13–14 January 1994 (Gaume et al., 2009; Koutroulis and Tsanis, 2010; Mari et al., 2010) and Almirida basin for 17 October 2006 (Grillakis and Tsanis, 2010; Mari et al., 2010; Tsanis et al., 2008, 2014) which have been thoroughly studied. Figure 3 presents an infrared METEOSAT snapshot at 00:00 UTC on 17 October 2006 corresponding to the accumulated water vapor of the atmospheric system causing the flash flood event in Almirida basin. The orange line shows the route of the cyclone passing through the blue points which correspond to the cyclone centers as estimated by MS scheme. In the figure, white dashed circles correspond to the radius of the cyclone centers and red circle to the radius of the red cyclone center which is the one in effect for the specific METEOSAT image. MS scheme estimation of the cyclone is accurate comparing the cyclone location and its radius to the actual phenomenon recorded in the METEOSAT image. The cyclone track has an eastward direction and at 00:00 UTC on 17 October, centered at a southwest position related to Crete's bounded area, it starts precipitating in agreement with (Grillakis and Tsanis, 2010).

4 Results/discussion

4.1 Precipitation vs. cyclones

The number of precipitation events per intensity category and season for the period of analysis is presented in Table 2. In addition, the percentage of the events which could be triggered by cyclones concerning the coincidence of precipitation and "affecting" cyclone appearance in sufficiently close distance from Crete's boundary are estimated. Most of the rain events occur in winter (50 % for mild rain, > 55 % for strong and heavy rain) followed with great difference from autumn and spring, consistent with (Koutroulis et al., 2010). Considering all the available gauge stations, an annual average of 110 mild rain, 30 strong rain and 10 heavy rain events occur at different locations in Crete.

According to Table 2 mostly strong and heavy rainfall is caused by cyclones. As a matter of fact, 70 % of the annual rain events for strong rain are likely to be related to cyclone activity and 76 % of the annual rain events for heavy rain. In contrast, 54 % of the annual rain events for mild rain might be triggered by a cyclone passage. Annually, 66 % of the rainfall events in Crete are associated with a cyclone in agreement with (Catto et al., 2012) and (Hawcroft et al., 2012) who approximately find 60–70 % contribution of extratropical cyclones to precipitation north of 30N. Taking into considerations the seasonal results of Crete, it appears that for both strong and heavy events rain-cyclone coincidence is greater in spring (up to 80 % for strong rain) followed by winter and autumn. The remaining precipitation events that are not found to be connected to cyclones are either local scale lows that cannot be captured from MS scheme or are provoked due to Cretan complex land topography and orographic effects.

4.2 Cyclones affecting crete: track analysis

Most of the "affecting" cyclones originate northwest and southwest of Crete and they have southeast and northeast directions accordingly for the majority of cases.

Figures 4 and 5 show in detail the variability of the cyclones' origination and location for each of the sectors we have considered both seasonally and annually. There follows a comparison of the cyclone centers relative frequencies within the sectors taking into consideration that the areas of the sectors are not equal.

In an annual basis, approximately 70–80 % of the cyclone centers originate northwest and southwest of Crete. More specifically, approximately 55 % of the cyclones are generated northwest and about 15 % southwest of Crete.

Regarding seasonality, it can be observed that winter has the greatest percentage of northwest cyclones (∼ 60 %) and spring the least (∼ 45 %) while the exact opposite holds for the cyclones originating from southwest directions. Also, the more intense the precipitation is, the greater percentage of cyclones originate southwest compared to northwest. This holds for all seasons but it is more profound in spring where northwest cyclones reach 40 % percent of the cyclones and southwest decrease to approximately 35 %. Both Flocas et al. (2010) and Trigo et al. (1999) agree that there is an observed increase of the North African tracks in spring compared to the other seasons in agreement to our findings. This difference between winter and spring is more profound for heavy rain events.

Overall, most cyclones for all rain categories originate principally from west directions. Northwest directions greatly outreach all the others except for heavy rain events in spring where most of the cyclones originate southwest. The increase of North African tracks is considered a dominant feature of the Mediterranean spring (Trigo et al., 1999).

The positions of the cyclones causing precipitation events to Crete are presented in Fig. 5. For both mild and strong rain the majority of the cyclones centers are located northern of Crete reaching approximately up to 60 and 50 % of the events, respectively. In comparison with mild rain, the cyclone centers located in the south become more frequent than the ones in the north when heavy rain occurs. Northwest and southeast sectors are those that principally contribute in the north and south directions respectively.

In the seasonal analysis, in all cases there are less north cyclone centers as precipitation gets more intense with proportional increase of cyclone centers located south. The most profound example of this behavior is spring where north cyclone centers decrease from 69 % in mild rain case down to 32 % for heavy rain and on the other hand south cyclone centers increase from 18 up to 47 %. In particular, southwest and northwest centers are the principal south and north cyclone centers in spring.

4.3 Cyclones affecting Crete: characteristics' histograms

A cyclone mechanism can be described by many parameters including its pressure, intensity, depth, radius and propagation velocity. These characteristics constitute measures of cyclonic systems' importance and influence (Simmonds and Keay, 2000).

The histograms of the values for these characteristics are presented in Fig. 6. The histograms concern the parameters of the cyclone centers which have a sufficiently close distance from the boundary we have defined for Crete. More specifically, according to their location they potentially affect Crete judging from their distance from the defined boundary and their radius.

According to the respective histograms, the values of pressure and radius follow normal distributions. On the other hand, intensity, depth and propagation velocity values have left skewed distributions. More than 85 % of the pressure values are in the range of 1002–1018 hPa with mean pressure 1010 hPa. So, most of the cyclone systems surrounding Crete are weak and moderate according to the classification of Maheras et al. (2001).

Approximately 80 % of the intensity values of the cyclonic centers extend from 0.3–1.1 hPa $^{\circ}$lat^{-2} and their mean approaches 0.86 hPa $^{\circ}$lat^{-2}. In addition, the majority of the cyclonic depth values are in the range 0.4–4.6 hPa giving a mean depth of 2.9 hPa close enough to 2.15–2.17 hPa mean depth found by Flocas et al. (2010) within eastern Mediterranean region. Also, the values extending from 3.2 to 5.4° lat concern 80 % of the cyclones' radius and the corresponding mean is 4.4° lat. This is in great agreement with Trigo et al. (1999) who approximately finds average cyclone radius 4.5° lat (or 500 km) in the Aegean region in winter and spring. Generally, the radius of Mediterranean cyclones is considerable smaller than that of Atlantic synoptic systems which reaches 18° (Lionello et al., 2006). Lastly, the majority of propagation velocity values are between 0.5 and 4.5 $\mathrm{m\,s^{-1}}$ having a mean of 2.8 $\mathrm{m\,s^{-1}}$. The propagation velocity range in which most of cyclone near appear includes 3.6–3.9 $\mathrm{m\,s^{-1}}$ characterizing eastern Mediterranean cyclone according to Flocas et al. (2010).

4.4 Cyclone-rain coincidence for Crete island: cyclone characteristics

In this section, we give a statistical overview of the cyclone characteristics for the cyclone systems associated with precipitation events in the island of Crete. Figure 7 demonstrates in box-whisker plots of pressure, intensity, depth, radius and propagation velocity of the cyclonic centers. The diagram of each characteristic shows for every rain category (*x* axis) and every season (background color band) the main statistical properties. The statistical significance of these characteristics is checked pair wisely for the different rain categories and seasons and the results are presented in detail in Tables 3 and 4 respectively. For the majority of pairs the differences between the populations of the characteristics are found to be significant. There follows an analysis for every cyclone feature according to Fig. 7.

The pressure diagram of Fig. 7 shows pressure decrease of the cyclone centers with the increase of precipitation. The lowest pressure values are observed in spring and the highest in autumn. The distribution of autumn pressures exhibits the smallest variations and winter the largest and this is the case for all cyclone center features. Also, for all seasons variability is smallest for heavy rain events. According to Table 3, pressure differences are statistically significant in all rain categories except strong-heavy events' which have significant differences in pressure only in spring. Concerning the different seasons, winter strong and heavy events' pressures do not have significant differences compared to annual pressures. Table 4 shows that the differences observed between the cyclone pressures for all the other seasons are significant.

The cyclone intensity for the different seasons and rain categories is also demonstrated. It appears from the graph that intense rain is associated with cyclones of greater intensity. In addition, the highest intensities are observed for winter and the lowest for autumn. Only for heavy rain events, for the majority of cases, cyclones are more intense in spring. Likewise, the depth of cyclonic centers associated with precipitation events shows an increasing magnitude with increasing rain intensity. This is expected taking into consideration that cyclone depth is considered to be a very satisfying measure for cyclone influence (Simmonds and Keay, 2000). The values of cyclonic depth are higher in winter period followed by spring and autumn. Generally, both intensity and depth have statistical significant differences for the rain categories and seasons except from a few cases which are not statistically significant. The corresponding results are presented in Tables 3 and 4.

Increasing magnitude is also observed for the radius of the cyclones effecting Crete. This is more evident for mild and strong rain. The radii of cyclones associated with heavy rain have negligible differences to those associated with strong rain especially in autumn which is also not statistically significant in contrast to the other seasons. Also, greater radius values are observed for winter cyclones followed by autumn and spring.

The last graph of Fig. 7 shows the cyclone propagation velocity. The propagation velocity of cyclones increases with the rain intensity. Thus, greater propagation velocity is observed for heavy rain compared to the other two rain categories. Additionally, higher cyclone velocities are observed in spring compared to the other seasons. The differences of propagation velocity for the rain categories are significant according to Table 3. Also, as shown in Table 4 statistical significant differences are found for the majority of propagation velocity seasonal pairs.

The characteristics of the cyclone centers whose appearance is associated with rain events in the island of Crete are presented in Fig. 8. In particular, the first column shows the average values of the characteristics for all three rain categories and the second column shows the average value for cyclone centers associated with heavy rain events. In order to identify possible patterns and trends in cyclone characteristics, the cyclone centers are considered according to their relative position to Crete (sectors as presented in Fig. 1).

For both average and heavy rain, the lower pressures are observed in spring followed by winter and autumn for all sectors. Generally, cyclones associated with heavy rain events demonstrate lower pressures than the average pressure. The different sectors have negligible variations except from the west sector which has the greatest pressures for both average and heavy rain in autumn and the lowest pressures in spring. This is more profound in heavy rain cases. Also, the north (N, NE, NW) cyclone centers have lower pressures than the south ones (S, SE, SW).

Cyclone intensity and depth seem to have relative behavior which is justified because depth is proportional to intensity (Simmonds and Keay, 2000). The lowest values are observed in autumn and the highest for winter and spring. Additionally, both intensities and depths are greater for heavy rain events. Annually, the west sector is found to have the greatest intensity and depth. Winter and spring are in agreement with this behavior with exception of autumn which has its greatest values in intensity and depth for southeast sector.

The cyclone radius is greater in winter and in most of the cases it has greater values for heavy rain in contrast to the average. Also, its lowest values are observed in autumn (west sector) and spring (northwest and northeast sector). The greatest radius magnitudes for all seasons are observed in the south sector.

The last cyclone characteristic presented in Fig. 8 concerns cyclone propagation velocity which demonstrates its greatest values in spring and lowest in autumn for the majority of cases. Also, north sector has the lowest propagation velocity values compared to the other sectors and NW, W, SW sectors have the greatest. Additionally the cyclone propagation velocity is greater for heavy rain rather than the average case.

The results depicted in Fig. 8 provide an insight into location specific characteristics of the cyclones associated with precipitation events in Crete. In most cases, the cyclone characteristics per sector presented in Fig. 8 confirm the general behavior of the cyclone characteristics demonstrated in Fig. 7. Generally, seasonal differences among

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the sectors are observed as well as extreme values for heavy rain events. Concerning the sectors been defined, the west sector stands out demonstrating the lowest and highest values for the majority of cyclone characteristics in spring and autumn which is more profound in heavy rain case. Also, spring cyclone centers located at the north sector are distinguished for the low pressure and propagation velocity values as well as intensity, depth and radius magnitudes which are considerable high, compared to the other sectors.

5 Conclusions

In this work the main characteristics of cyclones associated with precipitation events in Crete have been explored for a 30 year period (1979–2011). The identification, tracking and feature definition of the cyclones was accomplished with the aid of Melbourne University algorithm (MS scheme). This analysis allows us to better understand the behavior of atmospheric systems related to rainfall situations introducing a step by step methodology for the association of cyclones with rain. In addition, the study although of local nature, is concerned of great interest since Crete has a key location in the eastern Mediterranean basin.

It was found that for the majority of strong and heavy rain events, cyclones were detected nearby Crete and that the season of the greatest coincidence between rain and cyclones is spring followed by winter and autumn. In addition, it was verified that cyclones affecting Crete mainly originate from northwest followed by southwest. Passing from mild to heavy rain events, the proportional difference between the origination of the associated cyclone percentages is getting smaller. Also, the cyclone centers north of Crete were the main triggering mechanisms of mild and strong rain events followed by those located in the south. For events of greater rainfall this still applies, although the difference is slighter and especially in spring the majority of heavy rain events are caused by south cyclone centers.

The distribution of the values of the cyclone characteristics is normal for pressure and radius and left skewed for the rest of the characteristics. Moreover, increasing or decreasing trends can be distinguished for the characteristics of the cyclones associated with rainfall. A negative trend is observed for pressure and positive trends for intensity, depth, radius and propagation velocity with rain increase. Seasonally, in spring cyclones are more prone for lower pressures and greater cyclone propagation velocity while winter cyclones yield greater intensity, depth and radius. This behavior applies for the majority of the sectors considered around Crete, with some variations.

This study examines the characteristics of the cyclones associated with rainfall events in Crete. To the best of our knowledge, this is the first attempt to relate the characteristics of the cyclones such as pressure, depth and radius to rain intensity. Such information can be valuable and supplementary for forecasting purposes. Individually or in association with additional information, the development of a basic warning system for the management and mitigation of flood events can be achieved. Further analysis of the cyclonic tracks and characteristics projected by climate models can provide valuable information for the impact of global change on the atmospheric systems in the wider eastern Mediterranean.

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Table 1. The rain categories according to the daily rainfall amount.

Rain category	Rain amount ($\mathrm{mm\,day^{-1}}$)
Mild	10–50
Strong	50–100
Heavy	> 100

Table 2. Total number of precipitation events per season and per rain category for the period 1979–2011. Percent columns (%) represent the relative frequency of simultaneity of cyclone and rain.

	Mild Rain		Strong Rain		Heavy Rain		Mean coincidence %
	Events	%	Events	%	Events	%	
Annual	3402	54	966	70	278	76	67
Autumn	846	51	257	70	78	73	65
Winter	1720	54	540	68	159	76	66
Spring	760	59	156	75	37	81	72

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Table 3. Statistical significance results for the characteristics of "affecting" cyclones concerning the different rain categories. The statistical significant differences at 5 % significant level are noted with 1. Zero values followed by minus symbol (0–) are not significant in nor 1, 5 or 10 % significant level and plain zero values are significant at 10 % significant level.

Season	Mild-Strong	Mild-Heavy	Strong-Heavy
	Pressure		
Annual	1	1	0–
Autumn	1	1	0–
Winter	1	1	0–
Spring	1	1	1
	Intensity		
Annual	1	1	1
Autumn	1	1	0–
Winter	1	1	1
Spring	1	1	1
	Depth		
Annual	1	1	1
Autumn	1	1	0
Winter	1	1	1
Spring	1	1	1
	Radius		
Annual	1	1	1
Autumn	1	1	0–
Winter	1	1	1
Spring	0–	1	0
	Propagation Velocity		
Annual	1	1	1
Autumn	1	1	1
Winter	1	1	0
Spring	1	1	1

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Table 4. Statistical significance results for the characteristics of “affecting” cyclones concerning the different seasons. The statistical significant differences at 5 % significant level are noted with 1. Zero values followed by minus symbol (0−) are not significant in nor 1, 5 or 10 % significant level and plain zero values are significant at 10 % significant level.

Rain Category	Winter-spring	Winter-autumn	Winter-annual	Spring-autumn	Spring-annual	Autumn-annual
			Pressure			
Mild	1	1	1	1	1	1
Strong	1	1	0−	1	1	1
Heavy	1	1	0−	1	1	1
			Intensity			
Mild	1	1	1	1	1	1
Strong	1	1	1	1	0−	1
Heavy	0	1	0−	1	1	1
			Depth			
Mild	1	1	1	1	1	1
Strong	1	1	1	1	1	1
Heavy	1	1	1	1	0−	1
			Radius			
Mild	1	1	1	1	1	1
Strong	1	1	1	1	1	1
Heavy	1	1	1	0−	1	1
			Propagation Velocity			
Mild	0	1	1	1	1	1
Strong	1	1	0−	1	1	1
Heavy	1	0−	0−	1	1	0−

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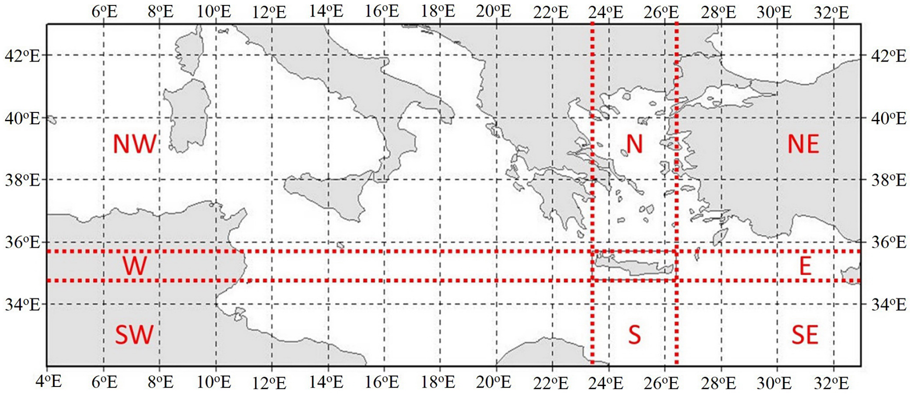

Figure 1. Geographical chart of the region analyzed where the sectors are displayed corresponding to the origin of the tracks.

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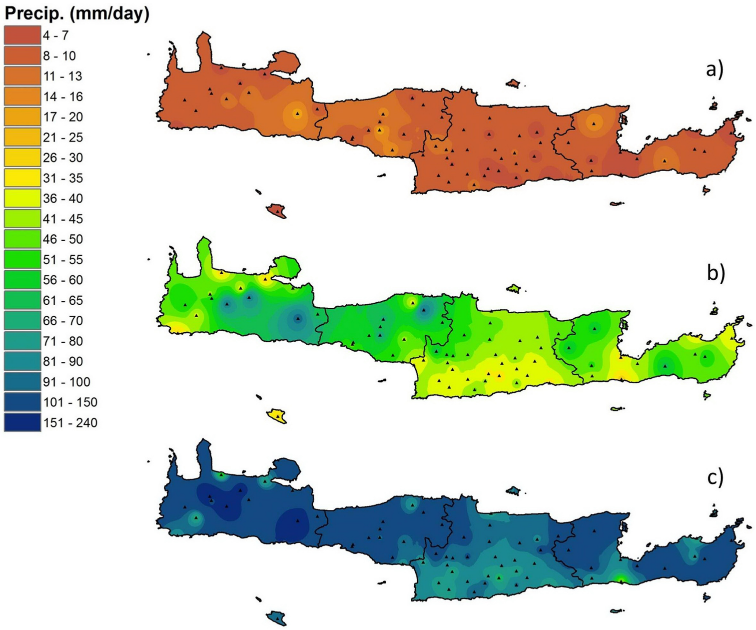

Figure 2. The precipitation of the gauge stations spatially interpolated by inverse distance weighting (IDW) for the **(a)** 50 percentile, **(b)** 95 percentile and **(c)** 99.5 percentile.

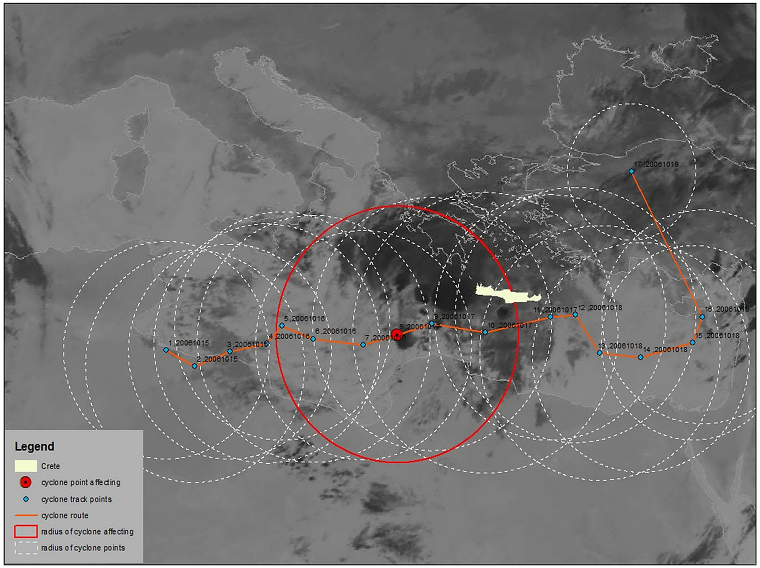

Figure 3. The route of the cyclone which caused the flash flood in Almirida on 17 October 2006. The background is the infrared METEOSAT image at 00.00 UTC on 17 October 2006.

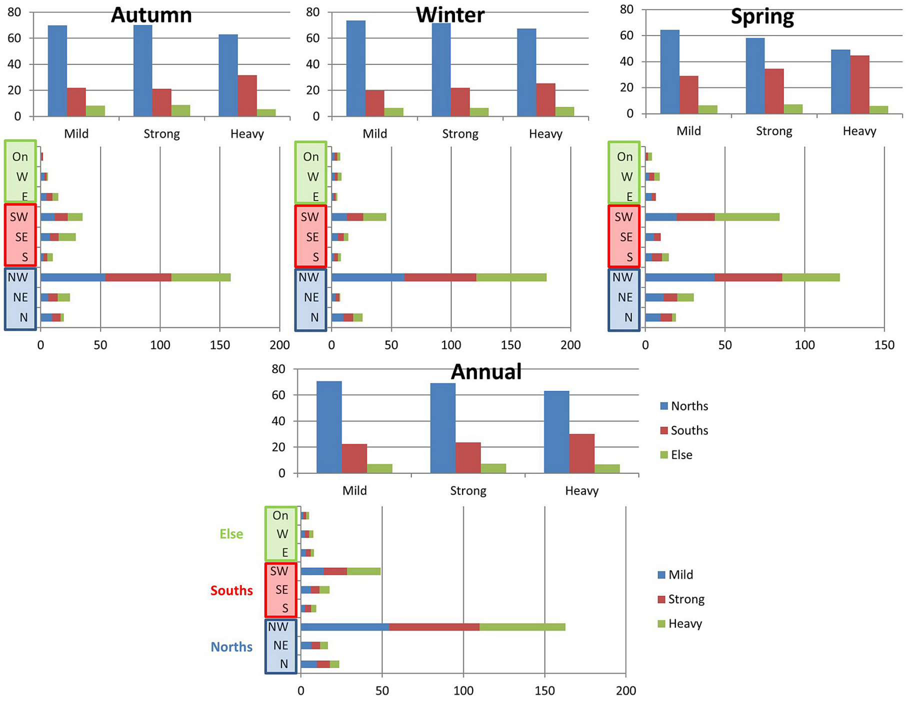

Figure 4. Annual and seasonal relative frequency (%) of the origination of cyclones affecting Crete, 1979–2011. The stacked bar diagrams concern every sector and the simple bar diagrams are the grouped results for north (N, NE, NW), south (S, SE, SW) and the rest (E, W, On) sectors.

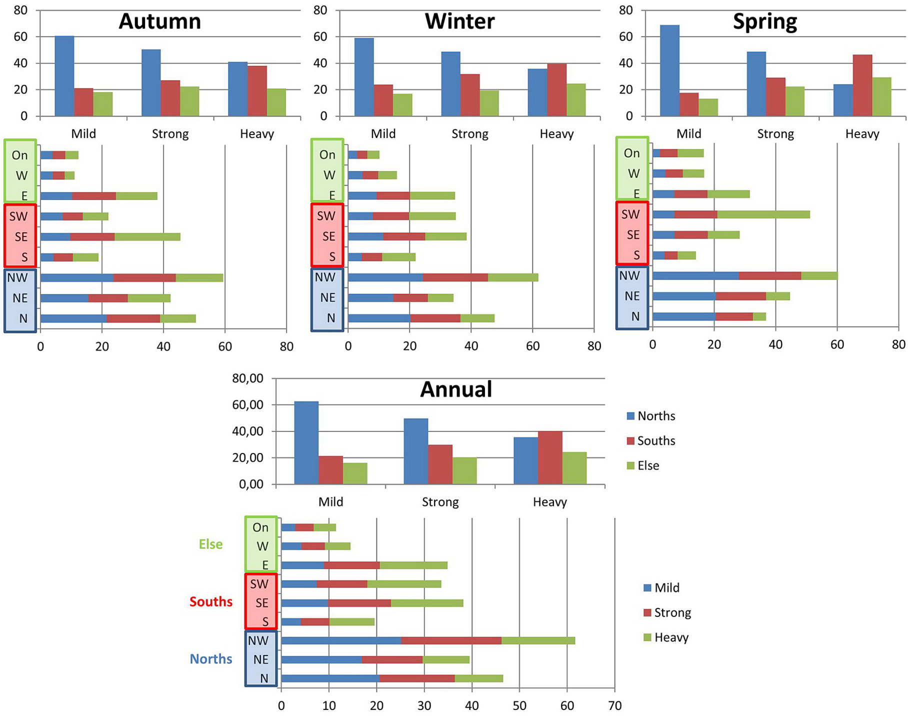

Figure 5. Annual and seasonal relative frequency (%) of the position of cyclones affecting Crete, 1979–2011. The stacked bar diagrams concern every sector and the simple bar diagrams are the grouped results for north (N, NE, NW), south (S, SE, SW) and the rest (E, W, On) sectors.

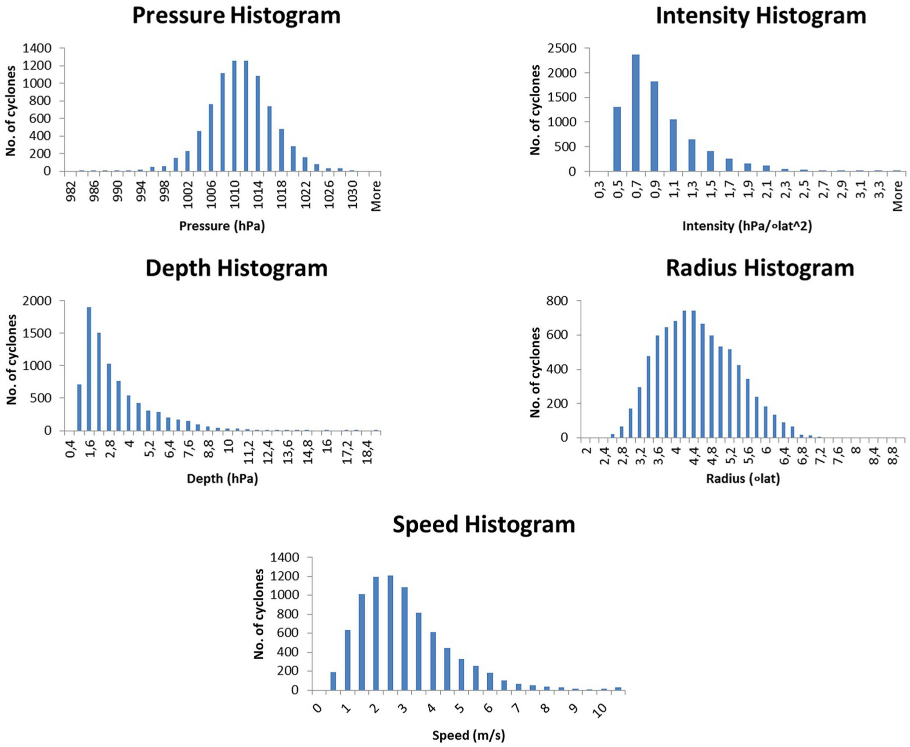

Figure 6. Histograms of the basic characteristics of the cyclone centers whose radius reach Crete domain.

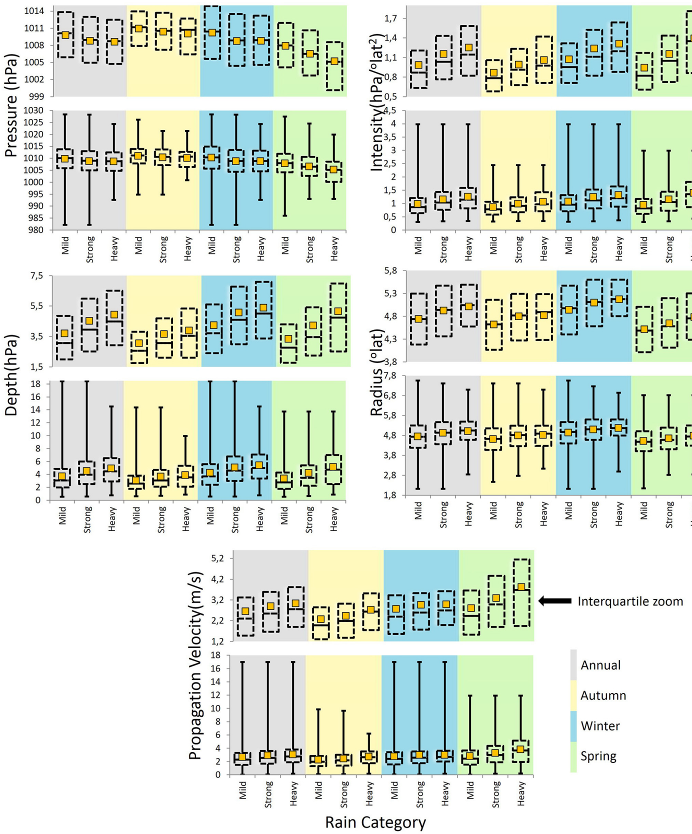

Figure 7. Seasonal and annual analysis of the basic characteristics of the cyclones triggering precipitation events to Crete island for the period 1979–2011, in box-whisker format.

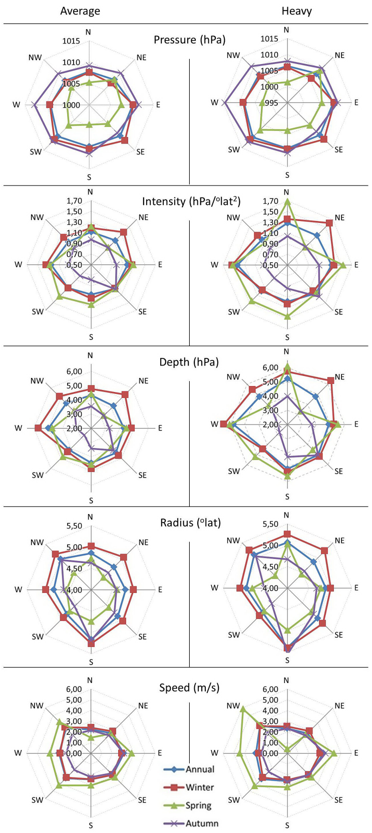

Figure 8. Seasonal and annual analysis of the basic characteristics of the cyclones triggering precipitation events to Crete island for the period 1979–2011. The left column concerns the average for all rain events and the right only heavy rain events.