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Medicanes Triggering Chlorophyll Increase

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Abstract: Studies have shown that hurricanes and typhoons, apart from being extreme weather phenomena, cause increases in marine chlorophyll-a concentrations and even phytoplankton blooms. Medicanes are the tropical-like Mediterranean cyclones that induce hazardous weather conditions as well. In this study, a couple of medicanes, over the central and eastern parts of the Sea, are examined for the first time in respect to their possible influence on chlorophyll concentrations. The affected area was delineated with the use of numerical model data, while the sea surface temperature and chlorophyll variations were assessed based on satellite-derived data. The results showed that medicanes trigger surface chlorophyll increases; after the cyclones' passage, the concentrations were higher compared both with those before and with the climatological monthly values over a large part of the affected area. The mechanisms proposed to explain hurricanes' favorable influence on chlorophyll concentration seem to be valid for medicanes as well. Area averaged chlorophyll concentrations presented analogous increases to the ones reported for hurricanes, though on a smaller scale. Despite the much lower intensity of medicanes compared with hurricanes, the observed increase in surface chlorophyll after their passage points to their favorable influence.

Keywords: Mediterranean; tropical-like cyclones; phytoplankton; sea surface temperature; satellite data; geographic information system (GIS)

1. Introduction

The Mediterranean Sea is characterized by a very high rate of cyclone formation and is ranked as one of the world's main regions for cyclogenesis [1–3]. In rare cases, the Mediterranean cyclones gain features of tropical cyclones: "eye", axisymmetry with spiral cloud bands, very strong surface winds and warm core [4,5]. Due to their similarities with hurricanes, these cyclones are called **Medi**terranean hurri**canes** or medicanes [4]. The associated extreme and hazardous weather conditions can cause significant damage over the sea and the coastal zones [6]. Medicanes usually begin as upper-level baroclinic disturbances (e.g., cutoff lows, troughs) and then evolve into tropical-like structures; this transition is highly dependent on upper-level potential vorticity anomalies and dry air intrusions, high low-level vorticity and surface heat fluxes, high moisture, and deep convection [4,7–10]. The above procedures involve sea surface temperature (SST) plus the upper atmospheric layers and differentiate medicanes from tropical cyclones, where SST plays the major role [7]. Medicanes are much weaker than hurricanes; however, a few of them have reached Category 1 of the Saffir–Simpson scale [11,12]. Heavy rainfall and deep convection, caused by these extreme lows, usually precedes their tropical-like phase during which precipitation is less and scattered in rainbands [13,14]. Climatological approaches have estimated the medicanes' frequency to ~1.5 per year for the whole basin [6,15,16]; they have also indicated the most common regions for medicane formation: the western Mediterranean (around the Balearic islands) and the Ionian Sea (often extended southward to the North African coast) [6,14,16,17]. The frequency of medicane formation is higher in autumn and winter, decreases significantly in spring and tends to zero during summer [6,14–16]; this preferred period for formation is another difference from tropical cyclones, which are formed during periods of high SST. A frequency decrease along with an intensity increase is predicted for medicanes in the following years [15,18–20].

Tropical cyclones have been studied in respect to their possible influence on chlorophyll-a (chl-a) concentration, as an indicator of phytoplankton growth, mainly with the use of satellite data and in some cases with field measurements. The studies refer both to hurricanes in the Atlantic ocean [21–27] including oligotrophic marine areas [23,27] and typhoons in the Pacific ocean [27–30]; their results indicate an increase in chlorophyll concentration and primary production and even phytoplankton blooms. A decrease in SST is observed in all cases, as it has been proposed for cyclones, due to upwelling, vertical mixing, and deepening of the mixed layer depth (MLD) together with cooling due to heat fluxes towards the atmosphere [31,32]. Most studies highlight the role of cyclone induced upwelling and wind mixing process in lowering SST and providing the upper sea layers with nutrients from below, resulting in enhanced phytoplankton growth and increased chl-a concentration [22,23,25,27,29,30]; the favoring role of heavy rainfall for the observed increase in chlorophyll is also proposed [22,27]. The high chlorophyll concentration after the passage of a cyclone is not attributed as a whole to new production triggered by the increased nutrient availability; an upward displacement of mid/deep chlorophyll maxima has been proposed as another reason [22–24].

The Mediterranean Sea is affected from time to time by medicanes, that could also have an influence on the Sea's primary production. However, relative studies have not been conducted until now, and this is exactly the attempt of the present work. It is noted that algal blooms are natural processes occurring under favorable environmental conditions. Various reasons, such as extreme meteorological conditions as those studied here, could lead to an increase in phytoplankton, which in turn could provoke substantial perturbations of the entire food web structure and functioning. In addition, for the oligotrophic Mediterranean environment, every factor that could lead to an increase in primary production is considered significant. Hence, the possible impact of medicanes on the Sea's surface chlorophyll concentration is explored here. The study is focused on events that affected the central or eastern parts of the basin, that are in general oligotrophic areas characterized as "non-blooming" [33] and reach their higher chlorophyll concentrations by the end of winter–beginning of spring period [34]. Three cyclones, that have been identified as tropical-like ones in bibliography, were examined. Numerical model data were used for delineating the sea area affected by the medicanes and satellite-derived data for computing the variations in SST and chlorophyll. An increase in chlorophyll concentrations was observed after the cyclones' passage for a very high percentage of the affected area in all cases, while the involved procedures seem to be the same as for hurricanes. The chl-a concentrations after the events were also higher than the climatological monthly values for a large part of the impacted region. Area averaged chlorophyll presented an increase which is comparable, though on smaller scale, to the one caused by hurricanes when affecting oligotrophic waters. Considering the lower medicanes' intensity compared to that of hurricanes, the results of the current study are, at least, supportive regarding their positive influence on surface chlorophyll concentration.

2. Materials and Methods

The Mediterranean tropical-like cyclones that are studied here, in respect to their possible influence on marine chlorophyll concentrations, have been identified as medicanes in bibliography. They were all formed east of the Strait of Sicily, affected a quite large area of the central-eastern part of the Sea and during their lifetime they presented sea level pressure below 1000 hPa.

The study area affected by the medicanes was delineated by the higher closed isobaric surface presenting symmetry at the time of minimum pressure—quite arbitrary although based on the axisymmetric structure of the medicanes—plus 10 m wind speed >17.5 m/s (i.e., gale force) [20,35] adjacent to the low pressures. For this procedure, the hourly data (mean sea level pressure and 10 m wind speed) from the European Centre for Medium-Range Weather Forecasts ERA5 high-resolution reanalysis project (ECMWF ERA5) were used (of 31 km native resolution and bilinearly interpolated at 0.125°). The track of the cyclone was based on the same data and was determined by the minimum pressure. The properties of tropical-like cyclones in the Mediterranean are usually studied using finer resolution numerical models; otherwise an underestimation in minimum pressure and wind intensity is possible. Therefore, the data used here for delineating the affected region, in the way described above, has possibly led to a smaller study area undoubtedly influenced by the extreme event.

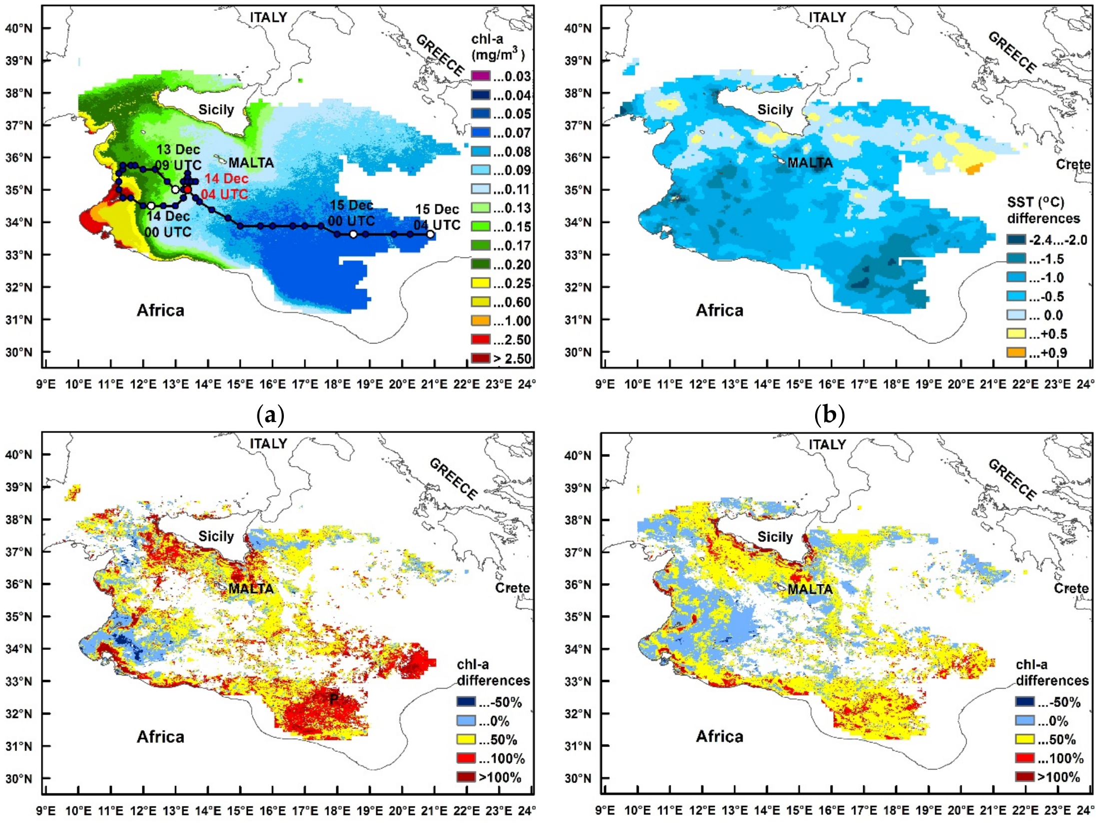
The response of the marine environment was assessed by calculating SST differences. The results presented here refer to the differences between 3 days before and after the events, while for selected areas an ~11-day time period centered on the events was considered for SST variations. The data used were derived from the high resolution (0.04°) SST daily mean (L4) product of the Copernicus Marine Environment Monitoring Service (CMEMS); this dataset (SST MED SST L4 REP OBSERVATIONS 010 021) is the nighttime Pathfinder V5.3 Advanced Very High Resolution Radiometer (AVHRR) product, provided by the National Oceanic and Atmospheric Administration (NOAA), reprocessed through an optimal interpolation algorithm for the production of daily gap-free maps. The chlorophyll data of the study also come from CMEMS: daily (OCEANCOLOUR MED CHL L3 REP OBSERVATIONS 009 073), weekly and monthly (OCEANCOLOUR MED CHL L4 NRT OBSERVATIONS 009 041) surface chlorophyll concentrations (at 1 km resolution) from multi-satellite observations. Further details for the CMEMS datasets used here can be found at http://marine.copernicus.eu. The possible influence of the meteorological phenomenon on chlorophyll concentrations was examined by calculating the percentage differences between the maximum concentrations of 5 days after the event and 5 days before it. It is noted that a time interval of 2 to 4 days for chl-a increases has been reported in cases of tropical cyclones [24,26,27]. The day just before the event was excluded, since chlorophyll increases have been found 1 day before a hurricane's passage [27]; in any case, during this day the available data were very limited. Chlorophyll percentage differences of the 5 days after the medicanes and the respective monthly climatological values of the period 1996–2016 were also calculated to highlight the significance of the influence. The above calculations were also performed on a weekly basis, using 8-day data as in other studies [23]. In all results, the absolute chlorophyll percentage differences that exceed 50%—the approximate difference reported between *in situ* observations and chl-a satellite data [36]—and could be considered more significant are mentioned separately. For the open sea oligotrophic area with distance from coast >50 km plus climatological chlorophyll concentration values <0.2 mg/m^3, the averages of the maximum chl-a values 5 days before and after the event were computed; a paired t-test was applied to check the statistical significance of these variations. Averaged daily values for SST and chl-a were computed for a period of ~11 days around the day of minimum pressure, for the areas along the cyclone's track (50 km width) and for areas that presented a large increase in chlorophyll concentration (P areas), in an effort to further explore the phenomenon. It is noted that even if the analysis of ERA5 did not depict the exact cyclones' track—a difficult task for numerical models—the along-track areas are at least areas very near to it; the P areas are all in the open sea and present low climatological chl-a concentration. It should be noted that the calculations of the area averaged chlorophyll concentrations are quite indicative due to lack of data at different area's locations each day. The major part of data processing was performed in the framework of a geographic information system (GIS).

The wind intensity and the total rainfall amount are commented as well. Regarding rainfall, the precipitation sum for the period one day before the event until one day after it was considered —as referred in the introduction, higher amounts of rain are expected just before the tropical-like phase of the cyclone. The precipitation data are TRMM (Tropical Rainfall Measuring Mission) daily values obtained through the Giovanni online data system.

3. Results

3.1. The Medicane of 13 to 15 December 2005

The cyclone of 13 to 15 December 2005 has been more than once recognized as a medicane [7,13,14,37]. The minimum pressure computed differs from study to study, e.g., 986 hPa [14], 980 hPa [37]. According to ERA5 reanalysis used here, the minimum pressure was 989.52 hPa and the maximum 10 m wind 25.38 m/s. The cyclone was formed over the southeast of Malta on 13 December, travelled first westwards and then moved to the east, gained its minimum pressure and continued its eastward track moving faster and increasing its central pressure. The isobaric surface used in this case for determining the medicane affected area was 1000 hPa. The area studied (of about 510,000 km^2) and the cyclone track, together with the mean 1998–2016 chlorophyll-a concentration for December, are shown in Figure 1a. The major part of the study area has been characterized as no blooming and its southwestern part as coastal [33].



(**a**) (**b**)

(**c**) (**d**)

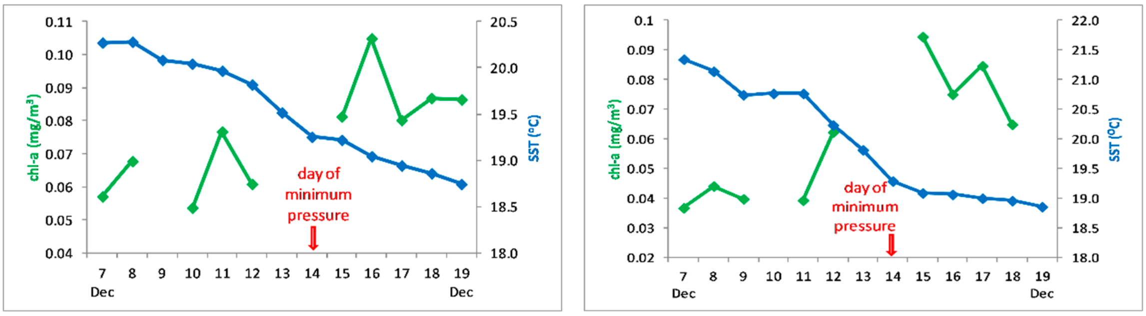
Figure 1. (**a**) The study area together with the mean 1998–2016 chlorophyll-a concentration for December and the medicane's track. Day and hour refer to the white dots while the red dot denotes the minimum pressure; (**b**) Sea surface temperature (SST) differences between 11 and 17 December 2005; (**c**) Chlorophyll percentage differences between the maximum concentrations of 5 days after the event (15–19 December 2005) and 5 days before (7–11 December 2005), P denotes the area of large chlorophyll increase referred in the text; (**d**) Same as (c) for the 5 days after the event and December 1998–2016 climatology.

SST differences between 11 and 17 December 2005 (Figure 1b)—3 days before and after the central day of the event (14 December)—revealed a drop over 95.5% of the area and presented differences <−1 °C for 40.6% and <−1.5 °C for 9.3% of the area. The region near the medicane's track and south of it, i.e., over the right side of the track, presented the maximum SST drop.

The differences between the maximum chlorophyll concentration of 5 days after the event (15–19 December 2005) and 5 days before the event (7–11 December 2005) are given in Figure 1c; 77.5% of the study area presented an increase in chlorophyll concentration, while over 30.4% of the area chlorophyll percentage increases were >50% and over 8.6% were >100%. It is noted that a large proportion of chlorophyll increases exceeding 50% was observed over the open sea and not near the coastal areas, especially over the oligotrophic southeast part of the study area. The absolute chlorophyll differences >50% (that could be considered as significant) were found for 31.9% of the study area and were by 95.3% increases. The comparison between the chlorophyll concentrations of the 5 days that followed the event with the 19-year climatological values for December is shown in Figure 1d. Chlorophyll values after the medicane's passage were greater than the climalogical ones for 63.0% of the area; these increases were >50% for 10.1% of the area, while more than doubled concentrations were observed for 2.2%. The absolute differences >50% covered 10.5% of the area and were by 96.2% increases. It is noted that over 76% of the area that presented a drop in SST (as presented in Figure 1b), a chl-a increase was observed. The maximum 10 m wind speed during the episode and the total precipitation between 12 and 16 December 2005—maximum values were recorded during the episode—are given in Appendix A (Figure A1). The large southeastern area of more than doubled chlorophyll concentrations was mainly affected by high winds and presented a decrease of 1 to 2 °C in SST; these findings denote that upwelling and wind mixing were the mechanisms that caused the observed chl-a increase. There are regions of significant chlorophyll increases that were affected by high winds and/or extreme rainfall. The northern coastal areas were affected by large precipitation amounts plus high winds, while SST presented a smaller decrease or a slight increase; the chlorophyll increase of this area should rather be attributed both to nutrients brought by precipitation and/or river discharges and wind mixing processes. An important chl-a decrease was observed over the southwest of the study area in a region of generally high concentrations that was affected by both large precipitation amounts and very high winds. The means of the maximum chlorophyll concentrations observed before and after the event for the open oligotrophic sea area were found to differ in a statistically significant way; they were 0.070 mg/m^3 and 0.087 mg/m^3 respectively, revealing a 24.3% increase, while SST mean dropped by 1.1 °C.

Chlorophyll percentage differences between the week after the event (19–26 December 2005) and the week before the event (3–10 December 2005) showed an increase for 81.7% of the area, with increases >50% covering 20.7% and those >100%, 3.7% of the area; the absolute differences >50% referred to 21.6% of the area and were by 95.7% increases (Figure A2a). These differences revealed that the enhanced chlorophyll concentrations were sustained and further confirmed, as the daily data did, that the largest chlorophyll increases were not observed along the medicane's track but over neighboring regions. Chlorophyll concentrations during the week after the event compared to December climatology (Figure A2b) were greater for 46.3% of the area, with the absolute differences above 50% referring to 3.3% of the area and being by 94.4% increases.

Over a 50 km width area along the medicane's track and for the area of chlorophyll increase marked with P in Figure 1c, mean chl-a and SST values were computed for the time period 7 to 19 December. For the area along the track of 14 December (Figure 2a) SST decreased by 1.5 °C and chl-a increased by 36.4%; for the area along the track of 15 December (not shown) the decrease in SST was 1.6 °C and the increase in chlorophyll 52.6%; the P area (Figure 2b) presented a cooling of 2.5 °C and an increase in chlorophyll of 51.6%. In all cases the SST drop began before the main day of the event, became more abrupt just before or during it and continued after it; chlorophyll mainly increased during the event or just after it while an increasing trend 2 days before was also implied (Figure 2b).



(**a**) (**b**)

Figure 2. Mean chlorophyll concentration and SST for the time period centered on the event examined (**a**) For the 50 km width area along the cyclone's track on 14 December 2005; (**b**) For the area of chlorophyll increase marked with P in Figure 1c.

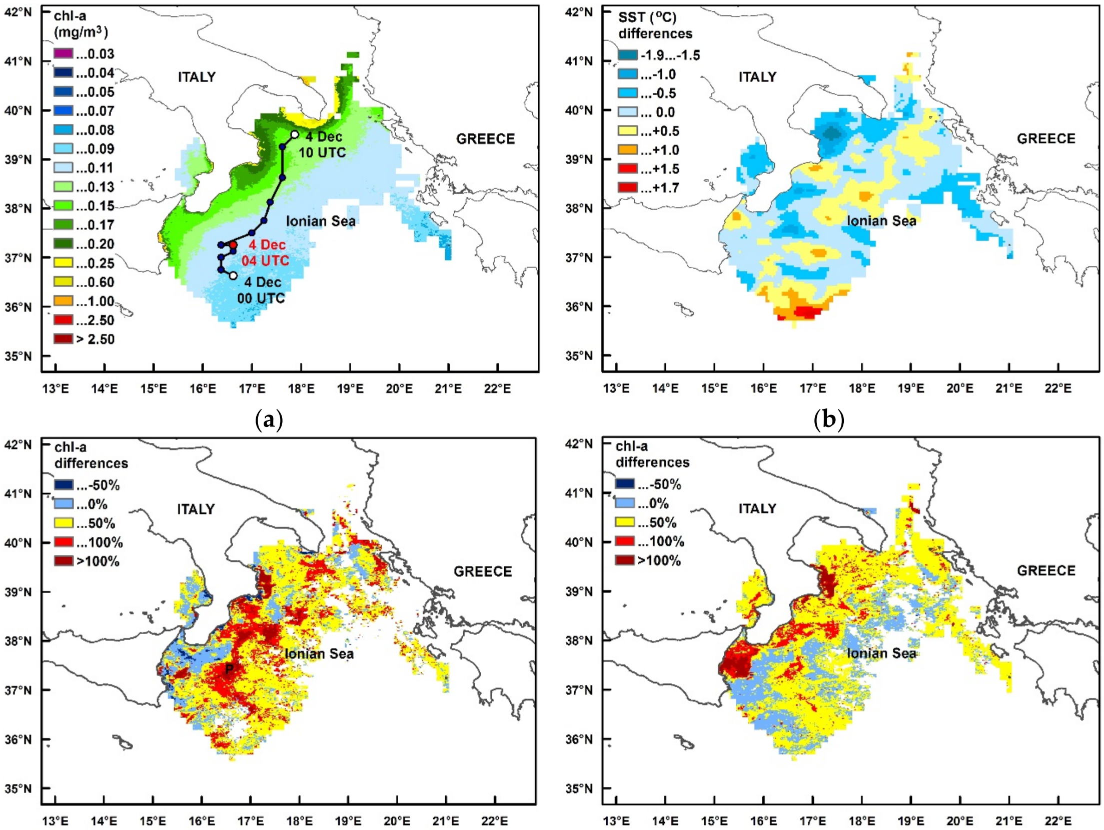
3.2. The Medicane of 4 December 2008

The cyclone of 4 December 2008 has been identified as a medicane with a minimum pressure of 990 hPa [14]. According to the model analysis used here, the minimum pressure was 986.7 hPa and the maximum 10 m wind speed 20.43 m/s; the pressure of 995 hPa was used for delineating the affected area. The phenomenon took place over the Ionian Sea between Italy and Greece; the cyclone was formed east of Sicily, gained its minimum pressure and moved north-northeastwards.

The study area of about 125,000 km^2 along with the track of the medicane and the 19-year monthly chlorophyll climatology map are shown in Figure 3a. The area studied here has been characterized, in general, as non-blooming with some intermittently blooming parts [33].

SST differences 3 days before and after the event (between 1 and 7 December 2008) are presented in Figure 3b; they revealed a decrease over 72.2% of the area, with values <-1 °C for 4.6% and <-1.5 °C for 0.6% of the data. The SST decrease, in this case, was much smaller than the one of the previous case and did not present a concrete pattern.

Chlorophyll concentration differences between the maximum values of 5 days after the event (28 November–2 December 2008) and 5 days before it (5–9 December 2008) were increases for 79.1% of the area (Figure 3c), while 26.2% of the area presented increases >50% after the event and 6.7% more than doubled concentrations. Absolute chl-a differences >50% referred to 27.8% of the data and were by 94.1% increases; many of them were observed over the open sea area presenting oligotrophic climatic characteristics. Over 58.8% of the area of SST decrease (presented in Figure 3b), an increase in chlorophyll was observed. The maximum chlorophyll concentrations of the 5 days after the event, compared to December climatology (Figure 3d), were found higher for 73.1% of the area, with differences >50% for 13.3% and more than doubled values for 3.8% of the data; the absolute differences >50% referred to 13.4% of the data and they were increases by 96.0%. In this case, the increase in chlorophyll concentration was observed along the medicane's track as well as in some coastal areas; similar to the previous case examined, chlorophyll increases were found to be significant over the open sea. A region over the southwestern part of the study area presented a significant chlorophyll decrease; it is surprising that chl-a concentration after the event was still greater than the climatological value. The maximum 10 m wind speed during the event and the precipitation sum of 3 to 5 December 2008 are shown in Figure A3. It is noted that the highest rainfall amount was recorded on 3 December, i.e., one day before the cyclone gained its tropical characteristics. A large part of the open sea that presented a large increase in chlorophyll concentrations was affected by both strong winds and heavy precipitation, while the coastal areas mainly by large rainfall amounts. Taking in mind that the SST decrease, in this case, was quite low, the increase in chlorophyll could be mainly attributed to mixing processes due to the very strong winds plus nutrients from rain. For the open sea oligotrophic area, the difference of the mean chl-a concentration before and after the event was again statistically significant. The values were 0.083 mg/m^3 before and 0.110 mg/m^3 after the cyclone, revealing a 32.5% increase; however, SST mean dropped by only 0.1 °C.



(**a**) (**b**)

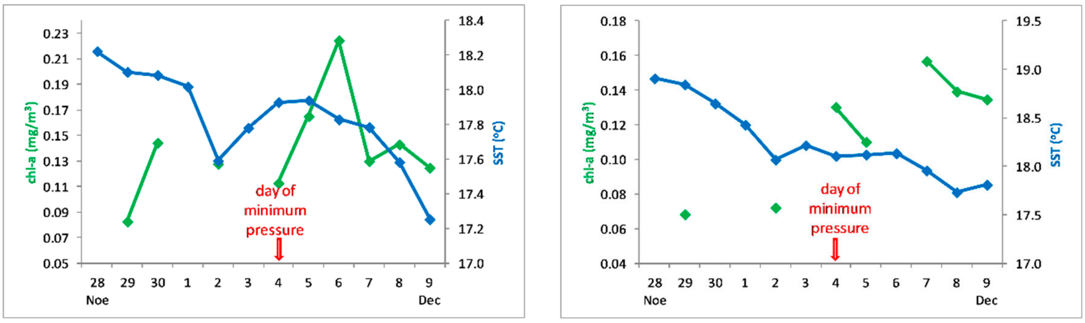
(**c**) (**d**)

Figure 3. (**a**) The study area together with the mean 1998–2016 chlorophyll-a concentration for December and the medicane's track. Day and hour refer to the white dots while the red dot denotes the minimum pressure; (**b**) SST differences between 1 and 7 December 2008; (**c**) Chlorophyll percentage differences between the maximum concentrations of 5 days after the event (5–9 December 2008) and 5 days before (28 November–2 December 2008), P denotes the area of large chlorophyll increase referred in the text; (**d**) Same as (c) for the 5 days after the event and 1998–2016 December climatology.

The week after the medicane (10–17 December 2008) compared to the one of the event (2–9 December 2008) presented chlorophyll increases mainly over the neighboring areas to the track (Figure A4a). The observed increases covered 73.4% of the area, they exceeded 50% for 15.8% and referred to more than doubled concentrations for 4.2% of the area; the absolute differences >50% were present for 16.1% of the data and they were by 97.9% increases. Chlorophyll concentration differences of the week after the medicane and the one before (24 November–1 December 2008) (not shown) revealed an increase for 96% of the area (increases >50% for 55.2% and >100% for 12.2%, while the absolute differences exceeding 50% that referred to 55.2% of the data were all increases); however, the time difference between these two weeks is quite large. The chl-a concentrations of the week after the event compared to the climatological values (Figure A4b) were found higher for 83.6% of the area, and the increases exceeded 50% and 100% for 17.7% and 3.8% of the data, respectively; the absolute differences >50% referred to 17.8% of the data and they were by 99.5% increases.

Mean daily chl-a concentration and SST for the 50 km width area along the medicane's track and for the P area of Figure 3c were computed for the time period 28 November to 9 December. A decrease in SST of 1 °C plus an increase in chlorophyll of 55.6% for the along-track area and of 1.2 °C and 128%

respectively for the P area were observed (Figure 4). The SST drop began a few days before the event while chlorophyll started increasing during it.



(**a**) (**b**)

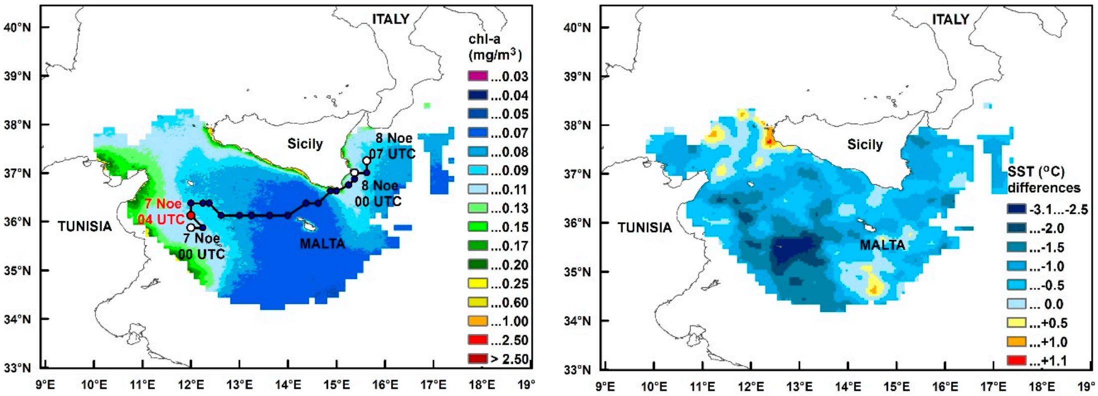
Figure 4. Mean chlorophyll concentration and SST for the time period centered on the event examined (**a**) For the 50 km width area along the cyclone's track on 14 December 2008; (**b**) For the area of chlorophyll increase marked with P in Figure 3c.

3.3. The Medicane of 7–8 November 2014

The medicane of 7–8 November 2014 has been named Qendresa by the Free University of Berlin and has been studied several times [9,38]. It was formed south of Sicily on 7 November 2014 and made landfall at Malta on 7 November and at eastern Sicily on 8 November; a minimum mean sea level pressure of 984 hPa was recorded at Malta [38]. According to the model analysis used here the minimum pressure was 991.6 hPa and the maximum 10 m wind speed 23.15 m/s; for determining the study area the isobaric surface of 1000 hPa was used.

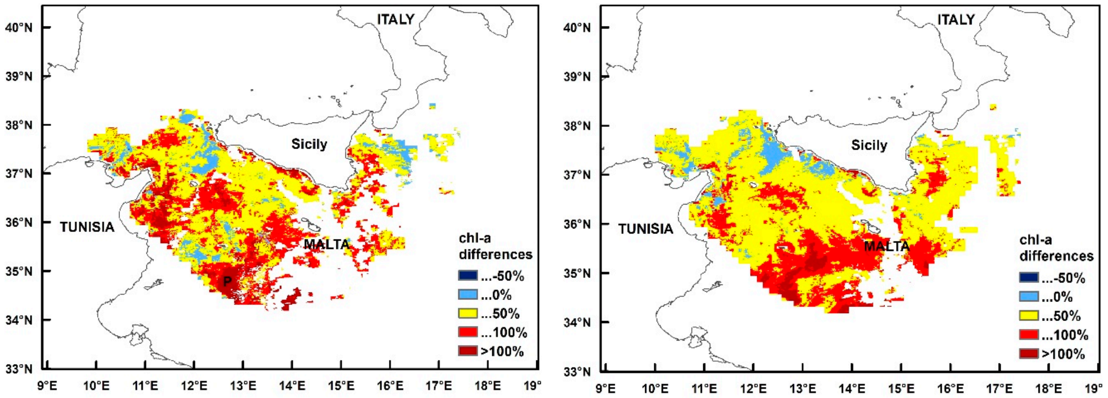
In Figure 5a, the cyclone's track and the study area (about 160,000 km^2) along with the November chlorophyll climatology are shown; this area has been, in general, characterized as a non-blooming one [33].

SST differences between 4 and 10 November 2014—3 days before and after the event—presented a decrease for 96.9% of the area and they were <−1 °C for 49.9% and <−1.5 °C for 20.8% of the area (Figure 5b); these decreases were the largest of the cases examined in this paper, and the maximum ones were mainly observed over the right side of the cyclone's track.



(**a**) (**b**)

Figure 5. *Cont.*



(**c**) (**d**)

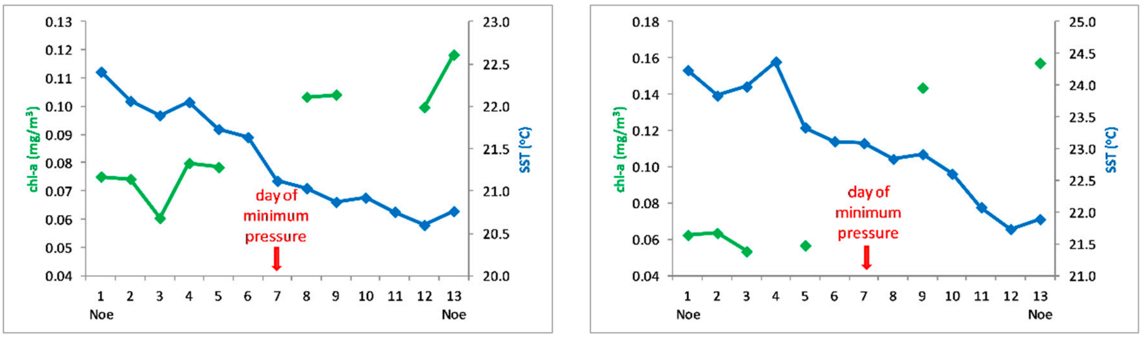
Figure 5. (**a**) The study area together with the mean 1998–2016 chlorophyll-a concentration for November and the medicane's track. Day and hour refer to the white dots while the red dot denotes the minimum pressure; (**b**) SST differences between 4 and 10 November 2014; (**c**) Chlorophyll percentage differences between the maximum concentrations of 5 days after the event (9–13 November 2014) and 5 days before (1–5 November 2014), P denotes the area of large chlorophyll increase referred in the text; (**d**) Same as (c) for the 5 days after the event and 1998–2016 November climatology.

The differences in maximum chl-a concentrations between 5 days after the event (9–13 November 2014) and 5 days before it (1–5 November 2014) that are shown in Figure 3c revealed an increase in chlorophyll for 91.1% of the study area; this increases exceeded 50% for 39.9% of the data, and the values were more than doubled for 10.5%. It is noted that over 89.4% of the area that presented SST decrease (presented in Figure 5b) an increase in chlorophyll was observed. The absolute chl-a differences >50% referred to 39.9% of the data and they were all increases. The chl-a concentrations of 5 days after the event compared to November climatology (Figure 5d) revealed higher values for 93.3% of the area, that were >50% and >100% for 29.1% and 4.4% of the data, respectively. The absolute chlorophyll differences >50% between the 5 days after the event and climatology were 29.1% of the data, and they were all increases. Both the above comparisons showed larger chlorophyll increases over the right side of the cyclone's track and over the oligotrophic open sea. The maximum 10 m wind speed during the event and the total precipitation for the period 6–8 November 2014 are given in Figure A5; it is noted that the higher rainfall amounts were recorded the day before (6 November) the cyclone gained its tropical characteristics. The area of the larger increase in chlorophyll (on the right side of the track) coincided with the area of the stronger winds and the higher precipitation amounts; in this case, the increased chlorophyll concentrations should rather be attributed to both upwelling and mixing processes plus the favoring role of precipitation. The mean chl-a concentrations, for the open sea oligotrophic area, presented a statistically significant difference before and after the event; the averaged chlorophyll value was initially 0.075 mg/m^3 and reached 0.119 mg/m^3, revealing a 58.7% increase. The SST mean decreased by 1.1 °C.

The chlorophyll differences between the week after the event (9–16 November 2014) and the week of the event (1–8 November 2014) that are given in Figure A6a, revealed increases for 94.8% of the area. These increases were >50% for 41.3% of the data and >100% for 6.9%; the absolute percentage differences exceeding 50% referred to 41.3% of the data, and they were all increases. Comparing the chlorophyll concentrations of the week after the medicane with November climatology (Figure A6b), the values were higher for 95.5% of the area, with differences >50% for 18.8% of the data and >100% for 0.5%; the absolute percentage differences exceeding 50% referred to 18.8% of the area and they were all increases.

Over the 50 km width area along the cyclone's track on 7 December and for the P area of Figure 5c that presented a significant chlorophyll increase, mean values were computed for chl-a and SST on a daily basis for the time period 1–13 November. Over the along-track area (Figure 6a) SST decreased by

1.8 °C and chl-a increased by 47.5%; the P area (Figure 6b) presented a decrease of 2.5 °C in SST and a chl-a increase of 145%. In this case also, the SST drop began before the main day of the event and continued a few days after it; chlorophyll increased during and after the event.



(**a**) (**b**)

Figure 6. Mean chlorophyll concentration and SST for the time period centered on the event examined (**a**) For the 50 km width area along the cyclone's track on 7 November 2014; (**b**) For the area of chlorophyll increase marked with P in Figure 5c.

4. Discussion

In all three cases studied, a post-medicane increase in surface chlorophyll concentrations was observed over a large percentage of the affected area. This chlorophyll increase, during the time period after the medicanes' passage, was revealed by the calculations performed both on a daily and weekly basis. The comparison between the chlorophyll concentrations after the events and the respective monthly climatology revealed higher values after the events over large areas as well. The relevant results are summarized in Table 1. If absolute percentage chlorophyll differences exceeding 50% are considered as more reliable (their percentage of increases are given in parenthesis in Table 1), chlorophyll increases characterized the whole study areas. It is noted that the 7–8 November case presented the wider area of chlorophyll concentration increase after the event. Analogous results can be derived by the chlorophyll values averaged over the open sea oligotrophic areas, the along-track areas and the areas presenting enhanced chlorophyll increases (P areas); in Table 2 the percentage increases in chlorophyll for these areas, during an ~11-day time interval centered on the cyclone passage, are shown. A decrease in SST was also observed in all cases; the SST differences between the values 3 days before and after the event, presented a decrease over 95.5%, 72.2%, and 96.9% of the area, respectively for the three cases examined. SST, during these days, dropped by more than 1 °C over 40.6%, 4.6%, and 49.9% of the study area for the three cases. The averaged SST values over the track areas and the P areas, during the ~11-day time interval centered on the medicane, revealed a more pronounced SST decrease; these decreases are summarized for all cases in Table 2. Again, the larger SST decrease (as the increase in chlorophyll) referred to the 7–8 November 2014 case, although the 13–15 December 2005 event presented a comparable SST drop.

Table 1. Chlorophyll increases in percentages of the affected area for the three medicanes, as revealed by the 5-day (5d) and the weekly (w) chlorophyll data before and after the event. The percentages of absolute chlorophyll differences exceeding 50% that were increases are given in parenthesis.

Medicane	Chlorophyll Increase after-before (Area %)	Chlorophyll Increase after-Climatology (Area %)
13–15 December 2005	5d: 77.5 (95.3) w: 81.7 (95.7)	5d: 63.0 (96.2) w: 46.3 (94.4)
4 December 2008	5d: 79.1 (94.1) w: 73.4 (97.9)	5d: 73.1 (96.0) w: 83.6 (99.5)
7–8 November 2014	5d: 91.1 (100) w: 94.8 (100)	5d: 93.3 (100) w: 95.5 (100)

Table 2. Chlorophyll percentage increase and SST decrease of their averaged daily values during a time period of ~11-days centered on the event, for the oligotrophic open sea area, the 50 km width along-track area, and the areas of positive chlorophyll differences (P-areas).

Medicane/Areas	Chlorophyll Increase (%)	SST Decrease (°C)
13–15 December 2005		
14 Dec track area	36.4	1.5
15 Dec track area	52.6	1.6
P area	51.6	2.5
Open sea area	24.3	1.1
4 December 2008		
4 Dec track area	55.6	1.0
P area	128	1.2
Open sea area	32.5	0.1
7–8 November 2014		
7 Nov track area	47.5	1.8
P area	145	2.5
Open sea area	58.7	1.1

Over near coast regions, characterized by higher chl-a climatological values than the rest of the study area, a significant decrease in chlorophyll concentrations was locally recorded in two cases (December 2005 and December 2008). Such a decrease has also been observed in a similar study for a coastal Pacific region [28], and the destruction of phytoplankton cells caused by the strong cyclone shear has been proposed as a possible reason [39]. Low chlorophyll concentrations have also been resulted for shelf regions from a model simulation study and have been attributed to upwelling of water originating below the mixed layer and characterized by decreased chl-a content [40]. A credible explanation could also be that water from the open sea is transferred into these areas due to the extreme phenomenon and reduces chlorophyll concentrations [41] or that the reinforced prevailing winds shift waters of high chlorophyll to the open sea. Concerning SST, it has been documented that hurricanes cause a decrease of several degrees by deepening the MLD some tens of meters [32]. They are expected to induce the largest SST drop on the right side of their track (northern hemisphere), where the winds are more intense, and the upwelling is maximized [31,32,42,43]. Such a pattern has been the result of a model study along with the maximum MLD [40] and has been observed in studies of tropical cyclones in respect to their influence on chlorophyll concentrations [22,25] coinciding with the regions presenting higher chlorophyll increases. Similarly, in all cases studied here, the stronger winds were also found on the right side of the medicanes' track; however, the maximum cooling was observed over this area in two out of the three cases. In the case of 4 December 2008 where the above characteristic was absent, the lower SST drop was induced over the affected area. In addition, this medicane moved rather faster compared to the others. For the tropical cyclones has been suggested that their speed is negatively related to their cooling effect [44], while model results have shown that slower moving storms induce deeper mixed layers [40]. An analogous pattern, with larger chlorophyll increases on the right side of the track, is implied by the results of this study and is clear enough for the 7–8 November case. It is noted that a quite large portion of the areas exhibiting a decrease in SST presented an increase in chlorophyll as well, 76%, 58.8%, and 89.4% for the three cases, respectively; the lower value refers to the 4 December 2008 case which was characterized by the smaller SST drop. In tropical cyclone cases, an abrupt SST drop coincides with the passage of the storm and SST continues decreasing after it. In the cases studied here, SST started decreasing some days before the event. This fact could be anticipated since upper-level disturbances that bring colder air masses pre-exist the formation of medicanes; another reason could be the mixing caused by the strong winds that prevail before the cyclone center reaches an area.

Comparisons in chlorophyll variations between the results of the present study and the ones for tropical cyclones could be made with the hurricane cases that have affected oligotrophic Atlantic regions. In a study of 13 hurricanes, for values averaged over the along-track area (a much wider area than the one examined here), chlorophyll increase exceeded 50% for only three of them [23]. These values are comparable with the results of the current study, even for the wide oligotrophic open sea areas (Table 2). However, while in hurricanes' cases, the maximum chlorophyll concentrations have been locally found much higher than the averaged values, the latter is not observed here. It is noted that in the same study [23], the largest SST drop was 2.6 °C; such a value was observed here over the P areas of two cases (Table 2). In addition, a cooling of 2 °C and a chlorophyll increase of 26.1%, averaged over a large area of maximum changes, has been reported for a hurricane that affected the northeast Atlantic oligotrophic area [27], similar to the results of the present study. All the above mentioned indicate that tropical-like Mediterranean cyclones can also cause significant chlorophyll increases; these increases are comparable to the ones caused by hurricanes, though on smaller scale likewise the intensity of medicanes compared to the one of hurricanes.

Although there is a lack in the daily available chlorophyll data (especially for the day before the event), chlorophyll seems to start increasing during the medicanes' approach, passage or just after it. Increased chlorophyll concentrations were observed the days after the event in a large portion of the affected area, revealed as well by the relevant calculations of the week that followed. An increase in chlorophyll that initiated during the hurricanes' passage with the high chl-a values lasting for the following weeks have also been reported for cases in oligotrophic Atlantic waters [23]. It is also noted that model experiments have shown that the center of the storm lags the area of increased chl-a by several kilometers [40].

The open sea areas, where a large percentage of chlorophyll increase was observed, were usually impacted by both strong winds and high precipitation amounts; regarding the P areas examined, the one of the 13–15 December 2005 case was mainly affected by strong winds. The open sea areas presented a decrease in SST by more than 1 °C and the P areas up to 2.5 °C. The role of precipitation in increasing chlorophyll by adding nutrients from the atmosphere seems more significant over coastal areas that were also affected by land runoff and river discharges.

The main mechanisms that have been proposed to explain the increased chlorophyll concentrations following tropical cyclones, are the cyclone-induced upwelling and the wind mixing; they cause a breakdown of the water column stratification and deepen the mixed layer, resulting in inducing nutrients from deeper layers to layers near sea surface, enhancing, therefore, phytoplankton growth. It has been found that the amount of nutrients (e.g., nitrate) that are brought from the deeper layers under the influence of a storm and can further support primary production and chl-a increase is smaller for faster moving, less intense, and less extensive storms [40]. The procedures of upwelling and mixing, mentioned above, have also been proposed for hurricanes affecting the oligotrophic Atlantic waters [23], where the highest chlorophyll increases have been found in September and October, i.e., in time periods when the stratification starts breaking down; in a November case, when the MLD is the deepest of the hurricane season, a chl-a increase <20% has been found. The MLD of the region examined in the above-mentioned study is up to ~40 m in September, up to ~60 m in October and

~80 m in November [45]. The mechanisms of cyclone induced upwelling and wind mixing could also be valid here. The MLD is ~40–100 m for the study area of 13–15 December 2005 event, ~40–70 m for the area affected by the 4 December 2008 cyclone and ~20–50 m for the one of 7–8 November 2014 [46,47]. In the medicanes' affected regions studied, the water column stratification also starts collapsing mainly by the end of fall and the beginning of winter; the MLD is in general maximized during February while it is still quite shallow during the time periods studied here [46,47]. Under these circumstances, it is possible that the MLD deepens under the influence of the cyclone-induced upwelling and the strong winds' mixing, causing the SST to drop and importing nutrients to the upper layers from below, enhancing primary production. Note that in the case of 7–8 November 2014, characterized by the shallower MLD, the most pronounced chl-a increases were observed.

An additional cause that has been documented for the increased chlorophyll concentrations caused by a hurricane's passage is an upward phytoplankton entrainment from the deep chlorophyll maximum (DCM) [22–24]. The above is further supported by the model study of [40] where the initial chlorophyll increase has been resulted from its redistribution within the mixed layer; the significance of the quite comparable depths of the DCM and the after-storm MLD for larger chl-a increases has been highlighted. Since Mediterranean is characterized almost all year long (with the exception of the end of winter) by a DCM in depths of 30 m in its western parts and up to 120 m in its eastern parts [48], such a procedure could have also taken part here. The favoring role of heavy rainfall in chlorophyll increase that has also been proposed in some studies [22,27] cannot be underestimated here since in many areas of increased chl-a concentrations large precipitation amounts were recorded; this is especially valid for the coastal areas as mentioned earlier.

5. Conclusions

The main results of this paper where three tropical-like Mediterranean cyclones (one November case and two December cases) were examined in respect to their influence on surface marine chlorophyll concentrations, could be summarized as follows:

(a) An increase in chlorophyll concentration was observed after the medicanes' passage in all cases exceeding 73.4% of the study area;
(b) Chlorophyll post-medicane values that were greater than the climatological ones referred at least to 46.3% of the affected area and in most cases to much wider regions, showing the significant influence of medicanes on the Sea's phytoplankton abundance and primary production;
(c) The above percentages were extremely high when absolute chlorophyll differences exceeding 50% were concerned;
(d) A drop in SST was observed which initiated some days before the event;
(e) The November 2014 case presented the largest chlorophyll increases, that were mainly observed on the right side of the cyclone's track, and the most pronounced SST cooling;
(f) The possible mechanisms for the observed chlorophyll increase caused by medicanes could be the cyclone induced upwelling and the wind mixing processes, a possible chl-a entrainment from the DCM plus a complementary favoring role of heavy precipitation at places;
(g) The increase in chlorophyll was comparable, though on smaller scale, to the one caused by hurricanes in oligotrophic environments.

The present study explored for the first time the influence of the tropical-like Mediterranean cyclones on the Sea's surface chlorophyll concentration. The findings showed that, though medicanes are of lower intensity compared to hurricanes, they also cause significant chlorophyll increases.

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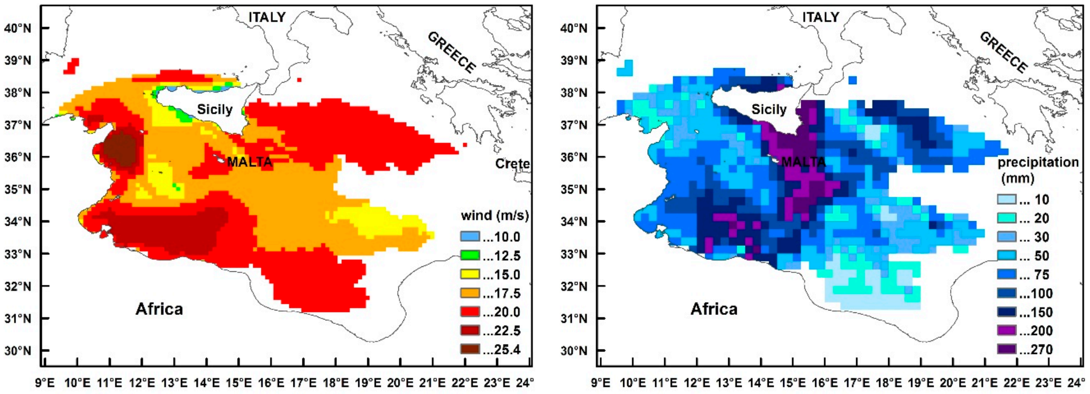
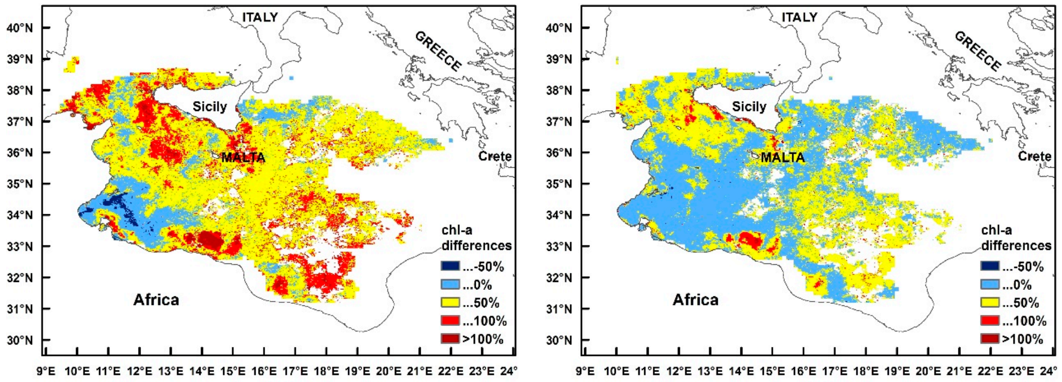
Appendix A

Here are given the maximum 10 m wind speed during the events, the total precipitation (of one day before each event till one day after) and the chlorophyll differences of the week after each medicane from the one before or during the event as well as from the monthly climatology.



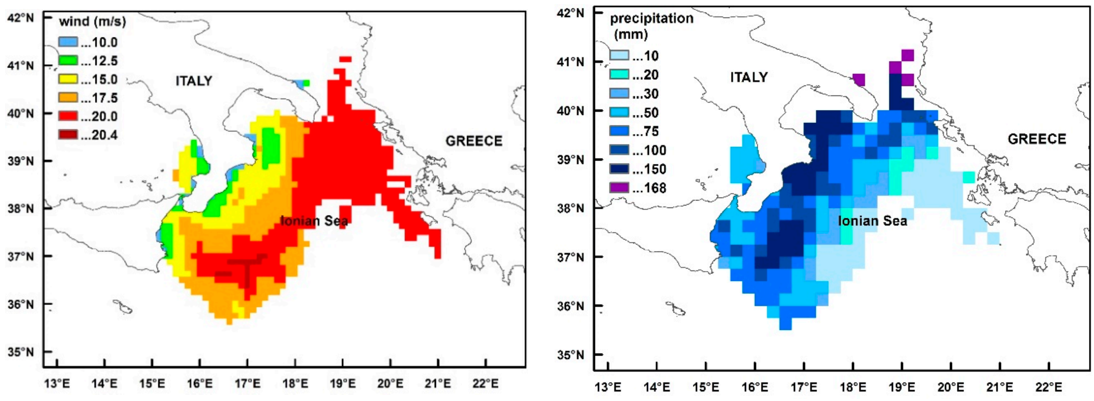
(a) (b)

Figure A1. (**a**) Maximum 10 m wind speed during the medicane of 13–15 December 2005; (**b**) Precipitation sum for 12–16 December 2005.



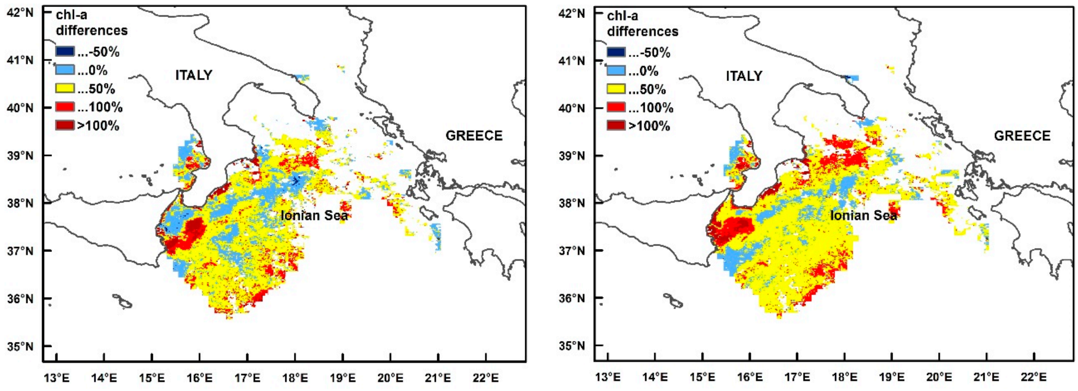
(a) (b)

Figure A2. (**a**) Chlorophyll percentage differences between the week after the event (19–26 December 2005) and the week before the event (3–10 December 2005); (**b**) Chlorophyll percentage differences between the week after the event (19–26 December 2005) and the climatological mean values for December.



(**a**) (**b**)

Figure A3. (**a**) Maximum 10 m wind speed during the medicane of 4 December 2008; (**b**) Precipitation sum for 3–5 December 2008.



(**a**) (**b**)

Figure A4. (**a**) Chlorophyll percentage differences between the week after the event (10–17 December 2008) and the week of the event (2–9 December 2008); (**b**) Chlorophyll percentage differences between the week after the event (10–17 December 2008) and the December climatological mean values.

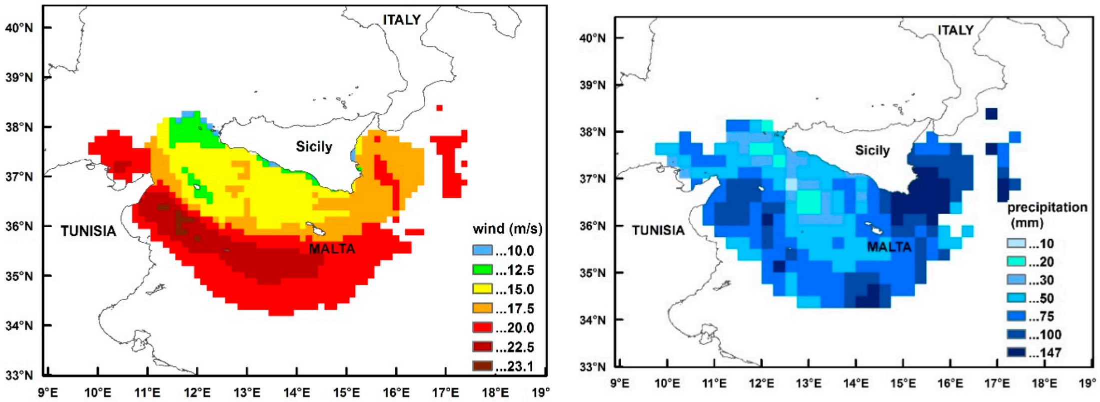
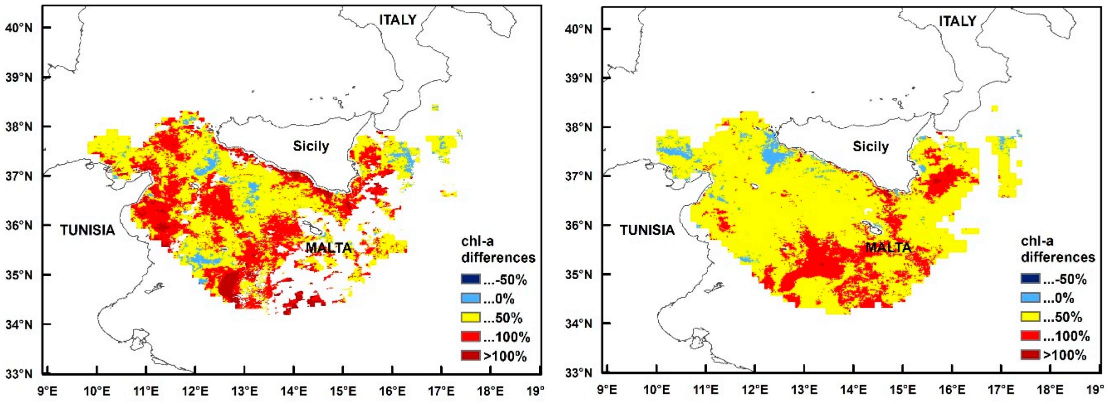


Figure A5. (**a**) Maximum 10 m wind speed during the medicane of 7–8 November 2014; (**b**) Precipitation sum for 6–8 November 2014.



(**a**) (**b**)

Figure A6. (**a**) Chlorophyll percentage differences between the week after the event (9–16 November 2014) and the week of the event (1–8 November 2014); (**b**) Chlorophyll percentage differences between the week after the event and the November climatological mean values.

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