

Key Points:

- Chlorophyll a, phytoplankton, nutrients, and oxygen concentration increase in the mixed layer during the passage of Mediterranean cyclones
- The presence of ocean structures such as eddies, gyres, and marine heat waves significantly affect the observed signal
- Warm- and cold-core eddies in turn affect the deepening of the medicanes

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Response of the Physical and Biogeochemical Marine Environment to the Passage of Mediterranean Cyclones in the Presence of Eddies, Gyres, and Marine Heat Wave

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Abstract Medicanes, a class of the most intense Mediterranean cyclones, are known to have a substantial influence on the physical and biogeochemical properties of the marine environment. Yet, our understanding of how this response under various precyclone sea conditions is still lacking. Here, we conducted a comprehensive analysis of 14 medicanes focusing on the two days before and after their observed maximum intensity. We analyzed the medicane's influence on surface and subsurface physical and biogeochemical properties and also their interactions with various ocean structures in the marine environment. Within the mixed layer, our findings reveal a consistent response to the passage of the medicanes, as they move across regions of warmer or colder sea surface temperatures (SST). Upon moving to warmer SST regions, the response is characterized by an increase in chlorophyll a (Chl a), phytoplankton biomass, nutrients, and dissolved oxygen, as well as a greater drop in the sea temperature, relative to cold SST regions. The presence of warm-core eddies and marine heat waves along the cyclone's track before maximum cyclone intensity significantly affects the dynamics of the medicane with a more pronounced deepening that drives stronger vertical mixing and upwelling than cold-core eddies. These processes favor the injection of nutrients into the ocean's upper layers, driving the observed increase in Chl a concentration and phytoplankton biomass. These findings provide new insights into how ocean-atmosphere coupling may affect extreme Mediterranean cyclones and how they can drive regional marine productivity and ecosystem dynamics.

Plain Language Summary A comprehensive analysis of 14 Mediterranean cyclones (Medicanes) between 2007 and 2021 revealed consistent patterns in their impact on the marine environment. On the last day before reaching maximum intensity, medicanes passing over warm sea surface temperature anomalies tend to release more heat to the atmosphere and achieve a higher intensification rate than cold SST anomalies. During the passage of these systems, surface concentrations of chlorophyll a, phytoplankton biomass, nutrients, and oxygen tend to increase inside the mixed layer. The most pronounced changes are observed in the presence of warm-core eddies, while cold-core eddies, in turn, show a neutral response. These findings suggest that the processes driving biogeochemical activity during medicanes are more complex and dynamic than previously understood.

1. Introduction

In the Mediterranean region, cyclone occurrence has long been known to be one of the highest in the world (Flaounas et al., 2022; Lionello et al., 2016; Petterssen, 1956). Although Mediterranean cyclones are comparatively less intense, smaller in size, and of shorter duration than their Atlantic counterparts (Campa & Wernli, 2012; Flaounas et al., 2022; Lionello et al., 2016; Trigo, 2006), their impact is significant due to the high population density in the region. The associated precipitation and extreme winds pose threats to ecosystems and the safety of over 480 million people (Flaounas et al., 2022).

Recently, the scientific community of the region has been paying increasing attention to a specific class of extreme Mediterranean cyclones known as “Medicanes” (Mediterranean hurricanes). Despite their low frequency of occurrence, they are responsible for significant damage to the land and coastal areas (see Menna et al., 2023 for a review). Medicanes can originate within the Mediterranean basin itself, commonly forming through mechanisms such as lee cyclogenesis or upper-level cutoff lows, as demonstrated in cases like Zorbas and Qendresa

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(Alhammoud et al., 2010; Toomey et al., 2022). While some may exhibit certain tropical-like features, they are not strictly analogous to tropical cyclones. Fundamental differences include their baroclinic genesis, tolerance to strong vertical wind shear, and development over cooler sea surface temperatures (Flaounas et al., 2022; Miglietta & Rotunno, 2019), which distinguish medicanes both dynamically and thermodynamically from true tropical systems.

The processes driving medicanes' intensification have been studied in several groups, including air-sea interaction and their presence along their tracks of specific structures of the ocean surface circulation, such as eddies and gyres (Bouin et al., 2020; Clementi et al., 2022; Jangir et al., 2023; Menna et al., 2023). For example, Jangir et al. (2023) addressed the impact of ocean warm-core eddies (WCE) on the intensification of medicanes, showing that the size of the eddy influences the deepening of the systems and related precipitation. In particular, larger eddies are associated with faster cyclone intensification and substantial amounts of rain. Conversely, cold-core eddies (CCEs) have no significant effects on precipitation-related characteristics. Cyclones passing over a WCE encounter higher SST, leading to increased evaporation and enhanced atmospheric water content, which contribute to intensified precipitation. Other modeling studies have investigated the role of air-sea interactions in the Mediterranean Sea (MS) (Karagiorgos et al., 2024; Mishra et al., 2024; Ricchi et al., 2019; Varlas et al., 2020).

The response of the marine environment to the passage of extreme cyclonic systems such as tropical cyclones has been studied in recent decades using theoretical, observational, and numerical approaches (Bonumaddi et al., 2022; Chai et al., 2021; Chowdhury et al., 2020; Latha et al., 2015; H. Li & Sriver, 2018; Liu et al., 2020; Menkes et al., 2016; Vincent et al., 2012; Zhang et al., 2021). Tropical cyclones have been observed to trigger significant phytoplankton blooms (Chowdhury et al., 2020; Liu et al., 2020; Shang et al., 2015). The conventional understanding of the mechanisms behind phytoplankton blooms suggests that cyclone-induced upwelling and vertical mixing may transport cold, nutrient-rich, or chlorophyll-abundant water to the euphotic layer, thereby triggering phytoplankton blooms. These blooms driven by tropical storms are crucial in understanding the ocean's mixing and biogeochemical processes (Chen et al., 2022). Moreover, strong cyclonic winds frequently lead to a drop in sea surface temperature (SST), which is a key factor in primary productivity (Latha et al., 2015). Furthermore, it has been shown that the presence of a preexisting CCE is integral to the formation of typhoon-induced phytoplankton blooms, actively enhancing both upper ocean dynamics and nutrient responses (Shang et al., 2015).

Considerable research has also been focused on the response of cyclones to sea surface anomalies associated with preexisting mesoscale eddies in the Mediterranean (Jangir et al., 2021, 2023). Only a few more studies have assessed the cyclone's impact on the marine environment and focus on most extreme weather events (Bouin et al., 2020; Clementi et al., 2022; Menna et al., 2023; Reale et al., 2026). Jangir et al. (2023) analyzed eight cyclones in the MS, and they found that cyclones passing over a larger WCE eddy induce a significant drop in SST attributed to mixing, consequently leading to intensified precipitation. By contrast, CCEs show a smaller drop in SST and no significant effects on precipitation-related characteristics. A case study done by Menna et al. (2023) for the Apollo cyclone (October 2021) showed that the presence of a cold cyclonic gyre (a gyre in the Mediterranean is a coherent structure driven by wind and/or topography and located in a fixed geographical area) in the path of the cyclone increases (decreases) the dissolved oxygen (DO), Chl *a* concentration, and productivity at the surface (subsurface layer). Moreover, they also found that the presence of a cyclonic gyre along Apollo's trajectory leads to a different response of the marine environment (no heat pump effect and no deepening of the mixed layer depth (MLD)) with respect to what is described in the scientific literature for the region (Bouin et al., 2020; Kassiss & Varlas, 2021). This confirms that the response of the marine environment to the passage of extreme weather systems may depend on preexisting ocean conditions (Menna et al., 2023).

In this work, we aim at filling this gap by trying to provide a comprehensive assessment of the response of the marine environment to the passage of medicanes systems by using a state-of-the-art cyclone track data set for the region (Flaounas et al., 2023) and physical and biogeochemical reanalysis products from the Copernicus Marine Service (CMEMS; Cossarini et al., 2021; Escudier et al., 2021; Teruzzi et al., 2021). In particular, we investigate how (a) the passage of cyclones impacts the marine environment at the surface and along the water column and (b) preexisting ocean structure and patterns (like WCEs or CCE or marine heat waves) may influence this response and the evolution of the system itself.

Section 2 describes the data and methods used in this study. Section 3 presents a comprehensive analysis of all 14 medicanes, examining their interactions with ocean circulation features and the response of the marine environment to the passage of the systems. Discussion and conclusion are present in Sections 4 and 5, respectively.

2. Data and Methods

2.1. Data

Fourteen cases of medicanes observed between 2007 and 2021 have been considered in this study, namely Janet (2007), Rolf (2011), Qendresa (2014), Xandra (2014), Anton (2015), Messala (2015), Zissi (2016), Trixie (2016), Numa (2017), Zorbas (2018), Andira (2020), Ianos (2020), Apollo (2021), and Blas (2021). Details on all the medicanes, a brief description of each event and their spatial and temporal location, are available in Table S1 in Supporting Information S1.

Hourly best-track data for cyclones retrieved from Flaounas et al. (2023) served as the basis for reconstructing the temporal evolution of the systems. The data set has been built by combining 10 different cyclone detection and tracking methods applied to the 0.25° spanning 1979–2020 ERA5 hourly data (see Flaounas et al., 2023 and reference therein for more details). The data set provides for each cyclone the time window of the event, the location of the system in coordinates of longitude and latitude, and the temporal evolution of the mean sea level pressure (MSLP) at the cyclone center. Additional atmospheric fields analyzed in this work, namely hourly 0.25° 6 hourly MSLP, wind speed (WS), shortwave and longwave radiations (QSW and QLW, respectively), latent and sensible heat fluxes (Qlat and Qsen, respectively), and SST, were also retrieved from ERA5 (Hersbach et al., 2020). Surface net heat fluxes (Qnet) were computed as in Menna et al. (2023).

$$Q_{\text{net}} = Q_{\text{SW}} - Q_{\text{LW}} - Q_{\text{lat}} - Q_{\text{sen}} \quad (1)$$

In order to identify structures of the ocean circulation and to characterize horizontal and vertical distribution of physical and biogeochemical properties in the marine environment, sea level anomaly (SLA), absolute dynamic topography (ADT), temperature and salinity profiles, MLD, chlorophyll a (Chl a), phytoplankton biomass, nutrients, and DO data were retrieved from the Copernicus Marine Service catalog. In particular we analyzed the following:

- Daily 0.125° SLA and ADT data for the MS from SEALEVEL_EUR_PHY_L4_MY_008_068 (<https://doi.org/10.48670/moi-00141>)
- Daily temperature and salinity profiles and MLD from the MEDSEA_MULTIYEAR_PHY_006_004 (https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1)
- Chl a, phytoplankton biomass, nutrients, and DO from the MEDSEA_MULTIYEAR_BGC_006_008 (https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3)

We acknowledge that using data sets with the same spatial resolution is always recommended in a study. However, here, we use ERA5 (0.25°) and SLA (0.125°) or ADT (0.125°) products, which have different spatial resolutions. The ERA5 products for the atmosphere are chosen here to be consistent with the cyclone track data set (Flaounas et al., 2023). Although CMEMS provides SLA and ADT data at a resolution of 0.25 and 0.125°, we opted here for the 0.125-degree ADT (SLA) data set to improve the accuracy in detecting the location of the eddies. Nevertheless, the spatial resolution limitations represent a real constraint, as the 12.5-km resolution of the SLA data is coarser for resolving small Mediterranean eddies, and this inherent limitation, which is beyond our control, may influence the precision of the results. Furthermore, observational data (i.e., satellite and in situ products) are generally preferred to reconstruct the dynamics of the marine environment, but they offer limited space and time coverage. Satellite observations, for example, primarily offer surface-level Chl a concentrations and lack information about subsurface dynamics. Reanalysis products, despite having inherent uncertainties, are the only available source providing high-resolution temporal and spatial data for the marine environment. This allows us to investigate complex interactions across different variables at different spatial scales, thereby offering insights that cannot be achieved through satellite and observational data alone. Finally, we want to stress here that ERA5 is the atmospheric forcing for the CMEMS reanalysis products. This guarantees a certain level of consistency between atmospheric and ocean variables analyzed in this study.

2.2. Methods

To assess the importance of different ocean structures and patterns on the deepening or shallowing of each system, we employed the Cressman spatial averaging (Cressman, 1959). The procedure involves calculating the mean value of MSLP, WS, and Qnet along the cyclone's tracks within a 1-degree radius around the center of the system, weighted by the inverse square distance from the center (Jangir et al., 2023). This analysis focuses on changes in the cyclone's central region, excluding areas beyond the defined radius. To isolate the effect of SST anomalies on the cyclone, we focus on the last 24–48 hr before maximum cyclone intensity (Max CI, defined as the point where the MSLP reached its lowest value).

A Hovmöller diagram showing the difference at various depths between the value of a certain variable (e.g., DO) 2 days before and 2 days after the passage of the system was used to evaluate possible changes in the ocean upper layer characteristics induced by the medicane. The Hovmöller diagram has been built in the upper 150 m of the water column and along the cyclone track, using a nearest-neighbor approach to identify the corresponding profiles. The period of 2 days before to 2 days after the cyclone was selected because the strongest oceanic response is typically observed within this timeframe.

Moreover, each cyclone was classified based on the governing ocean structure below it: WCE, CCE, marine heat wave (MHWs), or gyre. Both WCEs and CCEs were detected using the algorithm provided by Ivy Frenger (Faghmous et al., 2015; Frenger et al., 2013). This algorithm detects cyclonic and anticyclonic eddy activity. In general, cyclonic eddies are associated with CCEs, while anticyclonic eddies are associated with WCEs. Yet, recent studies indicate that there is a non-negligible number of inverse cyclonic WCEs and anticyclonic CCEs (e.g., Moschos et al., 2022; Ni et al., 2021). Inverse mesoscale SST anomalies were found not relevant in this context. In general, although these features can influence vertical nutrient transport and ocean-atmosphere interactions, their predominance during May–June (~70% frequency) does not temporally coincide with the typical medicane season, thus limiting their role in shaping the biogeochemical dynamics examined in this study. Nevertheless, to avoid misinterpretation, each analyzed eddy along the track of a cyclone was examined to ensure that the tracked cyclonic eddies were indeed CCEs and anticyclonic eddies were WCEs.

We used both ADT and SLA products for eddy identification, since previous studies have shown that SST data may not always capture subsurface features accurately (Ali et al., 2007), and thus, SLA and ADT are preferable for this purpose (Kodunthirapully Narayanaswami & Ramasamy, 2022; J. Li et al., 2023; Pegliasco et al., 2021). Moreover, Pegliasco et al. (2021) demonstrated that ADT captures ocean circulation features more accurately than SLA. Therefore, in this study, eddies have been detected by using ADT, while SLA-based analysis is included in the SI. MHWs and the cyclonic gyre locations in the cases of Ianos and Apollo were, respectively, identified as described by Jangir et al. (2024) and Menna et al. (2023).

3. Results

Figure 1a shows the tracks of all 14 medicanes, while Figures 1b–1o zooms into each of the medicanes' tracks overlaid on ADT and also includes red and blue dots (circles) that denote the center location of WCEs and CCEs, respectively. The name of the cyclones, translational speed (TS; kmph) two days before the maximum CI location, features present at the maximum CI location, date of Max-CI, minimum MSLP, and season of all 14 medicanes are reported in Table S1 in Supporting Information S1. When replacing the ADT with SLA, more sea structures are identified, although those features along the cyclone's path under investigation share the same anomaly as ADT (Figure S1 in Supporting Information S1). Similarly, we observe that the cyclonic eddies under investigation along the medicanes' path are CCEs, while anticyclonic eddies are WCEs (Figure S2 in Supporting Information S1).

Generally, case studies showed that the presence of a WCE along the cyclone track increases the intensity of the cyclone, while the presence of a CCE weakens the atmospheric system (e.g., Jangir et al., 2021, 2023; Z. Ma et al., 2013). We observed a similar behavior in our 14 case studies. To isolate the effect of the eddies on the system intensity, we focused on the time interval before the cyclone reached its Max-CI. Figure 2 shows eight scatter plots illustrating changes in various physical and biogeochemical properties as a function of SST change between 24 hr prior to and the time of Max-CI along the medicane's track; we denote it as SST anomalies $SST(L_{max}, t-1) - SST(L-1, t-1)$. Numa was removed from this analysis after a careful inspection of the data, realizing that this storm had a very high translational speed, resulting in a jump from one warm anomaly region to

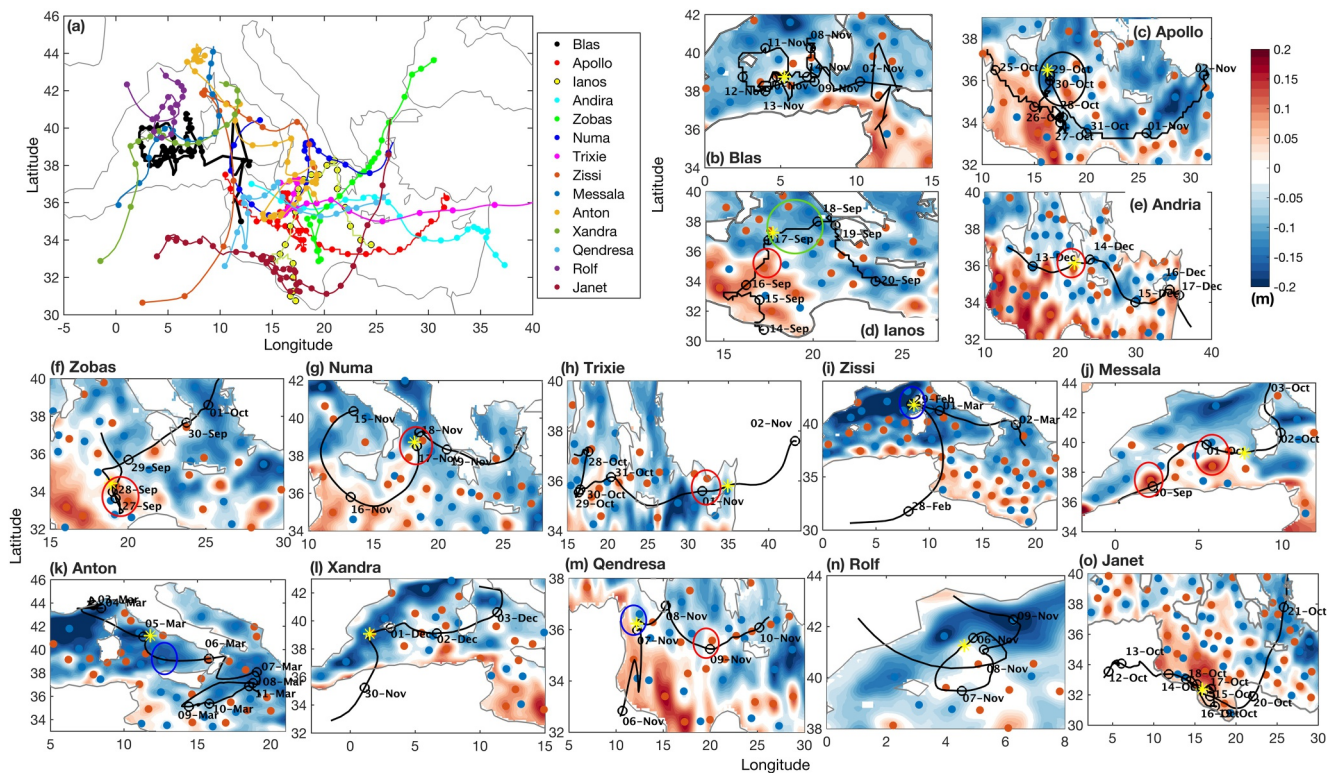


Figure 1. (a) Track of all 14 medicanes (2007–2021). (b–o) The paths of all 14 cyclones (solid black line). The color of the maps shows absolute dynamic topography data one day prior to the cyclone formation. The yellow stars in the plot show the location of maximum cyclone intensity. The red and blue circles represent the location of warm-core eddies and cold-core eddies, whereas the black circle represents the location of cyclonic gyres, and the green circle represents the location of the marine heat wave. The size of the circles along the cyclone path is proportional to mean sea level pressure.

another in 24 hr. Using our simplistic metric of calculating the SST difference along the path (Max-CI minus one day before), Numa got a negative SST anomaly because it jumped from a positive SST anomaly region to a less positive anomaly region, and these two regions were separated by a negative anomaly region (a saddle point). Panels a and b in Figure 2 show changes in NHF and MSLP (computed the same as Δ SST, i.e., along the medicane's path) to estimate the response of the medicane to spatial SST anomalies. The biogeochemical variables (e.g., Chl a, nitrate, and oxygen) were computed as the difference between their values 2 days after and 2 days before the Max-CI date and at the Max-CI location. This framework captures eddy-related (or regional SST anomaly) responses of the biogeochemical variables.

We find that before reaching the Max-CI, upward NHF is greater when a cyclone crosses a warm SST anomaly (positive Δ SST, Figure 2a). Consequently, the cyclones experience, in general, stronger intensification (Figure 2b). These results are statistically significant at the 0.05 confidence level. Figure 2b also shows that for every 1°C increase in SST anomaly, the cyclone's pressure decreases by 1.18 hPa, indicating a strong inverse relationship between SST anomaly and MSLP. These results are particularly impressive given the wide range of variations in the cyclone intensities, regions, and seasons.

We also observed a significant correlation (with 0.05 confidence level) between SST anomalies and both Chl a ($r = 0.73$) and nitrate concentrations ($r = 0.58$), suggesting that positive SST anomalies are associated with enhanced biogeochemical responses (Figures 2c and 2e). All the other variables, though indicating a positive trend, are not statistically significant (Figures 2d, 2f, and 2g). We performed similar computations for other proxies that is, $\text{SST}(\text{Lmax}, t-2) - \text{SST}(\text{L-1}, t-2)$, $\text{SST}(\text{Lmax}, t-1.5) - \text{SST}(\text{L-1}, t-1.5)$, and $\text{SST}(\text{Lmax}, t-1) - \text{SST}(\text{L-1}, t-1)$ and obtained comparable results (shown in Tables S2–S5 in Supporting Information S1). However, the correlation tends to weaken with increasing lag time. Thus, although warmer SST anomalies tend to promote biogeochemical enrichment, the magnitude and significance of this enrichment vary across the events due to the distinct characteristics of each system. Moreover, we found that WCEs tend to have a more positive

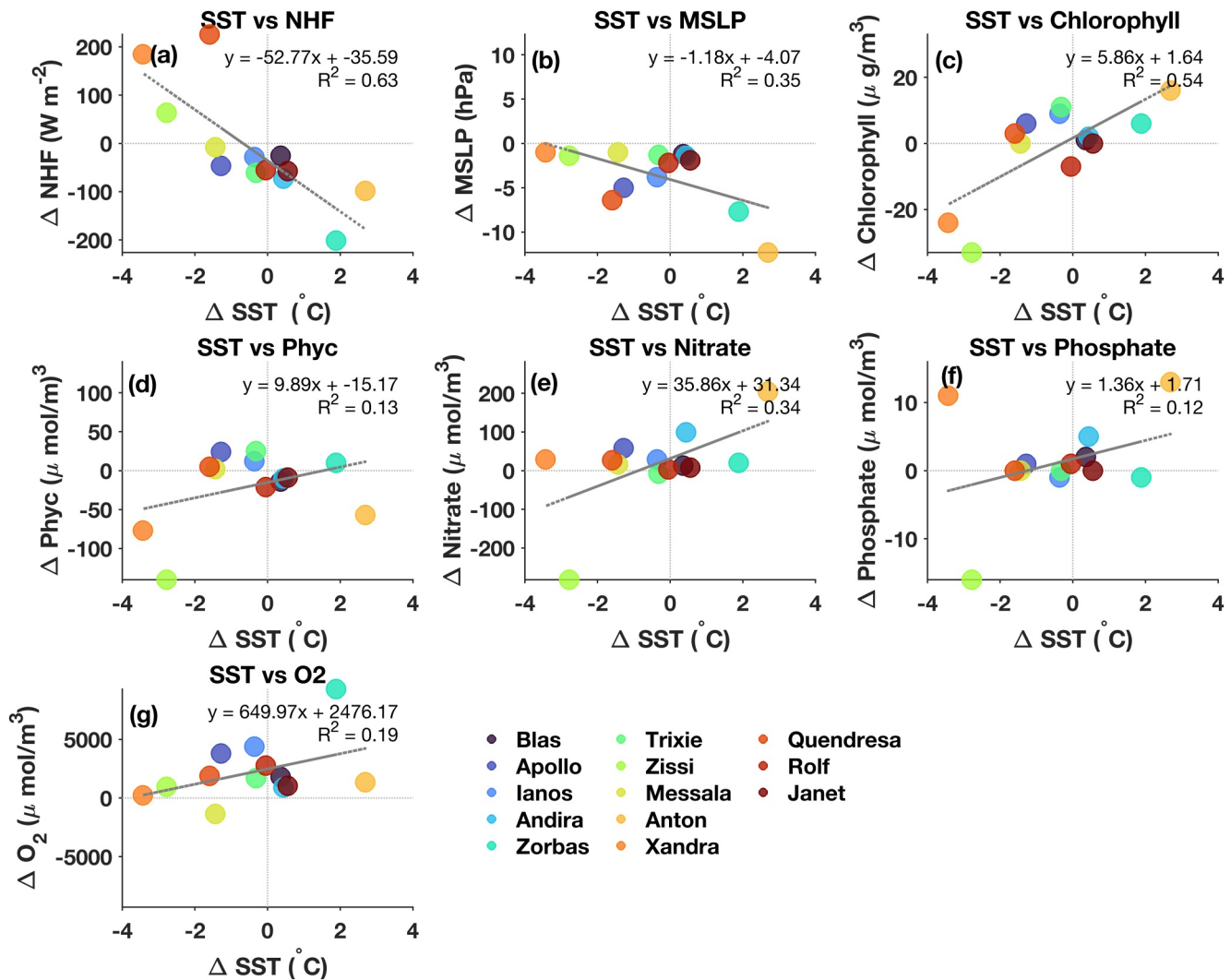


Figure 2. Figure representing the scatter plot between (a) net heat flux (NHF) difference (at max-CI location and time minus at max-CI location one day before) as a function of SST difference (SST at the location and time of maximum CI minus SST at the location and time one day prior, or SST anomalies $\text{SST}(L_{\text{max}}, t-1) - \text{SST}(L-1, t-1)$), (b) mean sea level pressure difference (at the same location and time as NHF) as a function of SST difference (same as in a), (c) SST difference and chlorophyll difference above the mixed layer depth (MLD) (d) SST difference and phytoplankton difference above the MLD, (e) SST difference and nitrate difference above the MLD, (f) SST difference and phosphate difference above the MLD, and (g) SST difference and O₂ difference above the MLD.

biogeochemical concentration at the mixed layer during the passage of the medicanes with respect to CCEs. One possible explanation is stronger surface winds and wind stress curl associated with the drop of the MSLP driven by warmer mesoscale SST anomalies (e.g., Chelton & Xie, 2010), which increases Ekman pumping upwelling and favors stronger mixing. Yet, in CCEs, eddy-induced upwelling processes during intensification may compensate for reduced vertical mixing, producing higher concentrations than those that would be expected from mixing alone.

Tropical cyclones and medicanes interacting with cyclonic ocean structures (gyres or eddies) can weaken the strength of the atmospheric system through negative feedback (Bender et al., 1993; Jaimes et al., 2011; Kodunthirapully Narayanaswami & Ramasamy, 2022; Lin et al., 2013; Lu et al., 2016; Menna et al., 2023). An important example of that is represented by the case of the medicane Apollo. This system crossed an area where a cold-core gyre was located on 28 October 2021 (Figure 1c, Figures S3a and S4 in Supporting Information S1). The system showed its maximum intensity on 29 October 2021 (Figure S3a in Supporting Information S1; minimum value of the MSLP field), when it was on top of the cold-core cyclonic ocean gyre, and then, its intensity decreased rapidly (Figure S4 in Supporting Information S1). In the case of medicane Ianos, MSLP decreased from

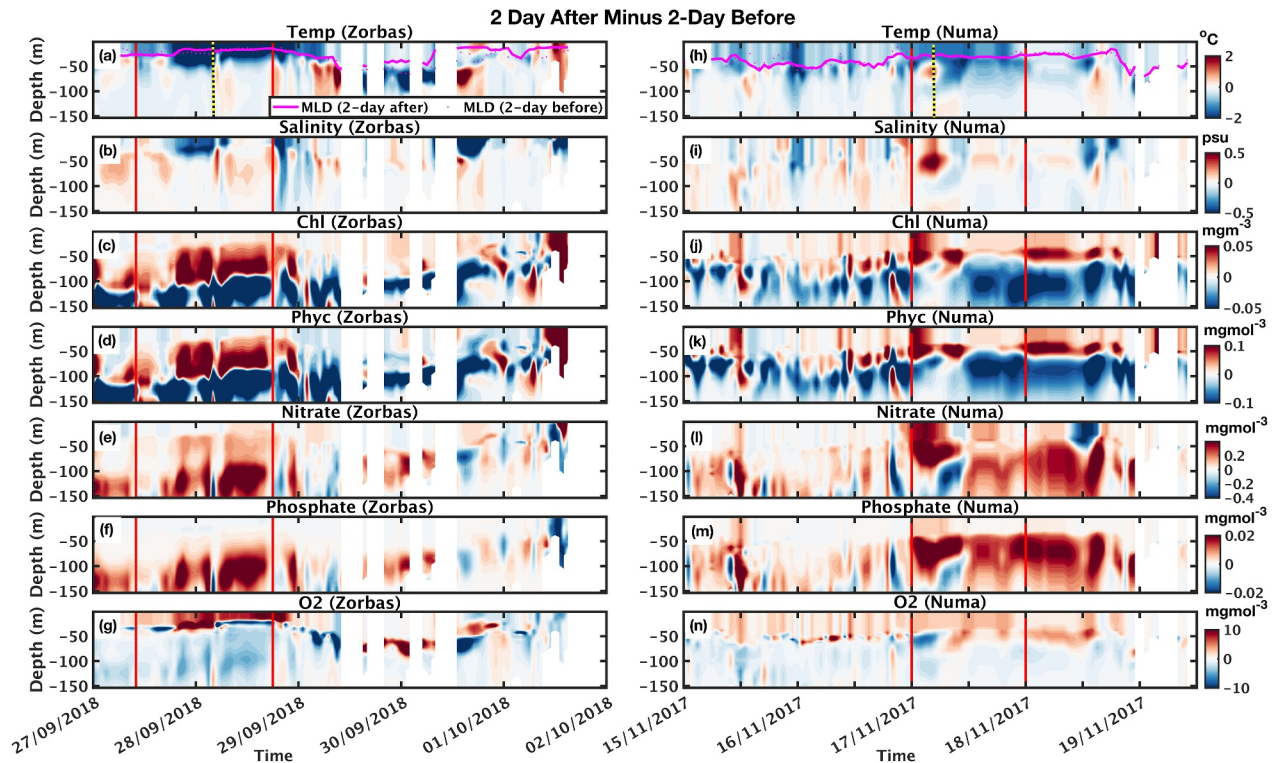


Figure 3. Vertical along-track difference in temperature (a and h), salinity (b and i), chlorophyll (c and j), phytoplankton (d and k), nitrate (e and l), phosphate (f and m), and oxygen (g and n) for the medicanes Zorbas (left column) and medicanes Numa (right column). Differences were calculated as the 2-day postcyclone values minus the 2-day precyclone values at each location along the cyclone tracks (x-axes show dates along the tracks, as in Figure 1). The magenta line denotes the mixed layer depth, the red boxes mark warm-core eddies' locations, and the yellow dotted line indicates the intensification location. Blank vertical stripes represent dates when the medicanes were over land.

about 1015 to 1000 hPa at Max-CI location (Figure S3b in Supporting Information S1). This deepening started in the presence of a WCE on 15–16 September 2020 and continued in the next days, driven by the presence of a warm pool associated with an MHW (highlighted by the green box in Figures S3b and S5 in Supporting Information S1). Similarly, a steep drop in MSLP was observed over the WCE location in cyclones Zorbas and Numa, presumably supported by the presence of WCEs (Figures 4c and 4d) and in accordance with the results presented in Figure 2b and Jangir et al. (2023). On the other hand, Medicanes Zissi and Qendresa, crossed a CCE during their intensification (Figures 1i and 1j). In these cases, the drop in the MSLP was slower during the interaction with the CCE (Figures S3e and S3f in Supporting Information S1). These distinct features collectively contribute to a comprehensive understanding of the diverse behaviors exhibited by cyclones across different ocean circulation structures.

To assess the impact of the medicanes on the physical properties (temperature and salinity) and biogeochemical properties (Chl a, phytoplankton biomass, nutrients, and oxygen concentration) of the water column, the vertical profiles of the temporal change in these variables (two days after minus two days before the passage of the medicanes) in the upper layer (150 m depth) have been plotted along the track of the cyclone. Here, we chose six different cases: (a) two medicanes crossing a WCE along their path (Zorbas and Numa), (b) two medicanes crossing CCE along their path (Zissi and Qendresa), and (c) two other special cases (Apollo and Ianos). The other cases are shown in Supporting Information S1 (Figures S7–S14).

3.1. Medicanes Interacting With WCE Along Their Path: Zorbas and Numa

Medicane Zorbas initially formed as an extratropical cyclone in the eastern Mediterranean. Later, it intensified and moved northward toward Greece (Figure 1f), reaching its maximum intensity (997 hPa) on September 29 with a maximum WS of 35 m/s (Figure S3c in Supporting Information S1). This cyclone encountered a WCE along its track on September 27–28 (Figure 1f), experiencing a sudden drop in MSLP (from 1016 hPa to 998 hPa

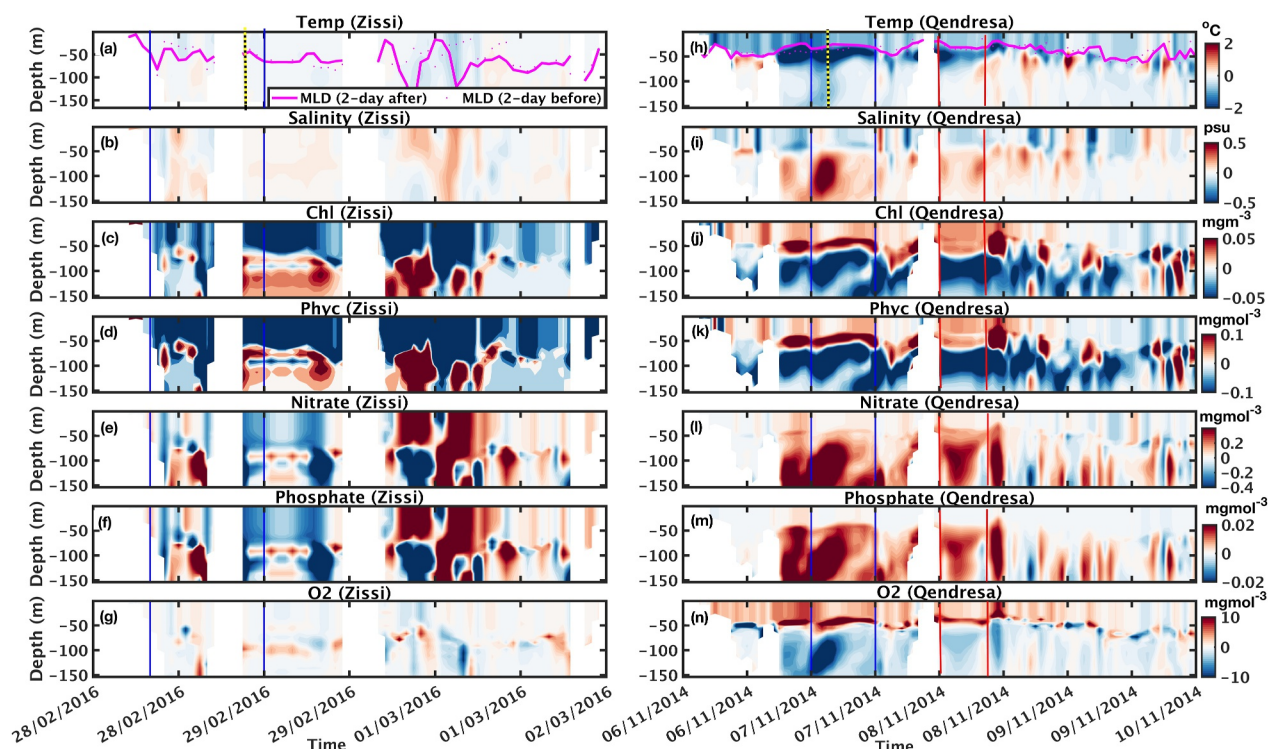


Figure 4. Same as Figure 3 but for medicane Zissi (left column) and medicane Qendresa (right column). The blue box represents the time during which the cyclone was above cold-core eddies.

over the eddy) and a dramatic increase in the WS (Figure S3c in Supporting Information S1). Temperature and salinity dropped in the upper layer along the track of the cyclone (Figures 3a and 3b). In general, SST cooling is a result of a combination of surface heat fluxes, turbulent mixing, and upwelling (e.g., Price et al., 2008; Zhang et al., 2021). However, the strongest change was observed at the WCE location, presumably due to higher turbulent fluxes (and evaporation) associated with such features (e.g., Byrne et al., 2014). The anomalies below the mixed layer indicate active vertical mixing and upwelling, but their limited magnitude and extent suggest these processes play a smaller role in determining the final profile.

Inside the WCE, the Chl a and phytoplankton (phyc) concentrations showed a clear increase in the upper 100 m, followed by a decrease below (100–150 m depth; Figures 3c and 3d), which indicates an uplift of the deep Chl a maximum (DCM) during the passage of the cyclone. We infer upwelling rather than vertical mixing because of the structure of the anomalies. In general, mixing would act to reduce positive anomalies and increase negative anomalies. We found that the DCM is below the MLD in all cyclones (Figure S6 in Supporting Information S1) except Andira, Zissi, and Anton because they occurred in the winter season. If vertical mixing at the mixed layer was the governing process, we would expect an increase in Chl a and phyc up at the top of the mixed layer and a decrease at the bottom of the mixed layer. Since the observed structure is a dipole below the mixed layer, it is better explained by an upward motion. Cyclone-induced subsurface mixing may also explain the dipole, but the general structures of the Chl a profiles before and after the storms indicate an upward shift, which is better explained by upwelling (Figure S6 in Supporting Information S1). Yet, the small positive anomalies at the mixed layer indicate that some upwelled Chl a and phyc reach the mixed layer and blend there. Furthermore, the temperature profile mostly does not indicate a warming of the thermocline, which would be expected if the heat pump mechanism was active (Emanuel, 2001; Zhang et al., 2021).

Nutrient concentrations (nitrate and phosphate) increased at both the surface and the subsurface along the entire trajectory, with particularly higher values observed at the WCE location (see Figures 3e and 3f). As nutrients generally increase with depth, the overall increase in these properties indicates an upwelling similar to those observed for Chl a and phyc. The DO concentration increased in the mixed layer and declined below (see

Figure 3g). This behavior is more pronounced at the WCE. The increase in DO above the mixed layer is due to lower surface temperatures, which enhance DO solubility.

Similar to Zorbas, during medicane Numa (15–20 November 2017), SST decreased along the entire track of this medicane (Figures 3h–3n, right), and notable heat loss was observed at the eddy location (Figure S3d in Supporting Information S1). Simultaneously, there was a consistent increase in Chl a and phytoplankton concentrations throughout the track at the surface and a decrease below the mixed layer, in particular over the WCE location at the surface (Figures 3j and 3k). Nutrient concentrations showed a substantial increase both at the surface and the subsurface, predominantly over the WCE location (Figures 3l and 3m). DO increases at the mixed layer, while no considerable change is seen below. Although other WCEs are present along the cyclone's track (Figure 1g and Figure S2 in Supporting Information S1), the impact is most pronounced at the WCE positioned near the Max-CI location, that is, on the seventeenth November over WCE (Figures 3h–3n). Overall, Medicane Numa exhibits a similar upwelling pattern as observed in Zorbas during cyclone intensification. However, surface mixing seems to be more active than Zorbas. This is particularly indicated by the pronounced increase in the concentration of the biogeochemical variables at the mixed layer in the morning of the seventeenth WCE. A possible explanation is that, relative to Zorbas, the DCM in Numa was closer to the MLD (Figure S14 in Supporting Information S1), allowing for mixing of higher concentrations up to the surface.

Despite the well-established relationship between the WCE and downwelling (Gaube et al., 2015; J. Ma et al., 2015; Tang et al., 2022), the cyclone-induced upwelling and mixing processes (He et al., 2024; John et al., 2024) can lead to an increase in surface Chl a concentration. This upwelling is further increased above the WCE, where wind stress curl is higher (Chelton & Xie, 2010). Another contributing factor is the cyclone's intensification in the presence of WCE, which results in stronger winds, more mixing, and, subsequently, higher surface Chl a levels (Liu et al., 2020). Our finding aligns with Liu et al. (2020), who elaborate on the shoaling of the MLD as a consequence of the interaction between tropical cyclones and anticyclonic eddies in promoting nutrient uptake through upwelling. They performed a case study on a specific tropical cyclone, showing enhanced surface Chl a levels and uplifted DCM to approximately 20 m over the southwestern Luzon Strait. The Chl a response in the upper ocean observed for Zorbas and Numa is similar to that described by Chai et al. (2021) for Typhoon Trami in the northwestern Pacific. There, the surface increase in Chl a is associated with entrainment of the DCM rather than a total increase in primary production.

3.2. Medicanes Interacting With CCE Along Their Path: Zissi and Qendresa

The response of the MS to the passage of Zissi indicates a very different behavior relative to the two previous cases. Figure 4 (left panels) depicts no significant change in temperature and salinity along the track but a notable change in Chl a, phytoplankton, and nutrient concentrations. Above the CCE, we see a generally opposite dipole pattern compared with the previous two cases (mostly negative anomalies at the surface and positive anomalies below). Moreover, there were no DCM and subsurface phytoplankton biomass maximum. The phytoplankton was still under winter dormancy condition, and the MLD was considerably deeper than the two WCE cases. As a consequence, the subsurface biomass maximum was mixed up to the surface, inducing a maximum concentration at the mixed layer and a decline below MLD. The cyclone-induced upwelling, together with stronger mixing, resulted in an opposite dipole in this case (Figure 4, left Panels). The overall neutral temperature and salinity patterns may be explained by the fast TS (Table S1 and Figure S15 in Supporting Information S1) of this cyclone before Max-CI, which limits the interaction time. Of all the events analyzed, those that occur in late autumn or winter are characterized by high atmospheric TS (Table S1 in Supporting Information S1). Indeed, Zissi was characterized by the highest TS among all analyzed events. Yet, our analysis indicated that small changes in physical properties do not necessarily indicate the same for the biogeochemical properties.

Cyclone Qendresa reached its intensity peak on 7 November 2014. This led to a drop in temperature and salinity (Figures 4h and 4i) and a significant increase in Chl a, phytoplankton, nutrient, and oxygen concentrations above the MLD (Figures 4j–4n). The overall pattern is similar to the two WCE cases, a vertical dipole with positive anomalies at the surface and negative anomalies below the mixed layer. Furthermore, according to Figure 1m, Qendresa is situated over a CCE on November 7 (at Max-CI), but 2 days later, it passed over a persistent WCE. Figures 4h and 4i indicates general mixing during cyclones along the path of the medicane. However, inside the CCE, the positive Chl a and phyc anomalies remain below the mixed layer, while in the presence of the WCE, they extend further upward and mix within the mixed layer. Over the WCE, it is 0.23 mg/m^3 , and over CCE, it is

0.012 mg/m³ for Chl a, and for phyc, it is 0.039 mg/mol³ (WCE) and 0.025 mg/mol³ (CCE). These differences highlight the combined impact of both the CCE and WCE within a single system. Above WCE, cyclones deepen, resulting in stronger winds and significant vertical mixing. The combined effect allows for the injection of nutrients into the surface. Above CCE, cyclones exhibit lower intensification and weaker vertical mixing. Cyclone-induced upwelling still occurs in CCEs, but it is weaker and, together with lower mixing, it is more active below the mixed layer (indicated by the dark red filaments below the mixed layer in Figures 4j and 4k).

The presence of a preexisting CCE plays an important role in promoting phytoplankton bloom by raising the isotherms during their intensification (McGillicuddy, 1997), leading to higher nutrient concentrations in the euphotic layer. When a cyclone arrives, wind stress curl acts to further upwell nutrients through the Ekman pumping mechanism (cyclone-induced upwelling). In addition, the cyclone's stronger winds support vertical mixing and transfer of nutrients to the surface. However, when compared to WCEs, cyclone-induced upwelling and vertical mixing in CCEs are expected to be weaker due to higher atmospheric stability. When a cyclone passes over a warm SST anomaly, the air becomes less stable, resulting in more efficient transfer of momentum from the upper levels to the surface and enhanced surface winds. As a consequence, wind stress curl (and upwelling) above the warm SST anomalies is increased (e.g., Chelton & Xie, 2010). Therefore, CCEs under the influence of a cyclone may not necessarily be favorable for increased biogeochemical activity. Our results suggest that the positive change in Chl a and phyc at the surface is not larger inside CCEs, supporting the above paradigm. Furthermore, the negative response at the surface observed during Zissi in this study is attributed to the seasonal cycle (surface maximum in the active biological season). At the specific time of the cyclone, the maximum Chl a and phyc levels were at the surface. Thus, cyclone-induced mixing acted to reduce the concentration at the surface and increase the concentration below the mixed layer. This means that although the response appears to differ in Zissi, the active physical mechanisms remain the same.

3.3. Intensification of Medicanes Due To Other Oceanic Features in Their Path

Two medicanes, Apollo and Ianos, were considered to be different from the other cases discussed above. A cold-core semipermanent cyclonic gyre was present at the time of the intensification of the medicane Apollo (Figure 2b; see also Menna et al., 2023). A considerable decrease in the SST was observed at the location of the cyclonic gyre (Figure 5a), whereas the concentration of the Chl a, phytoplankton, nutrients, and oxygen at the surface increased (Figures 5c–5g). The overall behavior here is similar to what has been observed in the presence of CCE, but the response is stronger over the gyre (presumably, because it is a more permanent and stable structure), that is, an upwelling motion that increases the nutrient concentrations and the DCM.

In the case of medicane Ianos (14–21, 2020), despite the presence of a WCE on September 16 (Figure 1), the Max-CI occurred later, on 17–18 September. Even though the cyclone started deepening at the WCE locations, it reached its maximum deepening rate at a later stage (Figure S3b in Supporting Information S1). An analysis of the SST field revealed a preexisting regional MHW in the Ionian Sea that might have been the reason for its strong intensification (Jangir et al., 2024). A marked decrease in temperature and an increase in the mixed layer nutrients, Chl a (also observed by satellite data, Figure S16 in Supporting Information S1), phyc, and oxygen concentrations were observed during the intensification phase (Figure 5, right panel).

3.4. Overview of All the Medicanes

Figures 6a–6i provides an overview of the response of the marine properties along the track and at the time of the Max-CI to the passage of the medicanes. Upon averaging all variables across the different oceanographic categories at Max-CI, namely no eddy (NE), WCE, MHW, gyres, and CCE, distinct patterns in physical and biogeochemical responses emerge (Figure 6). In general, the expected response of the temperature to a cyclone is cooling at the surface and warming at the subsurface if mixing is active (e.g., Zhang et al., 2021). Consistent with this, the temperature generally decreases across all categories above MLD. Yet, the temperature also decreases below the MLD, suggesting that vertical mixing has a smaller role in determining the final profile compared with upwelling and wind-induced turbulent fluxes. A notable example is medicane Apollo, which passed over a cyclonic gyre. Despite the presence of a CCE at a location of Max-CI, a considerable drop in SST was recorded. This anomaly is likely attributed to Apollo's unusually slow TS, which extended its interaction time with the ocean and enhanced mixing and cooling. In general, changes in salinity are smaller.

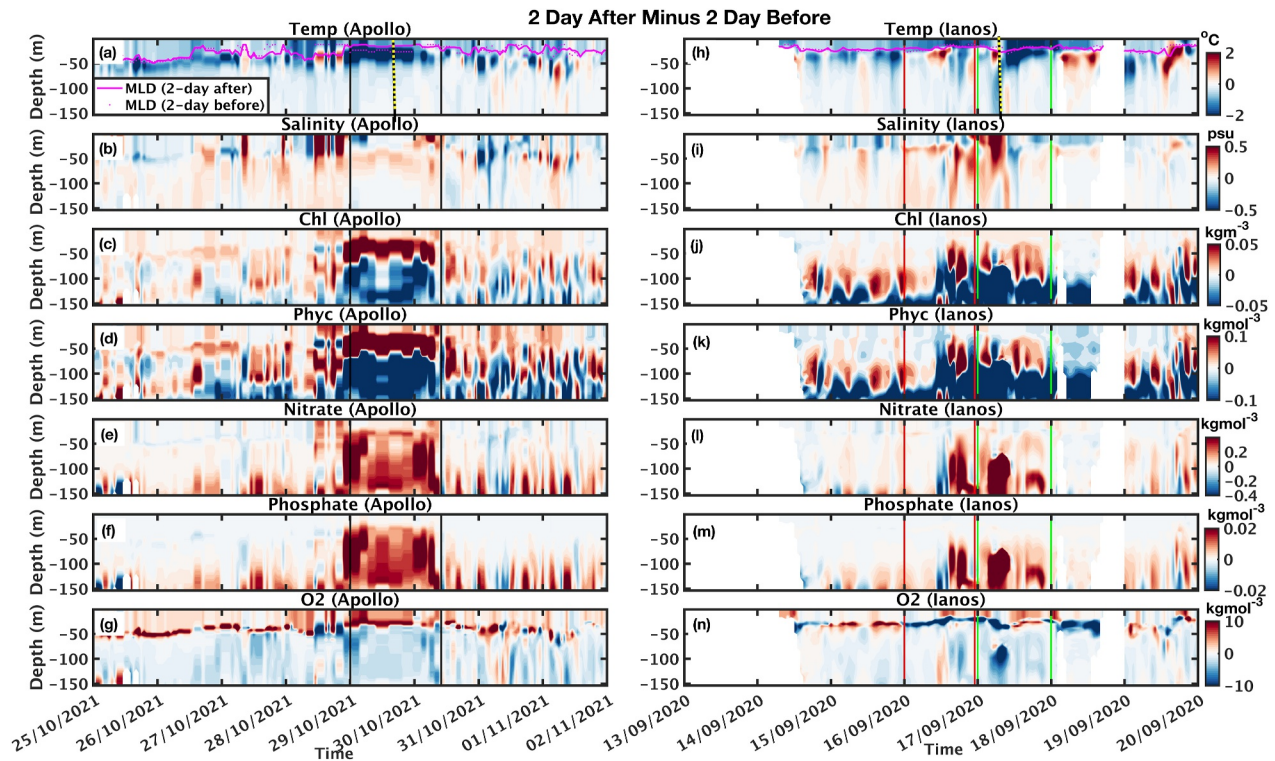


Figure 5. Same as Figure 3 but for hurricane Apollo (left column) and hurricane Ianos (right column). The black box indicates the time the hurricane spent over the cyclonic gyre, and the green box marks the time of the hurricane's intensification.

An increase in Chl *a* and phyc concentrations is observed both above and below the MLD in WCE, gyre, and MHW regions. In CCE regions, Chl *a* and phyc decrease below and above the MLD. The NE category is somewhat in between WCE and CCE, showing a decrease in concentrations at the surface and neutral behavior at the subsurface. Nutrient concentrations (nitrate and phosphate) exhibit an overall increase both above and below the MLD across all categories. However, the most pronounced enhancement in nutrient concentrations is observed in the WCE category, whereas the CCE category shows the weakest response (Figures 6a and 6b). Importantly, biogeochemical variables show more substantial relative changes (~20%–50%, see also Tables S6–S9 in Supporting Information S1) than physical variables (~0%–5%), underscoring the stronger biogeochemical sensitivity to cyclone forcing.

From Tables S6–S9 in Supporting Information S1, we observed compelling results indicating that the decrease in temperature is more pronounced 2 days after the event (relative to 2 days before) for the MHW and WCE categories, compared to the maximum CI minus 2 days case. Similarly, the mean chlorophyll concentration above the MLD shows a notable increase for these cases (Table S6 and S7 in Supporting Information S1). Below the MLD, a temperature decrease is evident across all categories for the 2 days after a minus two-day-before comparison; however, the magnitude of this decrease is greater for MHW and WCE than the maximum CI case. The chlorophyll concentration exhibits reduced values below the MLD and a stronger decrease in 2 days after the event, consistent with the expected upward transport of chlorophyll in MHW and WCE conditions (Table S8 and S9 in Supporting Information S1). These findings highlight the significant enhancement of biogeochemical variables and the associated cooling following the passage of a cyclone, driven by the influence of MHWs and WCEs. The positive correlations between biogeochemical variables and SST, particularly for SST–Chl *a* and SST–nitrate, are statistically significant, as shown in Figure 2 (also demonstrated in Tables S6 and S8 in Supporting Information S1). These results clearly indicate an increase in Chl *a* and nitrate concentrations following the cyclone across all categories. In contrast, other variables such as phytoplankton biomass, phosphate, and DO exhibit opposite or inconsistent responses, particularly in the CCE and NE regions (Tables S6 and S8 in Supporting Information S1). This variability likely explains why these variables show positive correlations with SST that are not statistically significant (Figure 2). Notably, nitrate concentrations remain elevated in the subsurface

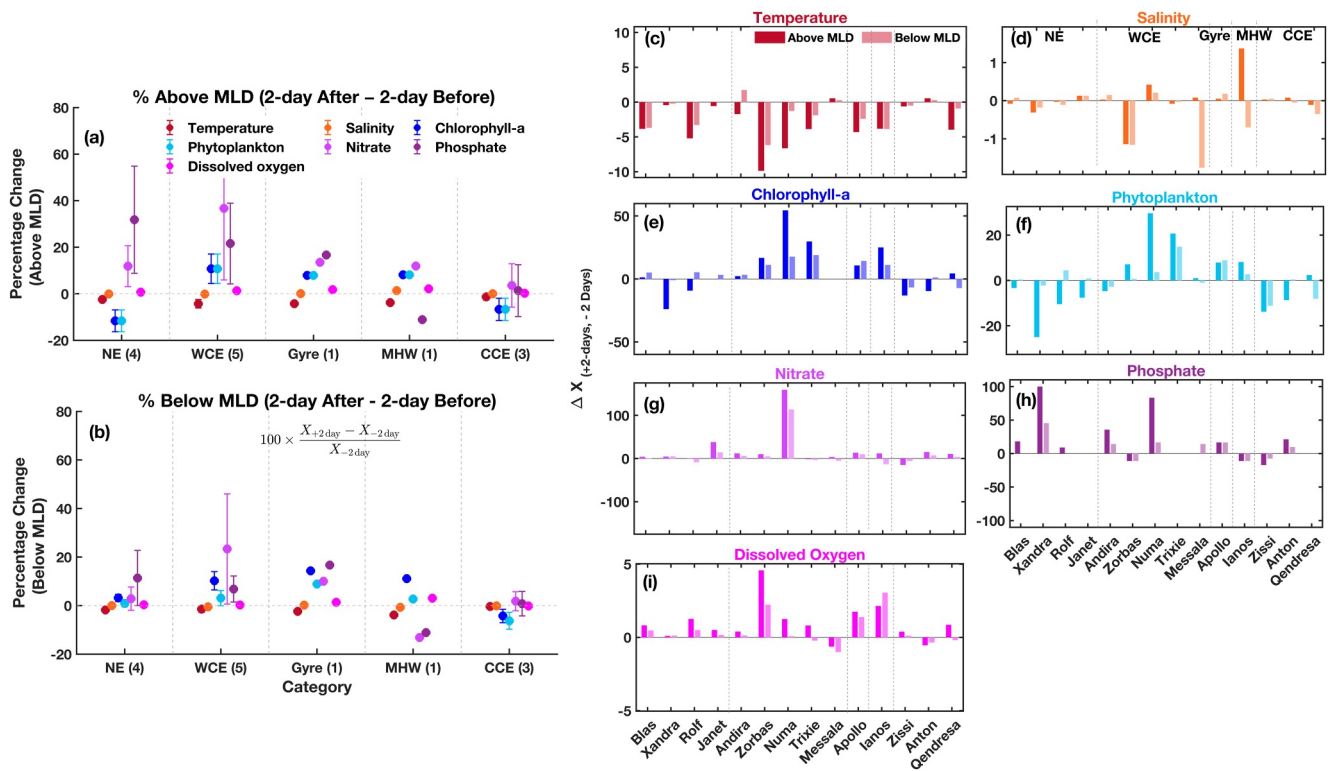


Figure 6. (a and b) The average percentage difference between 2 days after and 2 days prior and standard error for all the variables in each category, namely no eddy, warm-core eddy, gyre, marine heat wave, and cold-core eddies above (a) and below (b) mixed layer depth (MLD). (c) Percentage difference of depth average temperature above and below MLD between 2 days after the Max-CI (minimum mean sea level pressure) minus 2 days before, at the maximum CI location. (d–i) are the same as (c) for salinity, Chl a, phytoplankton, nitrate, phosphate, and oxygen concentration, respectively. Dotted black lines show the different categories of medicanes, mentioned above.

layers even after the cyclone, suggesting an upward displacement of nutrient-rich waters that enhances nutrient availability in the upper ocean.

To assess the consistency in the responses of the sea surface layer to the passage of the medicanes and also to allow for better focus on each variable, we calculated the physical and biogeochemical percentage differences (as in Figures 6a and 6b) for each of the medicanes separately (Figures 6c–6i). At the time of the max-CI, temperatures above the MLD clearly decreased after the passage of each medicane, whereas smaller differences were observed below the MLD. Salinity showed a mixed pattern, which may be a result of the ratio between precipitation and evaporation. This ratio seems to be different regardless of the category. An increase in Chl a and phyc is predominantly observed in the presence of warm SST anomaly cases (WCE and MHW), indicating that stronger vertical mixing in warmer water may facilitate their upward propagation to the surface (Figures 6e and 6f). The gyre also indicates an increase in Chl a and phyc, presumably due to its slow TS. Similarly, oxygen also increased over the warm SST anomaly cases and may be associated with a greater surface cooling. No clear signal is found in the nutrients.

An additional possible driver of the observed response in the physical and biogeochemical variables may be related to the TS. Medicanes Anton and Zissi were the fastest moving cyclones before reaching the Max-CI, whereas all other medicanes exhibited low TS (slow-moving cyclones) at the Max-CI location. For example, the rapid movement of Zissi resulted in limited interaction with the underlying ocean, which may be responsible for its unique characteristics (no temperature and salinity response over CCE) during the cyclonic event. In contrast, as already discussed, medicane Apollo had the slowest TS, and although it passed over a CCE at the Max-CI location, it exhibited similarity with the warm SST categories (WCE and MHW).

4. Discussion

Analysis of 14 medicanes passing over various MS features revealed overall SST cooling and an increase in surface Chl *a* concentration. This response results from a combination of wind-induced cooling and upwelling of cold, nutrient-rich water that stimulates phytoplankton growth. The prolonged duration of elevated Chl *a* concentration during upwelling events typically correlates with increased activity in the fisheries industry (Lumban-Gaol et al., 2021). Consequently, SST and Chl *a* might serve as key indicators for identifying favorable fishing grounds.

The implications of cyclone-induced mixing extend beyond immediate productivity gains. It is well established that such mixing significantly affects food web dynamics and the biological carbon pump. Medicanes, though smaller in scale, can generate comparable vertical mixing, bringing nutrient-rich waters from deeper layers to the surface where sunlight drives photosynthesis. This nutrient influx fuels phytoplankton blooms at the base of the marine food web, which in turn support higher trophic levels such as zooplankton, fish, and other marine organisms (Keerthi and Levi, 2021). Additionally, this productivity plays a key role in enhancing the biological carbon pump, wherein carbon is fixed by phytoplankton and ultimately transported to the deep ocean through sinking organic matter (Lutz et al., 2007; Platt et al., 2003), facilitating long-term carbon sequestration.

However, despite benefits such as enhanced productivity after passage of a medicane, cyclone-induced mixing also poses significant ecological risks. Increasing frequency and intensity of such events, possibly driven by climate change, could lead to excessive productivity, resulting in oxygen depletion at depth and the formation of hypoxic zones that are detrimental to marine life (Yang et al., 2024). In this context, our study is especially important as it sheds light on how medicanes interact with preexisting ocean conditions to shape the magnitude and direction of these biogeochemical responses. By examining both physical and biological feedback, we provide a more in-depth understanding of how these regional extreme events can influence ecosystem functioning and carbon cycling in the MS.

Furthermore, assessing the role of preexisting ocean conditions in the temporal evolution of systems can help improve the modeling and forecasting of extreme events in the MS. Since MS countries' economies are linked to marine ecosystem services, understanding how regional and global climate change affects cyclone frequency and characteristics (e.g., Reale et al., 2022) is essential. By unveiling interactions between cyclones and marine ecosystems, this work supports future pattern prediction and the economic potential of the MS. Coupled ocean-biogeochemical modeling can enhance projections of cyclone impacts on marine ecosystems, aiding both the scientific community and stakeholders like fishery managers. Our study lays the foundation for future work using coupled models to refine predictions of extreme weather effects on marine biogeochemistry in the MS. As shown by Sen et al. (2022), incorporating biogeochemical processes can significantly alter physical ocean projections, underscoring the importance of this approach.

5. Conclusions

Our analysis of 14 medicane cases reveals that MSLP drops are more pronounced over WCEs than CCEs, driven by latent heat release. Postmedicane passages, Chl *a*, and phytoplankton concentrations increase in the mixed layer due to upwelling of the DCM layer and enhanced mixing. Nutrients also rise in both the mixed and subsurface layers, with ~20%–50% increments in the presence of WCEs, CCEs, gyres, and MHWs. Compared to physical variables, biogeochemical variables exhibit a stronger response after the storm. Additionally, oxygen concentrations increase in response to cyclone-induced SST cooling.

Inside WCEs, the increase in Chl *a*, phyc, and oxygen concentrations is driven by cyclone-related mixing and upwelling. The WCEs intensified the cyclones due to higher release of heat fluxes, leading to stronger winds, enhanced mixing, more pronounced surface water cooling, and elevated surface Chl *a* levels (as observed by Liu et al., 2020). Moreover, cyclone-induced vertical mixing injects nutrients into the ocean's upper layer and drives significant phytoplankton blooms.

In the case of CCE, wind-driven upwelling is accompanied by an already higher MLD associated with eddy-induced upwelling. The lower increase in biogeochemical properties inside the mixed layer of CCEs found in this study can have two possible explanations. The first explanation is that the atmosphere above CCEs is more stable, which leads to weaker winds. As a result, cyclone-induced upwelling and mixing are weaker. The second explanation is the high cyclone TS that shortens the time of interaction with the eddy. Cyclones Anton and Zissi

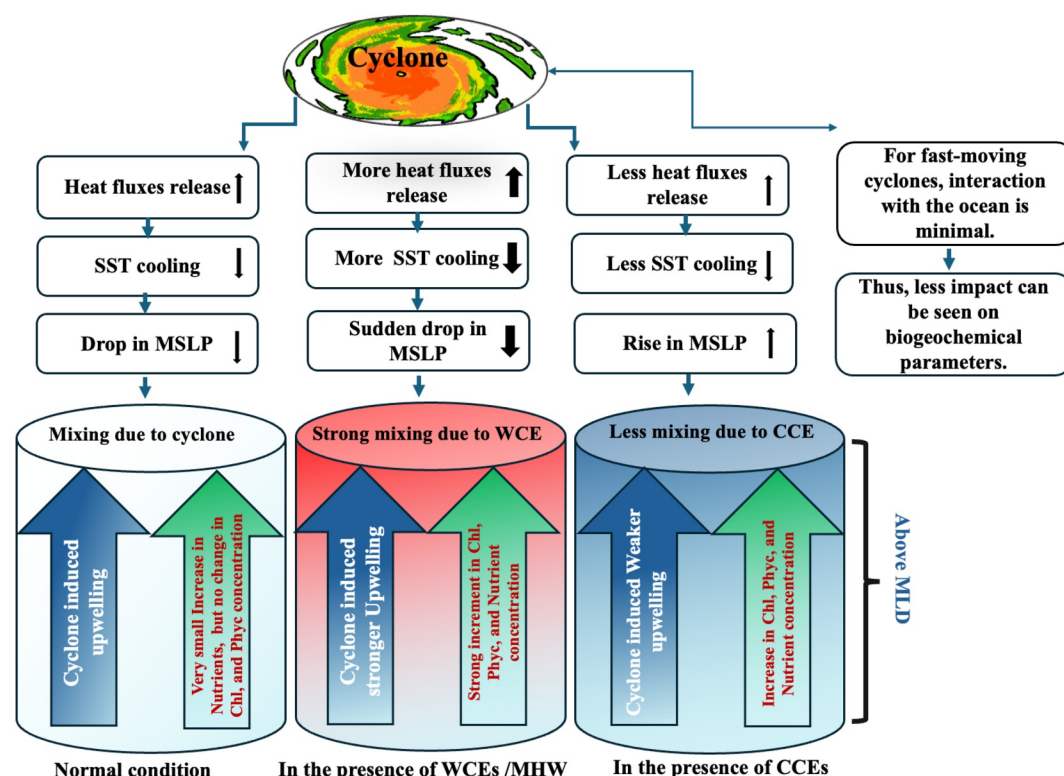


Figure 7. Schematic representation of the effect of medicanes on the physical and biogeochemical properties of the Mediterranean Sea in the presence of ocean circulation features (i.e., eddies and gyres). The size of the arrows represents the strength of the process.

(Max-CI above CCE) were the fastest moving cyclones, whereas all other cyclones exhibited low TS (slow-moving cyclones). Among these two, Zissi exhibited an exceptionally high TS.

In summary, the impact of cyclones on the marine environment is important and strongly modulated by the presence of eddies, gyres, and MHW along the cyclone's path (Figure 7). Additionally, the characteristics of the cyclone itself, including its TS, play a crucial role in shaping its influence on the ocean's biogeochemical properties. This interplay of environmental conditions and cyclonic characteristics collectively dictates the magnitude and extent of the cyclone's impact on the marine ecosystem.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

In this study, publicly accessible data sets were analyzed. Ocean temperature and salinity profile data were obtained from the Reanalysis product of Copernicus Marine Service (https://doi.org/10.25423/CMCC/MED-SEA_MULTIYEAR_PHY_006_004_E3R1). Data concerning atmospheric wind fields, heat fluxes, wind speed, and mean sea-level pressure were obtained from ([10.24381/cds.adbb2d47](https://doi.org/10.24381/cds.adbb2d47)). The biogeochemical variables, that is, chlorophyll, phytoplankton, nutrients, and oxygen profile data, were retrieved from the MEDSEA_MULTIYEAR_BGC_006_008(https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3). The daily sea-level anomaly data were obtained from <https://doi.org/10.48670/moi-00141>.

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Erratum

The originally published version of this article contained a typographical error. Coauthor Riccardo Martellucci's name was misspelled as Riccardo Marellucci. The error has been corrected, and this may be considered the authoritative version of record.