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Air–Sea Interactions and Biogeochemical Responses to Medicane Daniel

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Abstract: Medicane Daniel, formed on 4-12 September 2023, has stood out as the deadliest recorded storm in Mediterranean history. In this study, we investigate the role of sea features as contributors to the intensification of the Medicane Daniel. Our findings reveal the presence of a warm core eddy (WCE), high ocean heat content, and a moderate marine heat wave (MHW) at the location where Medicane Daniel intensified. These features were situated near the coastal region, facilitating the Medicane's intensification close to the coast. Consequently, the Medicane did not weaken significantly after landfall, leading to severe damage along the coast of Libya. These conditions favoured the Medicane's intensification and, due to high moisture convergence, contributed to significant precipitation at the eddy and MHW position. Importantly, observations from the high-resolution Surface Water and Ocean Topography (SWOT) satellite captured the WCE more accurately or in finer detail. This allowed for attribution of changes in biogeochemical properties -namely, chlorophyll, phytoplankton, nutrients, and dissolved oxygen concentrations due to eddy-induced vertical mixing and upwelling. The biogeochemical properties tend to increase over the WCE and MHW locations due to mixing and upwelling induced by the presence of the WCE and MHW. Our case-study analysis suggests that, under atmospheric cyclone conditions, subsurface mixing may be more influential within CCEs than upwelling driven by Ekman pumping, which, by contrast, may play a more prominent role within WCEs.

Key Words: Medicanes**,** eddies**,** Marine Heat Wave, deadliest Medicane, SWOT satellite, Biogeochemistry

Key Points:

- Along the path of Medicane Daniel, Warm Core Eddy (WCE), Ocean Heat Content, and Marine Heatwave (MHW) were present near the coastal region. Their combined presence enhanced precipitation, making Medicane Daniel a deadly storm.

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- SWOT satellite products better represent air-sea interaction due to their fine resolution over eddy regions.
- An increase in surface chlorophyll was observed after the cyclone passed over the WCE location. Positive Ekman pumping confirms that the increase was caused by cyclone-induced upwelling.
- Analysis of vertical profiles shows a decrease in surface temperature and an increase in chlorophyll and nutrient concentration above the mixed layer due to cyclone-induced mixing and upwelling.
- Cross-section analysis over the WCE location shows an upward shift in isotherms, leading to increased chlorophyll from cyclone-induced mixing and upwelling.

1. Introduction:

The Mediterranean region (MR) is recognized as a climate change hotspot (IPCC, 2021), warming at a rate up to 1.5 times faster than the global average (MedECC, 2020; Zittis et al., 2022; Khodayar et al., 2025). Positioned between the arid climate of North Africa and the temperate and wet climate of Central Europe, the MR is particularly vulnerable to future climate impacts. Surface temperature in this region is projected to continue increasing, but the precipitation tends to decrease (Cherif et al., 2020; Reale et al., 2022). As a consequence, the magnitude of extreme phenomena such as Mediterranean cyclones, marine heat waves (MHW), and intense droughts is projected to increase under future climate scenarios (MedECC, 2020; Hochman et al., 2021; Zittis et al., 2022).

Medicanes are a subcategory of Mediterranean cyclones, which can resemble hurricanes in both intensity and impact. They often bring torrential rainfall, flash floods, powerful winds, storm surges, and hazardous sea conditions. Such events pose significant risks, particularly to coastal communities and urban centers, threatening homes, livelihoods, and natural ecosystems (Hochman et al., 2021; Khodayar et al., 2025). Similar to Mediterranean cyclones, their intensity is projected to increase under future climate scenarios, but with lower frequency (González-Alemán et al., 2019). Despite their strong impact, the full extent of the damage medicanes inflict, both socially and economically, remains insufficiently understood. Moreover, their potential impact on ocean biogeochemistry is under-researched and often inadequately communicated, leaving a critical gap in public awareness and scientific insight.

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Medicanes are also known as 'tropical-like cyclones' because they have cyclone-like characteristics such as a cloud-free calm "eye," spiraling cloud bands, and strong winds near the vortex center. These features may be associated with the absence of fronts, weak vertical wind shear, and a warm core (WC) with an axisymmetric structure (Miglietta et al., 2019; Flaounas et al., 2022; Panegrossi et al., 2023). The formation of cyclones in the MR, including medicanes, is primarily driven by baroclinic instability and Rossby wave breaking (Raveh-Rubin and Flaounas, 2017; Flaounas et al., 2022). As these systems evolve and reach their mature stage, medicanes can intensify and be sustained through exchanges of heat and momentum at the air-sea interface (Emanuel, 2005). The development of intense Mediterranean cyclones is frequently associated with southward shifts of the polar jet, which enable air masses with high potential vorticity (PV) to enter the MR, thereby initiating baroclinic instability similar to that observed during extratropical cyclone development over open oceans (Flocas, 2000; Trigo et al., 2002; Nicolaides et al., 2006; Fita et al., 2007; Claud et al., 2010; Kouroutzoglou et al., 2011; Flaounas et al., 2015). Raveh-Rubin and Flaounas (2017) identified Rossby Wave Breaking (RWB) as a frequent precursor to Mediterranean cyclogenesis, while Flaounas et al. (2015) further emphasized that the cyclogenesis environment in the region is characterized by strong horizontal shear, driving these cyclones to follow a typical baroclinic life cycle. Furthermore, Flaounas et al. (2025) also highlight the importance of these atmospheric variables in the genesis and intensification of Medicane Daniel. However, in this manuscript, we primarily focus on the Atmospheric and oceanic precursor that are most directly associated with Daniel's intensification and associated precipitation.

Furthermore,, the role of underlying ocean eddies and MHW in modulating the deepening of a cyclone is often overlooked. Recent studies have highlighted the critical role of ocean eddies and MHWs in modulating cyclone's deepening in the MR (Jangir et al., 2023, 2024; Mishra et al., 2024; Strobach et al., 2024). In particular, Jangir et al. (2024) demonstrated the significant intensification of medicane Ianos due to the presence of a strong MHW, making it the only category 2 cyclone observed in the Mediterranean Sea (MS). In contrast, other medicanes such as Zorbas and Apollo intensified primarily due to the interaction with Warm Core Eddies (WCEs) along their paths. Mishra et al. (2024) reported that if we remove these SST anomalies from the path of medicane Ianos, the medicane will still form, but with a reduced intensity. Strobach et al. (2024) reported that ocean mesoscale eddies in the Eastern Mediterranean can significantly influence extreme weather, as shown during the heavy rainfall event in Israel that

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occurred from January 8 to 10, 2020. High-resolution coupled ocean-atmosphere simulations captured the event more accurately than uncoupled ones. The study by Strobach et al. (2024) highlights how eddies can enhance atmospheric moisture and meso-cyclone development, intensifying local extremes.

As efforts continue to enhance the accuracy of cyclone intensity forecasts, the potential influence of eddies MHW, and OHC remains a critical yet less explored aspect, particularly within the Mediterranean context. To improve the prediction of Mediterranean cyclones and mitigate associated risks, a deeper understanding of air-sea interaction processes and the role of pre-existing oceanic conditions in cyclone genesis and intensification is essential. Recent studies have increasingly focused on these dynamics, exploring how air-sea exchanges affect not only medicanes intensity but also the ocean's biogeochemical responses (Jangir et al., 2023; Menna et al., 2023; Scardino et al., 2024; Avolio et al., 2024). Notably, Jangir et al. (2023) highlighted the influence of WCEs on the intensification of medicanes, demonstrating that eddy size also plays a critical role; larger eddies tend to promote stronger cyclones and heavier rainfall. In this particular study, we show the influence of eddies and MHW on the intensity of medicane Daniel.

Most of the studies use the satellite SLA altimetry data from the Copernicus Marine Services (CMEMS) for the detection of eddies. Here, we also use the Surface Water and Ocean Topography (SWOT) satellite data, which are available at high spatial resolution. The SWOT satellite provides the first-ever global observations of ocean dynamics at sub-mesoscale spatial resolutions (1–100 km). While traditional satellite products, such as those from the Copernicus mission, offer spatial resolutions of approximately 25 km globally and 12.5 km in the MS, SWOT's advanced wide-swath altimetry overcomes these limitations by achieving resolutions as fine as 250 m to 2 km. This enhanced capability enables the detection of small-scale ocean features that were previously unresolved. SWOT observations confirm the widespread presence of sub-mesoscale eddies and internal waves, particularly energetic in regions like western boundary currents and the Antarctic Circumpolar Current (Archer et al., 2025; Tranchant et al., 2025). This high-resolution data is especially valuable for studying ocean-atmosphere interactions, such as the role of eddies in cyclone intensification. In particular, SWOT's ability to capture the structure, intensity, and evolution of eddies provides critical insight into how these features influence heat transport, vertical mixing, and the modulation of cyclone intensity due to eddies. Thus, SWOT marks a transformative step in advancing our

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understanding of fine-scale ocean processes and their implications for weather, climate, and marine biogeochemistry.

Cyclones are known to trigger substantial phytoplankton blooms (Shang et al., 2015; Chowdhury et al., 2020; Liu et al., 2020). These blooms are primarily attributed to cyclone-induced upwelling and vertical mixing, which transport cold, nutrient-rich, or chlorophyll-loaded water into the euphotic zone, stimulating phytoplankton bloom. Such storm-driven biological responses offer valuable insight into ocean mixing and biogeochemical dynamics (Chen et al., 2022). Additionally, strong cyclonic winds often cause a noticeable decrease in SST, which plays a crucial role in regulating primary productivity (Latha et al., 2015). There are few studies reported in the other ocean basins that indicate the enhancement of chlorophyll-a (Chl-a) concentration following the passage of a cyclone in the presence of eddies (Dutta et al., 2019; Zhang and Qui, 2020; Vidya et al., 2021) and MHW (Oliver et al., 2018; Jangir et al., 2024). Recently, a study by Scardino et al. (2025) reported the response of Mediterranean cyclones on ocean chlorophyll concentration, primarily using Bio-Argo floats. In contrast, our study offers a new perspective by utilizing subsurface profiles of a broader suite of biogeochemical variables, including chlorophyll, phytoplankton, nutrients, and oxygen concentration, complemented by multiple ocean satellite and reanalysis products. To date, such a comprehensive assessment has rarely been reported for the Mediterranean Sea. Here, we investigate the impact of Medicane Daniel on ocean biogeochemistry in the context of the SST anomalies along its path.

In this study, we highlight the co-occurrence of compound extreme events in the region prior to medicane Daniel's landfall. Specifically, we show that the intensification of medicane Daniel may have been driven by the combined influence of a WCE and an MHW. We examine the key atmospheric and oceanic factors that contributed to Daniel's development, ultimately making it one of the deadliest cyclones in the MS. The analysis also covers the critical role of the SWOT satellite in advancing air-sea interaction research; this is the first study to report the importance of SWOT data for air-sea interaction in the MS. Additionally, we investigate the medicane's impact on ocean biogeochemistry at the WCE location, providing insights into the underlying physical and biological processes that govern such interactions.

2. Medicane Daniel Synoptic Overview and Intensification: Daniel was formed in the MS from 4 to 12 September 2023. It was the deadliest cyclone in the Mediterranean basin during the satellite era. The cyclone originated from an upper-level cut-off low and brought exceptionally heavy rainfall to Greece and Libya, triggering severe floods and mudslides. These catastrophic events led to at least 5,898 fatalities in Libya (Hérincs, 2023; Normand et al., 2024). On September 2-3, a swift cold front traversed Central Europe, generating an upper-level trough that created a cut-off low near Greece by September 4. Named "Daniel" by the Hellenic National Weather Service, this cyclone brought severe thunderstorms to Greece, Turkey, and Bulgaria due to unstable atmospheric conditions and warm waters. Moving south-southwest, it stalled over the Central Mediterranean, evolving into a subtropical storm by September 7. By September 9, Daniel transitioned into a tropical-like storm, making landfall in Libya on September 10, causing catastrophic floods. Daniel dissipated into a low-pressure trough by September 12 (Hérincs, 2023; Normand et al., 2024). Storm Daniel brought intense winds of up to 120 km/h and delivered a total of 240 mm of rainfall over a 25-hour period (Normand et al., 2024). It caused catastrophic flash flooding in Derna on September 10, 2023, as torrential rains overwhelmed the river's delta outlet. The flood destroyed large parts of the city's buildings, infrastructure, and bridges, resulting in 8.8 million tons of debris. In Derna alone, 10% of houses were destroyed and 18.5% damaged. In other cities, such as Susah, approximately 28% of homes were destroyed, while Albayda, Al-Marj, and others also suffered heavy losses. Overall, the storm led to 5,898 deaths, 8,000 missing persons, 44,800 displaced individuals, and 18,838 homes damaged across Libya's northeastern coast, making it the deadliest African storm since 1900 (Normand et al., 2024; Katsanos et al., 2024).

3. Data and Methods:

3.1 Data sources and products used:

In this study, the best-track data for the medicane Daniel was obtained from the Zivipotty Cyclone Report database (https://zivipotty.hu/tcr.html). Eddy identification was based on daily SLA fields sourced from the CMEMS. Specifically, the dataset SEALEVEL_EUR_PHY_L4_NRT_OBSERVATIONS_008_060, with a spatial resolution of 0.125°, was utilized. To detect and characterize the MHW, daily SST data from the NOAA Optimum Interpolation SST V2 dataset (Reynolds et al., 2007) were used. This dataset has a spatial resolution of 0.25° and covers the period from 1981 to the present. The key atmospheric variables, including total column water vapor (which represents the sum of water vapor, liquid water, cloud ice, rain, and snow in a column extending from the surface of the Earth to the top of the atmosphere), total precipitation (TP), vertical integrated moisture divergence (VIMD), mean sea level pressure (MSLP), and 10-meter zonal and meridional wind components, daily

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radiative fluxes of shortwave and longwave radiations, (denoted as Q_{SW} and Q_{LW} respectively), turbulent heat fluxes of latent and sensible flux (denoted as Q_{lat} and Q_{sen} respectively) were retrieved from the ERA5 reanalysis (Hersbach et al., 2020). The surface net heat flux (Q_{net}) was derived from a combination of radiative and turbulent fluxes (Menna et al., 2023).

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

High-resolution SLA observations were obtained from the SWOT Level 3 satellite product, which offers 2 km spatial resolution, provided by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO; https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/swot-l3-ocean-products.html).

Lastly, biogeochemical parameters such as chlorophyll, phytoplankton, nutrients, and dissolved oxygen were accessed via the CMEMS from the product MEDSEA_MULTIYEAR_BGC_006_008, available at a 4-5 km spatial resolution, and 1-hr temporal resolution (https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3). Daily satellite chlorophyll products with 1 km spatial resolution have also been used in this study (Volpe et al., 2019; Volpe et al., 2018; Berthon et al., 2004), which are archived from Copernicus (https://doi.org/10.48670/moi-00298).

3.2 Methods: In this study, we investigate medicane Daniel. A detailed description of the event and the methodologies employed in the analysis are provided below.

3.2.1 Eddy and Marine Heat Wave (MHW) identification:

Eddy identification in this study followed the approach of Jangir et al. (2021, 2023) and Sun et al. (2017), based on geostrophic balance equations relating SLA to geostrophic currents. Zonal (u) and Meridional (v) velocity components were derived using equations 2, 3, and 4:

$$u = -\frac{g}{f}\left(\frac{dh}{dy}\right) \quad (2)$$

$$v = \frac{g}{f}\left(\frac{dh}{dx}\right) \quad (3)$$

$$V^2 = u^2 + v^2 \quad (4)$$

where u and v are the zonal and meridional components, g is the acceleration caused by gravity, f is the Coriolis parameter, h is the SLA, and V is the geostrophic current speed.

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Eddies were classified by analysing flow circulation and SLA patterns: anti-cyclonic circulation with a local SLA maximum indicated WCEs, while cyclonic circulation with a local SLA minimum indicated cold-core eddies (CCEs). This is consistent with previous findings, where WCEs in the Northern Hemisphere exhibited clockwise (anti-cyclonic) rotation, while CCEs rotated counterclockwise (cyclonic). The relation between anti-cyclonic eddies and WCEs along the cyclone's path was also verified by inspecting SST anomalies with respect to a boxcar average.

MHWs were identified using the definition by Hobday et al. (2016) and the software developed by Zhao et al. (2019) (https://github.com/ZijieZhaoMMHW/m_mhw1.0). An MHW is defined as a period of at least five consecutive days during which the daily SST exceeds the seasonally varying 90th percentile, based on a climatological reference period (1983–2021). Events separated by less than three days are treated as a single MHW. Daily SST anomalies were computed by subtracting the daily climatology. MHW intensity was classified following Hobday et al. (2018) into four categories based on the metric θ moderate ($1 \leq \theta \leq 2$), strong ($2 \leq \theta \leq 3$), severe ($3 \leq \theta \leq 4$), and extreme ($\theta \geq 4$).

Where

$$\theta = \frac{SST - SST_{climatology}}{SST_{90Th_{percentile}} - SST_{climatology}} \quad \text{.....................................(5)}$$

3.2.2 Computation of Ocean Heat Content

We have also calculated the OHC to assess the role of subsurface heat accumulation in driving compound extreme events, such as the co-occurrence of MHWs and cyclones. Since the ocean acts as a key energy source for cyclones by supplying heat and moisture, the passage of a cyclone typically extracts heat from the upper ocean, leading to a decrease in OHC. In this study, OHC is defined as the vertically integrated thermal energy from the surface down to the depth of the 20 °C isotherm (a proxy for the thermocline layer). The OHC was computed for the medicane using the following formulation (Equation 6):

$$OHC = \int_{h1}^{h2} \rho C_p T dz \quad \text{.......................................(6)}$$

where ρ is the density of the seawater, C_p is the specific heat capacity of the seawater at constant pressure, *p*, *h1* is the surface, *h2* is the bottom depth, and *T* is the temperature in °C.

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This approach allows us to quantify how much thermal energy is available in the upper ocean to potentially intensify cyclones and how this energy is depleted following cyclone passage.

3.2.3 Computation of Ekman pumping

Ekman pumping was computed using the wind stress components τ=(τ_x, τ_y) from ERA5, namely Eastward Wind Stress (EWSS) and Northward Wind Stress (NSSS). To compute the wind stress curl (∇×τ), the spatial derivatives of wind stress are used, and it is computed using equation 7:

$$curl(\tau) = \frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \quad \text{...(7)}$$

Then, the Ekman pumping velocity (w_e), introduced by Stern (1965) to account for the effect of the ocean currents on upwelling, is calculated using equation 8:

$$w_e = \frac{1}{\rho(f+\zeta)} \times curl(\tau) \quad \text{...(8)}$$

This vertical velocity reflects the upwelling (positive w_e) or downwelling (negative w_e) of water, and is a crucial mechanism through which cyclones influence oceanic nutrient transport, mixing, and biological productivity. Here, the relative vorticity (ζ) was computed from the zonal (u) and meridional (v) components of the surface current, as given in Equation (9):

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \quad \text{...(9)}$$

The Ekman transport vector components were computed from the wind stress and Coriolis parameter as:

$$M_x = \frac{\tau_y}{\rho f} \quad \text{...(10)}$$

$$M_y = \frac{\tau_x}{\rho f} \quad \text{...(11)}$$

where ρ is seawater density, and f is the Coriolis parameter (dependent on latitude). The vector field M=(M_x, M_y) was visualized using quiver plots to reveal the spatial structure and directional response of Ekman transport to cyclone wind forcing.

4. Results and Discussion

4.1 The presence of ocean features i.e., Eddies, Marine Heat Wave and Ocean Heat Content along the cyclone track and their Impact on cyclone intensity

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Figure 1a, b shows the SLA along the cyclone's track. At first, the medicane passed over a cluster of three anti-cyclonic WCEs between September 4 and 6, presumably contributing to its intensification (Jangir et al., 2023). This intensification is also supported by the presence of a MHW, as shown in Figure 1c–e (SI Figure 1), which reveals a moderate MHW at the intensification location on 9 September 2023. The presence of two extreme conditions, namely the WCE and MHW, at the intensification site near the coastal region may have contributed to making this the deadliest cyclone recorded in the MS (Figure 1). Rathore et al. (2022) and Jangir et al. (2024) highlighted the critical role of sudden intensification in Cyclone Amphan over the Indian Ocean and medicane Ianos over the MS, respectively, in the presence of MHWs along their paths. The findings of the current study are consistent with these observations, demonstrating that while cyclone genesis and intensification can occur independently of such features, the presence of WCEs and MHWs can significantly enhance the rate and magnitude of intensification over a shorter time.

Figures 1 mainly highlights the potential importance of ocean characteristics such as WCEs and MHWs in cyclone intensification, indicating that cyclone intensity increased in the presence of WCEs and MHWs. This behavior is similar to how cyclones in other ocean basins react to changes in intensification factors related to underlying eddies (Ali et al., 2007; Lin et al., 2013; Jangir et al., 2020; Jangir et al., 2023). When a cyclone encounters a WCE, the negative feedback loop between cyclone intensity and SST diminishes. Normally, cyclones absorb heat from the ocean, causing surface cooling through mixing and evaporation, reducing their intensity. However, if a WCE or MHW is present, the high SST persists longer, intensifying the cyclone and reducing the negative feedback effect (Bender et al., 1993; Jangir et al., 2024).

Furthermore, Cyclones also draw a significant portion of their energy from warm, deep ocean waters; therefore, quantifying the amount of this warm, deep water provides a more accurate measure of the energy available to the storm. OHC serves as this metric, indicating how much warm water a cyclone can convert into energy. Studies have shown that OHC is a far superior predictor compared to SST alone (Wada & Usui, 2007; Sharma and Ali, 2014; Lin et al., 2013; Law et al., 2011). Analysis of the OHC revealed that there is a significant amount of OHC at the intensification locations, providing the energy necessary for medicane Daniel to intensify. Approximately 120 KJ/cm² of heat was available from September 4th to 9th, even before the cyclone's intensification (Figure 1f-h & SI Figure 2). This accumulated heat at the

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intensification location is attributed to the presence of the eddy and the MHW, which decreases after the passage of the medicane on the 11th and 12th of September, 2023 (SI Figure 2). The presence of the accumulated heat in the form of OHC maintains intensity by reducing negative feedback that occurs due to the passage of the cyclone (Jangir et al., 2023; Jangir et al., 2024).

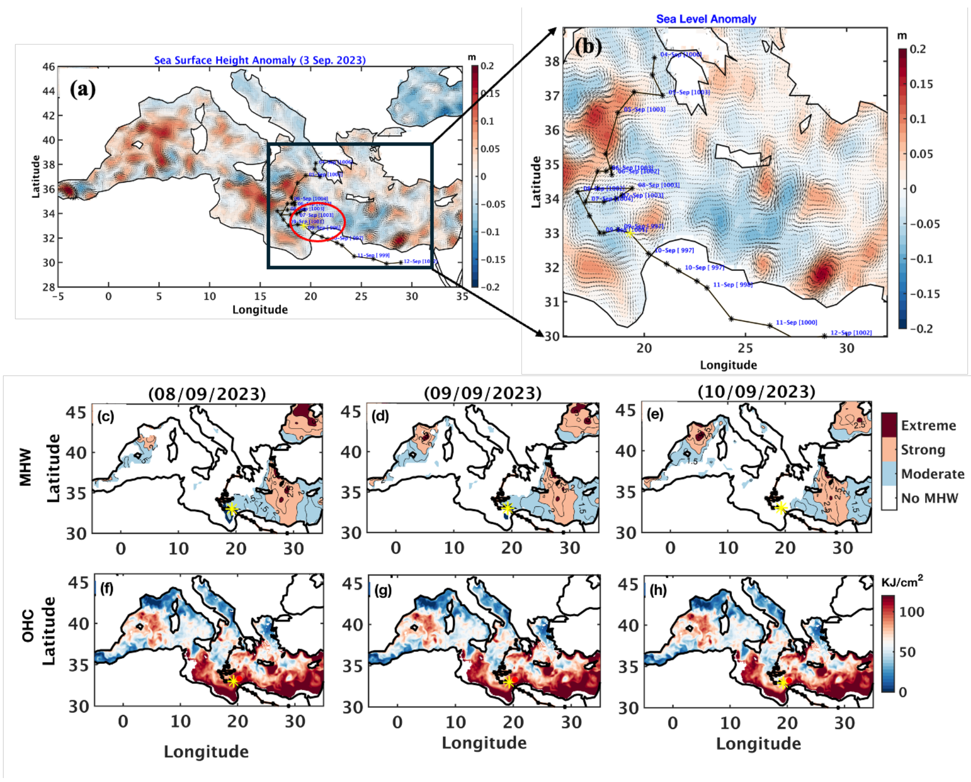

Figure 1: (a, b) Sea level anomaly in shading and geostrophic currents arrows, Medicane track overlaid on (c,e) Marine Heat Wave and (f,h) Ocean Heat Content, Yellow star represents the intensification location and the red dot on Ocean Heat Content showing the location of WCE.

4.2 The role of Atmospheric Precursors in the Intensification of Medicane Daniel

The MSLP, wind speed (WS), and net heat flux (NHF) along the cyclone's track are shown in Figure 2a. The MSLP, computed using the Cressman averaging method (Cressman, 1959), indicates moderate intensification when the storm passes over the WCE on 5 September (Figure 2a). Subsequently, from the 6th to the 7th, the medicane passes over a CCE region, and its intensity is reduced. Upon reaching the vicinity of Libya's coast on the 8th, it quickly intensifies. An additional WCE was present in the vicinity of the cyclone's path at that time,

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potentially further contributing to its fast intensification. This fast intensification is indicated by a drop in the MSLP and a sudden increase in WS near the eddy and MHW location (Figure 2a). Figure 2a shows that on September 7, 2023, the MSLP was 1003 hPa. Upon reaching the vicinity of the eddy, the MSLP dropped by 6 hPa to 997 hPa (Figure 2a) in 12 hours, and significant NHF were released at the cyclone's intensification location (Figure 2b-d and SI Figure 3), providing the energy necessary for the cyclone to intensify. The cutoff low persisted for two days (Figures 2b-d, SI Figure 3), even after the cyclone made landfall in Libya, resulting in significant damage along the Libyan coast.

Moisture processes play an equally important role in cyclone intensification. Their significane has been demonstrated in previous studies by Jangir et al. (2023) and Pytharoulis et al. (2018), emphasizing that elevated SST in the form of eddy or MHW is essential in providing moisture to a medicane via surface fluxes, enhancing convection. Additionally, Jangir et al. (2024) highlighted the importance of moisture convergence in the intensification of cyclones and increasing total associated precipitation. Thus, motivated by these findings, in this study we mainly focus on the cause of the intensification of the medicane Daniel and the extreme flood that occurred during the event.

The analysis of moisture convergence (i.e., mean vertically integrated moisture divergence) showed a pattern of moisture convergence along the cyclone's path. Notably, this convergence coincides with the eddy location at the intensification location on September 9th, 2023 (SI Figure 4). This alignment suggests that the eddy supplied the moisture needed for the cyclone's intensification. The interaction between the eddy and the medicane likely enhanced moisture availability, contributing to the storm's strengthening at that specific point in its path. Additionally, the total column water was notably high at the eddy and MHW locations. While this total water was present before the intensification location as well, it converged around the eddy at the intensification location (SI Figure 5), leading to substantial precipitation in that area (Figure 2e-g and SI Figure 6). The severe precipitation near the coastal region, primarily due to the presence of a WCE and MHW, significantly contributed to the extensive destruction along the Libyan coast. The WCE's influence intensified the cyclone by providing additional moisture and heat, leading to heavy rainfall. This heavy precipitation, concentrated near the coast, exacerbated the storm's impact, severely damaging the affected areas.

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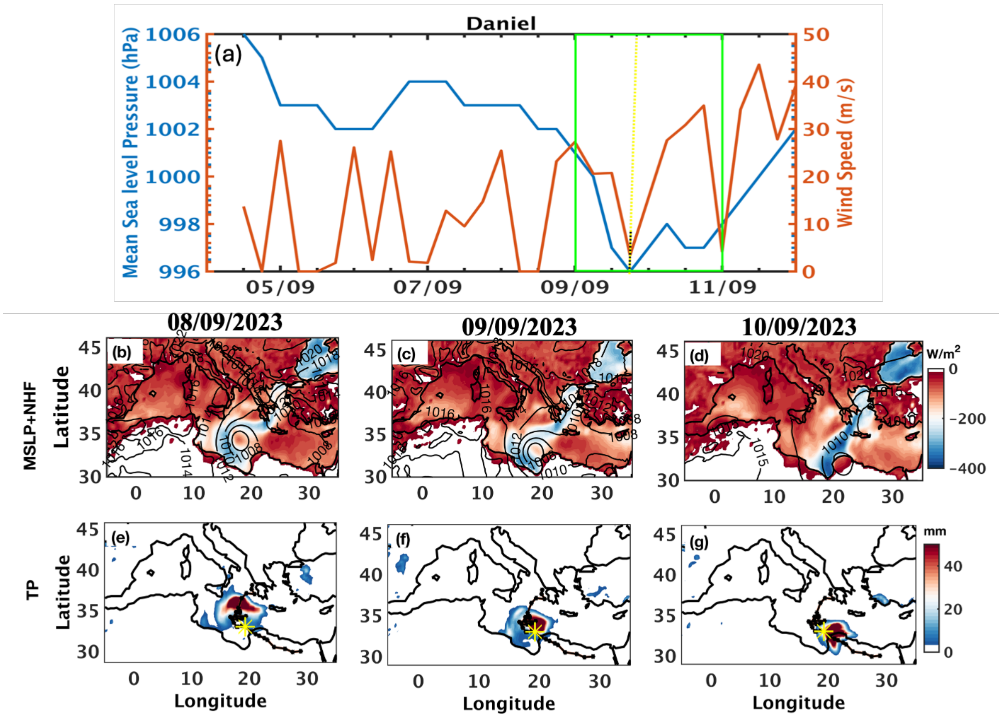

Figure: 2(a) Mean sea level pressure, wind speed, and net heat flux computed using the Cressman average along the track of the medicane Daniel. Medicane track overlaid on (b-d) Contours of the daily mean of MSLP overlaid on the daily mean of latent heat fluxes (positive downward), and (e-g) total precipitation during the cyclone, on the 8th, 9th and 10th September 2023. Yellow star represents the intensification location.

4.3 Use of SWOT satellite data in cyclone studies in the Mediterranean Sea

The SWOT mission offers high-resolution sea surface height anomaly (SSHA) or SLA data with unprecedented spatial detail, enabling precise detection of mesoscale and sub-mesoscale ocean features, such as eddies and fronts (Morrow et al., 2019). This can be valuable for studying cyclones, which interact strongly with oceanic eddies that influence storm intensity. Unlike traditional altimeters, SWOT's wide-swath coverage captures fine-scale structures generated by cyclone-induced mixing.

Here we show the SWOT swath passing over the location of the eddies along the track of medicane Daniel (Figure 3). In Figures 3a and 3b, the eddy initially appears small and low intensity in the CMEMS, and the cyclone is observed nearby. However, SWOT data reveals a

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more intense and extensive eddy structure with the cyclone positioned directly above it. Notably, Figure 3e shows a high post-cyclone increase in Chl-a concentration over both the eddy locations. Complementary to this, Figure 3 indicates enhanced Ekman pumping roughly at the same locations, likely contributing to the observed Chl-a increment over both eddies. These findings report the value of SWOT observations in capturing fine-scale oceanic features and dynamics, offering critical insights into cyclone-eddy interactions, vertical nutrient transport, investigating sub-mesoscale air-sea interactions, and improving coupled ocean-atmosphere models.

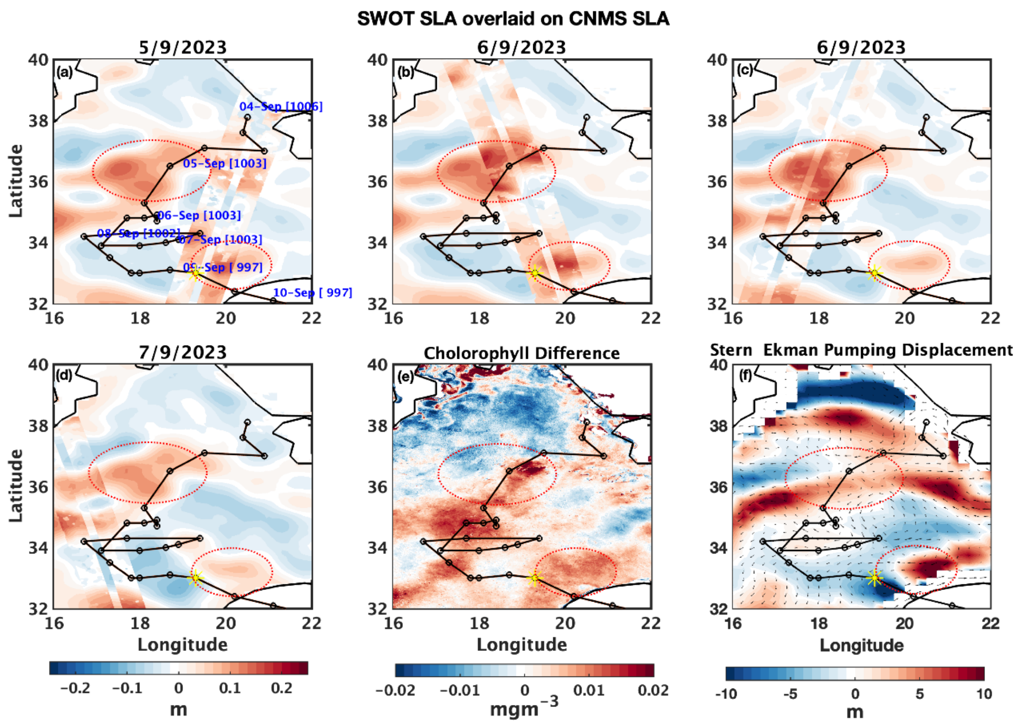

Figure 3: (a-d) The SWOT SLA swath (with resolution 2 km) overlaid on SLA from CMEMS *(12.5 km spatial resolution). (e) Satellite chlorophyll (2 km spatial resolution) before and after Storm Daniel. (f) Average (5-10 September 2023) Ekman pumping displacement and arrows of transport vector during the cyclone.*

4.4 Impact of medicane Daniel on ocean biogeochemistry

To investigate the impact of the medicane on oceanic physical and biogeochemical properties, we analyzed vertical profiles of key variables along the cyclone's track. The analysis focused on differences between two days after the cyclone's passage minus two days before (Figure 4a-g). The results reveal a notable decrease in temperature along the cyclone path, with the

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strongest cooling observed near the WCE and MHW locations. In contrast, Chl-a and phytoplankton concentrations at the surface exhibit a marked dipole at the subsurface. This biological response is attributed to cyclone-induced upwelling and vertical mixing. Enhanced nutrient availability at the subsurface layer allows for sufficient sunlight, and together with elevated oxygen concentrations, may foster increased surface Chl-a and phytoplankton biomass. Signs of this can be seen in the MHW region, where higher Chl-a concentrations reach the surface. But, unlike previous results (Jangir et al., 2026), medicane Daniel only shows a small increase in Chl-a at the surface in the MHW region. Profiles of temperature and Chl-a at the maximum cyclone intensity location and time (Figure 4h, i) reveal that the DCM was located far below the MLD, at around 140m depth. We already know that cyclone-induced upwelling was negative there (Figure 3f), indicating downwelling, so it cannot explain the increase in Chl-a at the surface. The profiles in Figure 4i are in agreement with the downwelling, showing a small decrease in the DCM depth. The subsurface crossings between the profiles in this figure indicate that a different mechanism was active, that is, cyclone-induced subsurface mixing. This mechanism is typically slower than turbulence in the mixed layer, but under storm conditions may become comparable. The gradual subsurface increase in Chl-a, as opposed to the vertical line observed in the mixed layer, suggests that subsurface turbulence is comparable to, but still weaker than, turbulence within the mixed layer.

To further investigate the underlying mechanisms, vertical cross-sections over the main WCE region were analyzed during the pre-storm, during storm, and post-storm phases (Figure 5). These sections reveal notable eddy-dependent subsurface changes associated with the passage of the medicane. As expected, during and after the passage of the storm, significant surface cooling is observed (panels b-d and h-i). In addition to the cooling observed within the mixed layer, three distinct circular-like cooling patterns are evident immediately beneath it. These may indicate a secondary circulation motion starting at the deep sub-surface (below 200m), which transfers deep cold water to the layers below the mixed layer. In this case, the two patterns on the right indicate an upwelling cell at the WCE boundaries and another at the CCE center. These circulation cells also create the Chl-a patterns of DCM upwelling inside the WCE, but they do not explain the dipole pattern above the WCE.

Figure 6 shows vertical profiles of Chl-a in two locations along the same line as in Figure 7a, one inside the CCE and one inside the WCE. These can guide us about the relevant active mechanisms. Inside the WCE, high Ekman pumping (Figure 3f) results in upwelling and

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upward shift of the DCM depth. Inside the CCE, Ekman pumping is less relevant - the DCM stays more or less at the same depth. Yet, the profiles in Figure 6a suggest that the dipole patterns inside the CCE in Figure 5k can be explained by subsurface mixing, which is stronger above the DCM. These observations suggest that although WCEs are generally associated with downwelling and reduced biogeochemical activity, the strong mixing and upwelling induced by the cyclone temporarily dominate this dynamic, leading to surface nutrient enrichment and increased biological activity. In the CCE, although the Ekman pumping is smaller (or negative), the higher DCM depth supports mixing of Chl-a to the surface through sub-surface mixing.

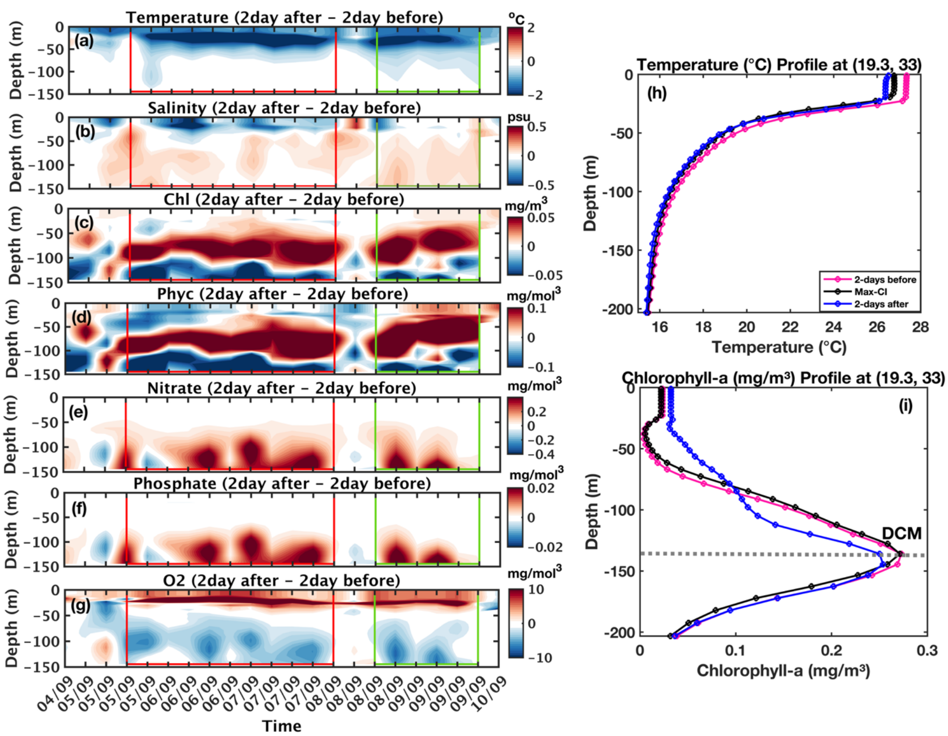

Figure 4: Profile of physical (a-d) and biogeochemical variables (e-g) along the path of the cyclone. The left panels represent the difference between two days after the event minus two days before the event. The red and green vertical lines in panels a-g bound the location of MHW and WCE along the track of the Mediterranean cyclone Daniel, respectively. The vertical dotted black mark marks the location of the cyclone's maximum intensity.

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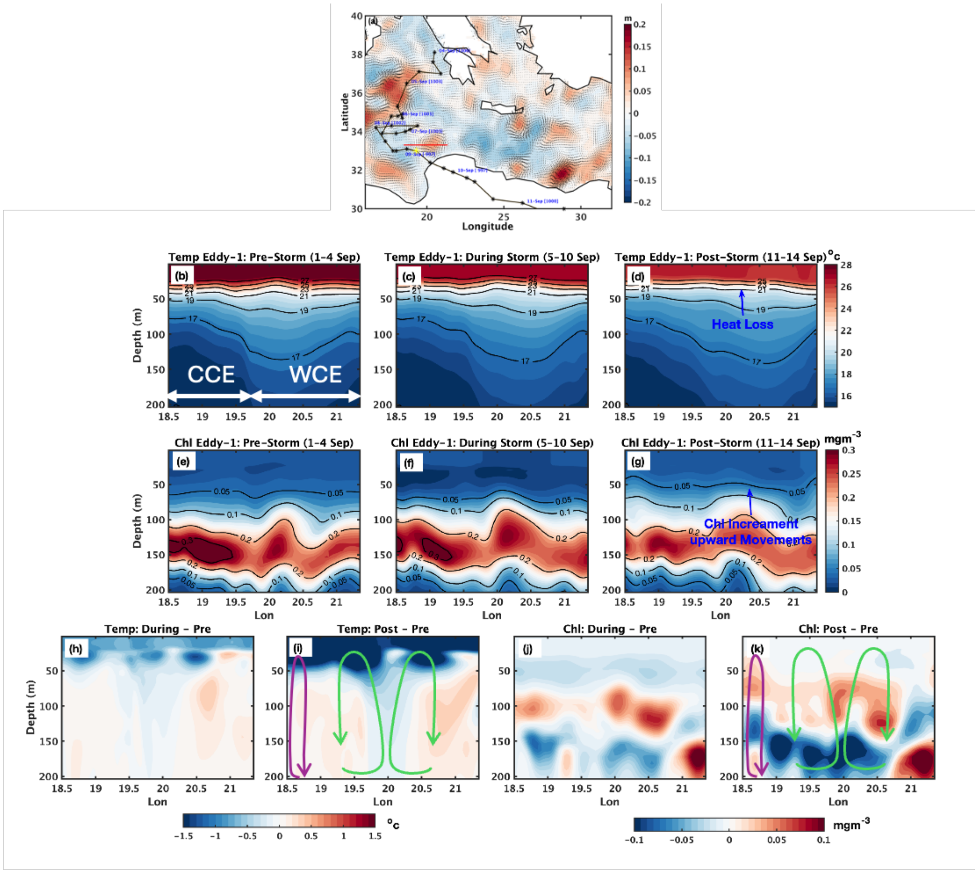

Figure 5: (a) Sea level anomaly and a red line representing the section over the second WCE, which is considered in the next panels. (b-d) Temperature profiles and isotherms before, during, and after the medicane along the section over the eddy. (e-g) Chlorophyll profiles before, during, and after the medicane along the section over the eddy. (h-i) The difference in temp during-storm minus pre-storm and post-storm minus pre-storm. (j-k) are the same as (h-j) for Chl-a. Green arrows represent the estimated location of a secondary circulation cell, and the purple arrow indicates subsurface mixing.

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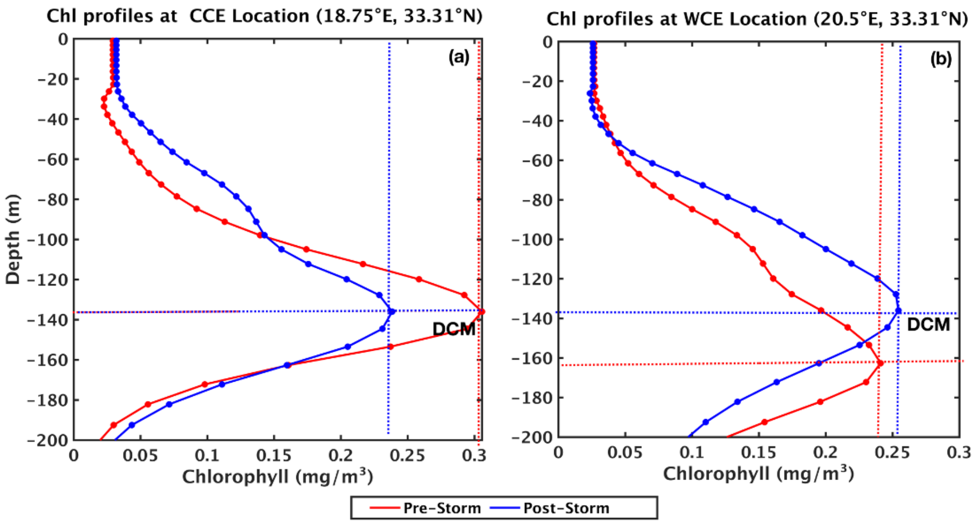

Figure 6: The Chlorophyll profiles before the storm (1–4 September), and after the storm (11–14 September) at the CCE location and WCE location.

5. Conclusions

This study has provided comprehensive insights into the intensification and impact of the medicane Daniel, which formed in the MS in September 2023. The findings show the significant role of oceanic and atmospheric variables in cyclone intensification, particularly the presence of WCE and MHW (Figure 7). These oceanic features reduced the negative feedback loop between cyclone intensity and SST, allowing the cyclone to maintain and even increase its intensity. This study also highlighted the importance of OHC in providing the energy necessary for cyclone intensification, with approximately 120 KJ/cm² of heat available at the intensification location over the WCE and MHW. Additionally, the convergence of moisture at the locations of the WCE and MHW, combined with the elevated total water column, contributed to the heavy precipitation observed in the coastal areas in Libya.

This study highlights the critical role of high-resolution SWOT data in advancing our understanding of air-sea interaction processes. While CMEMS data, with its coarser spatial resolution, suggests the presence of a weak eddy near the cyclone intensification region, SWOT's finer 2 km resolution reveals a high-intensity WCE precisely aligned with the cyclone's path. This enhanced detection capability provides a more accurate illustration of eddy characteristics and their influence on cyclone dynamics. Furthermore, satellite-derived Chl-a data indicate an enhanced bloom over the WCE location, supported by positive Ekman

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pumping values. These high values indicate cyclone-induced upward movement of water from deeper layers to the surface, bringing cold, nutrient-rich water to the surface, and boosting ocean productivity.

Subsurface profiles of physical and biogeochemical properties show a notable temperature decrease above the mixed layer depth, particularly over the WCE and MHW regions. The passage of the cyclone triggers vertical mixing, leading to an increase in surface nutrient concentrations. Combined with sufficient sunlight in the euphotic zone, this promotes a surge in surface Chl-a and phytoplankton productivity. Cross-sectional analysis further reinforces these findings: a clear upward shift in isotherms following the cyclone indicates heat loss and active upwelling over the WCE. Concurrently, the chlorophyll sections display an upward displacement and intensification of chlorophyll concentrations, confirming the strong biogeochemical response induced by the cyclone's passage over the WCE region.

In conclusion, the study of medicane Daniel emphasizes the need for a deeper understanding of both oceanic and atmospheric factors in predicting and mitigating the impacts of such cyclones in the MR. The findings suggest that, similar to tropical cyclones in other ocean basins, medicanes are strongly influenced by the interplay of oceanic heat content, eddies, and atmospheric dynamics, which together determine the intensity and destructiveness of these storms.

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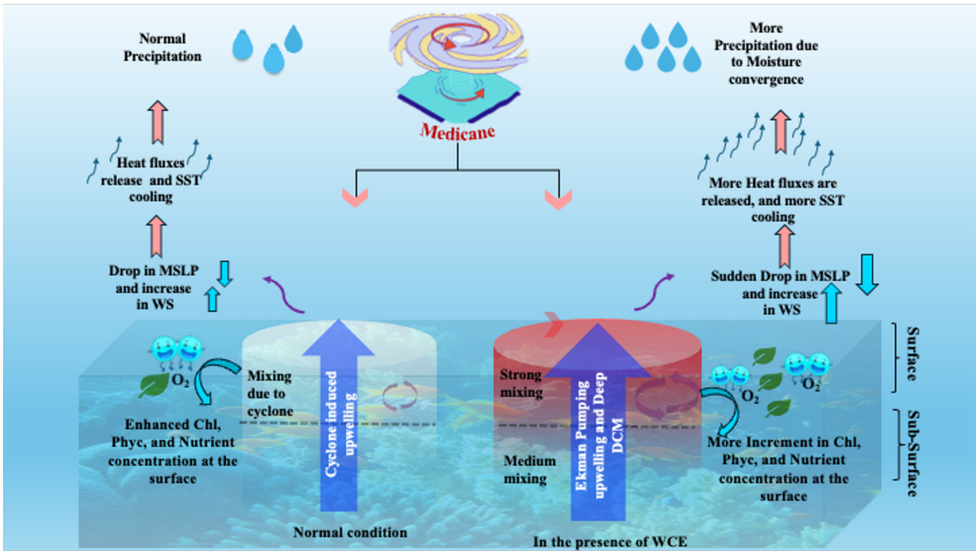

Figure 7: Schematic of the process responsible for the cyclone intensification over eddy and MHW and their impact on ocean biogeochemistry

Data Availability:

Data can be Archived from the links below-
https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3
https://doi.org/10.48670/moi-00298

Author Contributions:

B.J. contributed to the conceptualization of the study, data curation, formal analysis, and writing of the original draft.

E.S. served as the project investigator, contributed to conceptualization, provided resources and software support, supervised the research, and contributed to writing, review, and editing, as well as funding acquisition.

Competing Interests: The authors declare no conflict of interest.

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