Coastal Eddies as Vectors for Connectivity During the Summer in the Levantine Sea

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Abstract. The Levantine Basin, the easternmost part of the Mediterranean Sea, is one of the most oligotrophic marine environments worldwide. A pronounced gradient separates its relatively chlorophyll-enriched coastal zone from the severely depleted offshore waters, and the degree of connectivity between these regions shapes the distribution of biomass and nutrients. The connectivity between these two contrasted regimes is highly seasonal: during winter, deep mixing and enhanced lateral stirring promote basin-wide exchange, whereas in summer, strong stratification and a persistent alongshore current largely suppress cross-shore transport. Coastal mesoscale eddies are recurring features along the eastern Levantine margin, yet their subsurface structure and biogeochemical footprint remain poorly characterized. Here, we combine satellite imagery, autonomous glider transects, high-frequency (HF) radar measurements, and cruise-based profiles to examine the three-dimensional structure of these eddies and their role in summertime coastal–offshore exchange. Glider observations reveal a distinct vertical signature within the eddies, with warmer coastal-origin waters and a shoaling of the deep chlorophyll maximum (DCM) from approximately 120–130 m in surrounding offshore waters to approximately 50 m within the eddies. Independent cruise observations further show elevated silica and inorganic particulate matter concentrations extending below the surface, while HF radar measurements reveal dynamically coherent anticyclonic circulation within the coastal mesoscale eddies and their offshore propagation. Together, these multi-platform observations demonstrate that coastal mesoscale eddies are three-dimensional transport features that temporarily breach the summertime coastal–offshore barrier, carrying a coherent physical and biogeochemical coastal water-mass signature into ~~Here we examine how the limited summertime connectivity is affected by coastal mesoscale eddies, which are recurring features in this region. This is done through analysis of satellite imagery, autonomous glider transects, high-frequency (HF) radar measurements, and cruise-based nutrient profiles. Our observations show that these eddies can export considerable amounts of coastal biomass into offshore waters. The sampled eddies exhibited elevated surface chlorophyll and sea surface temperatures (SST), enhanced surface silica and inorganic particulate matter concentrations, and a shoaling and broadening of the deep chlorophyll maximum (DCM), all indicative of coastal origins. HF radar observations further revealed dynamically coherent anticyclonic circulation, supporting their role as active transport features rather than passively advected~~

surface patches. Our results demonstrate that coastal mesoscale eddies transport coastal water and their biogeochemical signatures into the open Levantine Basin. These findings establish coastal mesoscale eddies as episodic yet significant contributors to summer cross-shore exchange in [R1] one of the world's most oligotrophic marine regions.

1 Introduction

The Eastern Mediterranean Sea (EMS), particularly its easternmost sub-basin, the Levantine Basin, is among the most oligotrophic marine environments on Earth (Krom et al., 2005, 2014; Psarra et al., 2000). Extremely low concentrations of macronutrients, particularly phosphate, nitrate, and silicate, and correspondingly low primary productivity are defining characteristics of its offshore waters (Kress and Herut, 2001; Moutin et al., 2012; Pujo-Pay et al., 2011). Within this generally nutrient-depleted setting, a cross-shore gradient exists between the coastal region—where sediment-water interactions and terrestrial inputs can moderately enhance nutrient availability, chlorophyll concentrations, and primary production (Azov, 1986; Berman et al., 1984; Nixon, 2003; Krom et al., 2004; Kress and Herut, 1998; Raveh et al., 2015; Herut et al., 1999)—and the ultra-oligotrophic offshore waters (Crombet et al., 2011; Zohary and Robarts, 1998; Ignatiades et al., 2009). Although this contrast is weaker than in other coastal–offshore systems, including more productive regions of the Mediterranean Sea and stratified marginal seas influenced by stronger terrestrial inputs (Ben-Ezra et al., 2023; Solidoro et al., 2009; Powley et al., 2017; Han et al., 2012), it remains an important element of the ecological structure of the Levantine Basin (Reich et al., 2022; Herut et al., 2000; Raveh et al., 2015).

Exchanges between the coastal and offshore domains influence nutrient supply, primary production, and ecosystem functioning across the Levantine Basin (Ribera d'Alcalà et al., 2003; Siokou-Frangou et al., 2010). Periods of enhanced connectivity, reflecting increased coastal–offshore exchange and transport, can redistribute biomass and nutrient-enriched waters offshore (Barale et al., 2008; Alkalay et al., 2020; Katz et al., 2020) whereas reduced connectivity leaves the offshore region relatively isolated. The efficiency and pathways of this coastal–offshore exchange, therefore, play a central role in shaping regional biogeochemical variability.

Connectivity in the EMS exhibits strong seasonality (Estrada, 1996; Rosentraub and Brenner, 2007). During winter, vertical mixing deepens the mixed layer and injects nutrients into the euphotic zone (Siokou-Frangou et al., 2010; Barale et al., 2008), while submesoscale (typically ∼1–10 km) instabilities enhance lateral stirring (Lévy et al., 2012). Recent work indicates that such wintertime horizontal processes contribute substantially to the seasonal offshore chlorophyll increase (Fadida et al., 2026). These findings emphasize the role of submesoscale (∼1–10 km) and mesoscale (∼10–100 km) processes in regulating offshore enrichment during the winter.

In contrast, during the more stratified summer conditions, the connectivity regime changes markedly. Strong stratification suppresses vertical nutrient resupply, while the persistent alongshore current limits cross-shore exchanges, effectively decoupling the coastal zone from the offshore basin (Ozer et al., 2022; Verma et al., 2024; Akpınar, 2024). As a result, offshore waters remain extremely nutrient-poor, and coastal signals are typically confined nearshore. As such, any mechanisms capable

of intermittently bridging the coastal–offshore divide during summer are of particular interest, even if their overall contribution is episodic or spatially limited.

Mesoscale eddies are rotating structures with characteristic horizontal scales comparable to the first baroclinic Rossby radius, typically on the order of tens of kilometers in the Levantine Basin (Chelton et al., 1998; Kurkin et al., 2020). In satellite altimetry, they are commonly expressed as positive sea-surface height anomalies for anticyclonic eddies and negative anomalies for cyclonic eddies. Previous studies in the Mediterranean have primarily characterized large anticyclonic eddies using hydrographic observations, cruise measurements, drifters,[R1] and SSH-based analyses, focusing on their circulation, persistence, and physical structure (Zodiatis et al., 2023b; Moutin et al., 2012; Barboni et al., 2021; Poulain et al., 2013). More recently, regional numerical models have achieved sufficiently high spatial resolution to explicitly resolve coastal mesoscale eddies and their interaction with the Levantine boundary current, improving our understanding of their physical dynamics[R1] (Verma et al., 2024; Solodoch et al., 2023). However, their three-dimensional biogeochemical structure and role in coastal–offshore exchange remain poorly constrained by observations. The present study therefore examines coastal mesoscale eddies forming along the Levantine boundary current and investigates their role in facilitating coastal–offshore exchange.

Along the Levantine coast, coastal mesoscale eddies ~~and filaments~~[R1] are frequently observed during summer (Menna et al., 2012; Estournel et al., 2021; Efrati et al., 2013). Their formation has been attributed to wind-driven current separation, mesoscale instabilities, and bathymetric deflection of the coastal jet, as documented by high-resolution models, in situ observations, and satellite analyses (Akpınar, 2024; Gerin et al., 2009; Verma et al., 2024; Baaklini et al., 2024). While these structures are known to extend offshore and advect surface tracers (Gertman et al., 2010; Martin, 2003; Flos and Tintoré, 1990), their role in coastal–offshore exchange under summer stratification remains uncertain. During this season, the Levantine Basin is characterized by strong vertical stratification, extremely low surface nutrient concentrations, and a pronounced DCM (DCM) near the nutricline (Mignot et al., 2014; Teruzzi et al., 2021; Ediger and Yilmaz, 1996; Ben-Ezra et al., 2024). In other stratified coastal systems, mesoscale eddies have been shown to reorganize surface chlorophyll, DCM, and the nutrient field under stratified conditions (Cornec et al., 2021; Wang et al., 2018; Espinosa-Carreón et al., 2012; Xu et al., 2023). Although surface chlorophyll anomalies associated with coastal eddies in the Levantine Basin have previously been documented using satellite and in situ observations (Efrati et al., 2013; Baaklini et al., 2024), these studies were limited to the surface expression of the eddies, and no characterization of their three-dimensional water-column structure has been reported for this region.~~their impact on the vertical biogeochemical structure of the water column remains unquantified.~~[R1]

In this study, we investigate the role of coastal mesoscale eddies ~~and filaments~~[R1] as episodic pathways for summer cross-shelf exchange in the eastern Levantine Basin by characterizing their three-dimensional physical and biogeochemical structure.[R1]. Combining satellite-derived chlorophyll fields, HF radar surface currents, autonomous glider transects, and ship-based nutrient, major element particulate matter geochemistry and chlorophyll profiles, we identify coherent coastal eddies and quantify their propagation and kinematics.~~, and three-dimensional hydrographic and biogeochemical structure.~~[R1] ~~By comparing conditions within these features to the surrounding offshore background, we show that they transport a distinct coastal water-mass signature offshore, characterized by a shoaled DCM, elevated surface and subsurface chlorophyll, and enhanced nutrient concentrations.~~[R1] Since the offshore transport investigated here occurs through intermittent mesoscale events rather than per-

sistent background exchange, an event-scale approach was adopted (McNeil et al., 1999; Holte et al., 2013; Li et al., 2008). Such transient features can produce substantial local transport despite their episodic occurrence (Rubio et al., 2018; Feng and Ming, 2009; Chenillat et al., 2015) and may therefore not be adequately captured by seasonal or climatological averaging. ~~The objective of this study is therefore to characterize the physical and biogeochemical structure of individual transport events and assess their role in summertime coastal–offshore exchange.~~[R1] Our results provide the first observational evidence that coastal mesoscale eddies ~~and filaments~~[R1] can intermittently breach the summertime coastal–offshore barrier, transporting a coherent coastal physical and biogeochemical water-mass signature into one of the world's most oligotrophic marine regions.~~disrupt the summertime coastal–offshore separation in one of the world's most oligotrophic marine regions.~~[R1]

2 Data and Methods

2.1 Data

2.1.1 Satellite data.

This study was conducted using E.U. Copernicus Marine Service Information; Initial identification and selection of the investigated transport events were performed using L3 satellite observations (DOI: 10.48670/moi-00299), and only cases with clearly visible transport structures were retained. L4 (DOI: 10.48670/moi-00300) products were subsequently used for visualization and presentation of continuous spatial fields. A quantitative comparison between the L3 and L4 products is provided in Tables A1 A2, while Figs. A1 A2 present side-by-side comparisons of the corresponding figures. These comparisons demonstrate that the interpolation applied in the L4 products has a negligible influence on the detected eddy geometry and the quantitative metrics used in this study.[R1] Estimation of the mass concentration of chlorophyll-a in seawater (CHL) was derived from the gridded L4 daily ocean-color (1/100 degrees spatial resolution) data set. Data from several satellite missions (SeaWiFS, MODIS, MERIS, VIIRS-SNPP and JPSS1, OLCI-S3A) are combined to provide interpolated gap-free data sets (Volpe et al., 2018), using region-specific algorithms (Case-1 waters (Volpe et al., 2019), with new coefficients; and Case-2 waters (Berthon and Zibordi, 2004)). The images where all taken approximately at 13:00, which is generally when the satellite passes over the region.

Geostrophic currents were estimated using the Copernicus gridded Absolute Dynamic Topography (ADT) product~~altimetry product derived from satellite sea level anomaly (SLA) observations. In this product, SLA is computed relative to a 20-year mean dynamic topography reference period (1993–2012).~~[R1] ~~The altimetry observations analyzed in this study correspond to the 2018–2023 study period.~~[R1] DOI: 10.48670/moi-00142 , which provides Level-4 gridded geostrophic currents at a spatial resolution of 1/8 degrees.~~A gridded L4 product with a spatial resolution of 1/8 degrees.~~[R1]

Sea Surface Temperature (SST) was estimated with the Copernicus Ultra High Resolution Sea Surface Temperature Analysis L4 [R1] product DOI: doi.org/10.48670/moi-00172~~. A L4 gridded product~~[R1], with a spatial resolution of 1/100 degrees.

Satellite chlorophyll data were analyzed for all observational periods, including the June–July 2018 (M141) and June–July 2022 (M164) glider missions, the 30 July–3 August 2020 HF-radar observations, and the *N800* cruise sampling events on 30

July and 15 September 2020. SST data were analyzed for the two glider missions and to provide regional context (30 July 2020). Geostrophic currents derived from ADT were used solely to provide regional circulation context for the 30 July 2020 event.~~Satellite chlorophyll, SST, and altimetry data were analyzed for the same periods covered by the in situ observations: the 2018 and 2022 glider missions, the July–August 2020 HF-radar observations, and the 2020 *N800* cruise sampling periods.~~[R1]

2.1.2 High Frequency Radar

The Israeli coastal HF-radar network, operated by the Marine Engineering and Physics Laboratory at Tel Aviv University, consists of two WERA (WavE Radar; (Gurgel et al., 1999)) systems located at Ashkelon and Ashdod along the southeastern Mediterranean coast (Lorente et al., 2022). Each station operates in a monostatic configuration with co-located transmit and 12-element receive arrays, transmitting at a central frequency of 8.3 MHz and providing radial current coverage of up to approximately 180 km, depending on environmental conditions (Crombie, 1955; Barrick, 1977; Wyatt, 1991). The two sites are separated by roughly 25-km to optimize the overlap of their radial coverage for wave measurements (Hasselmann, 1971; Gurgel et al., 2006). This relatively close spacing ensures sufficiently large crossing angles between the two radar beams in the near field, improving the conditioning of directional inversions and enhancing the reliability of derived wave spectra. At the same time, the configuration constrains the region of robust two-dimensional current and wave mapping to about 75-km offshore, beyond which geometric dilution and weaker second-order backscatter reduce retrieval accuracy. The underlying radial measurements had a range resolution of approximately 300–750 m and a nominal angular spacing of 1°, with effective beamforming-related azimuthal averaging increasing from approximately $\pm 4°$ near the center of the coverage to $\pm 8°$ near its edges. Surface-current maps were interpolated onto a nominal x–y grid with approximately 1.4 km spacing.[R1] The current measurement dataset is related to continuous measurements conducted between July 30th[R1] and August 3rd[R1] 2020. Each radar was operating in 20-minute measurement cycles consisting of approximately three minutes of passive listening, used to identify a clean frequency band, followed by 17 minutes of active data acquisition. The resulting measurements were averaged to produce three current maps per hour. The analyses presented in this study are based on three-hour averages, corresponding to the mean of nine consecutive 20-minute radial and vector field maps taken to improve accuracy for the flow time-scales of interest. The three-hour average used in the analysis is 12:00-15:00 to coincide with the passage of the satellite over the region.

2.1.3 Glider Data

An autonomous underwater vehicle (SeaExplorer glider, Alseamar) equipped with a fluorometer by WetLabs and a CTD (conductivity, temperature, depth) by Sea-Bird was deployed for a variety of missions between the years 2018-2023. The missions (M141, M164) that coincided with summertime coastal eddies were analyzed for this study. The glider collected CTD and fluorescence data at very high spatiotemporal coverage through the upper 700 m of the water column. 360 dives were utilized from M141's mission between 26 June and 03 July 2018~~June/July 2018~~[R1], yielding a 118 km transect (repeated twice). 55 dives where utilized from M164's mission between 29 June and 02 July 2022~~in June 2022~~[R1], yielding an 85 km transect. Glider dives, horizontally spaced at 3 km intervals, were separated into descending and ascending profiles and treated as quasi-vertical measurements (1.5 km apart).

2.1.4 Cruise Data

N800 cruises — Data were obtained from a pelagic time-series station (*N800*; 32.52° N, 34.72° E) located 15 km offshore of the Israeli coast at a water depth of 832 m. The station was sampled approximately monthly throughout 2020.[R1] The results presented here correspond to sampling periods during which coastal mesoscale eddies~~filaments~~[R1] were observed to pass over the station (30[R1] July 2020 and 15[R1] September 2020), together with routine sampling conducted under non-eddy~~filament~~[R1] conditions for comparison. Background variability for dissolved nutrients and particulate constituents was calculated from the non-eddy sampling periods within the stratified season (April–November[R1] (D'Ortenzio et al., 2005)), excluding the July and September eddy-influenced sampling periods.[R1]

Sampling was conducted from the *R/V Mediterranean Explorer* using a rosette system equipped with 12 Niskin bottles. Hydrographic profiles were obtained with a Sea-Bird Electronics SBE19plusV2 CTD equipped with sensors for conductivity, temperature, fluorescence (used as a proxy for chlorophyll-a; (Zeng and Li, 2015)), turbidity, photosynthetically active radiation (PAR), and, for selected cruises, dissolved oxygen. Sampling was typically conducted between 10:00 and 13:00 local time, coinciding with satellite overpass of the region.

Particulate Fe, Si, and C (and other major element) concentrations were measured using thin-film X-ray fluorescence (XRF) at depths of 20, 100, and 180 m (Paulino et al., 2013). Organic matter (OM) and inorganic matter (IM) were estimated from thin-film XRF measurements of organic carbon and Si. OM was calculated as twice the measured organic carbon concentration, while IM was estimated assuming that Si constitutes 20 % of total inorganic particulate matter (Goldsmith et al., 2001).

Detailed descriptions of the sampling procedures and analytical methods for dissolved nutrients and major particulate elements measured by thin-film XRF are provided in Ben-Ezra et al. (2024). Analytical precision and limits of detection for the dissolved nutrient measurements are provided in Table A3.

Haifa Section Cruises — Haifa Section Cruises have been conducted by the *Israeli Oceanographic and Limnological Research Institute* twice a year (summer and winter) since 2002 (54 cruises to date). During these cruises, physical, chemical, and biological data are collected along a transect of eight stations extending from Haifa Bay into the open sea, perpendicular to the Israeli shelf. The chlorophyll measurements used in Fig. A4 represent the average of four summer cruises conducted during August–September of 2018–2021 and are presented to illustrate the typical chlorophyll transect under non-eddy conditions. For detailed cruise sampling and laboratory analysis methods, see[R1] Ozer et al. (2017).

2.2 Methods

Mesoscale eddies are commonly identified using sea-surface height (SSH) anomalies, as the associated sea-level expression provides a robust indicator of geostrophic circulation for large open-ocean vortices[R1] (Dufau et al., 2016; Amitai et al., 2010; Pegliasco et al., 2021). In the Mediterranean Sea, SSH-based analyses have successfully characterized mesoscale eddies with typical diameters of approximately 60–130 km, including those in the Algerian Basin, where their spatial scales are well resolved by gridded altimetry products[R1](Pessini et al., 2018, 2020; Cotroneo et al., 2016). The coastal eddies investigated here, however, are substantially smaller. These features typically have diameters of only 30–40 km and develop immediately

adjacent to the coastline. Although the DUACS gridded altimetry product has a nominal grid spacing of 0.0625° (∼7 km), its effective spatial resolution during the study period was approximately 0.125° (∼14 km), meaning that eddies of this size are represented by only a few independent observations, while coastal proximity further increases uncertainty due to land contamination and interpolation [R1] (Birol et al., 2025). The limited representation of these smaller coastal features in SSH is also evident in Fig. 1, where the coastal eddies are clearly expressed in the chlorophyll field and, to a lesser extent, in SST, whereas only the largest offshore feature is clearly discernible in the SSH field. Ocean-colour imagery directly traces the transport of chlorophyll-rich coastal waters, providing a more suitable observational framework for delineating the offshore extent of these transport events. Consequently, chlorophyll fields were used for eddy identification throughout this study, while HF-radar observations were used to validate the circulation and propagation of the tracked coastal eddies.[R1] The following analyses were designed to identify episodic offshore transport events associated with coastal mesoscale activity and characterize their physical and biogeochemical signatures. Two complementary approaches were applied. First, offshore chlorophyll anomalies were identified to estimate the extent of transported coastal waters and associated chlorophyll redistribution. Second, a frontal analysis was applied to characterize the dynamically active boundaries of these features and enable HF-radar collocation and kinematic analysis.

2.2.1 Identification and characterization of coastal mesoscale eddies

The analyses were performed sequentially using satellite chlorophyll images as the primary detection tool. Daily satellite observations were first examined to identify offshore chlorophyll features associated with coastal mesoscale transport. These features were then cross-referenced with the timing and locations of available autonomous glider missions, research cruises, and HF-radar observations to identify events for which complementary physical, biogeochemical, and kinematic measurements were available. Three coincident events were selected for detailed analysis.[R1]

Following the event selection, the analyses were performed using the sequential procedure described below. Satellite chlorophyll observations were used to delineate the offshore transport features and quantify their geometry and chlorophyll redistribution, while coincident glider and HF-radar observations were incorporated where available to characterize their three-dimensional structure and surface kinematics, respectively.[R1]

Step 1 – Define the offshore analysis domain

An offshore analysis domain was first defined using the 700 m isobath (Fig. 1, dashed black line). Only chlorophyll anomalies located seaward of this contour were considered, because the objective was to identify coastal waters that had been transported beyond the continental shelf and slope into the open Levantine Basin. Along this section of the Levantine coast, the continental margin is narrow and steep, with the transition from the shelf to the deep basin occurring over approximately the 200–1000 m depth range. The 700 m contour therefore provides a representative mid-slope boundary, and small shifts in the selected isobath have limited influence on the detected offshore features because of the steep bathymetric gradient.[R1]

Step 2 – Estimate the daily offshore background

The offshore background chlorophyll concentration was calculated independently for each daily map to account for temporal variability in offshore conditions. The background was computed from pixels located seaward of the 700 m isobath using the mean chlorophyll concentration between the 20th and 80th percentiles. Restricting the calculation to this percentile range reduced the influence of very low values and localized high-chlorophyll features that could bias the background estimate.[R1]

Step 3 – Detect offshore chlorophyll anomalies

A daily detection threshold C_{th} was defined as twice the mean offshore background chlorophyll concentration,[R1]

$$C_{\mathrm{th}} = 2\overline{C}_{\mathrm{bg}} \tag{1}$$

where $\overline{C}_{\mathrm{bg}}$ is the mean daily offshore background chlorophyll concentration. This conservative threshold was selected empirically to isolate robust offshore chlorophyll anomalies associated with transported coastal waters while minimizing the inclusion of weak offshore background variability.[R1]

Step 4 – Delineate offshore transport features

Contiguous regions exceeding the threshold were identified as individual offshore chlorophyll features (magenta lines in Fig. 2, 3B, 4B). The three events selected for further analysis were those that coincided with independent observations from autonomous gliders, research cruises, or the HF-radar system. The detected features were interpreted as coastal mesoscale eddies on the basis of their coherent geometry and the complementary physical and biogeochemical observations presented in the following. The horizontal surface area of each eddy was calculated by converting the dimensions of the latitude–longitude grid cells into spherical cell areas and summing the area of all pixels contained within the corresponding satellite-derived mask.[R1]

Estimation of chlorophyll redistribution

For the two eddies sampled by autonomous gliders (Figs. 3 and 4), satellite-derived surface masks were integrated with glider chlorophyll profiles to estimate the three-dimensional chlorophyll anomaly associated with each eddy (Figs. 5 and 6). Profiles collected within the eddy interior, $C_{\mathrm{eddy}}(z)$, were compared with reference profiles, $C_{\mathrm{ref}}(z)$, obtained from adjacent offshore waters outside the eddy (black dotted rectangles in Figs. 3 and 4). A total of 30 eddy and 30 reference profiles were used for the 2018 mission (M141), and 15 eddy and 15 reference profiles for the 2022 mission (M164). The vertical chlorophyll anomaly was defined as[R1]

$$\Delta C(z) = C_{\mathrm{eddy}}(z) - C_{\mathrm{ref}}(z) \tag{2}$$

where positive values represent chlorophyll enrichment relative to the offshore reference profile and negative values represent depletion. Both positive and negative contributions were retained in the subsequent integration. The vertically integrated chlorophyll anomaly per unit area ΔC_{int} was then calculated as[R1]

$$\Delta C_{\mathrm{int}} = \int_{0}^{z_{\max}} \Delta C(z)\, dz \tag{3}$$

where $z_{\max}$ is the maximum depth over which both the eddy and reference profiles were defined. Finally, the total chlorophyll anomaly associated with each eddy was estimated as[R1]

$$\Delta C_{\mathrm{total}} = A_{\mathrm{eddy}}\, \Delta C_{\mathrm{int}} \tag{4}$$

where A_{eddy} is the satellite-derived horizontal surface area of the eddy.[R1]

~~The following analysis was designed to identify offshore chlorophyll anomalies associated with coastal mesoscale transport and quantify their offshore extent and chlorophyll redistribution. A conservative threshold of twice the mean offshore background chlorophyll concentration was empirically selected to isolate robust offshore chlorophyll anomalies associated with coastal-origin mesoscale features while minimizing inclusion of weak offshore background variability. The offshore background was calculated independently for each daily map from waters deeper than 700 m, using the mean chlorophyll concentration between the 20th and 80th percentiles to reduce the influence of very low values and localized high-chlorophyll features. The 700 m isobath was used as an operational offshore boundary because the objective was to identify coastal waters that had been transported beyond the continental shelf/slope region into the open Levantine Basin. Along this part of the Levantine coast, the shelf break and upper slope are narrow and steep, with the transition from shelf to deep basin occurring over approximately the 200–1000 m depth range. The 700 m contour therefore provides a representative mid-slope boundary, and small shifts of this contour have limited influence on the detected offshore features because of the sharp bathymetric gradient.[R1]~~

~~Contiguous regions exceeding the threshold were labeled as individual eddies. The horizontal surface area of each eddy was calculated by converting grid-cell dimensions on the latitude–longitude grid into true spherical cell areas and summing over all cells within the mask. To quantify the three-dimensional chlorophyll anomaly associated with each eddy, these surface detections were combined with glider-derived vertical profiles. Profiles collected within the eddy interior, $C_{\mathrm{eddy}}(z)$, were compared with a reference profile, $C_{\mathrm{ref}}(z)$ obtained from adjacent offshore waters outside the eddy. The vertical anomaly profile was defined as $\Delta C(z) = C_{\mathrm{eddy}}(z) - C_{\mathrm{ref}}(z)$, both positive and negative contributions retained to allow for the possibility of net depletion as well as enrichment. The vertically integrated anomaly per unit area is $I = \int_{0}^{z_{\max}} \Delta C(z)\, dz$, $z_{\max}$ is the maximum depth over which both the eddy and reference profiles are defined. The total anomaly volume is then $V = A_{\mathrm{eddy}}\, I$, where A_{eddy} is the horizontal area of the detected eddy.[R1]~~

2.2.2 Gradient-based detection of the eddy frontal boundary

For the eddy sampled within the HF-radar observation domain (Fig. 2), the satellite-derived eddy mask obtained in Section 2.2.1 served as the starting point for frontal-boundary detection. Rather than searching the entire chlorophyll field for fronts, the analysis was restricted to the previously detected eddy to isolate its dynamically active transport boundary.[R1]

Step 1 – Delineate the offshore eddy

The offshore eddy was first identified using the chlorophyll-anomaly detection procedure described in Section 2.2.1. (magenta outline in Fig. 2[R1]

Step 2 – Calculate chlorophyll gradients

Horizontal chlorophyll gradients were calculated in metric units within the satellite-derived eddy mask. Restricting the analysis to this region excluded unrelated fronts elsewhere in the satellite image.[R1]

Step 3 – Identify the frontal boundary

A gradient threshold, G_{th}, was defined as the 90th percentile of the chlorophyll-gradient magnitude within the satellite-derived eddy mask,[R1]

$$G_{\mathrm{th}} = P_{90}\left(|\nabla C|_{\mathrm{eddy}}\right) \tag{5}$$

where P_{90} denotes the 90th percentile of chlorophyll-gradient magnitudes within the detected eddy.[R1]
Pixels satisfying[R1]

$$|\nabla C(\mathbf{x})| \geq G_{\mathrm{th}} \tag{6}$$

were classified as frontal pixels. This criterion isolated the sharp chlorophyll gradient separating the frontal limb from the immediately adjacent offshore background.[R1]

Step 4 – Extract the frontal polygon and track eddy propagation

Frontal pixels were grouped into connected regions, and an isocontour was extracted to form a continuous polygon representing the frontal limb of the eddy (shaded magenta region in Fig. 2A-E). Because the eddy propagated predominantly toward the northeast, the northeasternmost pixel of the frontal polygon was used as a representative tracking point. Its position was tracked between consecutive days to determine the eddy's propagation pathway and calculate its propagation velocity (white dot in Fig. 2A-E).[R1]

Step 5 – HF-radar collocation and kinematic analysis

The frontal polygon was subsequently collocated with HF-radar surface-current observations (Fig. 2F-J). A manually selected eddy center was used to determine the radial direction at each HF-radar measurement location, and the measured current vectors were projected onto the tangential direction to obtain azimuthal velocities. Maximum, minimum, and mean azimuthal velocities were calculated from all HF-radar measurements contained within the frontal polygon, providing estimates of the eddy's rotational intensity.[R1]

~~After identifying the offshore transport feature, an additional analysis was performed to isolate its dynamically active frontal boundary for HF-radar collocation and kinematic analysis. We applied a combined gradient–amplitude detection method to daily satellite chlorophyll fields. Horizontal chlorophyll gradients were first computed in metric units to quantify spatial frontal intensity. A robust gradient threshold (G_{thr}) was then defined from offshore values as the 90th percentile of the gradient magnitude, $|\nabla C| \geq G_{\mathrm{thr}}, \quad G_{\mathrm{thr}} = \mathrm{percentile}_{90}\left(|\nabla C|_{\mathrm{offshore}}\right),$ isolating regions of anomalously strong horizontal gradients relative to background offshore variability. To ensure that detected features also corresponded to elevated chlorophyll concentrations, an adaptive amplitude threshold (C_{amp}) was applied, $C \geq C_{\mathrm{amp}}, \quad C_{\mathrm{a}}$ retains only statistically significant chlorophyll anomalies above the offshore background level. Pixels satisfying both the gradient and amplitude criteria, and located seaward of the −700 m isobath, were combined to form a preliminary eddy mask. Connected-component labeling was then used to isolate spatially coherent structures, and the largest structure was selected for each day. Its boundary was extracted using isocontour reconstruction to obtain a closed polygon representing the northeastern frontal limb of the coastal mesoscale eddy, corresponding to the leading edge of the eddy as it propagates eastward. This polygon was used to collocate HF-radar observations. A manually selected eddy center was used to compute the radial direction at each HF measurement point, and azimuthal velocities were obtained by projecting the HF vectors onto the tangential direction. Maximum, minimum, and mean azimuthal speeds were computed from all HF measurements falling within the frontal polygon. This approach isolates the dynamically coherent frontal region of the eddy and enables estimation of both rotational strength and downstream propagation.~~[R1]

3 Results

3.1 Regional context: summertime mesoscale activity and basin-scale biogeochemical structure

A basin-scale snapshot of summer surface conditions in the Eastern Mediterranean Sea (30 July 2020) reveals a close correspondence between mesoscale circulation and surface chlorophyll distributions (Fig. 1). Offshore regions occupied by persistent anticyclonic mesoscale eddies with~~characterized by anticyclonic circulation and~~[R1] elevated sea surface height (SSH), for example, the Shikmona Gyre and Cyprus Eddy (Robinson and Golnaraghi, 1994; Bergamasco and Malanotte-Rizzoli, 2010; Zodiatis et al., 2023a), are associated with uniformly low chlorophyll concentrations, consistent with strong stratification and suppressed nutrient supply (Krom et al., 1992; Belkin et al., 2022). In contrast, cyclonic eddies~~features~~[R1] identified by de-

pressed SSH, such as the Rhodes Gyre (Robinson et al., 1991; van Leeuwen et al., 2022), coincide with locally enhanced surface chlorophyll, reflecting their upwelling-favorable dynamical setting.

Along the southern Levantine coast, surface chlorophyll concentrations are not uniformly elevated relative to the offshore basin. Instead, enhanced coastal chlorophyll is primarily observed downstream of the Nile River Delta, the dominant source of nutrient-rich coastal waters in the region (Nixon, 2003; El-Rayis and Abdallah, 2006; Oczkowski et al., 2009). This downstream asymmetry is evident in the distribution of coastal mesoscale features: anticyclonic eddies located west of the Nile Delta (upstream) exhibit little to no surface chlorophyll enhancement (Fig. 1A,C - 31.5° N, 28.75° E), whereas anticyclonic eddies ~~and filamentary structures~~[R1] east of the Delta (downstream) display pronounced surface chlorophyll signatures (Fig. 1A), (Fadida et al., 2026).

Against this basin-wide background, during summer, a sequence of mesoscale meanders and eddies is embedded in the Levantine along-shore coastal current (Fig. 1A-C). Unlike the offshore anticyclonic features, these downstream coastal eddies exhibit elevated surface chlorophyll concentrations despite their anticyclonic nature. The associated sea surface temperature field (Fig. 1B) further indicates that these features are composed of relatively warm coastal-origin waters that are advected along the shoreline.

The regional snapshot further shows that coastal mesoscale features are dynamically connected to the larger-scale circulation. In particular, one of the downstream coastal eddies is observed to extend offshore and merge with the Shikmona Gyre (33.41° N, 34.25° E), suggesting a direct pathway by which Nile-influenced coastal waters can be transferred into the open sea. This basin-scale context highlights coastal eddies~~and filaments~~[R1] as a distinct class of mesoscale features whose biogeochemical signature reflects both their dynamical structure and their upstream conditioning within the coastal boundary current.

3.2 Eddy coherence, kinematics, and propagation

To determine whether the downstream coastal features identified in Fig. 1 represent dynamically coherent mesoscale eddies rather than transient surface tracer patches, we analyzed a series of collocated satellite chlorophyll imagery and HF-radar surface current measurements from 30 July to 3 August 2020 (Fig. 2). Here, we consider the feature dynamically coherent if the HF-radar velocity field exhibits organized anticyclonic rotation around the eddy and rotational velocities exceed the downstream propagation speed, indicating internal circulation rather than passive advection. Over five consecutive days, satellite observations captured the downstream evolution of a coastal anticyclonic feature, whose leading northeastern frontal segment advanced seaward along the Levantine coast.

Tracking the displacement of this frontal boundary indicates that the eddy propagated at a mean speed of approximately 0.155 m s^{-1} (∼13.6 km day^{-1}). Concurrent HF-radar measurements reveal a well-defined azimuthal circulation that is spatially collocated with the chlorophyll-defined eddy boundary. Maximum tangential velocities ranged from 0.11–0.36 m s^{-1} on 30 July, 0.30–0.64 m s^{-1} on 31 July, and 0.37–0.73 m s^{-1} on 1 August, 0.14–0.93 m s^{-1} on 2 August, and 0.05–0.67 m s^{-1} on 3 August, with mean values ranging from 0.21 to 0.68 m s^{-1} over the same period.

At all stages, the measured azimuthal velocities exceeded the downstream propagation speed by a factor of two to six, indicating that the feature was dominated by rotational motion rather than simple advection by the background flow. The

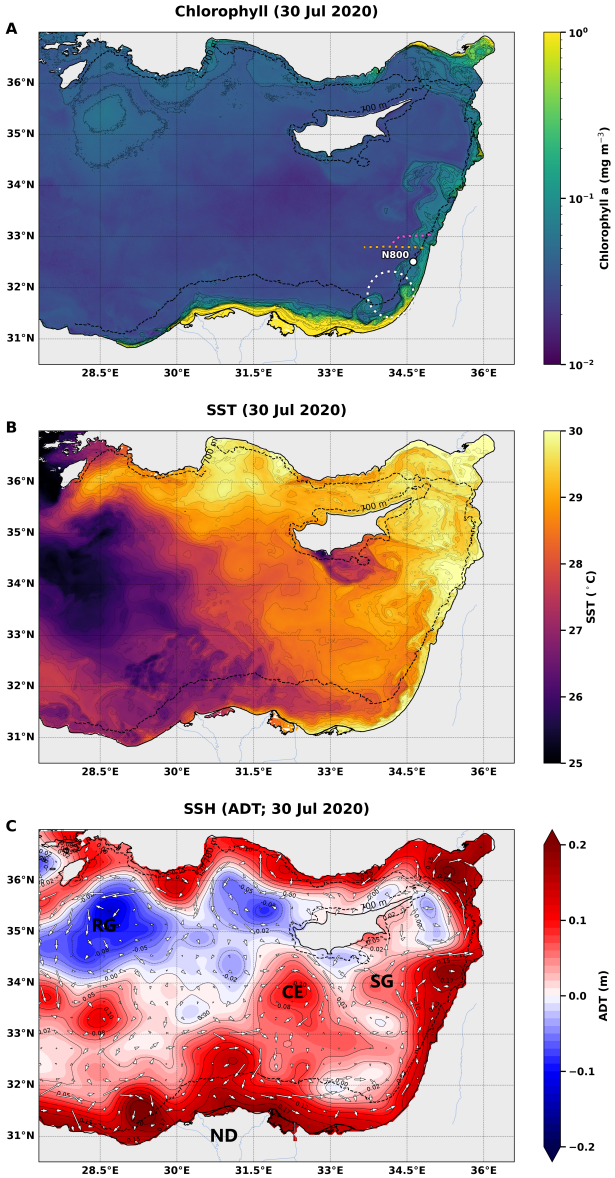

Figure 1. Summer surface conditions in the Eastern Levantine Basin on 30 July 2020. A. Surface chlorophyll (mg m^{-3}), highlighting a sequence of mesoscale eddies extending downstream of the Nile River Delta and progressing cyclonically across the basin. The 700 m isobath is shown as a black dotted line. Dotted amber line shows the glider path on mission M141, magenta line shows the glider path on mission M164. White dot shows location for TS station N800 and white dotted circle shows the coverage region for the HF radar.[R1] B. Sea surface temperature (SST) and C. Absolute dynamic topography (ADT) and geostrophic currents derived from satellite altimetry for 30 July 2020. Locations of significant regions such as Rhodes Gyre (RG), Cyprus Eddy (CE), Shikmona Gyre (SG), and the Nile River Delta (ND).

persistence of a closed anticyclonic circulation over multiple days confirms that the observed structure represents a dynamically coherent mesoscale eddy.

3.3 Eddy structure from glider observations

To characterize the three-dimensional structure of coastal mesoscale eddies during summer stratification, we analyzed two independent autonomous glider missions that intersected coastal eddies identified in satellite imagery (Fig. 3, 4). Although separated by four years (2018 and 2022) and sampling different eddies, both missions revealed remarkably similar vertical physical and biogeochemical structures. Together, these observations demonstrate that coastal mesoscale eddies consistently transport a distinct coastal water-mass signature into the offshore Levantine Basin.~~To characterize the three-dimensional structure of coastal mesoscale eddies during summer stratification, we analysed two independent autonomous glider missions that intersected coastal eddies identified in satellite imagery. These observations allow direct comparison between the vertical structure within the eddy interior and the surrounding offshore waters. The first case corresponds to the June–July 2018 event (Fig. 3), while the second corresponds to the June–July 2022 event (Fig. 4). The two case studies are presented separately before comparing their common characteristics.~~[R1]

3.3.1 Physical structure

In the 2018 glider mission (Fig. 3), the eddy interior exhibited a coherent hydrographic structure characteristic of an anticyclonic mesoscale eddy. Density surfaces were displaced downward within the eddy, consistent with downwelling-favorable circulation (Fig. 3G), while satellite SST (Fig. 3D–F) and CTD measurements (Fig. 3H) revealed elevated temperatures extending from the surface to approximately 60 m depth relative to the surrounding offshore waters. Together, these observations indicate that the eddy transported a relatively warm coastal-origin water mass into the offshore Levantine Basin. A comparable warm-core signature was also evident in satellite SST during the 2022 event (Fig. 4 D–F). Although CTD measurements were unavailable during this mission because of an instrument malfunction, the satellite observations demonstrated a similar surface thermal structure, indicating that both eddies were associated with the offshore transport of relatively warm coastal waters. This common physical signature provides the framework for comparing their biogeochemical structures, described in the following section.[R1]

~~The first glider mission, conducted during June–July 2018, sampled a coastal eddy over a period of approximately 12 days. Within the eddy interior, chlorophyll concentrations were elevated throughout the upper water column, and the DCM markedly shoaled, from depths of approximately 120–130 m in ambient offshore waters to about 50 m inside the eddy. Potential density contours exhibited downward displacement within the eddy, consistent with anticyclonic structure and indicating the absence of local upwelling. Sea surface and subsurface temperatures within the eddy were slightly higher than in surrounding offshore waters, consistent with the advection of coastal-origin water masses. Taken together, these observations show that the 2018 eddy was associated with a coherent reorganization of the hydrographic structure and vertical chlorophyll distribution, characterized by elevated surface concentrations and a shallow DCM despite downwelling-favorable dynamics. A second glider mission intersected a coastal eddy off of northern Israel in late June 2022 (Fig. 4). Although this mission did not include in situ~~

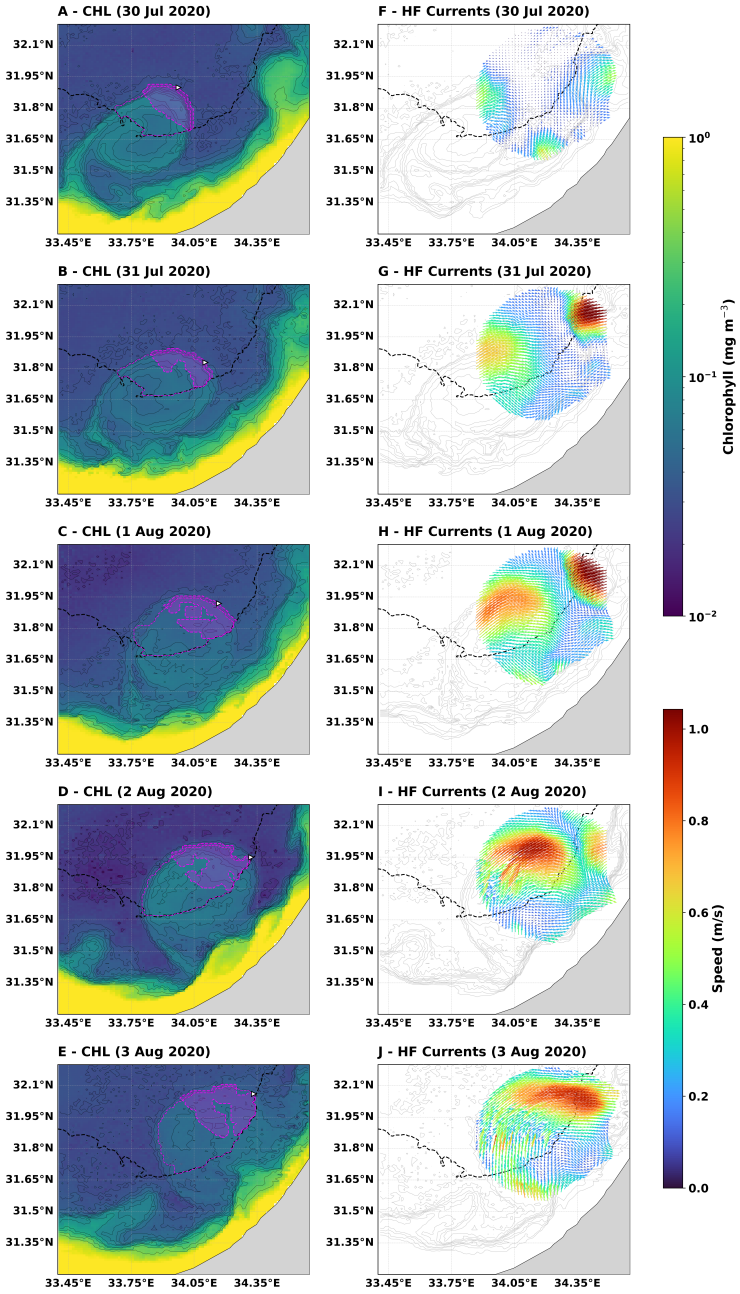

Figure 2. Satellite and HF-radar observations during 30 July–3 August 2020. (A–E) Daily surface chlorophyll maps. The magenta line indicates the identified Chl anomaly and the shaded magenta region marks the frontal boundary used to collocate HF-radar velocity measurements with the chlorophyll-defined mesoscale eddy. The white dot shows the north-easternmost pixel in the eddy area used to calculate eddy propagation velocity across successive days. (F–J) HF-radar surface currents overlaid on CHL contours.

~~measurements of temperature or density due to a CTD malfunction, chlorophyll profiles nonetheless revealed a similarly shoaled DCM within the eddy interior relative to adjacent offshore waters. The repetition of this vertical chlorophyll structure in an independent eddy supports the generality of the observed three-dimensional response.~~[R1]

3.3.2 Biogeochemical structure

Both eddies exhibited a vertical chlorophyll structure that was clearly distinct from adjacent offshore waters (Fig. 3G, 4G). The DCM shoaled from its typical summer depth of approximately 100–120 m in the pelagic Levantine Basin to approximately 50 m, corresponding to the characteristic summer DCM depth over the continental shelf(Fig. A4). Concurrently, chlorophyll concentrations were elevated throughout the upper water column, resulting in a broader vertical chlorophyll distribution than observed in adjacent offshore waters.[R1] ~~Following the characterization of the vertical structure, we next estimated the magnitude of offshore chlorophyll redistribution associated with these events. To quantify the offshore influence of coastal eddies, vertical chlorophyll anomaly profiles were computed by subtracting reference profiles sampled outside the eddy from profiles collected within the eddy interior (Fig. 5 for the 2018 eddy and Fig. 6 for the 2022 eddy). These anomaly profiles were vertically integrated and combined with the offshore surface area of each eddy to estimate the excess chlorophyll stock associated with offshore transport.~~[R1] The vertical redistribution of chlorophyll was further quantified using chlorophyll anomaly profiles calculated relative to adjacent offshore waters (Methods). Both eddies exhibited a similar anomaly structure, consisting of positive anomalies extending from the surface to approximately 100 m and negative anomalies below the DCM (Fig. 5, 6). Despite the pronounced negative anomaly at depth, the vertically integrated chlorophyll anomaly remained positive in both cases. Vertical integration of the anomaly profiles yielded net chlorophyll anomalies of approximately 1,500 kg distributed over an offshore area of about 1,430 km^2 for the 2018 eddy, and approximately 3,500 kg over about 980 km^2 for the 2022 eddy.[R1] ~~For the 2018 eddy (Fig. 5), the vertically integrated chlorophyll anomaly was positive, reflecting both elevated surface concentrations and a spatially extensive shoaled DCM. The offshore portion of the eddy extended over an area of approximately 1430 km^2, yielding an estimated excess chlorophyll stock of approximately 1500 kg transported offshore. A similar analysis was performed for the 2022 eddy (Fig. 6). Despite differences in eddy size and sampling geometry, the vertically integrated anomaly was again positive. Over a combined offshore surface area of approximately 980 km^2, this corresponded to an estimated excess chlorophyll stock of approximately 3500 kg. The vertical structure of the anomaly exhibited two contrasting layers in both glider missions: a positive anomaly extending from the surface to approximately 100 m, and a negative anomaly below this depth. The negative anomaly reached its maximum near approximately 100 m in the 2018 eddy and approximately 130 m in the 2022 eddy, indicating a redistribution of chlorophyll within the water column rather than a uniform increase at all depths. Despite the presence of a pronounced negative anomaly at depth, the vertically integrated anomaly remained positive in both cases. These estimates therefore indicate that coastal mesoscale eddies can produce a net positive offshore chlorophyll anomaly during summer stratification, with event-scale export magnitudes that vary depending on eddy characteristics.~~[R1] The reproducibility of this vertical chlorophyll structure in two independent glider observations motivated comparison with the offshore *N800* time-series station to determine whether a similar biogeochemical signature was evident in repeated ship-based observations.[R1]

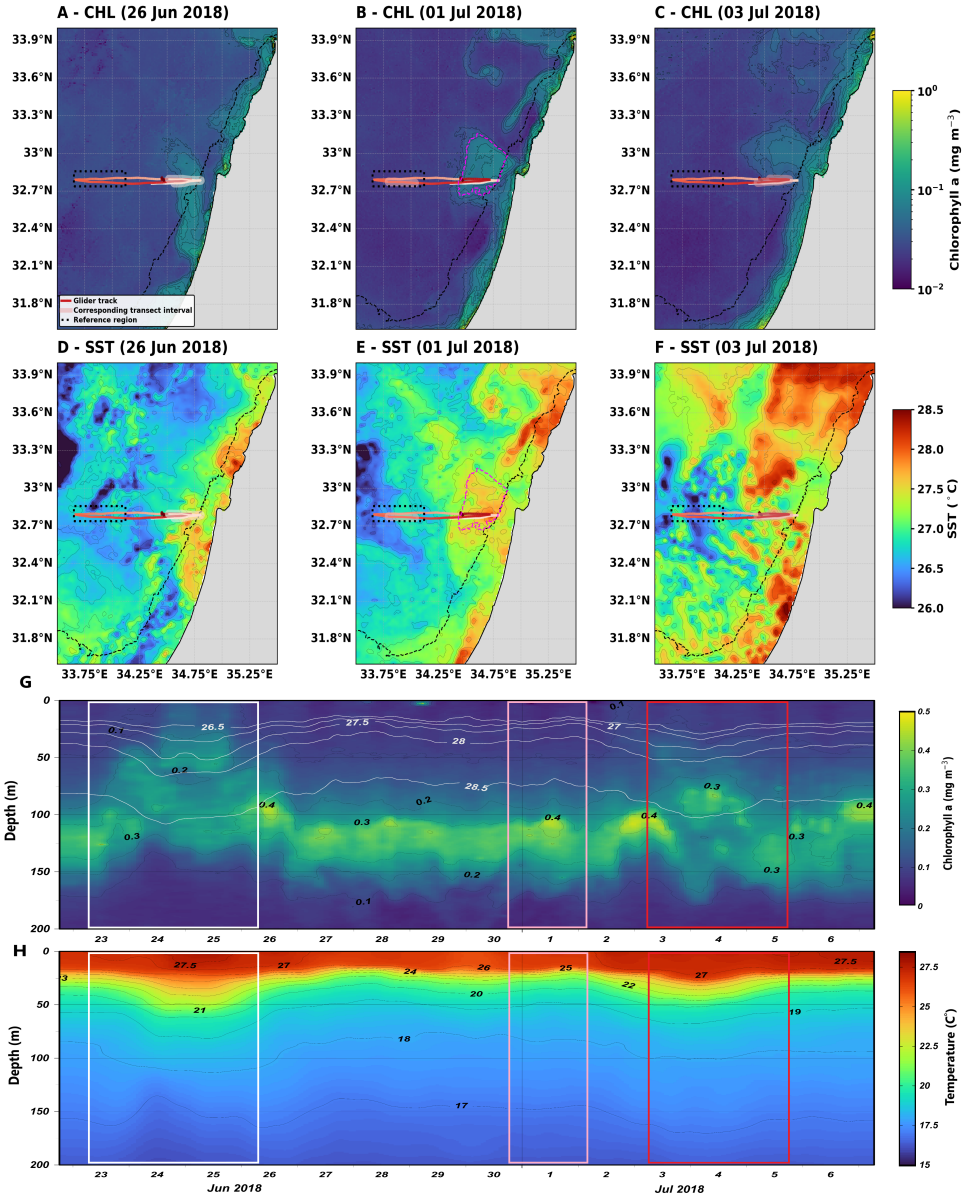

Figure 3. Satellite and glider observations of a coastal eddy during June/July 2018. (A–C) Surface chlorophyll on 26 June, 1 July, and 3 July, with the cumulative glider trajectory colored by time progression. Lightened segments mark the position of the glider at the time of each satellite image. In (B), the magenta contour delineates the identified offshore eddy feature used for the surface-area and chlorophyll-stock calculations. The black dotted rectangle marks the region used for calculation of background conditions. (D–F) Corresponding sea surface temperature (SST) fields for the same dates, shown over the same spatial domain.[R1] (G) Glider-derived chlorophyll section (mg m^{-3}), with density anomaly contours (white). Colored rectangles indicate the portions of the transect corresponding to the satellite snapshots, using the same color progression as in (A–C). (H) Glider-derived temperature section (°C), with the same highlighted intervals as in (D).

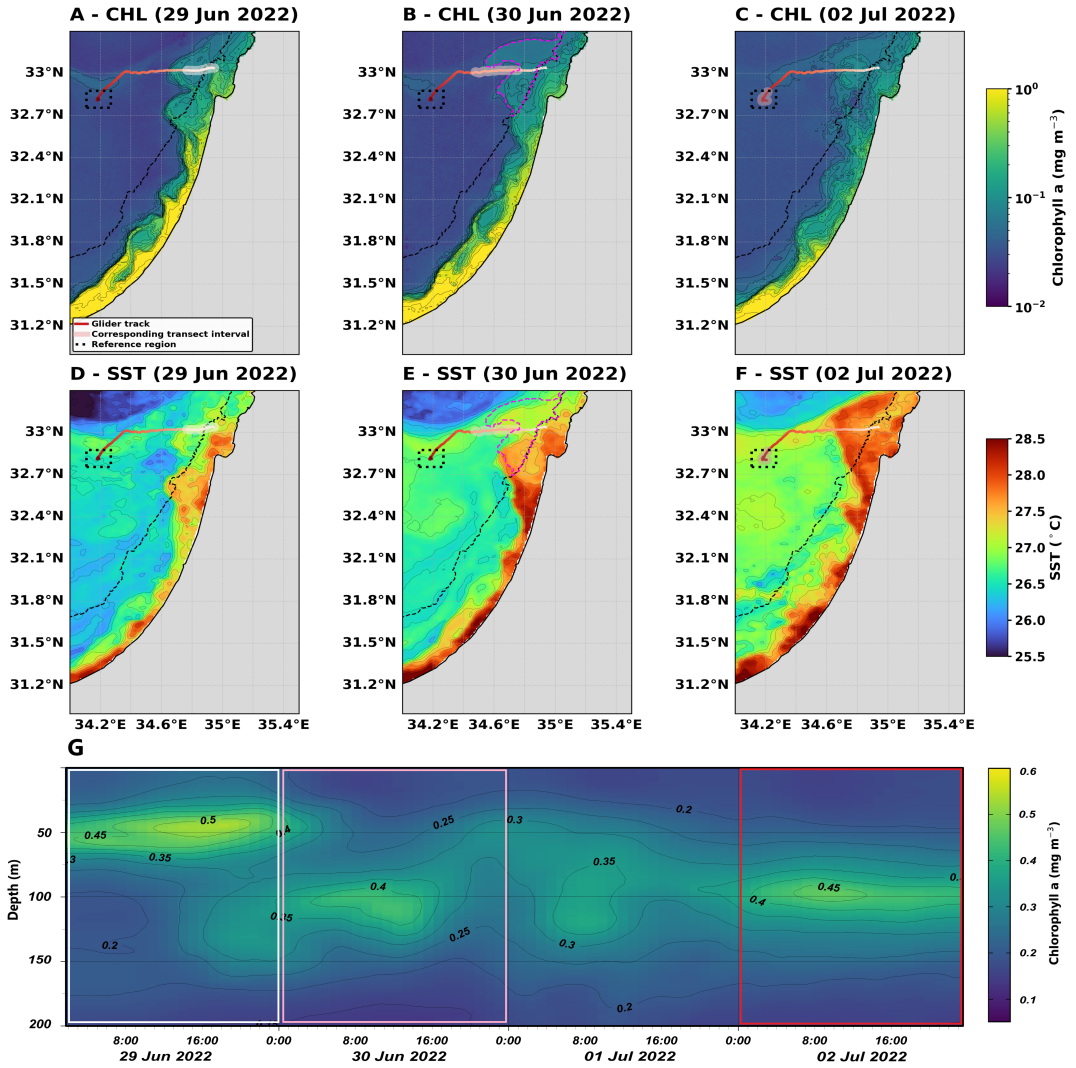

Figure 4. Satellite and glider observations of a coastal eddy during June–July 2022. (A–C) Daily surface chlorophyll with the cumulative glider trajectory overlaid and colored by time progression. Lightened segments mark the position of the glider at the time of each satellite image. In (B), the magenta contour delineates the identified offshore eddy feature used for the surface-area and chlorophyll-stock calculations. The black dotted rectangle marks the region used for calculation of background conditions. (D–F) Corresponding sea surface temperature (SST) fields for the same dates, shown over the same spatial domain.[R1] (G) Glider-derived chlorophyll section (mg m^{-3}), with colored rectangles indicating the corresponding portions of the transect, using the same color progression as in (A–C).

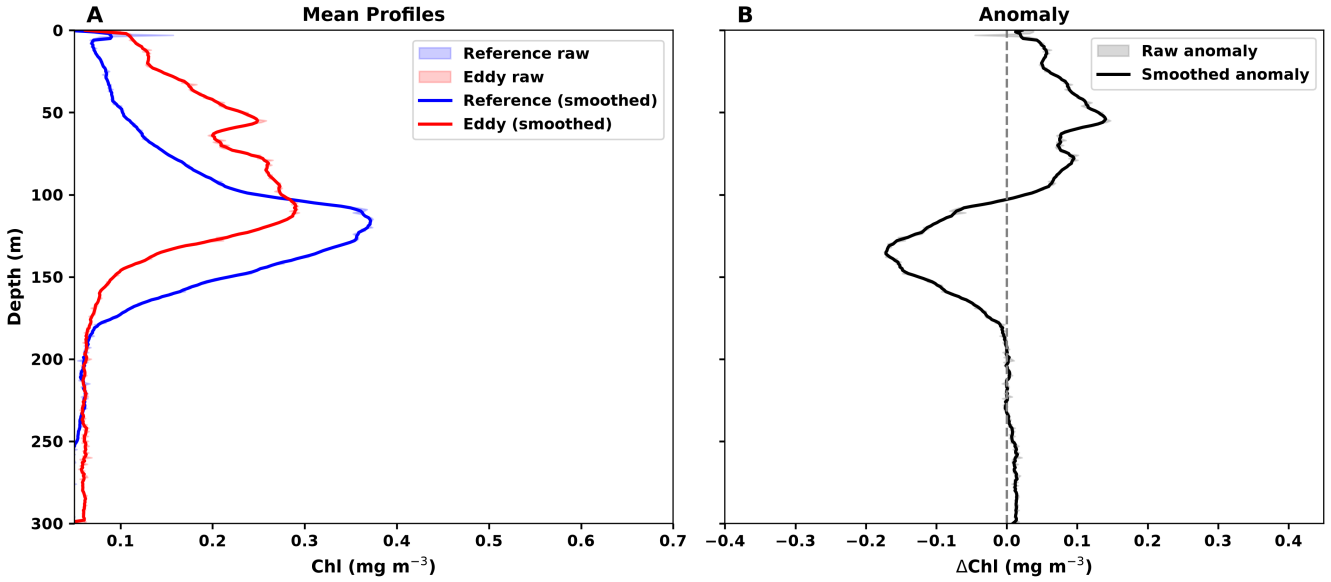

Figure 5. A. Depth profiles of chlorophyll from glider mission M141[R1] during the reference period (28–29 June 2018; blue) and the eddy period (24–26 June 2018; red). (B) Chlorophyll anomaly profile (eddy minus reference; black). Shaded and solid lines denote raw and smoothed profiles, respectively.

3.4 Time-series observations of transported coastal waters

The glider observations revealed a consistent vertical biogeochemical structure associated with coastal mesoscale eddies. To determine whether this transported coastal signature could also be identified independently in repeated offshore observations, we analyzed hydrographic and biogeochemical measurements from the *N800* time-series station during months influenced and not influenced by coastal mesoscale eddies.~~Ship-based observations at a fixed offshore location provide independent evidence of coastal water-mass influence, as reflected in the in situ biogeochemical properties. Station *N800*, located near the continental slope, was sampled approximately monthly throughout 2020, enabling comparison between background summer conditions (June and August) and two sampling periods influenced by coastal mesoscale eddies (July and September).~~[R1]

Satellite-derived surface chlorophyll imagery indicates that the July and September sampling periods coincided with the passage of coastal mesoscale eddies over the *N800* station (Fig. 7A–B). During these periods, the station exhibited distinct changes in dissolved nutrients, particulate constituents, and the vertical chlorophyll structure relative to the non-eddy summer background.~~July and September sampling periods coincided with times when coastal mesoscale eddies propagated over or immediately adjacent to the fixed offshore station *N800* (Fig. 7A–B).~~[R1] ~~Background variability for dissolved nutrients and particulate constituents was calculated from the non-eddy months within the stratified period shown in Fig. 7 (April–November),~~

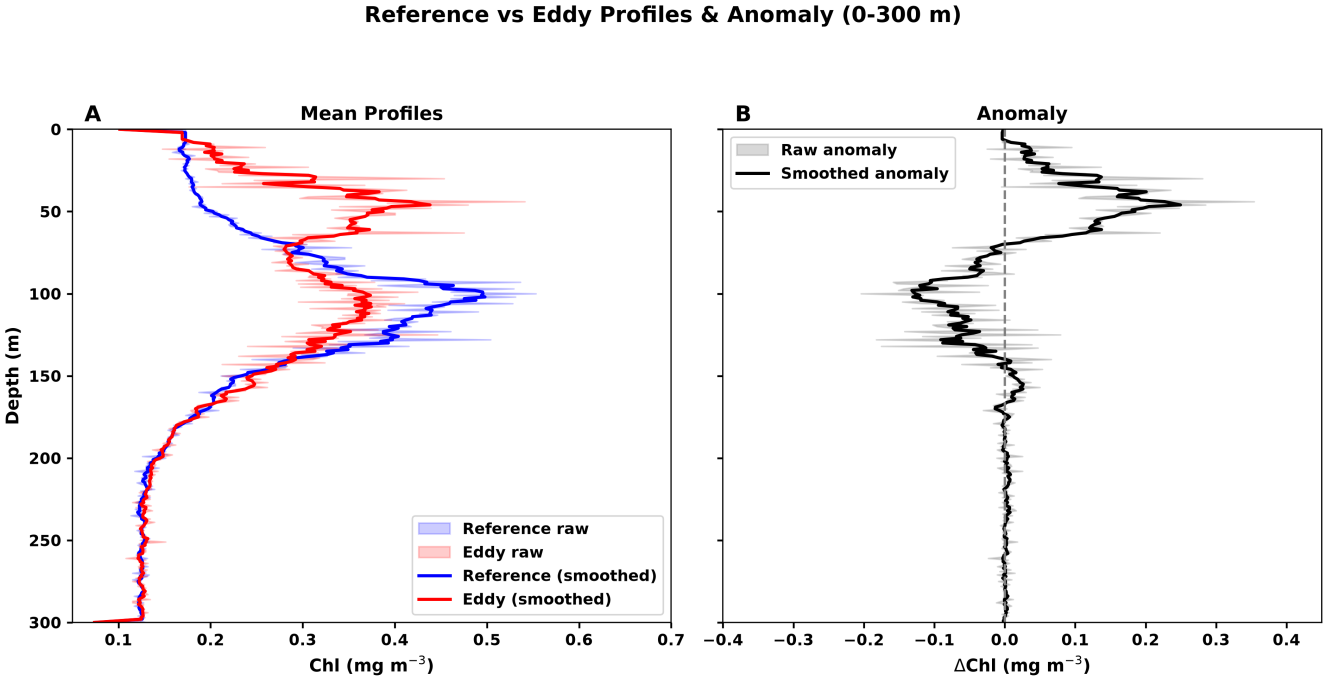

Figure 6. Depth profiles of chlorophyll from glider mission M164[R1] during the reference period (2–3 July 2022; blue) and eddy period (29 June 2022; red). (A) Raw and smoothed profiles. (B) Chlorophyll anomaly profile (eddy minus reference).

~~excluding the eddy-influenced periods (July and September).~~[R1] At *N800*, dissolved silica concentrations in the upper water column increased during the July and September eddy-influenced periods (Fig. 7C). In July, the increase was largely confined to the surface layer, whereas in September, elevated concentrations extended to 50 m depth. Relative to the non-eddy background within the stratified period, upper-layer silica concentrations increased from $0.81 \pm 0.14\ \mu M$ to $1.48\ \mu M$ in July within the upper 20 m ($\Delta Si = 0.67\ \mu M$). In September, upper 50 m concentrations increased from $0.76 \pm 0.14\ \mu M$ to $1.65\ \mu M$ ($\Delta Si = 0.89\ \mu M$). These anomalies exceeded the background variability by factors of approximately 5 and 6, respectively. These changes coincided with enhanced particulate inputs (Fig. 7D). Total inorganic particulate matter, integrated over the upper 180 m from measurements collected at 25, 100, and 180 m, was substantially elevated during July and September relative to the non-eddy background. Mean concentrations increased from $11.5 \pm 6.2\ \mu g\ L^{-1}$ to $31.8\ \mu g\ L^{-1}$ in July and $35.5\ \mu g\ L^{-1}$ in September, corresponding to anomalies of $20.3\ \mu g\ L^{-1}$ and $24.0\ \mu g\ L^{-1}$, respectively. These enhancements exceeded the background variability by factors of approximately 3 and 4, respectively. Particulate Fe concentrations (Fig. 7E) were also elevated during the eddy-influenced periods, with July enrichment extending through the upper 100 m and September enrichment through the upper 180 m. Relative to the non-eddy background within the stratified period, Fe concentrations increased from 0.022 ± 0.017 to 0.102 in July within the upper 100 m, and from 0.028 ± 0.018 to 0.092 in September within the upper 180 m. These increases exceeded the background variability by factors of approximately 5 and 4, respectively.

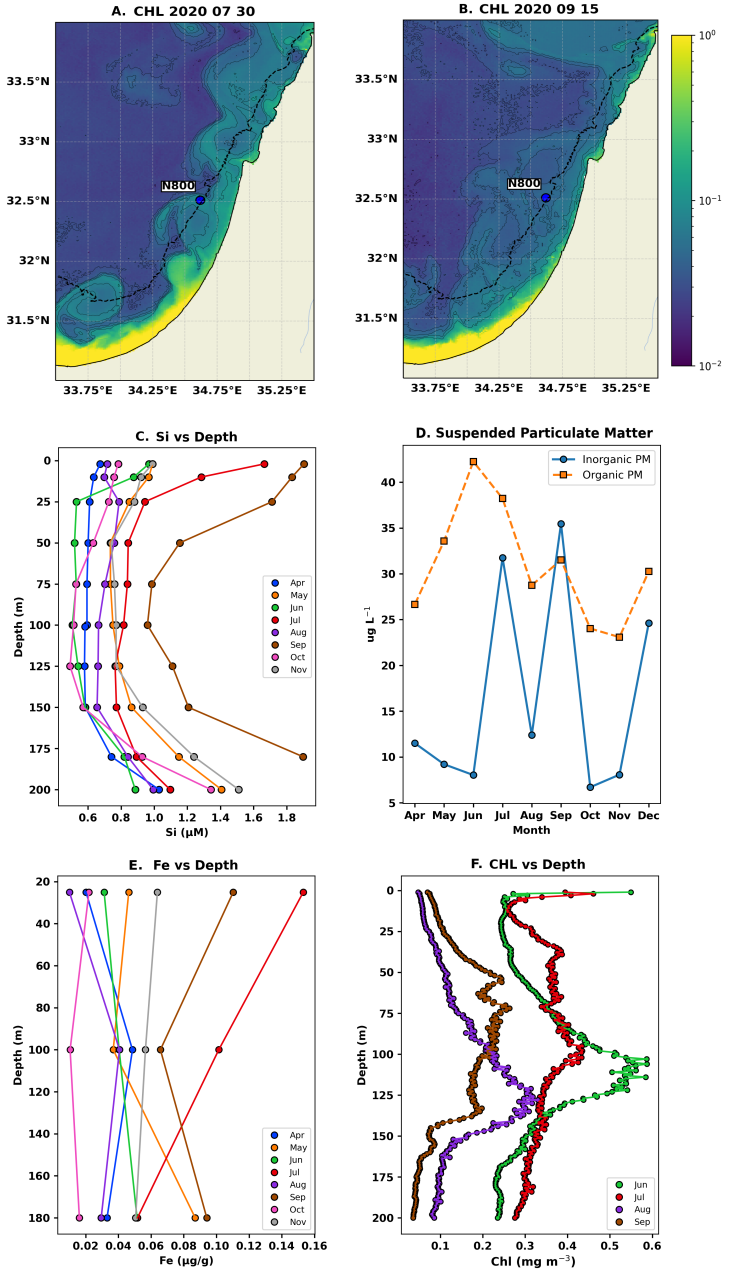

Figure 7. Monthly variability in dissolved and particulate properties at time-series station *N800*. (A–B) Satellite-derived surface chlorophyll fields corresponding to the anomalous sampling dates. (C) Vertical profiles of dissolved silicic acid Si(OH)4 (μM). (D) Monthly integrated suspended particulate matter. (E) Vertical profiles of particulate Fe (μg g^{-1}). (F) Vertical profiles of chlorophyll fluorescence (mg m^{-3}).

The vertical chlorophyll structure also differed from the typical offshore summer profile (Fig. 7F). ~~Concurrent with these changes in dissolved and particulate constituents, the vertical chlorophyll structure (Fig. 7F) differed from typical summer conditions.~~[R1] Profiles from June and August exhibited the characteristic offshore Levantine summer pattern, with a pronounced DCM at 120–130 m. In contrast, the July and September profiles showed a broadened chlorophyll distribution and a reorganization of the vertical structure, including enhanced concentrations higher in the water column. While the increase remained associated with the top of the nutricline, as in background conditions, chlorophyll concentrations were elevated over a thicker depth range extending upward to 50 m in July and 35 m in September, resulting in a shoaled and, in some cases, bimodal DCM.

Together, these observations provide independent support for the glider-derived observations of chlorophyll redistribution, with both datasets showing a shoaled and broadened DCM during eddy influence. The *N800* time-series further extends these observations by revealing concurrent increases in dissolved Si and inorganic particulate matter (including particulate Fe, but not total organic matter), providing additional evidence of the biogeochemical signature of transported coastal waters. ~~Together, these observations show that at a fixed offshore location, the passage of coastal mesoscale eddies is associated with higher dissolved nutrient concentrations and increased inorganic particulate matter (including particulate Fe, but not total organic matter), accompanied by a broadening and upward redistribution of chlorophyll relative to typical stratified summer conditions.~~[R1]

4 Discussion

4.1 Summertime connectivity and the role of coastal mesoscale eddies

During summer stratification, the Eastern Mediterranean Sea is generally characterized by weak coastal–offshore connectivity. Strong vertical stratification suppresses nutrient resupply to the surface, while the persistent alongshore boundary current limits cross-shore exchange, effectively isolating the offshore Levantine Basin from coastal influences (Estrada, 1996; Rosentraub and Brenner, 2007; Ozer et al., 2022). The Levantine Basin is recognized as a distinct biogeochemical and ecological province within the Mediterranean Sea, characterized by extreme oligotrophy, strong nutrient limitation, and unique hydrodynamic conditions relative to other Mediterranean regions (Ayata et al., 2018). Under these conditions, lateral transport of coastal waters into the open sea is generally expected to be minimal.

The results presented here identify coastal mesoscale eddies as intermittent features that can locally disrupt this summer isolation by transporting chlorophyll and associated biogeochemical signatures from the coastal zone into offshore waters. These eddies form along the coastal boundary current and propagate downstream while maintaining a dynamically coherent internal circulation, as evidenced by HF-radar observations showing rotational velocities that substantially exceed their translational speed (Chelton et al., 2011; McWilliams, 1985). While the coastal eddies examined here are smaller and propagate more rapidly than the larger open-ocean anticyclones described elsewhere in the Mediterranean, both exhibit the characteristic kinematics of coherent vortices, with internal rotational velocities greatly exceeding translational speeds, allowing water masses to remain trapped within the eddy core during propagation [R1](Sutyrin et al., 2009; Poulain et al., 2021). Although biological tracers

may exhibit small spatial offsets relative to the underlying dynamical structures, chlorophyll distributions have been shown to provide reliable indicators of mesoscale circulation features when combined with HF-radar observations (Fanelli et al., 2024; Navarro and Ruiz, 2006). The close agreement observed here between the chlorophyll-defined frontal boundary and the regions of strongest azimuthal velocity suggests that any such offset was small relative to the scale of the eddy and does not affect the interpretation of its kinematics. Similar mesoscale features have been documented along the Levantine coast in observations and models (Menna et al., 2012; Efrati et al., 2013; Estournel et al., 2021; Baaklini et al., 2024), and satellite data indicate that they recur during summer (Akpınar, 2024; Verma et al., 2024). Their episodic nature suggests that a portion of coastal–offshore exchange during the stratified season occurs through discrete transport events rather than persistent background exchange. Importantly, the significance of these events does not lie in their contribution to the annual cross-shore transport budget, nor in replacing the much stronger basin-scale connectivity that characterizes winter. Rather, their importance lies in temporarily overcoming the strong coastal–offshore separation that normally persists during summer. In this sense, the primary comparison addressed in this study is between offshore waters influenced by coastal mesoscale eddies and the surrounding offshore environment under typical summer conditions, rather than between summer and winter transport regimes. By transporting a coherent coastal water-mass signature into the oligotrophic offshore basin, these eddies create transient connections between two regions that are otherwise largely isolated during the stratified season.~~Their episodic nature suggests that a portion of coastal-offshore exchange during the stratified season occurs through discrete transport events. Taken together, these results indicate that coastal mesoscale eddies act as intermittent pathways for cross-shore exchange during summer stratification in the Eastern Mediterranean, intermittently extending offshore and exporting vertically structured coastal water masses into an otherwise weakly productive environment. This mechanism complements wintertime mixing and submesoscale stirring, highlighting the role of mesoscale dynamics in shaping seasonal connectivity in ultra-oligotrophic systems.~~[R1]

4.2 Vertical structure and coastal water-mass signatures

The influence of coastal mesoscale eddies extends beyond surface tracer redistribution and involves a consistent reorganization of the upper water column. Glider observations demonstrate that eddy interiors are characterized by elevated chlorophyll concentrations and a pronounced shoaling and broadening of the DCM relative to background offshore conditions. Such a shallow DCM contrasts with the deep, well-defined offshore DCM typically observed during summer stratification in the Levantine Basin (Mignot et al., 2014; Teruzzi et al., 2021; Ediger and Yilmaz, 1996; Ben-Ezra et al., 2024).

The vertical structure of these features provides insight into their underlying dynamics and origin. In the primary glider case (Fig. 3), the broadened and shoaled DCM occurs in conjunction with downward-displaced density surfaces, consistent with anticyclonic, downwelling-favorable circulation. This combination rules out local upwelling as the driver of enhanced upper-layer chlorophyll and instead indicates lateral advection of a preconditioned coastal water mass into the offshore environment, a mechanism also reported in other stratified boundary current systems (Espinosa-Carreón et al., 2012; Cornec et al., 2021; Xu et al., 2023). Elevated surface and subsurface temperatures observed within the eddy are consistent with this interpretation. Independent ship-based observations at the time-series station *N800* provide additional evidence supporting these findings. Periods influenced by coastal mesoscale eddies were characterized by elevated Silicate concentrations in the upper water

column, increased amounts of fine-grained inorganic particles, and a modified vertical chlorophyll structure. Consistent with this interpretation, CTD observations at station *N800* show lower surface salinity and higher surface temperature during the July eddy (Fig. A1A,B), indicative of coastal-origin water previously described for the southeastern Levantine Basin (Ozer et al., 2022). Rather than exhibiting the typical, well-defined DCM, chlorophyll began increasing at the top of the nutricline, as under normal conditions, but the distribution was broadened and intensified upward, extending to depths of approximately 35–50 m. Independent cross-shelf cruise observations show that the chlorophyll maximum is typically bottom-associated at approximately 50–60 m (the average depth of the shelf in this region) over the continental shelf, before deepening beyond the shelf break to form the well-defined offshore DCM at approximately 100–130 m (Fig. A4), supporting the interpretation that the shallower chlorophyll structure observed within the eddy retains a coastal shelf signature.[R1] A plausible mechanism is that, as the coastal eddy forms, its current is sufficiently strong to resuspend the uppermost sediments of the adjacent shelf, which includes fine-grained sediment. This resuspended layer contains benthic phytoplankton (Rubin-Blum et al., 2022) and is likely enriched in nutrients due to in situ heterotrophic bacterial activity. Consequently, the eddy core is transported from the shelf into pelagic waters, carrying elevated dissolved and particulate nutrient concentrations (Fig. 7). The dissolved nutrients introduced to pelagic waters have the capacity to stimulate new primary production which, combined with sinking particles with benthic phytoplankton attached, contribute to the observed enhanced chlorophyll signal. Vertical chlorophyll structure at station *N800* closely resembled that observed during the glider missions. Although anomaly profiles were not explicitly calculated for the *N800* data, the vertical distributions during eddy-influenced months showed enhanced chlorophyll in the upper 100 m and comparatively reduced concentrations at greater depths, consistent with the two-layer anomaly structure identified from the glider analysis. PAR profiles from the *N800* cruises (Fig. A3C) further showed a divergence beginning near 40 m, with lower subsurface PAR during the July and September eddy periods relative to the June and August reference profiles. This reduction in light penetration provides a plausible mechanism for the observed deep chlorophyll suppression. The elevated chlorophyll concentrations and increased suspended particulate matter associated with eddy influence likely enhanced light attenuation in the upper water column, further reducing subsurface PAR and contributing to the negative anomaly at depth, consistent with established relationships between particle concentrations, optical attenuation, and underwater light availability (Babin et al., 2003; Neukermans et al., 2014; Morel and Maritorena, 2001). Coastal waters in the Eastern Mediterranean receive terrestrial and benthic nutrient inputs; however, anti-estuarine circulation and rapid biological uptake limit the accumulation of nutrients and prevent the development of a persistent cross-shore nutrient gradient (Kress and Herut, 1998; Ben-Ezra et al., 2023; Krom et al., 2010). Consequently, coastal biogeochemical signals are often short-lived or spatially heterogeneous, and may only become clearly expressed offshore when transported within mesoscale features (Efrati et al., 2013). The recurrence of these vertical signatures across various sampling strategies suggests that the observed reorganization reflects a persistent property of the advected water mass rather than transient biological responses to local forcing.

4.3 Event-scale offshore redistribution under stratified conditions

The vertical reorganization associated with coastal mesoscale eddies results in a measurable redistribution of chlorophyll within the offshore water column. By combining vertically integrated chlorophyll anomaly profiles with the offshore surface area of

individual eddies, the results provide event-scale estimates of the excess chlorophyll transported offshore during summer stratification (1500-3500 kg per eddy). Similar event-based approaches have been used to assess eddy-driven transport in other oligotrophic systems (Gerin et al., 2009; Martin, 2003). For both glider-sampled eddies, the vertically integrated chlorophyll anomaly was positive, reflecting the combined effects of elevated surface concentrations and a shoaled DCM relative to background offshore conditions. Although the absolute magnitudes differed between events, the consistent sign of the anomaly indicates that coastal mesoscale eddies can act as net exporters of chlorophyll and nutrients into the offshore Levantine Basin during summer.

In an ultra-oligotrophic system such as the eastern Levantine Basin (Krom et al., 2005; Herut et al., 2000), even modest event-scale anomalies may be biogeochemically relevant. Background offshore chlorophyll concentrations are extremely low, and phytoplankton biomass during summer is largely confined to a narrow depth range near the nutricline (Mignot et al., 2014; Teruzzi et al., 2021). More generally, oligotrophic ecosystems are particularly sensitive to physical transport processes because biological production is strongly constrained by the availability and redistribution of nutrients and biomass, allowing mesoscale and submesoscale circulation features to exert a disproportionate influence on ecosystem structure and productivity (Levy et al., 2001). Because eddy occurrence is episodic and interception by in situ platforms is limited, these estimates cannot be robustly extrapolated to seasonal or basin-wide budgets and should be interpreted as first-order, event-scale indicators of offshore redistribution.

4.4 Broader context and limitations

Coastal eddies ~~and filaments~~[R1] have been shown to facilitate cross-shelf exchange in a range of boundary current systems, often transporting nutrient rich waters offshore and enhancing biological productivity (Flos and Tintoré, 1990; Espinosa-Carreón et al., 2012; Wang et al., 2018). In many of these regions, however, coastal–offshore contrasts in nutrients and biomass are substantially larger than in the Eastern Mediterranean, and background productivity is higher.

The Levantine Basin represents a limiting case, where nutrient concentrations and surface chlorophyll are among the lowest observed globally (Krom et al., 2005; Pujo-Pay et al., 2011). In this context, the presence of detectable biogeochemical signatures associated with coastal eddies highlights that even modest coastal enrichment can be preserved and transported offshore when embedded within dynamically coherent mesoscale structures. The Eastern Mediterranean therefore provides a useful natural laboratory for examining eddy-driven exchange under ultra-oligotrophic conditions. Beyond the redistribution of chlorophyll and nutrients, mesoscale and sub-mesoscale transport processes may also influence the composition and organization of offshore plankton communities. In oligotrophic environments, where biological responses are often strongly resource-limited, episodic coastal inputs transported by mesoscale features may affect ecosystem structure in addition to biomass distribution. More broadly, fronts, filaments, and mesoscale circulation features are increasingly recognized as important organizers of biological heterogeneity in oligotrophic oceans, influencing the spatial distribution of plankton communities and the transfer of energy across multiple trophic levels (Prants, 2022; Yang et al., 2023; Garcia et al., 2026; Hernández-Hernández et al., 2020; Hernández-Hernández et al., 2021). The coastal location and relatively small size of these features present challenges for conventional SSH-based analyses. Gridded altimetry products in the Mediterranean typically have resolutions compara-

ble to the regional Rossby radius and may only partially resolve mesoscale structures forming close to the coastline, where land contamination and interpolation further increase uncertainty. Consequently, the chlorophyll signal provides a more direct tracer of coastal-origin transport for the events investigated here. In addition to their small spatial scale and coastal location, the relatively rapid evolution of these coastal eddies likely further limits their detectability in gridded SSH products. Unlike the larger offshore mesoscale eddies that can often be tracked continuously over weeks to months, the surface expression of the coastal eddies investigated here evolves on much shorter timescales. Successive chlorophyll observations, and SST where thermal contrast is sufficient, indicate that individual events typically persist for several days to approximately one week before undergoing substantial changes in position, morphology, or intensity. As a result, ocean color and SST provide the most effective means of identifying and tracking these transient coastal features, whereas their SSH signature is often weak or unresolved.[R1] The present results complement previous SSH-based descriptions of Levantine mesoscale circulation and long-lived anticyclones (Barboni et al., 2021) by resolving the biogeochemical imprint of smaller coastal transport features. Likewise, whereas BOUM observations emphasized the properties of large anticyclonic eddy interiors (Moutin et al., 2012), the present work focuses on coastal-origin water masses exported offshore and their vertical biogeochemical signatures.

The conclusions drawn here are subject to several observational limitations. Interception of coastal mesoscale eddies by autonomous gliders and ship-based sampling is inherently opportunistic and constrained by platform trajectories and sampling schedules. In addition, the export estimates rely on assumptions regarding eddy geometry, representativeness of vertical profiles, and the choice of background reference conditions. While these assumptions are physically motivated and internally consistent, they introduce uncertainty that limits quantitative extrapolation beyond the sampled events. Although the present work focuses on individual events, the recurrent occurrence of coastal mesoscale activity suggests that their cumulative contribution to offshore exchange warrants future statistical investigation.

5 Conclusions

Coastal mesoscale eddies provide an intermittent but effective pathway for cross-shore exchange during summer stratification in the Eastern Mediterranean, exporting coastal water into the otherwise isolated offshore Levantine Basin. Although these features are predominantly anticyclonic and typically associated with downwelling and low productivity in pelagic regions, their formation in proximity to the coast allows them to entrain relatively enriched waters. As a result, they transport elevated chlorophyll, nutrients, and suspended particulate matter offshore, along with a distinct vertical structure characterized by a shallow, often bimodal DCM. The analysed coastal mesoscale eddies extended over offshore areas of approximately 1200–1430 km^2 and were associated with positive vertically integrated chlorophyll anomalies corresponding to estimated offshore redistribution of approximately 1500–3500 kg of chlorophyll per eddy. The transported water masses exhibited a shoaling of the DCM from typical offshore depths of approximately 120–130 m to 50 m within the eddy interior and were accompanied by elevated nutrient and particulate signatures. These findings highlight how mesoscale dynamics can modify the expected biogeochemical role of anticyclonic eddies and emphasize their importance as episodic drivers of offshore redistribution in ultra-oligotrophic environments.

Data availability. This study has been conducted using E.U. Copernicus Marine Service;

DOI: 10.48670/moi-00300 (product name: $OCEANCOLOUR_MED_BGC_L4_MY$).

DOI: 10.48670/moi-00142 (product name: $SEALEVEL_EUR_PHY_L4_NRT_008_060$).

DOI: 10.48670/moi-00172 (product name: $SST_MED_SST_L4_NRT_OBSERVATIONS_010_004_c_V2$).

HF Radar data is available at: https://app.hubocean.earth/catalog/dataset/f0b38644-7cb3-4fdc-bec7-081c52b591fa/hf-radar?

Glider data from mission M141 is available at:
https://app.hubocean.earth/catalog/dataset/52369e62-41c0-487f-91d1-9b8c01a8b618/glider-mission-m141?

Glider data from mission M164 is available at:
https://app.hubocean.earth/catalog/dataset/267dc865-1d7f-4f3d-8560-ce456b3903c4/glider-mission-m164?

Cruise data from the *N800* station is available at: https://haifauniversity.shinyapps.io/Public_Download_app_06_2022/

Cruise data from the *Haifa Section* cruises is available at:
https://app.hubocean.earth/catalog/dataset/7a463a3e-972b-4034-a348-309440e64408/haifa-section-cruises-chlorophyll-2018-2021?

Appendix A

Table A1. Sensitivity of offshore eddy surface-area estimates to the use of L3 and L4 satellite chlorophyll products. The same detection procedure described in Section 2.2.1 was applied independently to L3 and gap-filled L4 chlorophyll fields for the dates shown in Fig. A1. Absolute and relative differences were calculated as L4 minus L3, with the relative difference expressed as a percentage of the L3 estimate. The comparison shows negligible sensitivity of the detected offshore surface area to product level for both events.

Eddy event	**Date**	**L3 area (km^2)**	**L4 area (km^2)**	**Difference (km^2)**	**Difference (%)**
2018 glider event	1 July 2018	1431.6	1433.0	+1.4	+0.09
2022 glider event	30 June 2022	1202.8	1202.8	0.0	0.00

Table A2. Sensitivity of eddy propagation velocity estimates to the use of L3 and L4 satellite chlorophyll products. The frontal-boundary detection procedure described in Section 2.2.2 was applied independently to L3 and gap-filled L4 chlorophyll fields for the dates shown in Fig. A2. Propagation velocities were calculated from the displacement of the detected frontal boundary between consecutive satellite images. Absolute differences were calculated as L4 minus L3. The comparison demonstrates negligible sensitivity of the estimated propagation velocity to product level.

Period	**L3 velocity (km day^{-1})**	**L4 velocity (km day^{-1})**	**Difference (km day^{-1})**
30 Jul – 31 Jul 2020	14.47	14.47	0.00
31 Jul – 1 Aug 2020	11.81	11.81	0.00
1 Aug – 2 Aug 2020	14.94	14.94	0.00
2 Aug – 3 Aug 2020	13.57	12.45	-1.12

Table A3. Analytical precision and limits of detection (LOD) for dissolved nutrient measurements used in the *N800* analysis.

Determinant	Usual range (nM)	Precision	LOD (nM)	Detector
DIP	0–125	2	6	LWCC
Nitrate	0–1000	63	13	1 cm cell spectrophotometer
Ammonium	0–500	6	5	JASCO fluorometer
Silicate	0–2000	7	11	1 cm cell spectrophotometer
TDP	0–200	5	2	LWCC

Author contributions. Y.F. compiled, processed, and analyzed the satellite and glider data. T.O. collected and processed the glider data. T.BE., M.D.K., A.T., and M.T. collected, processed, analysed, and interpreted the cruise data. Y.T. collected and processed the HF radar data.

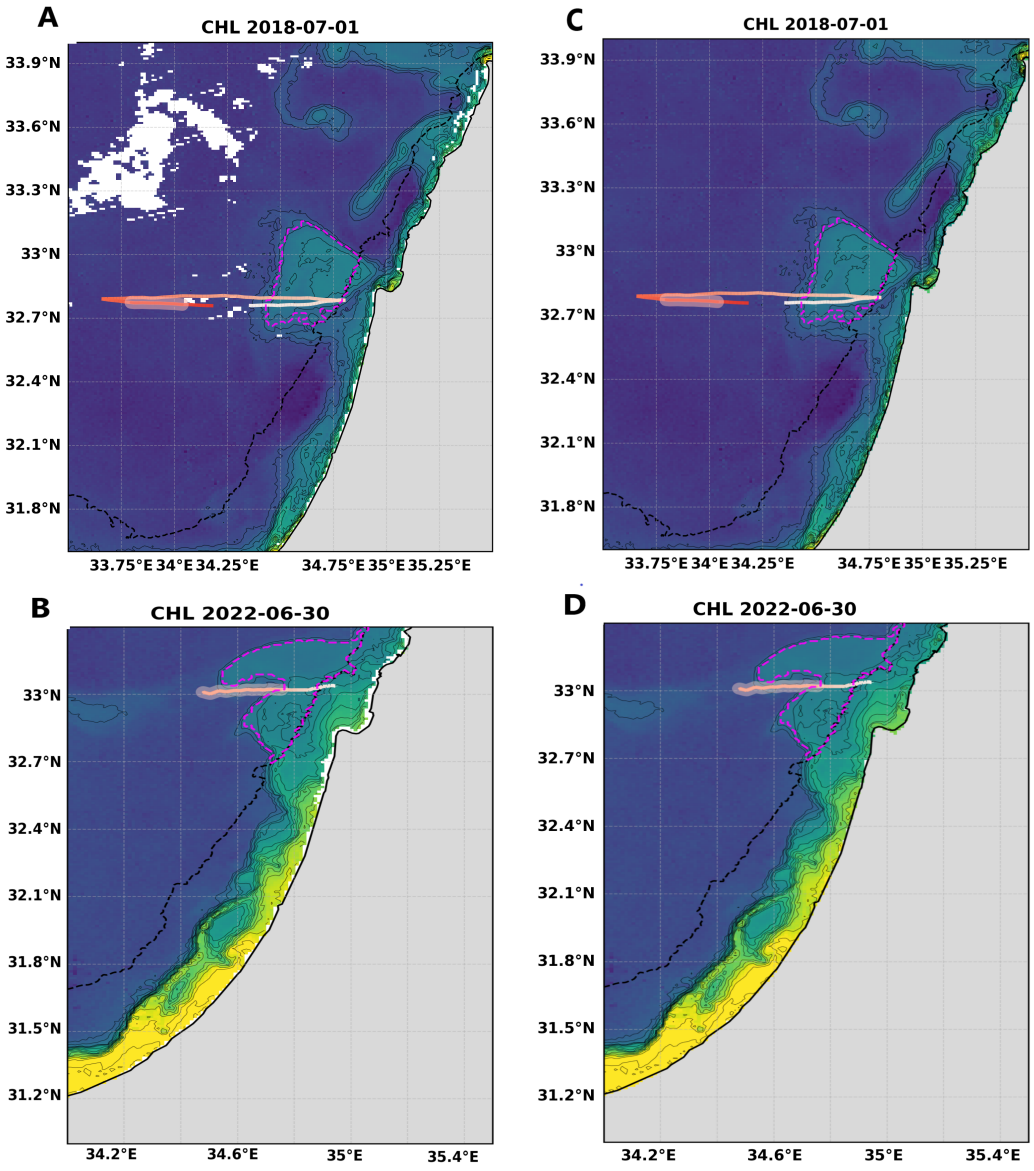

Figure A1. Comparison of L3 and L4 satellite chlorophyll products for the two coastal mesoscale eddies identified using the detection method described in Section 2.2.1 and presented in Fig. 3A and Fig. 4A. (A, B) L3 chlorophyll fields for 1 July 2018 and 30 June 2022, respectively. (C, D) Corresponding L4 chlorophyll fields for the same dates. Magenta contours indicate the offshore eddy boundaries identified using the procedure described in Section 2.2.1. The black dashed line denotes the 700 m isobath, and the glider trajectories are overlaid for reference. The comparison shows that the same offshore transport features are identified in both products, while the gap-filled L4 fields provide a more spatially continuous representation of the chlorophyll distribution.

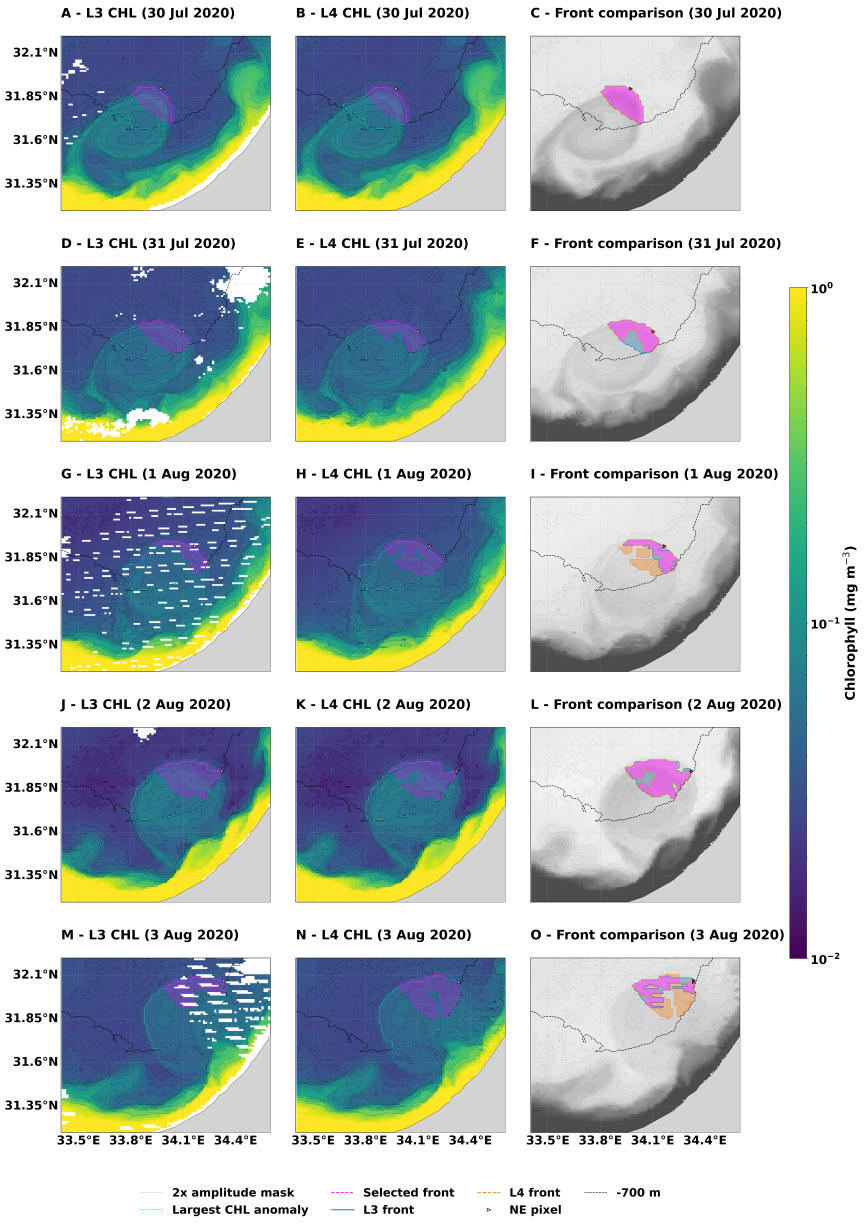

Figure A2. Comparison of L3 and L4 satellite chlorophyll products for the coastal mesoscale eddy analyzed using the frontal-boundary detection method described in Section 2.2.2 and the HF-radar analysis presented in Fig. 2. (A–E) L3 chlorophyll fields from 30 July to 3 August 2020. (F–J) Corresponding L4 chlorophyll fields for the same dates. Magenta contours indicate the eddy frontal boundaries identified using the gradient-based detection procedure described in Section 2.2.2. The black dashed line denotes the 700 m isobath. The comparison demonstrates that the same dynamically coherent coastal mesoscale eddy and its frontal boundary are identified using both products, while the gap-filled L4 fields provide a more spatially continuous representation of the chlorophyll distribution.

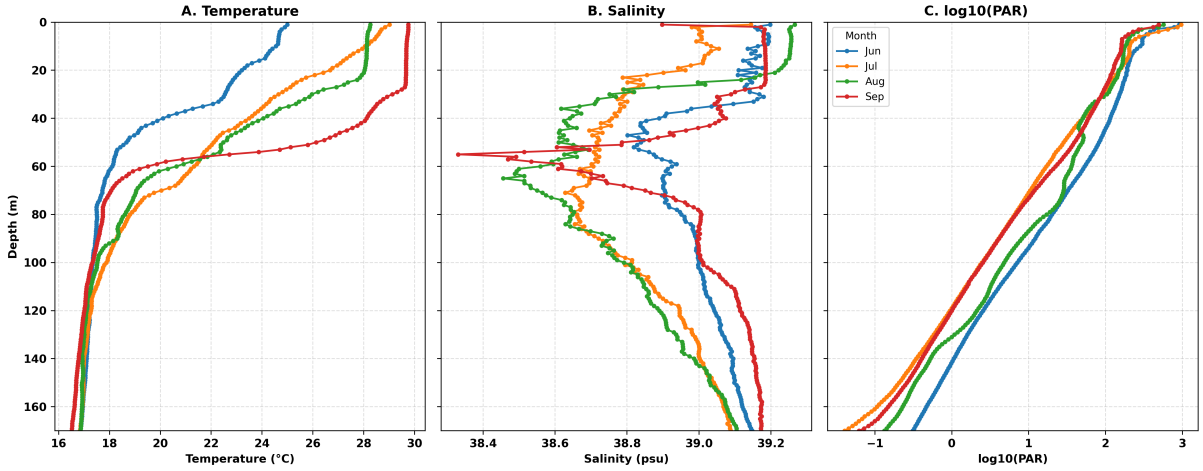

Figure A3. Vertical profiles of A. **temperature**, B. **salinity**, and C. $\log_{10}(\mathrm{PAR})$ at station *N800* during June–September 2020. Profiles are derived from individual ship-based measurements and shown from the surface to 170 m depth. Photosynthetically active radiation (PAR) was recalculated from measured values using a 3 m depth-smoothed moving average prior to log-transformation.

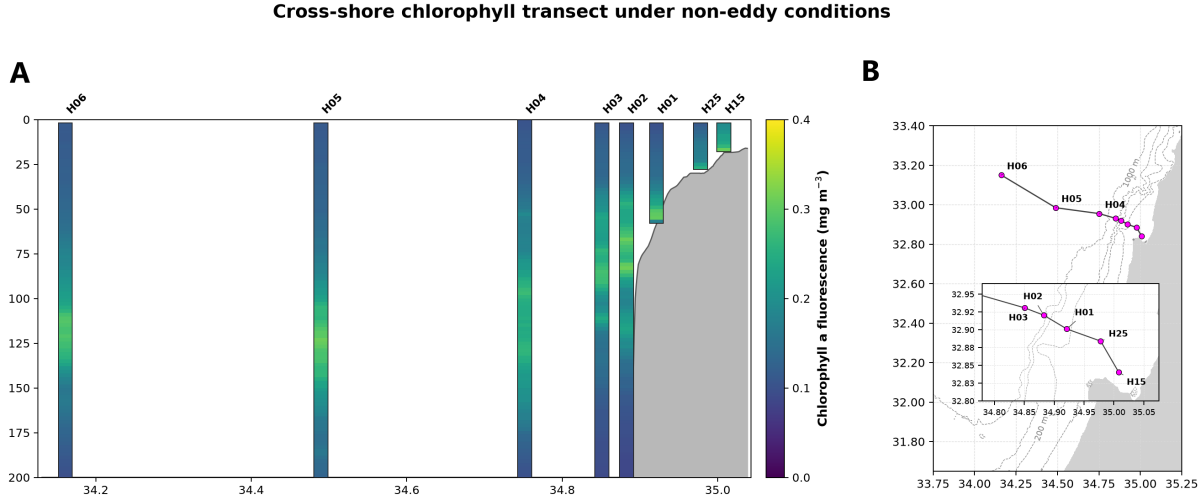

Figure A4. A. Mean summer (August–September) chlorophyll transect across the continental shelf based on the Haifa Section cruises (2018–2021). The section represents the average of repeated summertime CTD measurements of the eight sampling stations shown in panel (B), extending from the nearshore shelf to the open Levantine Basin. The transect illustrates the characteristic transition from the bottom-associated coastal chlorophyll maximum over the continental shelf to the DCM in offshore waters.

Y.L. and E.B. oversaw the research. Y.F., Y.L, M.D.K., T.O., T.BE. and E.B. interpreted the results. Y.F. led the writing of the paper with contributions from all coauthors.

Competing interests. The authors declare they have no competing interests.

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