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. Here we examine how the limited summertime connectivity is affected by coastal mesoscale eddies, which are a 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 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 $\sim$1–10 km)instabilities enhance lateral stirring (Lévy et al., 2012). Recent work indicates that such wintertime horizontal processes contribute substantially to the seasonal offshore chlorophyll increase (Fadida et al., 2026). These findings emphasize the role of submesoscale ($\sim$1–10 km) and mesoscale ($\sim$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, and SSH-based analyses, focusing on their circulation, persistence, and physical structure (Moutin et al., 2012; Barboni et al., 2021). The present study instead 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 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 deep chlorophyll maximum (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), their impact on the vertical biogeochemical structure of the water column remains unquantified.

In this study, we investigate the role of coastal mesoscale eddies and filaments as episodic pathways for summer cross-shelf exchange in the eastern Levantine Basin. 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 features and characterize their propagation, kinematics, and three-dimensional hydrographic and biogeochemical structure. 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. Since the offshore transport investigated here occurs through intermittent mesoscale events rather than persistent 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. Our results provide the first observational evidence that coastal mesoscale eddies and filaments can intermittently disrupt the summertime coastal–offshore separation in one of the world's most oligotrophic marine regions.

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. . 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 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). The altimetry observations analyzed in this study correspond to the 2018–2023 study period. DOI: 10.48670/moi-00142. A gridded L4 product with a spatial resolution of 1/8 degrees.

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

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.

2.1.2 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 in June/July 2018, yielding a 118 km transect (repeated twice). 55 dives where utilized from M164's mission in June 2022, 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).

2.1.3 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 current measurement dataset is related to continuous measurements conducted between July and August 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-
125 hour average used in the analysis is 12:00-15:00 to coincide with the passage of the satellite over the region.

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 results presented here correspond to sampling periods during which coastal filaments were observed to pass over the station (July 2020 and September 2020), together with routine sampling conducted
130 under non-filament conditions for comparison.

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,
135 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).

140 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 A1.

2.2 Methods

The following analyses were designed to identify episodic offshore transport events associated with coastal mesoscale activity
145 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 Detection of high-chlorophyll offshore eddies

150 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.

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

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

with 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

$$I = \int_0^{z_{\max}} \Delta C(z)\, dz,$$

where $z_{\max}$ 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.

2.2.2 Gradient-based detection of the eddy frontal boundary

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,

$$|\nabla C| \geq G_{\mathrm{thr}}, \qquad G_{\mathrm{thr}} = \mathrm{percentile}_{90}\left(|\nabla C|_{\mathrm{offshore}}\right),$$

thereby 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,

$$C \geq C_{\mathrm{amp}}, \qquad C_{\mathrm{amp}} = 1.5 \times \mathrm{percentile}_5(C_{\mathrm{offshore}}),$$

which 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.

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 characterized by anticyclonic circulation and 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., 2023), are associated with uniformly low chlorophyll concentrations, consistent with strong stratification and suppressed nutrient supply (Belkin et al., 2022). In contrast, cyclonic features identified by depressed 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 east of the Delta (downstream) display pronounced surface chlorophyll signatures (Fig. 1A), (Fadida et al., 2026).

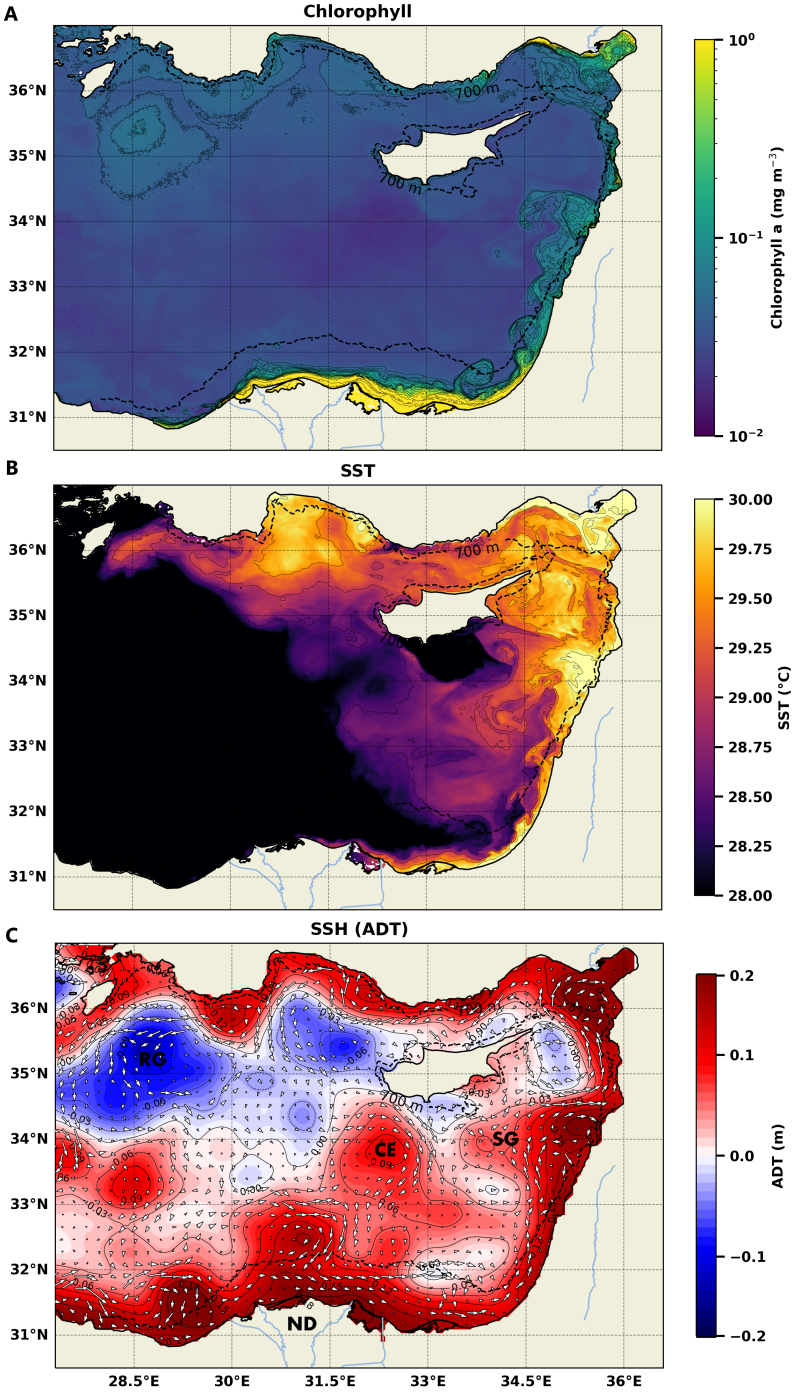

Figure 1. Summer surface conditions in the Eastern Levantine Basin on 30 July 2020. A. Surface chlorophyll (mg m^{-3}), highlighting a sequence of mesoscale eddies extending downstream of the Nile River Delta and progressing cyclonically across the basin. The 700 m isobath is shown as a black dotted line. 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)..

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 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} ($\sim$13.4 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 persistence of a closed anticyclonic circulation over multiple days confirms that the observed structure represents a dynamically coherent mesoscale eddy.

3.3 Three-dimensional structure of the eddies

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.

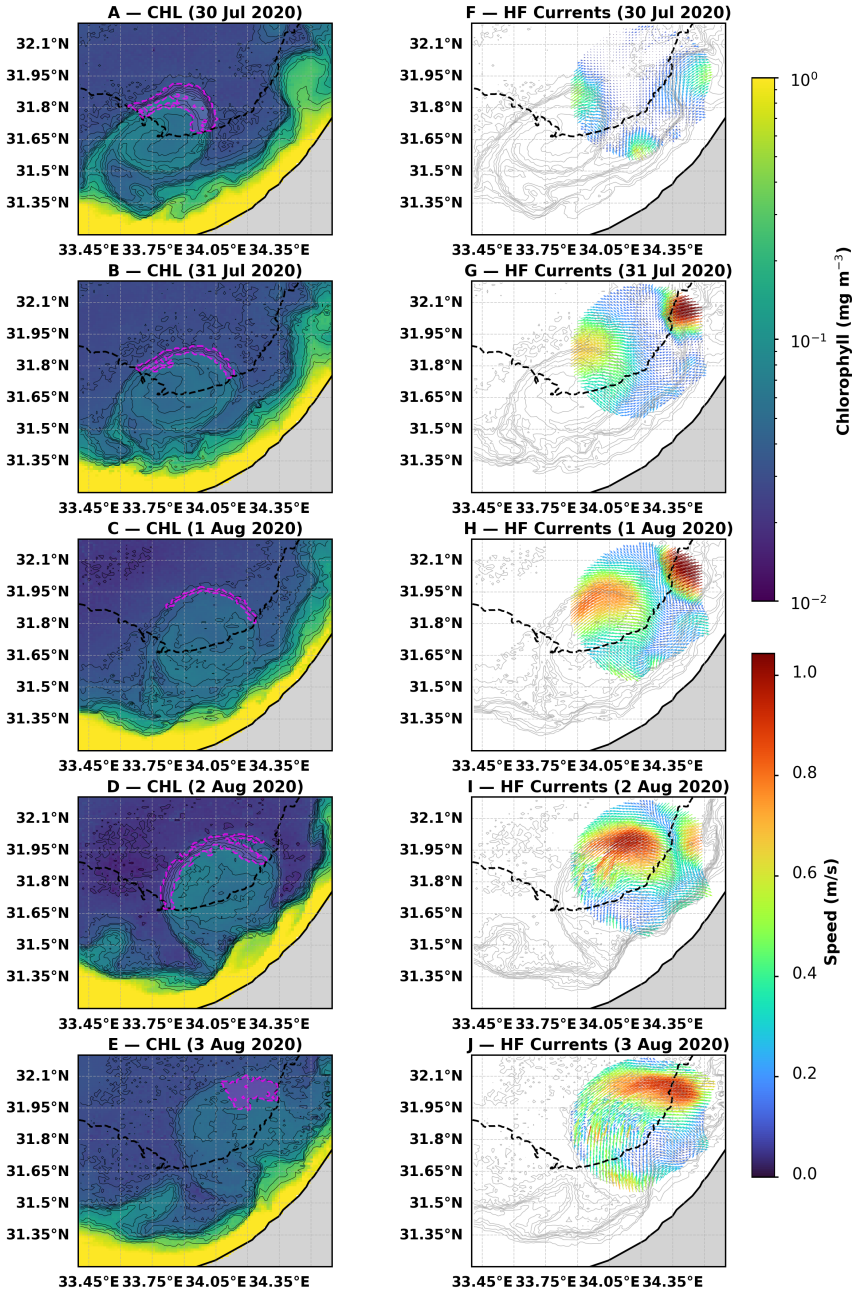

Figure 2. Satellite and HF-radar observations during 30 July–3 August 2020. (A–E) Daily surface chlorophyll maps. The magenta line indicates the identified frontal boundary used to collocate HF-radar velocity measurements with the chlorophyll-defined mesoscale feature. (F–J) HF-radar surface currents overlaid on CHL contours.

The first glider mission, conducted during June–July 2018, sampled a coastal eddy over a period of approximately 12 days (Fig. 3). 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 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.

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.

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.

3.4 Biogeochemical footprint of the 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

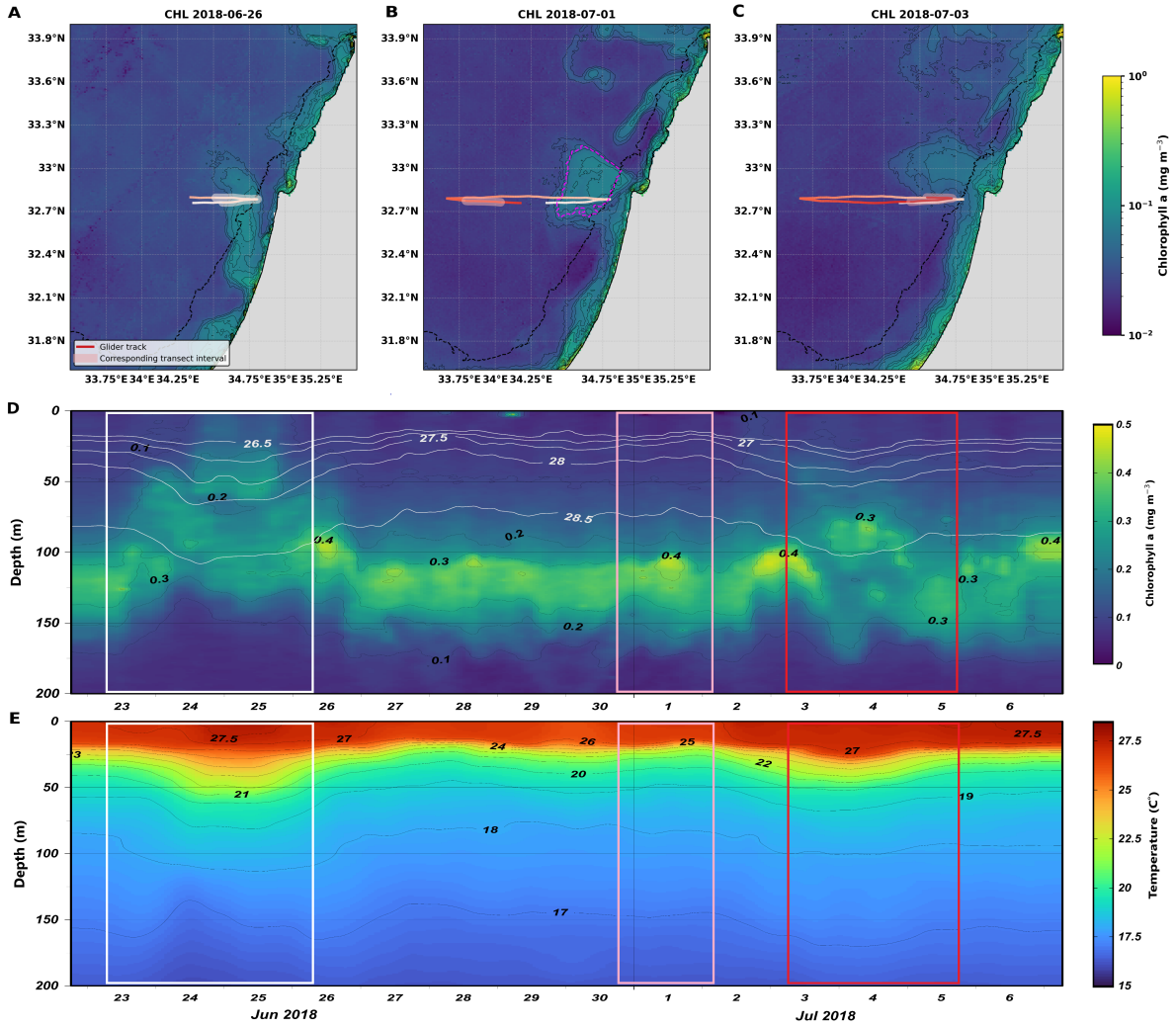

Figure 3. Satellite and glider observations of a coastal eddy during June/July 2018. (A–C) Surface chlorophyll on 26 June, 1 July, and 3 July, with the cumulative glider trajectory colored by time progression. Lightened segments mark the position of the glider at the time of each satellite image. In (B), the magenta contour delineates the identified offshore eddy feature used for the surface-area and chlorophyll-stock calculations. (D) 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). (E) Glider-derived temperature section (°C), with the same highlighted intervals as in (D).

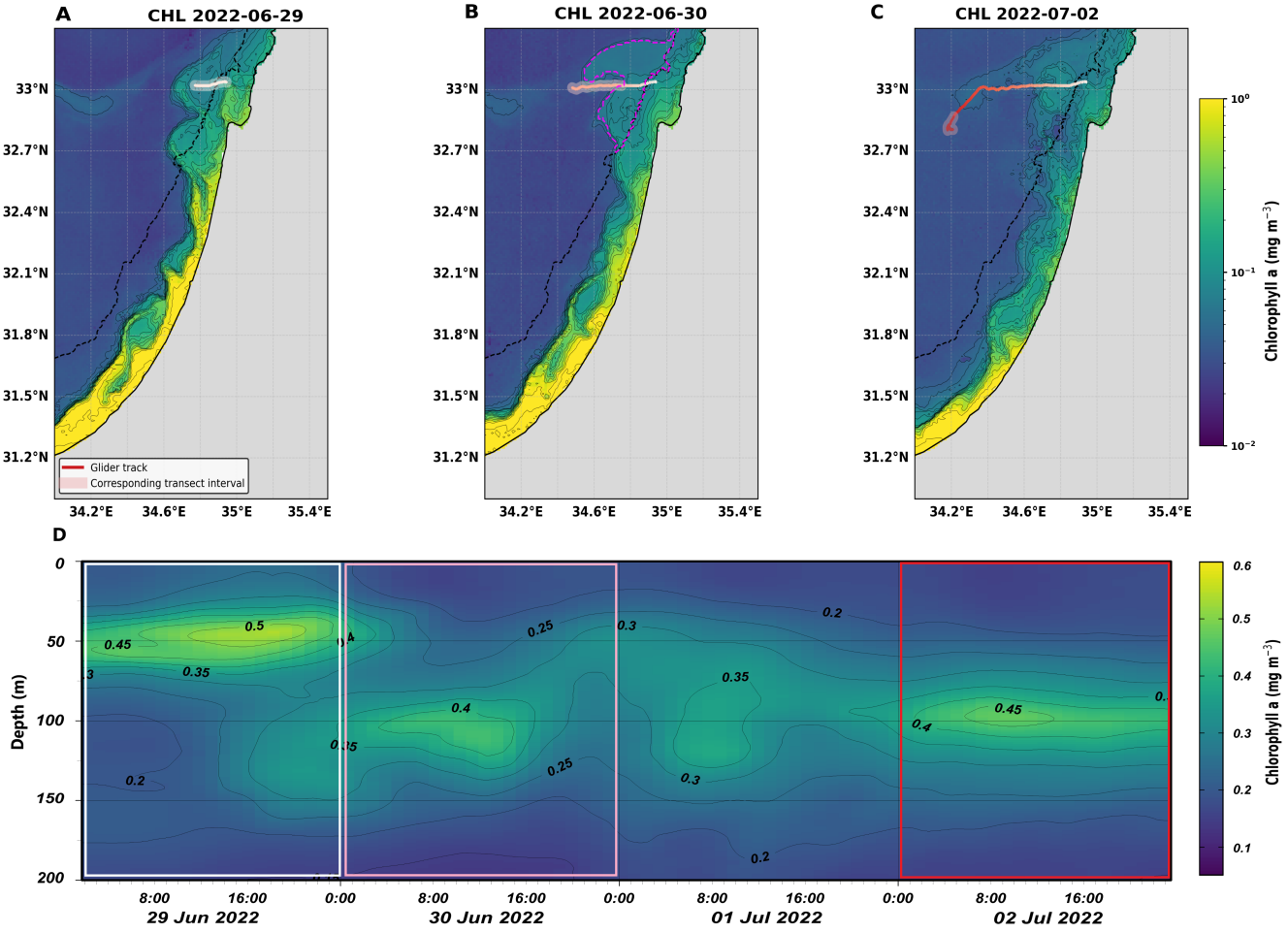

Figure 4. Satellite and glider observations of a coastal eddy during June–July 2022. (A–C) Daily surface chlorophyll with the cumulative glider trajectory overlaid and colored by time progression. Lightened segments mark the position of the glider at the time of each satellite image. In (B), the magenta contour delineates the identified offshore eddy feature used for the surface-area and chlorophyll-stock calculations. (D) 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).

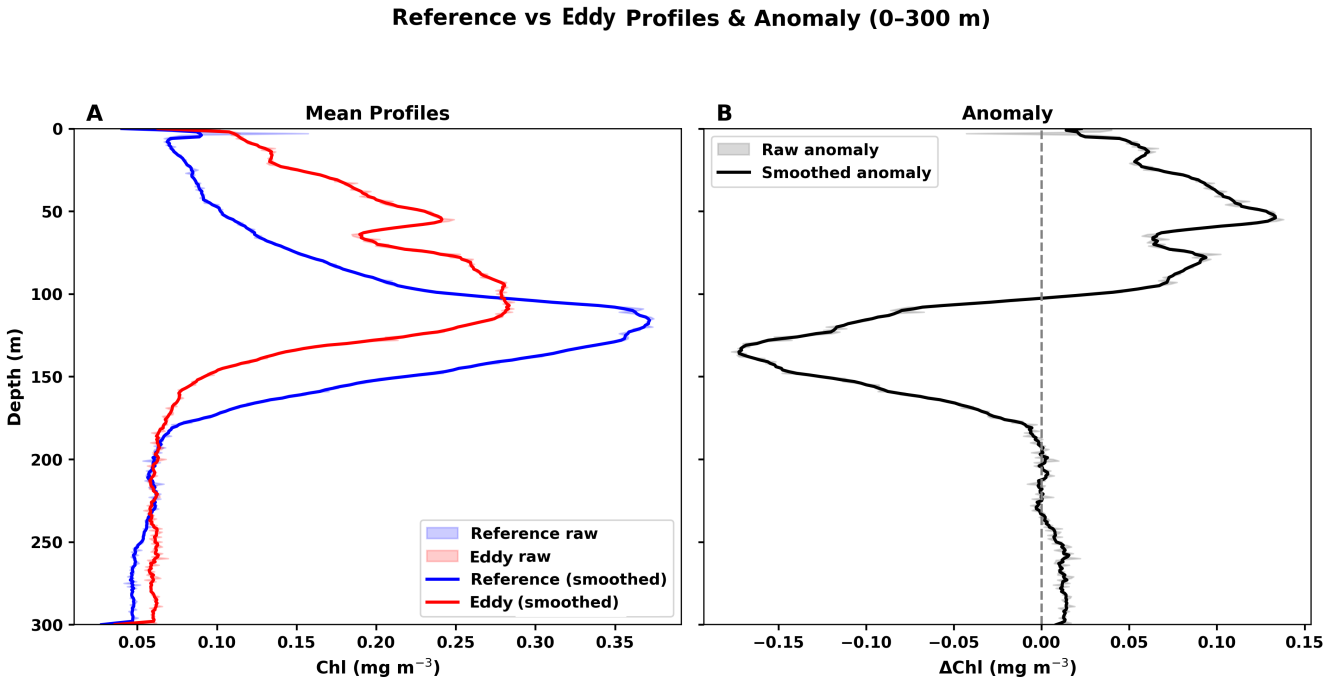

Figure 5. A. Depth profiles of chlorophyll during the reference period (28–29 June 2018; blue) and the eddy period (24–26 June 2018; red). (B) Chlorophyll anomaly profile (eddy minus reference; black). Shaded and solid lines denote raw and smoothed profiles, respectively.

throughout 2020, enabling comparison between background summer conditions (June and August) and two sampling periods influenced by coastal mesoscale eddies (July and September).

Satellite-derived surface chlorophyll imagery indicates that the 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). 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 (D'Ortenzio et al., 2005)), excluding the eddy-influenced periods (July and September).

At N800, dissolved silica concentrations in the upper water column increased during the July and September eddy-influenced periods (Fig. 7C). (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

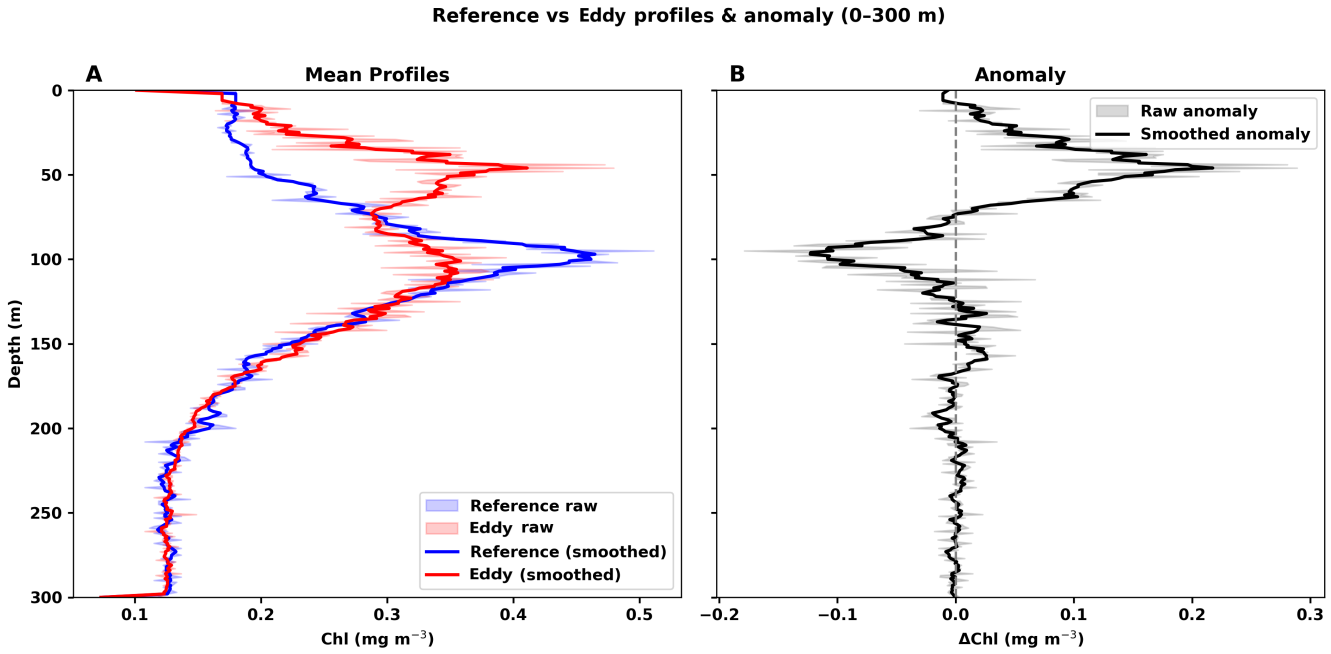

Figure 6. Depth profiles of chlorophyll during the reference period (2–3 July 2022; blue) and eddy period (29 June 2022; red). (A) Raw and smoothed profiles. (B) Chlorophyll anomaly profile (eddy minus reference).

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.

Concurrent with these changes in dissolved and particulate constituents, the vertical chlorophyll structure (Fig. 7F) differed from typical summer conditions. Profiles from June and August exhibited the characteristic offshore Levantine summer pattern, with a pronounced deep chlorophyll maximum (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 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

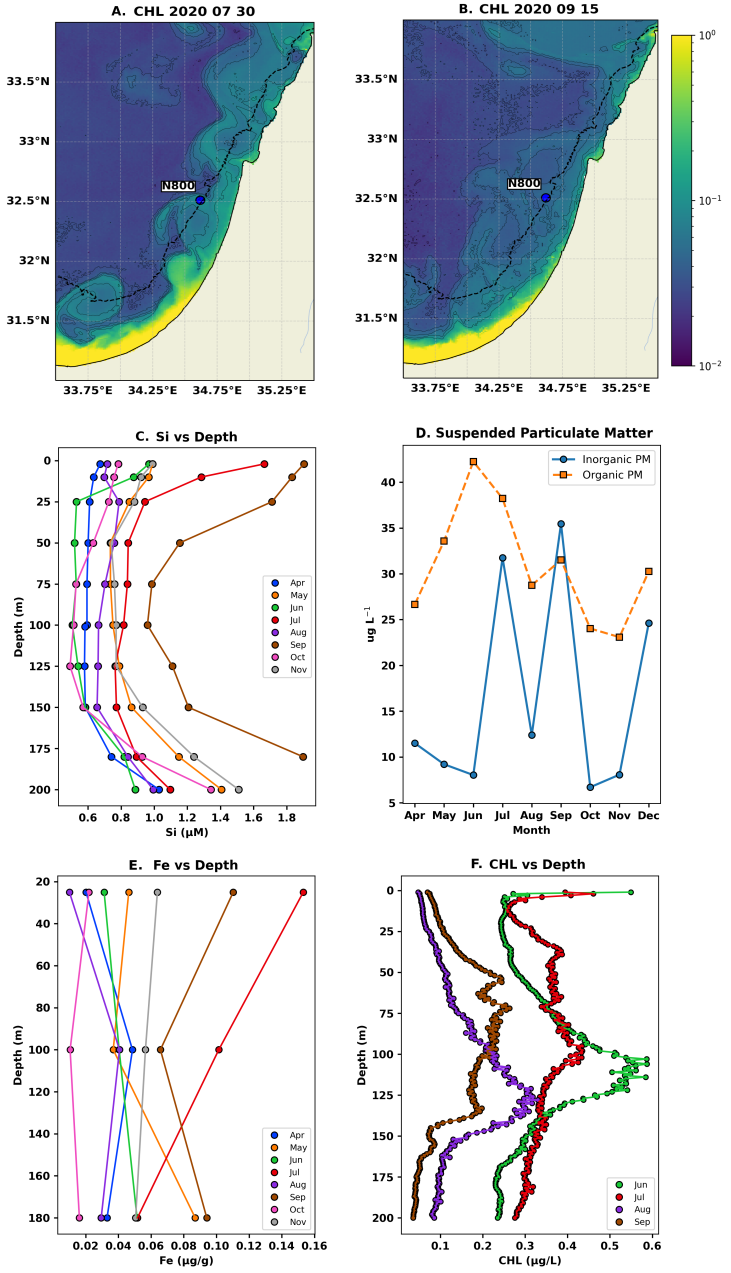

Figure 7. Monthly variability in dissolved and particulate properties at time-series station N800. (A–B) Satellite-derived surface chlorophyll fields corresponding to the anomalous sampling dates. (C) Vertical profiles of dissolved silicic acid Si(OH)4 (μM). (D) Monthly integrated suspended particulate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

organic matter), accompanied by a broadening and upward redistribution of chlorophyll relative to typical stratified summer conditions.

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). 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. 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 (Lévy et al., 2012), highlighting the role of mesoscale dynamics in shaping seasonal connectivity in ultra-oligotrophic systems.

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 (Cornec et al., 2021; Espinosa-Carreón et al., 2012; 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 deep chlorophyll maximum (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. 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. A1C) 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 sig-

nals 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 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 chloro-

phyll 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 comparable 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. 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 980–1430 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: $SST_MED_SST_L4_NRT_OBSERVATIONS_010_004_c_V2$).

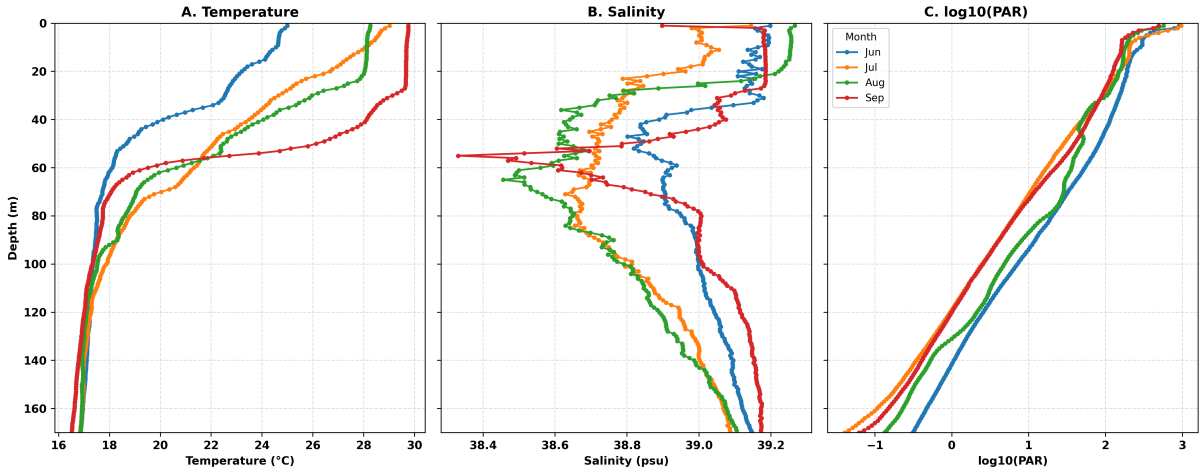

Figure A1. Vertical profiles of A. **temperature**, B. **salinity**, and C. $\log_{10}(\mathrm{PAR})$ at station N800 during June–September 2020. Profiles are derived from individual ship-based measurements and shown from the surface to 170 m depth. Photosynthetically active radiation (PAR) was recalculated from measured values using a 3 m depth-smoothed moving average prior to log-transformation.

Appendix A

Table A1. 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. 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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