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Key Points:

- Adaptive Lagrangian sampling guided by SWOT, combined with high-frequency and high-precision measurements, targeted fine-scale features
- Contrasting regional and fine-scale nutrient distributions were observed across the front and within the southern anticyclonic eddy, associated with SWOT sea surface height
- A mechanism for nutrient supply from the more oligotrophic eddy interior to surrounding waters through isopycnal fluxes was identified

Supporting Information:

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

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Ocean Circulation Modulating the Nutrient Distribution and Fluxes at Regional and Fine Scales: A Case Study in the Northwestern Mediterranean Sea

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Abstract In the oligotrophic ocean, nutrient distribution plays a key role in controlling primary production via upward fluxes. In spring 2023, the BioSWOT-Med cruise investigated how fine-scale ocean dynamics influence nutrient availability in the Mediterranean Sea. Combining SWOT satellite observations with targeted Lagrangian high-resolution sampling, the study focused on a 50 km domain encompassing contrasting waters across the North Balearic Front and a fine-scale anticyclonic eddy. Clear contrasts appeared in nutriclines depths and gradients and in nutrient diapycnal fluxes. Within the eddy, isopycnals and nutriclines were deepened and vertical nutrient gradients weakened, limiting local supply despite turbulence associated with near-inertial waves. Nevertheless, along-isopycnal gradients and lateral stirring generated nutrient transport from the eddy toward surrounding waters, the eddy acting counterintuitively as a nutrient relay. SWOT-resolved fine-scales reveal previously unresolved interactions between physical dynamics and nutrient availability, particularly important for biogeochemical and ecosystem functioning in oligotrophic regions.

Plain Language Summary In the Mediterranean Sea, surface waters are very low in nutrients, which limits the growth of microscopic algae, the phytoplankton, at the base of the ocean food web. These nutrients typically originate from deeper waters and are brought up into sunlit surface waters through mixing processes. In spring 2023, the BioSWOT-Med research campaign studied at an unprecedented resolution how ocean currents shape the distribution of nutrients in the North Balearic Front, using a new satellite (SWOT) and instruments deployed from a ship and autonomous float. The study focused on two water masses with different properties, separated by a narrow ocean front, as well as on a swirling current feature called an anticyclonic eddy. The measurements showed that nutrient availability, as determined by proximity to the surface layer, differs north and south of the NBF (regional scale) but are also strongly modulated by oceanic turbulent features such as the sampled eddy (fine scale). Specifically during our field cruise, the eddy trapped water with fewer nutrients and redistributed them to already more productive waters in its surroundings. These results show that even transient small ocean structures can have a big impact on where and how much nutrients are available, with possible consequences for marine life and carbon cycling.

1. Introduction

In oligotrophic and low-energy systems, in the absence of significant nutrient inputs from land or the atmosphere, the vertical supply of macronutrients, primarily nitrate and phosphate, from deep waters to the euphotic zone, is fundamental to marine ecosystem productivity and diversity (Dai et al., 2023; Richardson & Bendtsen, 2019). In such environments, nutrient vertical distribution is typically organized into three layers: a surface nutrient-depleted surface layer, where biological uptake exceeds supply and nutrient concentrations approach zero; a nutrient-replete deep layer, where remineralization dominates in the absence of light; and an intermediate transition zone, the “nutricline”, where nutrient concentrations increase sharply with depth. The depth and steepness of the nutricline are critical in determining nutrient availability in the environment (Cermeno et al., 2008), thereby influencing phytoplankton community structures and new primary production.

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Nutricline large-scale patterns are shaped by general circulation, water mass properties, and regional biogeochemical regimes (Gerace et al., 2025; Wilson & Coles, 2005). Superimposed on these broad-scale features, fine-scale physical processes, spanning the mesoscale (10–100 km) to submesoscale (1–10 km) range and evolving over days to months, including eddies, filaments, and fronts, are increasingly thought to play a key role in modulating the biogeochemical processes and planktonic distribution (Hernández-Hernández et al., 2020, 2021). While the influence of large and persistent mesoscale features such as major eddies on nutrient distribution in oligotrophic regions has been documented worldwide (Ascani et al., 2013; Johnson et al., 2010; Moutin & Prieur, 2012; Omand & Mahadevan, 2013; Pascual et al., 2017), the role of smaller mesoscale and submesoscale dynamics remains less well constrained due to their transient nature and the observational challenges they pose (Bosse et al., 2017; Lévy et al., 2012; Nencioli et al., 2011).

Numerical models have consistently indicated that fine-scale processes play a significant role in shaping vertical nutrient distributions in oligotrophic regions. They include submesoscale dynamics driven by sharp density and vorticity gradients (Levy et al., 2001), eddy–wind interactions (McGillicuddy et al., 2007), ageostrophic secondary circulations and Ekman transport (Mahadevan and Leif, 2008), as well as nonlinear biogeochemical interactions (Lévy & Martin, 2013). However, their empirical validation has long been limited by the scarcity of high-resolution, co-located physical and biogeochemical observations (Barone et al., 2022).

The Mediterranean Sea, a low-energy oceanic system characterized by weak tides and moderate mesoscale circulation, is considered one of the most oligotrophic regions of the world's ocean overall (D'Ortenzio & Ribera d'Alcalà, 2009). At the basin scale, it exhibits pronounced longitudinal variability in nutrient distribution: the Western basin is generally marked by shallower nutriclines and steeper vertical nutrient gradients than the Eastern basin (Moutin & Prieur, 2012; Moutin & Raimbault, 2002; Pujo-Pay et al., 2011; Pulido-Villena et al., 2021). In the Northwestern basin, the North Balearic Front (NBF) hosts a climatological salinity-driven frontal zone (La Violette et al., 1990) acting as a hydrological and dynamical barrier (Mancho et al., 2008), separating colder, saltier, and more productive northwestern waters originating from the Northern Current and regions of deep convection (Houpert et al., 2016; Macias et al., 2018; Severin et al., 2014; Testor et al., 2018), from the warmer, fresher, and oligotrophic Atlantic waters recently entering from the south (Barral et al., 2021; García et al., 1994; Millot & Taupier-Letage, 2005; Seyfried et al., 2019). The NBF exhibits distinct seasonal regimes alternating between phases of biomass accumulation and oligotrophic conditions (D'Ortenzio & Ribera d'Alcalà, 2009), and plays a key role in the nutrient budget and planktonic ecosystem of the northwestern Mediterranean (Estrada et al., 1999), with frontal dynamics structuring phytoplankton distributions across scales. Despite this well-established role, little is known about the influence of the front and its dynamics on the exchange of water mass properties, leaving open questions about the mechanisms controlling nutrient fluxes across and within the frontal zone.

Within this context, the BioSWOT-Med cruise (Doglioli & Gregori, 2023) took place in spring 2023. Leveraging the novel capabilities of the SWOT (Surface Water and Ocean Topography) satellite mission (Morrow et al., 2019), combined with a high-resolution, adaptive Lagrangian sampling strategy, it provided unprecedented in situ observations at and across the front under contrasting dynamical regimes during a post-bloom period. South of the front, a small anticyclonic eddy was also targeted (Rolland et al., 2026), offering a unique opportunity to assess how fine-scale circulation influences nutrient distributions and shapes the nutricline. Using high-resolution and precision nutrient measurements, we aim to describe and characterize nutrient distributions across and within the front, from regional to fine scales, to evaluate how local dynamics modulate vertical nutrient structures and to shed light on the coupled biogeochemical–physical processes that regulate new nutrient supply in oligotrophic environments.

2. Materials and Methods

2.1. Adaptive and Lagrangian Sampling Strategy

The BioSWOT-Med cruise was conducted aboard R/V *L'Atalante* (Doglioli & Gregori, 2023) from 20 April to 15 May 2023, during a mid-spring post-bloom period typically characterized by low surface phytoplankton biomass and nutrient concentrations (D'Ortenzio & Ribera d'Alcalà, 2009). The cruise targeted the NBF under SWOT track #3 (Figure 1a), guided by the SPASSO software (<https://spasso.mio.osupytheas.fr/>; (Rousselet et al., 2025)) and an initial SWOT map from April 6 provided by CNES. An adaptive sampling strategy was implemented to investigate three distinct water masses across the NBF: a more productive one north of the front (referred to as

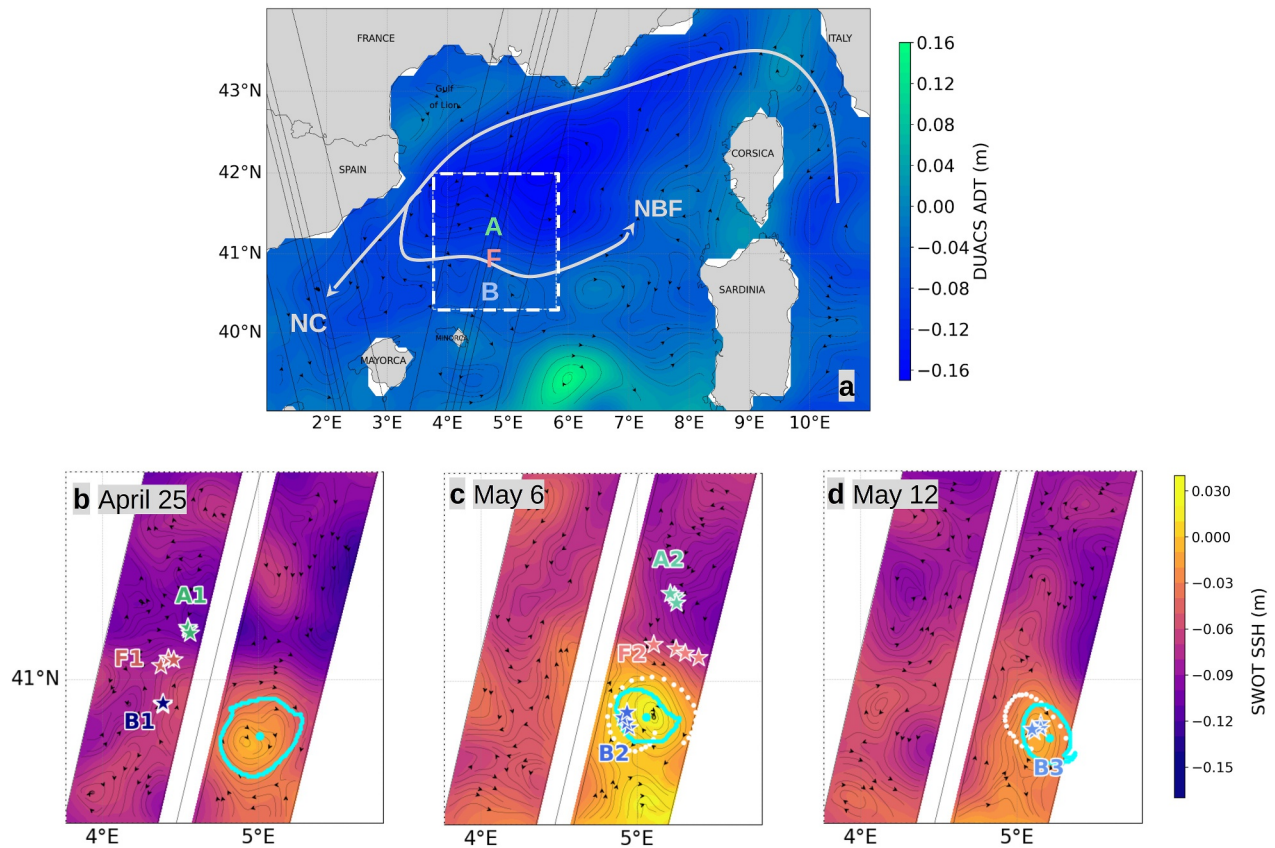


Figure 1. Ocean dynamics during the BioSWOT-Med cruise and sampling locations. Panel (a): Northern current and NBF over DUACS ADT (m) on May 6, white dashed box shows zoom for panels (b–d). Panels (b–d): colored stars indicate stations A (green), F (pink) and B (blue), sampled on (b) Apr 24–27, (c) May 4–7, and (d) May 12–13 on SWOT sea surface height (m) on Apr 27 (b), May 6 (c), May 12 (d). Position of the eddy center (cyan dot) and particles trapped in it for at least 10 days (cyan contour) for the three Lagrangian sampling periods. Panels (c–d) white dots locate the BGC-Argo trajectory on May 2–9 and May 10–16 respectively; black lines show (a) DUACS and (b–d) SWOT-derived geostrophic surface currents.

“A”), a more oligotrophic and less productive one south of the front (“B”), and the frontal zone itself (“F”). Then, an horizontal sampling across the front, including instruments such a thermo-salinograph, a multiparametric Moving Vessel Profiler, floats, and drifters measurements, enabled a precise identification of the NBF. Vertical sampling was then conducted in each water mass using a Lagrangian strategy, during which the ship drifted for 24 hr within the identified water mass (referred to as “Lagrangian stations”) while vertical measurements were planned every 6 hr (at 06:00, 12:00, 18:00, and 00:00 UTC). Vertical sampling included a Niskin-CTD carousel, nets, a pumping system, ADCPs, a Vertical Microstructure Profiler and gliders, allowing high-frequency monitoring of physical and biogeochemical processes. The three water masses were sampled twice: first between April 24–28 (A1, F1, B1; Figure 1b), and again between May 4–7 (B2, F2, A2; Figure 1c), with a final station in southern waters (B3) on May 12–13 (Figure 1d). Samplings in southern waters included two Lagrangian stations in an anticyclonic eddy (B2–B3) and a reference station outside the eddy (B1).

2.2. Fine-Scale Altimetry, Lagrangian Diagnostics and Eddy Tracking

The in situ targeting of fine-scale oceanic features was enabled by the newly launched SWOT satellite. Unlike traditional 1D altimeters, SWOT provides 2D maps of SSH across a 150 km swath with a spatial resolution of 7–10 km—an order of magnitude finer than conventional nadir altimetry (AVISO/DUACS, 2024; Ballarotta et al., 2019), enabling the detection of fine-scale ocean features (Ardhuin et al., 2025; Tchonang et al., 2025; Tranchant et al., 2025; Verger-Miralles et al., 2025; Villas Bôas et al., 2025; Wang et al., 2024). During its fast-sampling phase (April–June 2023), SWOT provided one to two observations per day in selected regions, offering a unique insight into upper-ocean dynamics (D’Ovidio et al., 2019).

The generation, trajectory, and coherence of the anticyclonic eddy were reconstructed using a pseudo-Lagrangian retention parameter method (Lehahn et al., 2011; D'Ovidio et al., 2013; Rousselet et al., 2025) based on 25-day backward particle advection by SWOT-derived VarDyn geostrophic velocity fields (Le Guillou, 2026), allowing identification of retentive structures and inference of the eddy's origin and evolution (detailed method in Text S1 in Supporting Information S1).

2.3. Hydrographic Context

Hydrological profiles were obtained using a Sea-Bird CTD, with data averaged to a 1 m vertical resolution. Conservative temperatures, absolute salinities, and potential density anomalies (σ_θ) were computed using the TEOS-10 package (<https://www.teos-10.org/software.htm> Wright et al. (2010)). The mixed-layer depth (MLD) was determined using the threshold density difference method (depth where density exceeds that at 3 m by 0.03 kg m⁻³; De Boyer Montégut et al. (2004)). Fluorescence measurements were calibrated against in situ chlorophyll-*a* concentrations using a least squares regression between discrete samples and sensor fluorescence. The deep chlorophyll maximum (DCM) was defined as the depth of the local maximum in chlorophyll-*a* concentration ($\mu\text{g L}^{-1}$) derived from fluorescence. The lower boundary of the euphotic layer (EL) was estimated as the depth at which only 1% of the surface irradiance remained, based on measurements made at 12:00 UTC.

2.4. Nutrient Data

2.4.1. Nutrient Sampling and Analysis

Samples for nitrate + nitrite (referred to as nitrate, N) and phosphate (P) determinations were collected from Niskin bottles and analyzed onboard within 2–12 hr using a segmented flow analyzer (AAIII HR Seal Analytical) following Aminot and K  rouel (2007). Quantification limits (QL) were 0.05 $\mu\text{mol L}^{-1}$ for nitrate and 0.02 $\mu\text{mol L}^{-1}$ for phosphate. A total of 28 vertical profiles were collected with a resolution optimized for the photic and nutricline layers: 2 and 5 m in the upper layer, every 10 m between 10 and 100 m, every 50 m between 100 and 200 m, and every 100 m between 200 and 500 m. When phosphate concentrations were below the QL (241 of 453 samples), additional analyses were performed in the laboratory using a high-sensitivity method combining a 1 m Liquid Waveguide Capillary Cell and an auto-analyzer (Zhang & Chi, 2002), achieving a detection limit of 0.002 μM (Text S2.1 in Supporting Information S1). This added 207 measurements to the data set. All concentrations <QL were set to zero for analysis (26 out of 453).

A BGC-Argo float (WMO: 1902605–Provior CTS4 SUNA) equipped with a CTD and SUNA nitrate sensor was deployed near station B2. Its trajectory followed the edge of the anticyclonic eddy (Figures 1c and 1d). To better resolve the photic and nutricline layers, the standard sampling cycle was modified to a 6-hr frequency, reaching depths of 300–400 m. Vertical resolution was 2 dbar from 0 to 10 m, 20 dbar from 10 to 300 m, and 50 dbar below. On May 9, the SUNA experienced a malfunction, reducing resolution to 5 dbar (0–200 m) and 10 dbar below, with a 24-hr data gap. The nitrate data set spans May 2–16 and includes 55 profiles, with a 0.5 μM limit of quantification (Johnson et al. (2021), see the calibration procedure in Text S2.3 in Supporting Information S1).

Nutrient vertical distributions and nutricline properties were analyzed as functions of both depth (Baham  n et al., 2003) and density (Omand & Mahadevan, 2015) (see Text S2.4 in Supporting Information S1 for definitions and methods).

2.5. Microturbulence and Nutrient Fluxes

Microstructure measurements were performed with a VMP-250 from Rockland Scientific (Ferron et al., 2014; Osborn, 1980). A total of 80 profiles were sampled at the Lagrangian stations (Rolland et al., 2026). Methodology employed to obtain the diapycnal diffusivity K_z and diapycnal nutrient fluxes is detailed in Text S4 in Supporting Information S1.

3. Results

3.1. Characterization of Regional Circulation and Fine-Scale Dynamics

The NBF region sampled (Figure 1a) presented a sharp north–south ADT gradient and a strong eastward geostrophic jet (notably at station F2, Figure 1c). This front separated the northern water mass A, characterized by

a cyclonic circulation and a local ADT minimum of -0.164 m in the zone of winter convection, from the southern water mass B, exhibiting higher ADT values with a local maximum of 0.154 m. SWOT SSH revealed finer-scale circulation patterns, including a distinct anticyclonic eddy in the right swath (Figure 1b–1d).

Contrasting north-south hydrographic structures were revealed by CTD profiles (see details in Figure S3a and Table S3a in Supporting Information S1). Northern waters A were consistently colder and fresher than southern waters B, with surface conservative temperatures between 16.1 and 16.9°C at A1/A2 compared to 17.0 – 17.6°C at B1/B2 and absolute salinity ranging 38.53 – 38.55 g kg $^{-1}$ at A1/A2 and 38.17 – 38.47 g kg $^{-1}$ at B1/B2. Stations A1/A2 were also characterized by shallower DCMs (32–46 m) and higher mean chlorophyll-*a* concentrations in the photic layer (0.24 – 0.25 $\mu\text{g L}^{-1}$), whereas southern stations B1/B2 exhibited deeper DCMs (48–64 m) and lower chlorophyll-*a* (0.14 – 0.20 $\mu\text{g L}^{-1}$). Frontal stations F1/F2 showed intermediate hydrographic properties and the deepest DCMs. MLDs remained shallow throughout the sampling period, shallower than 8 m.

The pseudo-Lagrangian analysis reveals that the eddy sampled at B2 and B3 stations within the SWOT swath formed on April 19 and dissipated on June 1, suggesting a lifetime of at least 45 days. The possibility that the eddy was no longer detected after 1 June cannot be excluded as it moved beyond the coverage of SWOT. During the two sampling periods (15 and 22 days after its formation), the eddy was highly coherent, with a large fraction of particles trapped continuously since its generation (Figures 1c and 1d). The eddy had formed south of the NBF and traveled southeastward (0.5° from its origin). The SWOT-based numerical trajectories are in agreement with the trajectory of the BGC-Argo float (white dots on Figures 1c and 1d). Lagrangian advection diagnostics indicate that the water masses trapped within the eddy predominantly originated from the west of the sampling position (Figure S1a in Supporting Information S1). The latter coupled with the eddy formation, south of the NBF, suggests that trapped waters may be young Atlantic waters, consistent with its low salinity content. The analysis suggests a locally generated, transient structure, rather than a detachment from the North Balearic Front. The eddy exhibited strong dynamical coherence with a deepening of the isopycnals at least until a 500 m depth (see Text S3a in Supporting Information S1) compared to Lagrangian stations located outside the eddy. Eddy stations B2 and B3 exhibited markedly different structures. Station B3 showed a temperature decrease to $16.8 \pm 0.9^{\circ}\text{C}$, salinity increase to 38.24 ± 0.00 g kg $^{-1}$ and MLD deepening to 25 ± 10 m and the DCM reached 90 ± 10 m with low chlorophyll-*a* (0.07 ± 0.01 $\mu\text{g L}^{-1}$). Density profiles showed a deepening of the isopycnals compared to Lagrangian stations located outside the eddy.

The BGC-Argo float (May 2–16) followed the eddy's periphery, overlapping stations B2 and B3 (Figures 1c and 1d). Surface temperatures ranged from 15.9 to 18.6°C (mean: $17.3 \pm 0.6^{\circ}\text{C}$), salinity from 37.94 to 38.44 g kg $^{-1}$ (mean: 38.18 ± 0.09 g kg $^{-1}$). MLDs varied between 7 and 53 m (mean: 22 ± 13 m), and DCMs between 57 and 84 m (mean: 70 ± 8 m).

3.2. Nutrient Distribution and Fluxes

3.2.1. NBF Regional Background

All N and P profiles displayed near-zero surface concentrations but marked contrasts in the EL across the NBF (2, a and c). Mean N and P concentrations were systematically higher in northern stations (0.72 – 1.10 μM for N; 0.016 – 0.027 μM for P at A1/A2) than in southern stations (0.11 – 0.38 μM for N; 0.006 – 0.012 μM for P at B1/B2). This contrast persisted at 500 m depth, with consistently higher nutrient concentrations in A1/A2 relative to B1/B2 (see detailed values in Table S3a in Supporting Information S1).

Nitracline and phosphacline depths (Figures 3a and 3c) were shallower in northern stations (ranging 24–53 m for N and 48–61 m for P) than in southern stations (61–67 m for N and 66–74 m for P). Vertical nitrate and phosphate gradients ($d\text{N}/dz$ and $d\text{P}/dz$; Table S3a in Supporting Information S1) followed a similar pattern, being stronger in the north (up to 0.16 $\mu\text{M m}^{-1}$ for nitrate) and weaker in the south (0.06 – 0.07 $\mu\text{M m}^{-1}$), consistent with the overall north–south biogeochemical contrast across the NBF.

Over density surfaces (Figures 2b and 2d), the highest N and P concentrations were observed within the eddy stations (B2/B3). Consistently, N and P depletion densities (Figures 3c and 3d) were greater in the northern stations (A1/A2) than in the southern ones (B1/B2). Diapycnal gradients ($d\text{N}/d\sigma$ and $d\text{P}/d\sigma$) followed a similar pattern (detailed values in Table S3a in Supporting Information S1), with stronger gradients at A1/A2 and weaker within the eddy stations (B2/B3).

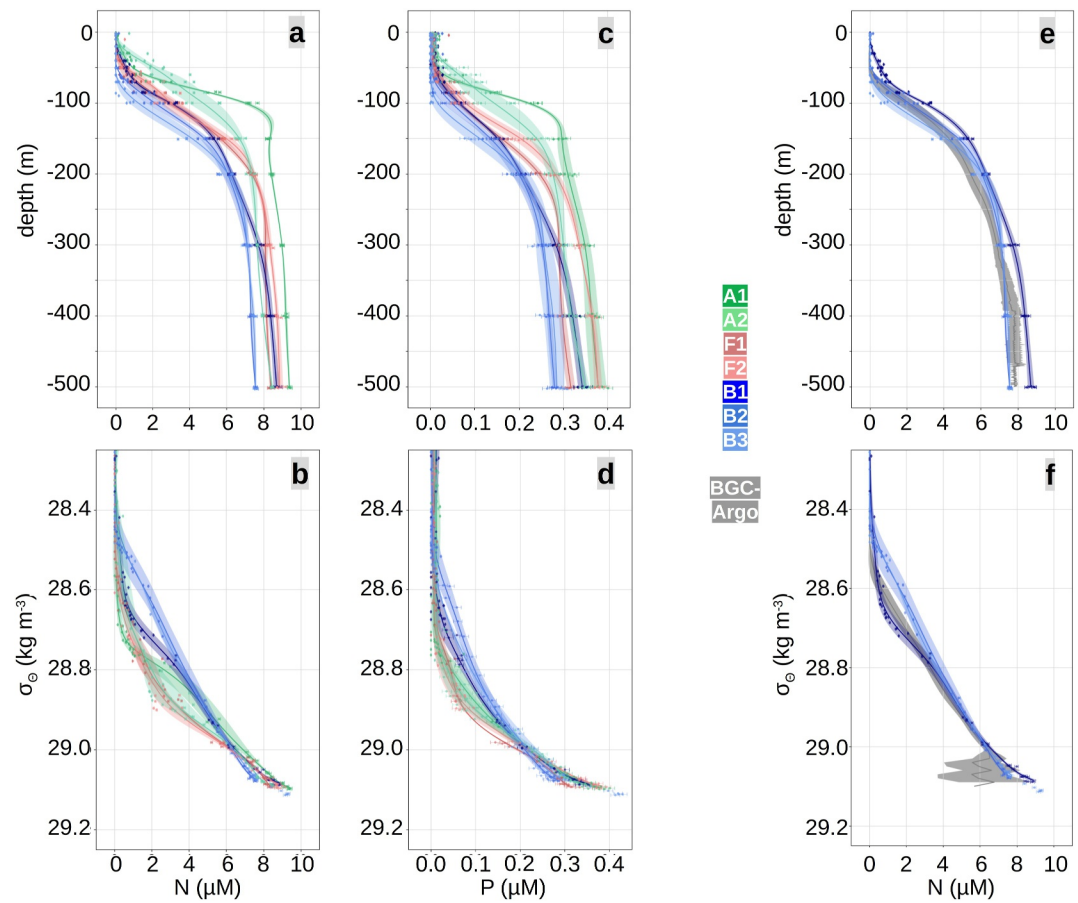


Figure 2. Nutrient concentration profiles (in μM) plotted against (a), (c) depth and (b), (d) σ_θ , collected during the BioSWOT-Med campaign in water masses A (green), F (pink), and B (blue), for nitrate (N; a, b) and phosphate (P; c, d). Nitrate profiles at stations B2 and B3 (blue colored dots and lines) overlaid on the BGC-Argo float mean nitrate profile (gray line) and standard deviation (gray shading), plotted against (e) depth and (f) density. In all panels (a)–(f), dots represent discrete sample values at specific depths, while solid lines and shaded areas show time-averaged B-spline interpolations (De Boor, 1978; Ullah & Finch, 2013) with associated standard deviations at each station.

Highest diapycnal fluxes across the nutricline layer are encountered in the northern waters (A1), with values of 0.20 and $0.007 \text{ mmol m}^{-2} \text{ d}^{-1}$ for N and P. Lowest values were found for N in the front (F1) with values of $0.03 \text{ mmol m}^{-2} \text{ d}^{-1}$, and south to the front (B1 and B2) for P with values of $0.002 \text{ mmol m}^{-2} \text{ d}^{-1}$. Detailed turbulence and nutrient flux values for all Lagrangian stations are presented in Table S3a in Supporting Information S1.

3.2.2. Fine-Scale Anticyclonic Eddy

Marked differences appeared between outside (B1) and inside (B2–B3) the anticyclone (Figures 2e and 2f). B2/B3 had lower mean nutrient concentrations, deeper and weaker nutriclines. In particular, B3 showed the lowest mean N and P in the EL (N: $0.15 \pm 0.10 \mu\text{M}$; P: $0.001 \pm 0.001 \mu\text{M}$) and at 500 m (N: $7.96 \pm 0.81 \mu\text{M}$; P: $0.318 \pm 0.066 \mu\text{M}$). Nitracline and phosphacine depths reached 86 ± 11 and $103 \pm 18 \text{ m}$ respectively, with weak vertical gradients (N: $0.06 \pm 0.01 \mu\text{M m}^{-1}$; P: $0.003 \pm 0.001 \mu\text{M m}^{-1}$). Over density, B3 had the highest depletion densities (N: $28.49 \pm 0.02 \text{ kg m}^{-3}$; P: $12.46 \pm 0.02 \text{ kg m}^{-3}$) and weakest diapycnal gradients (N: $28.66 \pm 0.05 \text{ mmol kg}^{-1}$; P: $0.698 \pm 0.107 \text{ mmol kg}^{-1}$).

BGC-Argo nitrate profiles (May 2–16) along the eddy edge presented concentrations similar to B2/B3 in depth coordinates (Figures 2e and 2f) with a nitracline depth interval of 52–90 m (mean $70 \pm 9 \text{ m}$) and gradient interval of 0.04 – $0.09 \mu\text{M m}^{-1}$ (mean $0.06 \pm 0.01 \mu\text{M m}^{-1}$) (Figures 3a and 3b). Over density, depletion limits ranged

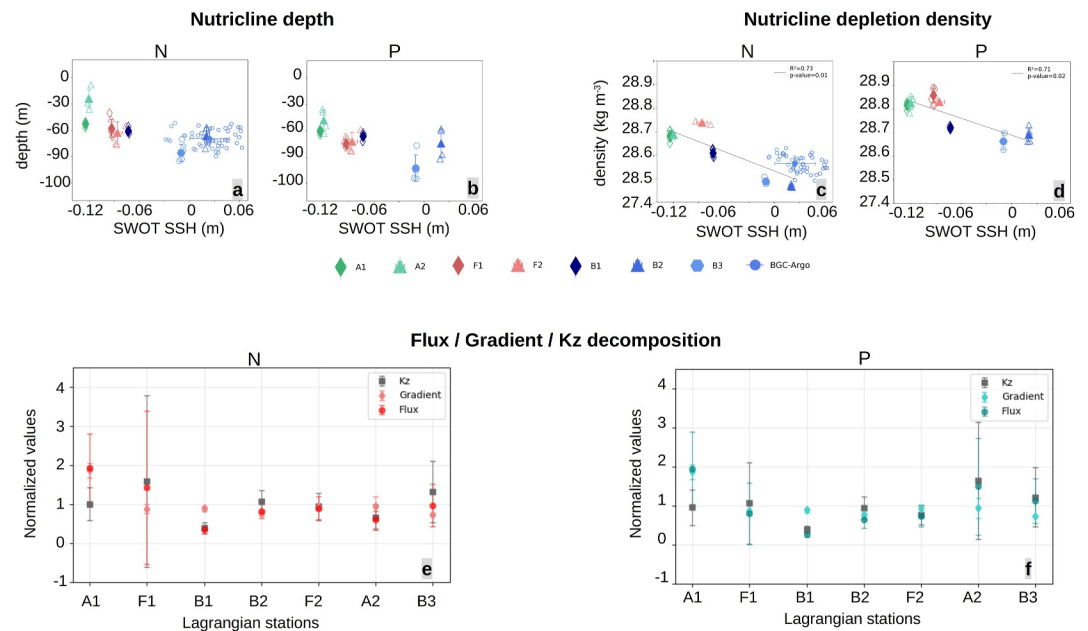


Figure 3. Nutricline depths (a), (b) and density, (c), (d) plotted against SWOT sea surface height anomaly for nitrate (N; a, c) and phosphate (P; b, d). Symbol shapes indicate station identity: diamonds for A1, F1, and B1; triangles for A2, F2, and B2; and hexagons for B3. Circles represent BGC-Argo float data. Solid-colored symbols correspond to mean values at Lagrangian stations and from the BGC-Argo float. Linear regressions are computed based on mean values. Mean fluxes, gradients and Kz at Lagrangian stations, for (e) N and (f) P, and standard deviation. Normalized values were obtained by dividing the gradients, Kz and fluxes obtained at each of the seven Lagrangian stations by their respective means calculated across all seven Lagrangian stations. Kz at Lagrangian station were obtained by the mean of Kz in the nutricline layer (Text S4 in Supporting Information S1 for details).

28.49–28.63 kg m⁻³ (mean 28.56 ± 0.03 kg m⁻³) and gradients 11.86–17.19 mmol kg⁻¹ (mean 14.25 ± 1.22 mmol kg⁻¹) (Figures 3e and 3f).

Inside the eddy (B2–B3), nutrient fluxes are intermediate and above (below) the average for N (P) at 0.07–0.12 (0.003–0.005) m⁻² d⁻¹.

3.3. Local Relation Between Nutricline and Fine-Scale Features

Nutricline characteristics obtained on depth coordinates plotted against SWOT SSH (Figure 3a–3d) showed spatial contrasts but no significant correlation in terms of p -value ($p = 0.08$ – 0.91) and coefficients of determination ($r^2 = 0$ – 0.47). In density space (Figure 3e–3h), nitrate depletion densities and diapycnal gradients were significantly correlated ($p = 0.01$ – 0.02 , $r^2 = 0.70$ – 0.76).

4. Discussion

The oligotrophic conditions resulting in near-detection-limit surface nutrients make resolving fine-scale biogeochemical variability challenging. Recent in situ studies have increased sampling resolution to capture physical–biogeochemical interactions (Hernández-Hernández et al., 2020; Tzortzis et al., 2021). The BioSWOT-Med campaign further advanced these approaches through a high-resolution adaptive Lagrangian design enabled by SWOT. Combining high-frequency vertical sampling, nanomolar phosphate detection, and B-spline interpolation provided robust estimates of nutricline characteristics at fine scale. Agreement between ship-based and BGC-Argo observations, despite higher uncertainty in the latter, confirms the capability of both approaches to capture fine-scale nutrient variability.

4.1. Contrasted Nutrient Distribution at Distinct Scales

At the regional scale, nutrient distributions across the NBF reflected water mass origin and large-scale processes. Shallow nutriclines, steep gradients, and high productivity in the north were consistent with wintertime deep convection (Houpert et al., 2016; Testor et al., 2018) and the large-scale cyclonic circulation of the northern region (D'Ortenzio et al., 2014), maintaining the front and transporting deep nutrients toward the EL. In contrast, southern waters exhibited deeper nutriclines and lower productivity, indicative of more oligotrophic conditions. Profiles collected during BioSWOT-Med were broadly consistent with climatological nutrient fields for the Western Mediterranean Sea over the 1981–2004 period (Belgacem et al., 2021), although systematically lower N and P concentrations in the EL likely reflected post-bloom conditions and strong biological uptake. Both data sets describe a marked north–south gradient in nutrients, which in cruise observations appears compressed over a narrower spatial scale (70 km) within the frontal region, suggesting that regional circulation sharpens basin-scale nutrient gradients. These contrasts align with previous descriptions of the northwestern Mediterranean Sea as a system characterized by distinct oligotrophic regimes (D'Ortenzio & Ribera d'Alcalà, 2009) and established NBF dynamics and mesoscale productivity patterns (Estrada et al., 1999, 2014; García et al., 1994).

Interestingly, contrasts in nutrient distribution extended to 500 m, with a nutrient variability in and out the eddy comparable to previous basin-scale observations (Moutin & Prieur, 2012), suggesting that fine-scale features bring more complexity to the historical view of longitudinal nutrient gradient throughout the Mediterranean basin.

Previous studies have reported a significant relationship between SSH and subsurface nutrient structures (Barone et al., 2019, 2022; Siegel et al., 1999; Wilson & Coles, 2005) at large scale, based on long-term observations. These works highlighted the variability of the physical–biogeochemical coupling at seasonal and regional scales. The significant relationship we identify here between SWOT SSH and nutricline properties in density space (Figures 3c and 3d) reveals this coupling at an unprecedented fine scale.

4.2. Diapycnal Fluxes Variability

The range of diapycnal fluxes across the nutricline observed during BioSWOT-Med is comparable to other oligotrophic regions (Du et al., 2017; Lewis et al., 1986), though the data set exhibits substantial variability. Normalized diapycnal flux variations across stations (Figures 3e and 3f) allow assessment of the relative contributions of nutrient gradients and K_z . At the first station north of the front (A1), N and P fluxes are primarily controlled by elevated nutrient gradients, with nutriclines at 53 and 61 m above the euphotic depth (68 m) (Table S3a in Supporting Information S1), enabling nutrient supply to support biological activity. Elsewhere, flux variability is mainly turbulence-driven. In the oligotrophic waters south of the front outside the eddy (B1), low K_z results in weak fluxes despite average gradients. Inside the eddy (B2–B3), weaker vertical gradients are offset by enhanced turbulent mixing, partly associated with near-inertial wave trapping (Rolland et al., 2026), increasing diapycnal fluxes. Nevertheless, deepened nutriclines (86 m for N, 103 m for P), likely resulting from isopycnal depression (McWilliams, 2016) and a trapping effect (D'Ovidio et al., 2013) (Figures 1c and 1d), place most nutrients near or below the EL (94 m), limiting their availability to surface production (McWilliams, 2016; D'Ovidio et al., 2013).

4.3. Isopycnal Flux Induced by Anticyclonic Eddy

Fine-scale structures influence lateral nutrient transport across eddy boundaries (Cao et al., 2024; Gupta et al., 2022; Lee & Richard, 2000). The subsurface nutrient pool displaced deeper within the eddy constitutes a reservoir. Observed nutrient concentrations along isopycnals (Figures 2b and 2d), between 28.4 and 28.8 kg m^{−3} were higher inside than outside the eddy, establishing lateral gradients consistent with nutrient export toward surrounding waters. Lateral isopycnal fluxes from the eddy toward the southern surrounding waters were estimated using maximum N and P gradients and a horizontal diffusivity $K_h = 20 \text{ m}^2 \text{ d}^{-1}$ consistent with structures of this scale (Kersalé et al., 2016; Nencioli et al., 2013), yielding lateral isopycnal fluxes of 51.6 and 1.2 mmol m^{−2} d^{−1} for N and P.

Across the front, higher nutrient concentrations in the eddy relative to northern waters also suggest redistribution at the regional scale. Maximum lateral gradient is estimated at 4.2×10^{-5} (1×10^{-6}) $\mu \text{M m}^{-1}$ for N (P). Typical lateral eddy diffusivity associated with surface conditions in relatively energetic frontal regions range 2,000–3,000 m² s^{−1} (Colas et al., 2013; Hahn et al., 2014; Klocker & Abernathey, 2014). This is consistent with a

scaling of the form $K_h = \gamma L_{mix} \sqrt{(2 * EKE)}$, with the mixing length scale L_{mix} chosen equal to an eddy radius of 25 km, the mixing efficiency being chosen equal to 0.35, and the eddy kinetic energy taken from Poulain et al. (2012) equal to $0.25 \text{ m}^2 \text{ s}^{-2}$. On the other hand, K_h tends to decrease rapidly with depth. In the absence of estimates for the NBF region, we use $K_h = 1,000 \text{ m}^2 \text{ s}^{-1}$ resulting in a lateral south-north nutrient flux of $3,630 (520) \text{ mmol m}^2 \text{ d}^{-1}$, comparing for N with Spingys et al. (2021) and for P with Gupta et al. (2022).

4.4. The Multiple Role of a Fine-Scale Anticyclonic Eddy in Nutrient Redistribution

The BioSWOT-Med in situ observations provided a coherent picture of the complex role of fine-scale dynamics in structuring nutrient distributions. The sampled anticyclonic eddy exhibits a clear imprint on the vertical and horizontal organization of nutrients: the vortical structure induces a deepening of isopycnals, effectively displacing a pool of relatively nutrient-poor waters from the surface to below the EL. Enhanced turbulence, likely caused by the trapping of near-inertial waves, leads to moderately elevated diapycnal fluxes which remain at depth and do not lead to an increased supply of nutrients into the EL.

However, this view does not fully capture the dynamical role of the eddy. The waters thus pushed below form a subsurface nutrient reservoir and induce pronounced nutrient gradients along isopycnal surfaces, with higher concentrations inside the eddy than the surrounding waters. Such isopycnal gradients, combined with lateral stirring and diffusion associated with the vortex instabilities and interactions with surrounding flows, support a net isopycnal transport of nutrients from the eddy toward its periphery.

In this sense, and somewhat counterintuitively, the most nutrient-depleted waters encountered during the campaign are a potential nutrient relay for the surrounding, in particular across the NFB toward the more productive northern region, questioning the permeability of the front. These observations strongly suggest that fine-scale structures, even when transient and apparently unfavorable to local productivity, can modulate nutrient redistribution and thus play a key role in sustaining biogeochemical processes in oligotrophic environments.

5. Conclusions

This analysis provides a new perspective on the role of fine-scale dynamics in modulating biogeochemical oligotrophic conditions, emphasizing how fine-scale circulation transiently shapes nutrient distribution and fluxes in oligotrophic regions, where ecosystems are highly dynamic and strongly sensitive to nutrient availability (Hernández-Hernández et al., 2020, 2021). Our results suggest that the sampled eddy paradoxically constitutes a nutrient supply across distinct scales via lateral stirring and diffusivity. Further analysis of other terms of the nutrient budget, for which numerical modeling appears particularly well suited, would allow a better characterization of the role and importance of these lateral transfers. Given the ubiquity of fine-scale structures in the ocean (McWilliams, 2019; Su et al., 2020; Taylor & Thompson, 2023) and the projected expansion of oligotrophic regions under climate change (Bopp et al., 2001; Fu et al., 2016; Gerace et al., 2025), this study opens exciting perspectives on the synergetic impacts of fine-scale circulation across larger spatial and temporal scales.

Conflict of Interest

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

Availability Statement

The SWOT L3 LR SSH 2 km (Expert v2.0.1) product (NASA/JPL and CNES), is produced and made freely available by AVISO and DUACS teams as part of the DESMOS Science Team project (AVISO/DUACS, 2024).

ADT were obtained from the European ocean gridded L4 SSH 0.125° reprocessed product E.U. Copernicus Marine Service Information, 2024.

The BioSWOT-Med data sets (hydrographic and nutrient measurements from the Lagrangian stations and the BGC-Argo float) are available at Joël et al. (2025).

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