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Turbulent erosion of a subducting intrusion in the Western Mediterranean Sea

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Abstract. Frontal zones within the Western Alboran Gyre (WAG) are characterized by a density gradient resulting from the convergence of Atlantic and Mediterranean waters. Subduction along isopycnals at the WAG periphery can play a crucial role in upper ocean ventilation and influences its stratification and biogeochemical cycles. In 2019, physical parameters (comprising temperature, salinity, turbulent kinetic energy dissipation rates) and biogeochemical data (oxygen and chlorophyll-a) profiles were collected in transects along the northern edge of the WAG. Several intrusions of subducted water with elevated oxygen, chlorophyll-a and spice anomaly were identified towards the center of the anticyclone. These features had elevated kinetic energy dissipation rates on both their upper and lower boundaries. Analysis of the turbulent fluxes involving heat, salt, oxygen, and chlorophyll-a demonstrated a net flux of physical and biogeochemical properties from the intrusions to the surrounding ocean. Either the turbulent or diffusive convection mixing contributed to the observed dilution of the intrusion. Other factors (e.g., water column density stability, variability of the photic layer depth, and organic matter degradation) likely played a role in these dynamics. Enhanced comprehension of the persistence and extent of these features might lead to an improved quantitative parametrization of relevant physical and biogeochemical properties involved in subduction within the study zone.

1 Introduction

The Mediterranean Sea is characterized by a shallow circulation cell and a complex upper-layer circulation featuring numerous quasi-permanent eddies and fronts (Tanhua et al., 2013; Capó et al., 2019; Barral et al., 2021; Bonaduce et al., 2021; Zarokanellos et al., 2022; Sánchez-Garrido and Nadal, 2022). The main 12 Mediterranean thermal fronts were listed by Belkin and Cornillon (2007), whereas a recent work by Sudre et al. (2023) captured an even more complex scenario. Specifically, frontal zones in the Alboran Sea (Western Mediterranean basin) are characterized by a density gradient resulting from the

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convergence of Atlantic and Mediterranean waters (Fedele et al., 2022; Garcia-Jove et al., 2022). The Atlantic jet strongly influences the formation of two large-scale anticyclonic gyres within the Alboran Sea (the Eastern and Western Alboran Gyres, WAG; **Fig. 1A**) with a smaller cyclonic gyre typically situated in between (Brett et al., 2020; Sala et al., 2022; Sánchez-Garrido and Nadal, 2022).

Ocean subduction, defined as the physical transfer of water from the mixed layer into the ocean interior (Williams, 2001), plays a pivotal role in upper-ocean ventilation and stratification. It also exerts a profound influence on biogeochemical cycles, thereby contributing to the export of greenhouse gases and the vertical transport of organic carbon (Omand et al., 2015; Olita et al., 2017; Stukel et al., 2017; Ruiz et al., 2019; Zarokanellos et al., 2022). The vertical component of ocean current velocity is typically much smaller than its horizontal counterparts, but areas characterized by meandering frontal features associated with mesoscale eddies are expected to exhibit elevated subduction rates (van Haren et al., 2006). Indeed, vertical velocities of up to 55 m d^{-1} have been observed in the Western Alboran Sea front (Capó and McWilliams, 2022; Garcia-Jove et al., 2022; Rudnick et al., 2022), and net submesoscale subduction rate has been estimated at 0.3 m day^{-1} (Freilich and Mahadevan, 2021). Mesoscale turbulence contains more energy than submesoscale patterns (Storer et al., 2022), although submesoscale features can generate larger vertical velocities than mesoscale structures within frontal zones (Mahadevan, 2016; Ruiz et al., 2019). The relationship between submesoscale velocity and turbulence within the boundary layer has been explored in prior studies under conditions of turbulent thermal wind balance (Crowe and Taylor, 2018; McWilliams, 2021) and symmetric instabilities (Thomas et al., 2013; Bachman et al., 2017; Zhou et al., 2022). However, so far there has been limited research that specifically identifies occurrences of quasi-balanced subsurface vertical velocity and examines how turbulence responds to such instances.

Vertical motion at fronts is driven by frontogenesis, instability processes, nonlinear Ekman effects, and filamentogenesis (Klein and Lapeyre, 2009; Mahadevan, 2016; Mahadevan et al., 2020a; McWilliams, 2021; Capó and McWilliams, 2022; Garcia-Jove et al., 2022). Instabilities have also been identified as a key source of turbulence and energy dissipation at oceanic fronts (D'Asaro et al., 2011; Carpenter et al., 2020; McWilliams, 2021). Subsurface intrusions carry physical (temperature and salinity) and biogeochemical properties (oxygen and chlorophyll-a) characteristic of the surface mixed layer along isopycnals and extend downward and laterally. Intrusions are often identified because of the co-occurrence of subsurface maxima in oxygen, particulate organic carbon with anomalous temperature and salinity properties (i.e., spice; Omand et al., 2015). Intermittent intrusions subducting along the outer periphery of mesoscale and submesoscale structures have previously been identified (Johnston et al., 2011; Llort et al., 2018; Chapman et al., 2020; Johnson and Omand, 2021; Chen et al., 2021; Capó and McWilliams, 2022; Freilich et al., 2024). This study measures the turbulent erosion of a subducting intrusion at fronts within the Western Alboran Gyre (WAG), a major mesoscale feature in the western Mediterranean Sea. Data were collected in the framework of the Coherent Lagrangian Pathways from the Surface Ocean to Interior (CALYPSO) project onboard the R/V *Pourquois Pas?*, that aimed to examine subduction features in close proximity to the unstable front that developed along the northern edge of the WAG (Mahadevan et al., 2020).

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Previous studies have investigated turbulence data collected with microstructure probes in both the surface (Cuypers et al., 2012; Forryan et al., 2012; Vladoiu et al., 2021) and deep (Ferron et al., 2021; van Haren, 2023) regions of the Western Mediterranean Sea. However, this work represents the first comprehensive investigation of turbulence in a context of mesoscale-submesoscale subduction at frontal zones within the WAG. This paper begins with a comprehensive description of water column properties and a turbulence dataset. We then conduct an examination of physical and biogeochemical properties across frontal transects to identify and characterize subducting features. Finally, we calculate the turbulent erosion of a selected intrusion of interest.

2 Material and methods

2.1 Sampling strategy and profile inventory

The study zone is highly dynamic and significantly influenced by the eastward-flowing Atlantic jet that sustains the WAG (Sánchez-Garrido and Nadal, 2022). The jet is characterized by a pronounced frontal zone, exhibiting a density contrast of up to 1.0 kg m^{-3} at its boundaries (Oguz et al., 2014).

We conducted five transects across the salinity front identified through operational modeling and satellite estimations in the northern edge of the WAG between March 28th and April 4th 2019 (**Fig. 1B**). Temperature and salinity conditions in the upper water column were sampled, resulting in a total of 136 profiles (mean depth: 231 m). Turbulence data were collected on 43 stations (mean depth: 219 m) during the campaign. With the exception of a single station, all stations featured duplicate microstructure profiles, from which the mean value between these replicates was computed. Furthermore, we obtained 22 dissolved oxygen and chlorophyll-a profiles (mean depth: 284 m) concurrently with the microstructure profiles.

2.2. Temperature, salinity and derived variables

Temperature and salinity data were acquired using a Teledyne RD Instruments Underway Conductivity Temperature Depth (UCTD) profiler, as detailed by Rudnick and Klinke (2007). The sampling rate is 16 Hz, with the UCTD falling velocity ranging between 1.5 and 3.5 m s^{-1}. The spatial resolution between UCTD cycles was approximately 1 km, given a cruise speed of 3 m s^{-1} knots during recovery. The UCTD downcasts were post-processed for sensor alignment, salinity spikes correction and were binned using a spline interpolation onto a vertical grid of 1 m. A comprehensive description of data post-processing procedures can be found in Dever et al., (2019). Key oceanographic parameters, including absolute salinity, conservative temperature, Brunt–Väisälä frequency (N^2), density ratio and Turner angle and spice were computed using the Gibbs Sea Water oceanographic toolbox of TEOS-10 (https://www.teos-10.org/pubs/gsw).

N^2 serves as an indicator of water column vertical stability and was determined using equation (1):

$$N^2 = -\frac{g}{\rho_w}\frac{\partial \rho}{\partial z} \qquad (1)$$

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where g represents gravitational acceleration (9.8 ms^{-2}), ρ_w is a reference seawater density (1025 kg m^{-3}), and $\partial\rho/\partial z$ denotes the variability of potential density with depth. The density ratio quantifies the vertical contributions of conservative temperature and absolute salinity to the stability of the water column (following the Thermodynamic Equation of Seawater – 2010; IOC et al., 2010). The Turner angle, as outlined by McDougall et al., (1988), was computed to identify water column conditions, including double diffusivity (thermal diffusivity or salt fingering), stability, and instability regimes. Seawater spice, defined as the temperature and salinity variability along isopycnals, was employed to discern water masses with similar density, but varying temperature and salinity characteristics (McDougall et al., 2021). Spice anomaly was computed with respect to the mean spice profile computed in a temperature-salinity space and obtained including all spice profiles of the dataset. Furthermore, mixed layer depth was determined using a density threshold of 0.03 kg m^{-3} relative to the reference density at 10 m depth, as proposed by de Boyer Montégut et al. (2004). Isopycnal strain, which measures the stretching or compression of isopycnal surfaces, was calculated as the vertical gradient of isopycnal displacement (Pinkel et al., 1991). This displacement is defined as the difference between the actual depth of each isopycnal and its expected depth based on the mean density profile.

2.3. Detection of subducting intrusions

Observational evidence of water being subducted from the upper ocean layer to below the mixed layer was observed by leveraging the high spatio-temporal resolution of the underway data collected by the UCTD. The presence of subsurface intrusions in a frontal transect was semi-automatically detected from the vertical profiles, based on subsurface spice and temperature anomalies. The detection algorithm proceeds as follows: I) Compute average spice on isopycnals for the campaign (auto). II) Compute spice anomaly on an isopycnal for each profile phase (auto). III) Detect subsurface anomalies in spice anomaly using a peak-finding algorithm based on peak prominence (auto). IV) Retain anomalies with at least 5 samples (i.e., 1.5 m; auto) and occur coherently over more than 3 consecutive profiles (manual).

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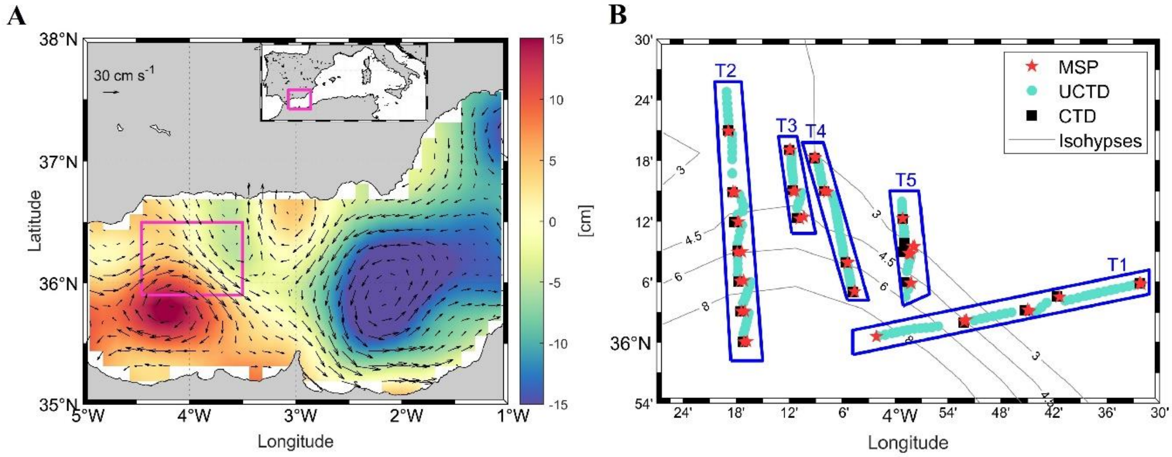

Figure 1. (A) Map of the Alboran Sea showing the mean absolute dynamic topography (colors) and geostrophic currents (arrows) on March 30th-31st, 2019. The purple inset shows the location of the sampling effort, detailed in panel (B), where blue rectangles denote the sampling stations selected for transect (T#) analysis. T1 was realized on March 29th, T2 on March 30th and T3-T5 on March 31st. Isohypses of absolute dynamic topography are depicted as gray lines. Red stars, cyan circles and black squares correspond to sampling stations for the microstructure profiler, underway CTD and CTD, respectively. Daily absolute dynamic topography and geostrophic current data were downloaded from https://data.marine.copernicus.eu/.

2.4. Dissolved oxygen and Chlorophyll-a

We equipped a SeaBird 911plus CTD probe with a SeaBird 43 dissolved oxygen sensor and a WET Labs ECO-AFL/FL fluorometer to assess dissolved oxygen and chlorophyll-a concentrations, respectively. The CTD data underwent bin-averaging to achieve a vertical resolution of 0.5 m and was subsequently calibrated using in situ data. Dissolved oxygen estimates were aligned with measurements obtained through Winkler titration (n = 67; Mahadevan et al., 2020b), while chlorophyll-a estimates derived from fluorescence were calibrated against data from fluorometric determinations (n = 140; Alou-Font et al., 2019). A high level of agreement was found between in situ measurements and CTD-derived estimations, as evidenced by coefficient of determination (R^2) values of 0.99 for dissolved oxygen and 0.85 for chlorophyll-a.

Oxygen and chlorophyll-a anomaly on isopycnals were computed following equation (2):

$$X_a = X_\rho - \bar{X}_\rho \quad (2)$$

where X_a represents the variable (i.e., oxygen or chlorophyll-a) anomaly, X_ρ denotes the observed value at a specific density and $\bar{X}_\rho$ is the mean property value corresponding to this density.

2.5. Horizontal ocean currents

Horizontal current magnitude and direction were collected using a hull-mounted Teledyne RDI Ocean Surveyor Acoustic Doppler Current Profiler (ADCP) operating at a frequency of 150 kHz and with a vertical bin size of 4 m. Detailed post-processing procedures for ADCP data have been exhaustively documented in Mahadevan et al. (2020b) and Cutolo et al.

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(2022). Shear squared was calculated from ADCP data as the sum of the squares of the vertical gradients of the horizontal velocity components (Gregg, 1989).

2.6. Turbulent kinetic energy dissipation rates

Various methods have been employed to quantify turbulent mixing (e.g., integral approaches, finescale parameterizations and direct microstructure measurements; Thorpe, 2005; Shroyer et al., 2018). In this study, we present turbulence dissipation rates observations and derived parameters (Thorpe, 2005) collected using a free-falling microstructure profiler (MSS90D; Sea & Sun Technology). The probe was equipped with two microstructure shear sensors (PNS6), with the final turbulent dissipation rate calculated as the mean of the two shear probe estimates. The profiler's buoyancy was adjusted to achieve a sinking velocity between 0.6 and 0.7 m s^{-1} and the data sampling occurred at a frequency of 1024 Hz but was internally averaged to 512 Hz to comply with signal degradation along the 1.2 km probe cable. Post-processing and turbulent dissipation rate calculations were carried out using the microstructure profiler processing toolbox developed by Schultz et al. (2022). We fine-tuned instrument-specific parameters according to the microstructure profiler employed in this study (e.g., sampling frequency, sensors calibration and sensitivity, distance of other sensors to the shear sensor's tip), while the threshold parameters for data validation from Schultz et al. (2022) were retained.

Kinetic energy dissipation rates (ε) were computed as per equation (3):

$$\varepsilon = 15\nu\overline{\left(\frac{\partial u}{\partial z}\right)^2} \qquad (3)$$

where ν represents the kinematic molecular viscosity and $\overline{(\partial u/\partial z)^2}$ is the spatial average of vertical shear variation with depth (Taylor, 1935). Turbulent dissipation rates from both shear probes were treated separately, averaging all shear spectra within 1 m vertical bin. The shear spectrum results were iteratively fitted to the Nasmyth (Nasmyth, 1970) reference shear spectrum and the deviation of the observed spectrum with respect to the Nasmyth's was used for data quality check. A detailed description of the data processing procedure was described in Schultz et al. (2022). We performed data-averaging at 1-meter depth intervals, excluding the initial 15 meters of each profile, to mitigate the noise arising from ship motion and wave-breaking (D'Asaro, 2014).

The microstructure data exhibited good agreement (R^2 = 0.89) between the two shear sensors (n=8957; **Supplementary Fig. 1A**), with a stronger correlation observed under elevated turbulence conditions ($\varepsilon > 10^{-7}$ W kg^{-1}) compared to calmer waters ($\varepsilon < 10^{-7}$ W kg^{-1}). Another quality control parameter was the magnitude of the pseudo dissipation rates originated from the profiler high frequency vibrations, consistently one order of magnitude lower than turbulent kinetic energy dissipation rates (**Supplementary Fig. 1B**) and predominantly (36.9%) falling within the range of $1.0 \cdot 10^{-10}$ to $1.6 \cdot 10^{-10}$ W kg^{-1}.

2.7 Turbulent fluxes

Vertical diffusivity (K_z) is computed according to equation (4):

$$K_z = \gamma \frac{\varepsilon}{N^2} \quad (4)$$

where the mixing efficiency is $\gamma = 0.2$ (Gregg et al., 2018; Mouriño-Carballido et al., 2021; Lozovatsky et al., 2022), ε is the turbulent kinetic energy dissipation rate and N^2 denotes the squared buoyancy frequency.

We determine turbulent heat (in units of W m^{-2}) and salt fluxes (kg m^{-2} s^{-1}) following Sheehan et al. (2023) and equations (5) and (6):

$$Q_H = -\rho C_p K_z \frac{\partial\theta}{\partial z} \quad (5)$$

$$Q_S = 10^{-3}\left(-\rho K_z \frac{\partial S}{\partial z}\right) \quad (6)$$

where ρ is seawater density, C_p is the specific heat capacity of seawater (3850 J kg^{-1} °C^{-1}), $\partial\theta/\partial z$ corresponds to the vertical gradient of conservative temperature, and $\partial S/\partial z$ indicates the vertical gradient of absolute salinity. Furthermore, turbulent fluxes of dissolved oxygen and chlorophyll-a (in units of mg m^{-2} s^{-1}) were estimated using equations (7) proposed by Williams et al. (2013):

$$Q_X = -K_z \frac{\partial X}{\partial z} \quad (7)$$

where ∂X denote the variable (i.e., oxygen or chlorophyll-a) vertical gradient with depth.

Our analysis primarily focused on the subducting intrusion identified along transect 2 during the 2019 CALYPSO campaign (**Fig. 1B**). The limited number of microstructure profiles precluded a comprehensive analysis of spatiotemporal intrusions variability along the other transects. To assess the physical and biogeochemical conditions around the subducting intrusion boundaries, we calculated the mean conditions within 5 m inside and outside the intrusion boundaries.

3 Results

3.1 Water column stability and turbulent kinetic energy

High mixing was observed in the surface layer, with localized turbulence peaks in the subsurface water column. Turbulent kinetic energy (TKE) values displayed considerable variability, with 43.8% of observations falling between $1.3 \cdot 10^{-9}$ and $4.0 \cdot 10^{-9}$ W kg^{-1} (mean ± standard deviation: $8.2 \cdot 10^{-9} \pm 2.4 \cdot 10^{-8}$ W kg^{-1}), with a peak (11.2%) identified in the range of $2.0 \cdot 10^{-9}$ to $2.5 \cdot 10^{-9}$ W kg^{-1}. An analysis of ε probability distribution by depth intervals indicated that 95% of deep ε values were comprised between 10^{-9} and 10^{-7} W kg^{-1} (**Fig. 2A**). In contrast, surface and mid-water depths exhibited a lower proportion (53% and 77%, respectively) within this ε range. Surface waters (<25 m) were characterized by elevated ε values, with 25% and 12% of the data falling within the ranges of 10^{-7}-10^{-6} and 10^{-6}-10^{-5} W kg^{-1}, respectively.

Elevated homogeneity in the shallow water column vertical structure was observed. Indeed, the probability distribution of Brunt–Väisälä frequency (N^2) by depth intervals (**Fig. 2B**) indicated lower stratification in the surface and mid-water layers, where approximately 81% and 67% of values were lower than $0.2 \cdot 10^{-4}$ s^{-2}, respectively. Conversely, the deeper portion (>50 m) of the water column exhibited stronger stratification, with an increased proportion (70%) of N^2 estimations

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exceeding 0.3 10^{-4} s^{-2}. These patterns were reflected in water column regimes. Examination of Turner angle values revealed a predominantly stable water column, accounting for 74% of the dataset (**Fig. 2C**). However, these stability conditions exhibited notable variations with depth. The shallow layer displayed a more varied scenario with a near-equal distribution between statically unstable and doubly stable conditions. In contrast, the mid-water column featured the highest proportion (27%) of diffusive regimes and the deep layer was primarily characterized (83%) by double stable conditions.

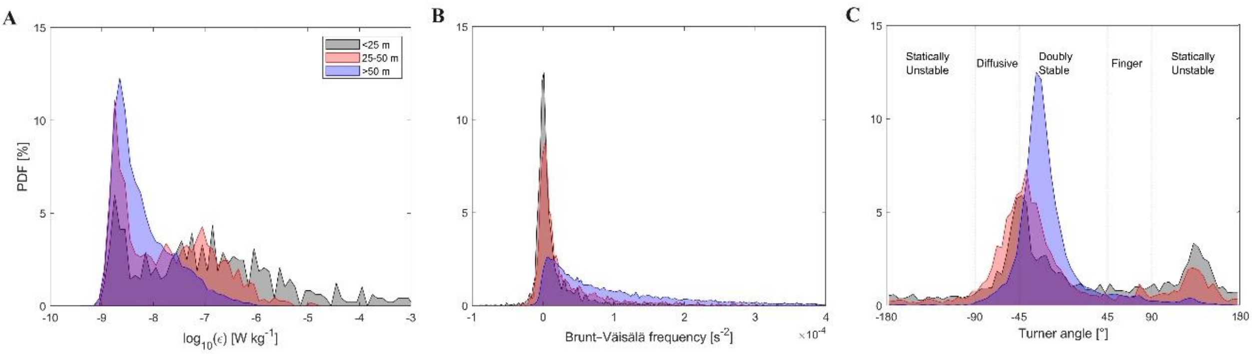

Figure 2. Probability distribution frequency (PDF) by depth intervals for turbulent kinetic energy dissipation rates (A), Brunt–Väisälä frequency (B) and Turner angle values (C). Colored shaded areas in panels correspond to different depth intervals, with gray: 15-25 m; red: 26-50 m; blue: depths >51 m. The names in panel (C) reflect the water column regime according to the Turner angle value (McDougall et al., 1988).

3.2 Transects across the Western Alboran Gyre front

A noticeable depression in the isopycnals was consistently observed in all the transects extending towards the interior of the anticyclone (**Fig. 3** and **Supplementary Fig. 2-6**). The highest ε below the mixed layer was detected adjacent to zones featuring elevated vertical density gradients and deepening along the isopycnals in transects 2 (**Fig. 3**). A deepening of positive spice anomalies from approximately 50 to 100 m was observed at the start of transect 1 and from 15-35 km of transect 2. Subducting intrusions were observed along all transects, except for transect 3, possibly owing to its shorter length (approximately 12 km; **Fig. 3** and **Supplementary Fig. 2-6**). The mean thickness of subducting intrusions was computed at 14.2 m (standard deviation: 9.4 m), ranging from a minimum of 1.7 to a maximum of 42.2 m.

The subduction is likely occurring along the front and not necessarily along the tilted isopycnal. Enhanced ε and diffusivity values were noted in proximity to the base of the mixed layer and in the vicinity of subducting intrusion boundaries (**Fig. 4**). Furthermore, diffusive water column conditions were identified along the upper boundary of the subducting intrusion in transect 2 (**Fig. 3D**) and adjacent to the subducting intrusions within transects 1 and 4. Positive isopycnal strain values were observed at both edges of the subducting intrusion initially, with a predominant concentration of positive values indicating stretching of isopycnal surfaces primarily at the bottom edge as subduction progressed. The current data along transect 2 illustrated a horizontal velocity magnitude exceeding 60 cm s^{-1} within the interior of the anticyclone, while lower values were observed on its periphery. The subducting intrusion, identified beneath the superficial high-velocity patch and within a zone

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of elevated shear squared (primarily due to a negative vertical gradient of the zonal velocity component; **Fig. 3**), was characterized by a horizontal velocity estimated at approximately 0.5 m s^{-1}.

A deepening of the well oxygenated surface layer towards the center of the anticyclone was observed in transects 1 and 2 (**Supplementary Fig. 2** and **Fig. 3**, respectively). Elevated dissolved oxygen anomaly concentrations (>0.5 mg l^{-1}) were detected inside the subducting intrusion along transect 2 (**Fig. 3**), with high values deepening from approximately 50 to 120 m. Similarly, anomalous high chlorophyll-a anomaly values were found near the 30 km of transect 2, with anomaly concentrations of up to 1.4 mg m^{-3} detected at a depth of 100 m.

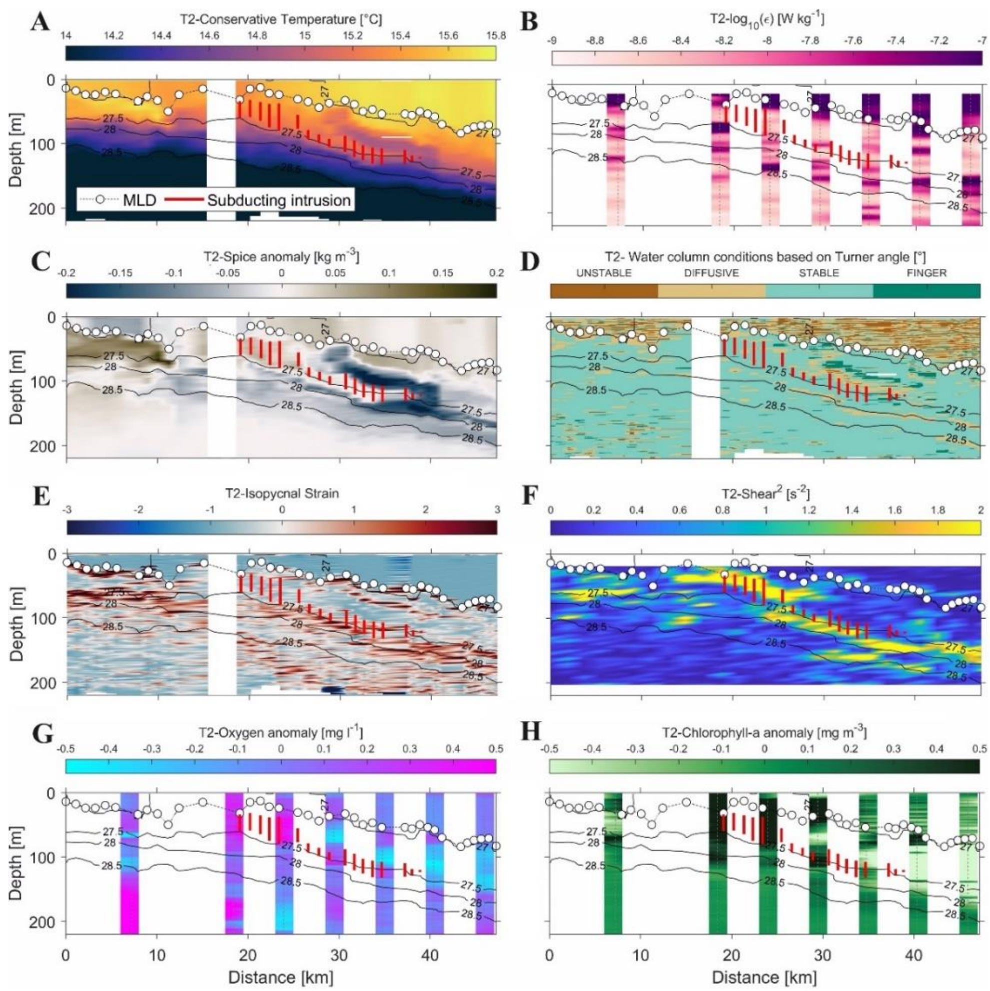

Figure 3. Profiles of conservative temperature (A), turbulent kinetic energy dissipation rates (B), spice anomaly (C), water column conditions based on Turner angle estimations (D), isopycnal strain (E), share squared (F), dissolved oxygen anomaly (G), and chlorophyll-a anomaly (H) estimations acquired along transect 2 of the 2019 CALYSPSO campaign. Isopycnals are represented as black lines, while the mixed layer depth and subducting intrusions are denoted by colored points and lines, respectively. The distances between stations were calculated starting from the northernmost sampling point.

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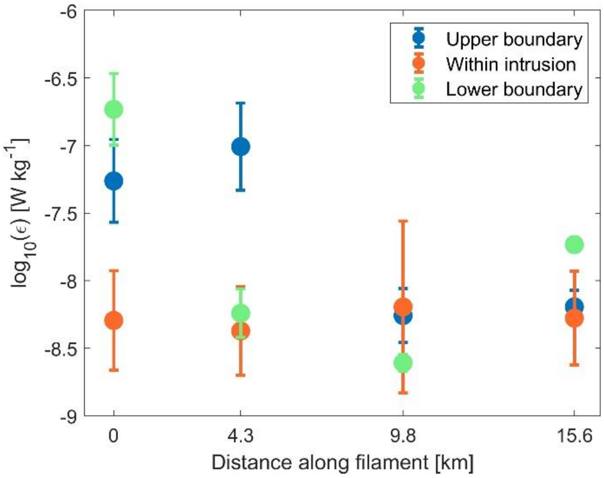

Figure 4. Mean turbulent kinetic energy values within the intrusion and at its upper and lower boundaries (5 m from the intrusion edges). The errorbars represent the measurement standard deviation.

3.3 Turbulent fluxes around the subducting intrusion

We focused our analysis of the microstructure profiles to transect 2 during the 2019 CALYPSO campaign due to its higher horizontal resolution (**Fig. 1B**). Turbulent fluxes within the interior of the transect 2 intrusion exhibited reduced values compared to water column around both intrusion edges (**Supplementary Fig. 7**). Notably, turbulent fluxes exhibited higher magnitudes within the first two profiles sampling the edges of the subducting intrusion in comparison to the subsequent two profiles (**Fig. 5**). Turbulent fluxes around the intrusion boundaries resulted in a net loss of heat, oxygen and chlorophyll-a properties from within the intrusion to the surrounding ocean, while salinity increased (**Table 1**). Heat, oxygen and chlorophyll-a turbulent fluxes exhibited negative values (i.e., indicating downward direction) at the base of the intrusion, while salt fluxes displayed positive values (i.e., upward direction) at both boundaries of the intrusion. Positive heat flux values were consistently recorded near the upper intrusion boundary at all sampling stations, although more variability was observed in oxygen and chlorophyll-a fluxes. The mean absolute values for turbulent fluxes indicated reduced heat, oxygen and chlorophyll-a fluxes near the upper boundary in contrast to the intrusion's base. Specifically, the upper heat flux accounted for only 35% of the magnitude observed near the base of the intrusion, while the upper oxygen and chlorophyll-a fluxes represented 68 and 63%, respectively, of the corresponding bottom flux magnitudes. The fluxes uncertainty was provided in **Supplementary Table 1**.

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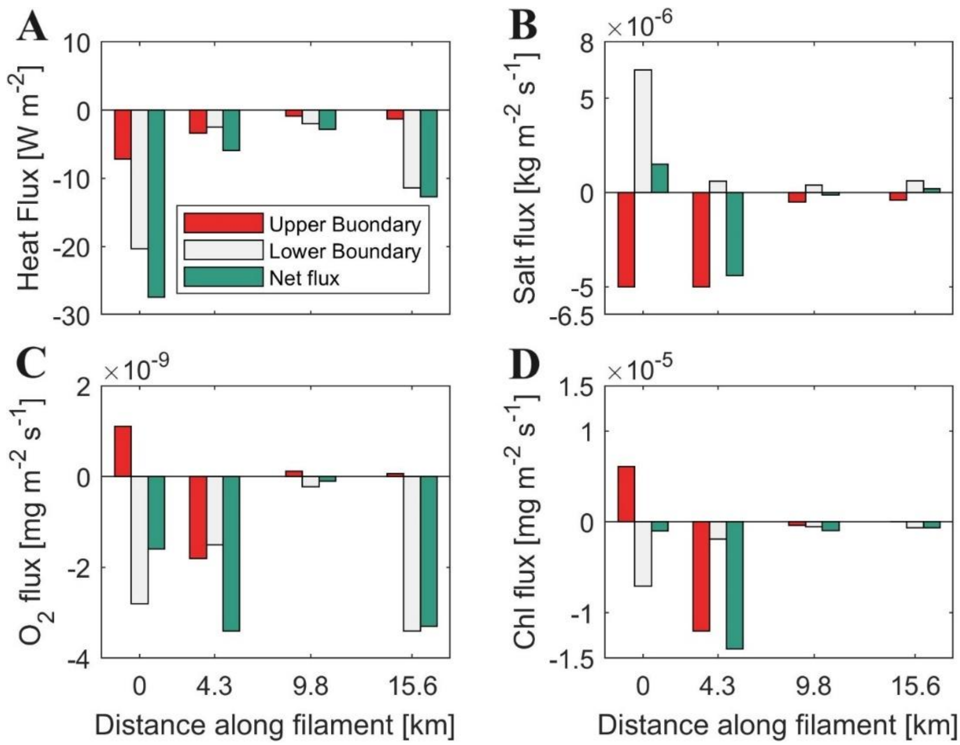

Figure 5. Estimations of turbulent fluxes of heat (A), salt (B), oxygen (C) and chlorophyll-a (D) along the upper and lower boundaries of the subducting intrusion identified within transect T2 of the 2019 CALYPSO campaign and the resulting net flux (in green). The distances between the four stations where the fluxes were calculated (as shown in Supplementary Figure 7) along the subducting intrusion are provided. Positive (negative) values for the turbulent fluxes represent a gain (loss) of the respective variables within the interior of the intrusion.

Table 1. Mean (± 95% confidence interval) conservative temperature, absolute salinity, dissolved oxygen and chlorophyll-a conditions within the subducting intrusion identified along transect T2. The distances between the four stations, the intrusion mean depth and thickness are provided.

Distance [km]	**Depth** [m]	**Thickness** [m]	**Temperature** [°C]	**Salinity** [g kg^{-1}]	**Oxygen** [mg l^{-1}]	**Chlorophyll-a** [mg m^{-3}]
0	47	25.9	15.28 ± 0.05	37.03 ± 0.03	7.74 ± 0.07	1.81 ± 0.12
4.3	59	42.2	15.27 ± 0.06	37.04 ± 0.04	7.84 ± 0.10	2.16 ± 0.28
9.8	99	13.3	15.16 ± 0.03	37.10 ± 0.03	7.43 ± 0.05	1.38 ± 0.13
15.6	120	24.9	14.91 ± 0.06	37.15 ± 0.07	7.16 ± 0.04	0.68 ± 0.02

4 Discussion

4.1 Turbulent kinetic energy dissipation rates in the Western Alboran Sea

The TKE dissipation rates in our study were (mean: $8.2 \cdot 10^{-9}$ W kg^{-1}) found to be comparable to those reported in previous investigations involving microstructure data in the Mediterranean Sea. For instance, Cuypers et al. (2012) calculated mean TKE values of approximately 10^{-8} W kg^{-1} below the seasonal pycnocline. Our TKE estimates unveiled an intermediate turbulent environment, between the Mediterranean energetic and quiescent regions (mean: $5.2 \cdot 10^{-8}$ and $4.7 \cdot 10^{-10}$ W kg^{-1} , respectively; Vladoiu et al., 2021). Interestingly, our findings exhibited a closer resemblance to the TKE observed west of the Gibraltar Strait, where the mean TKE was $4 \cdot 10^{-9}$ W kg^{-1} in the ocean interior (Fernández-Castro et al., 2014).

The observed peaks in TKE dissipation rates were predictably situated in shallow ocean regions influenced by wave breaking, in close proximity to the base of mixed layer (Zippel et al., 2022) and near the boundaries of subducting intrusions (**Fig. 3**). However, other peaks were detected at deeper levels and did not appear to correlate with aforementioned factors. Mixing processes in the stratified ocean below the mixed layer are often attributed to vertical shear extending below the MLD, penetrative convection and the breaking of internal waves (MacKinnon et al., 2013). The Western Alboran Sea may be influenced by the eastward propagation of internal waves traveling along isopycnals generated by the interaction of tidal currents with bathymetry at the Gibraltar Strait (Thorpe, 2007; Alpers et al., 2008; Bolado-Penagos et al., 2023). While symmetric instabilities have been identified as effective mechanisms for geostrophic energy dissipation in the ocean interior (Zhou et al., 2022), the positive sign of the potential vorticity associated with subducting water in the study area (Freilich and Mahadevan, 2021) suggests that the conditions required for this process to occur may not be met. Another plausible explanation for the deep TKE peaks could be provided by dissipation associated with subducting intrusions that may have gone undetected by our methodology. Conducting future surveys with mooring and/or glider deployments to identify internal waves within the study zone could significantly advance our comprehension of their spatiotemporal variability and their role in generating deep turbulence along isopycnals.

4.2 Water column regimes

The convergence of Atlantic and Mediterranean waters in the study zone resulted in a robust stratification of the water column, characterized predominantly by doubly stable conditions. Along isopycnals and at the upper boundary of the subducting intrusion (**Figure 3**), we observed instances of diffusive convection regimes. While diffusive convection is typically associated with thermohaline staircases and is more commonly found at higher latitudes (Kelley et al., 2002; van der Boog et al., 2021), the presence of horizontal variability in temperature and salinity conditions in our study area may lead to the formation of coherent subducting intrusions associated with double diffusive convection (Kelley et al., 2002; Schmitt, 2009). Freilich and Mahadevan (2021) proposed that the specific pathway of subducting intrusions along isopycnals in the study zone could be generated by a combination of mesoscale (geostrophic) frontogenesis and submesoscale (ageostrophic) dynamics.

The subducting intrusion transports subsurface water column properties into the deeper ocean, undergoing erosion along its pathway through a combination of turbulent and diffusive mixing. This dynamic process results in a modification of its inherent properties.

4.3 Turbulent erosion of the intrusion

The elevated TKE diffusivity rates in the surface layer, coupled with an increase in stratification with depth can potentially account for the higher diffusivity and turbulent fluxes observed at the start of the intrusion's subduction compared to stations sampled further along the subduction path. Moreover, physical and biogeochemical properties of the subducted water resembled surface conditions more closely than those of the deep layer, resulting in reduced fluxes along the upper boundary of the intrusion compared to the lower boundary (with the exception of the station located at 4.3 km).

The turbulent erosion of the subducting filament led to an overall decrease in temperature, oxygen and chlorophyll-a content within the filament, while salinity increased (**Table 1**).The slight increment in oxygen and chlorophyll-a concentration observed at the second station within the intrusion may be attributed to either downward fluxes detected at the first station, indicating a supply of biogeochemical properties from the surface layer into the intrusion interior, or in situ phytoplankton production (the photic layer was estimated to be around 60 m deep; **Supplementary Fig. 8**).

However, these diapycnal fluxes were too weak to induce a significant dilution of the intrusion, as daily fluxes (**Supplementary Table 2**) were orders of magnitude smaller than the mean property values within the intrusion. These estimates did not account for double-diffusive mixing fluxes characteristic of thermohaline staircases, as such features are predominant at greater depths in the Western Mediterranean Sea (Onken and Brambilla, 2003; Schroeder et al., 2016; Ferron et al., 2021). Along the upper boundary of the intrusion, diffusive convection regimes were identified, resulting from the subduction of warmer and less saline water by the intrusion. Despite of this, an estimate of diffusive convection mixing indicated that these fluxes were generally an order of magnitude lower than turbulent fluxes, suggesting a limited impact on intrusion dilution or enrichment (**Supplementary Table 2**).

In addition to turbulent and diffusive convection mixing, various factors contribute to the typical vertical variability in ocean temperature and salinity. These factors include the attenuation of solar irradiation, the evaporation-precipitation budget, water column density stability and isopycnal mixing. Conversely, the decline in oxygen and chlorophyll-a content with depth can be attributed to the deepening of the photic layer, distance from the atmospheric-ocean boundary layer, and processes such as remineralization, respiration, and grazing. The modification of the typical vertical variability in biogeochemical properties induced by subducting intrusions might have profound impacts on ecosystem dynamics within the study zone.

4.4 Biogeochemical significance of subducting intrusions

The Atlantic Jet, which enters the Mediterranean through the Strait of Gibraltar, coupled with coastal upwelling events, transforms our study area into one of the most productive zones in the Mediterranean despite the Mediterranean Sea's well-known status as an oligotrophic basin (Reale et al., 2020; Sánchez-Garrido and Nadal, 2022). The outer boundary of the WAG

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has also been identified as a stirring region where properties of the water column are continually exchanged as they are advected towards the center of the anticyclone (Brett et al., 2020; Sala et al., 2022). Subduction of the intrusion may enhance particulate organic carbon export below the mixed layer, reducing its exposure time to remineralization (Freilich et al., 2024). This process contributes to one of the highest export rates observed in the Mediterranean Sea based on sediment trap and particle size distribution profiles data (Ramondenc et al., 2016). Additionally, the mixing associated with subducting intrusions may facilitate the reorganization of phytoplankton communities, traditionally stratified in the photic layer (Mena et al., 2019) and their proliferation. This is especially significant, as nitrates are nearly depleted in the shallow layer north of the WAG (Oguz et al., 2014; Lazzari et al., 2016; García-Martínez et al., 2018). It has been demonstrated that oceanic fronts might act as aggregation areas for planktonic organisms, becoming important foraging areas for higher trophic layers (Acha et al., 2015). Moreover, the transport of chlorophyll-a towards the center of the WAG could lead to an increase in the biomass of diel vertical migrant zooplankton, which tends to be more abundant in the inner part of the gyre compared to its periphery (Yebra et al., 2018).

5 Conclusions

The Western Alboran Gyre is a dynamical feature characterized by high spatiotemporal variability arising from the convergence of Mediterranean and Atlantic waters. Indeed, the northern edge of the WAG water column exhibited notable spatial variability in both physical and biogeochemical characteristics. Specifically, the inner part of this gyre featured higher temperature, current velocity, oxygen content and chlorophyll-a concentration compared to its periphery. Moreover, there was an observable deepening of enhanced Brunt–Väisälä frequency and turbulent kinetic energy dissipation rates towards the anticyclone's center.

The investigation of spice anomaly spatial variability allowed the identification of several subducting intrusions occurring beneath the mixed layer depth, extending from the gyre's outer region towards its center. High turbulent kinetic energy dissipation rates were evident at both the upper and lower boundaries of these intrusions, complemented by localized peaks at deeper levels. The specific factors contributing to these heightened dissipation rates at deeper levels remain elusive.

The turbulent fluxes of heat, salt, oxygen and chlorophyll-a along the intrusion boundaries revealed a consistent net loss of physical and biogeochemical properties from within the intrusion to the surrounding ocean. From a biogeochemical perspective, the subduction intrusion holds significance as it has the potential to amplify the export of particulate organic carbon below the mixed layer. Additionally, it may contribute to the enhancement of diel vertical migrant zooplankton biomass and facilitate the proliferation of phytoplankton communities. Notably, mixing due to turbulence or diffusive convection contributed little to the observed variation in temperature, salinity, oxygen or chlorophyll-a within the intrusion interior. Other factors, such as water column density stability, variability of the photic layer depth, and organic matter degradation, likely played a role in these dynamics.

While our present study has provided valuable insights into the subduction of intrusions and their turbulent erosion within the Western Alboran Gyre, significant gaps remain in our understanding of the spatiotemporal variability of subducting intrusions. Future targeted surveys that specifically address the persistence and extent of these features might improve quantitative parametrizations of key physical and biogeochemical property subduction. Explorations encompassing a broader surface of the WAG may reveal asymmetries in intrusion subduction between the WAG's edges and offer an estimate of the total subduction occurring within the WAG.

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