

1 Intense and localized export of selected marine snow types at eddy 2 edges in the South Atlantic Ocean

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13 Abstract

14 The Biological Carbon Pump (BCP) comprises a wide variety of processes involved in transferring organic carbon from the
15 surface to the deep ocean. This results in long-term carbon sequestration. Without BCP, atmospheric CO₂ concentrations would
16 be around 200 ppm higher. This study reveals that ocean dynamics at mesoscale and submesoscale could have a major impact
17 on particulate organic matter (POM) vertical distribution. Our results suggest that intense submesoscale frontal regions, such
18 as those between mesoscale eddies, could lead to an important accumulation and transport of particulate organic matter (POM)
19 from the mixed layer depth (MLD) down to the mesopelagic zone. To reach these conclusions, a multifaceted approach was
20 applied. It included in-situ measurements and marine snow images from a BGC Argo float equipped with an Underwater
21 Vision Profiler (UVP6), satellite altimetry data, and Lagrangian physics diagnostics. We focused our study on three intense
22 features in marine snow distribution observed during the 17-month long float mission in the Cape Basin, southwest of Africa.
23 These features were located in the frontal region between mesoscale eddies. Our study suggests that a particle injection pump
24 induced by a frontogenesis-driven mechanism has the potential to enhance the effectiveness of the biological pump by
25 increasing the depth at which carbon is injected into the water column. This work also emphasizes the importance of
26 establishing repeated sampling campaigns targeting the interface zones between eddies. This could improve our understanding
27 of the mechanisms involved in the deep accumulation of marine snow observed at eddy interfaces.

28 **1 Introduction**

29 The open ocean plays a critical role in mitigating climate change by storing carbon dioxide (CO₂) away from the atmosphere
30 for long periods of time (Boyd et al., 2019). This carbon storage occurs over decades to thousands of years and relies on two
31 well-established mechanisms that create a gradient of dissolved inorganic carbon (DIC) between the surface and deep regions
32 of the ocean and enhances DIC concentrations at depth. These mechanisms are known as the biological pump and the solubility
33 pump (or physical pump). The solubility pump transports cold, dense, and DIC-rich waters to the deep ocean, as part of the
34 ocean's overturning circulation, primarily in high-latitude regions (Sarmiento and Gruber, 2006). The biological carbon pump
35 (BCP), on the other hand, involves the export of particulate organic carbon (POC) from surface waters below the euphotic
36 depth, and operates worldwide. The BCP encompasses a wide range of processes, from the fixation of atmospheric CO₂ by
37 phytoplankton activity, to carbon sequestration into the deep ocean (Le Moigne, 2019). The BCP contributes also to
38 approximately 90% of the dissolved inorganic carbon (DIC) gradient between surface and deep ocean (Boyd et al., 2019).
39 Without the BCP atmospheric concentrations of the greenhouse gas CO₂ would be approximately 200 ppm higher than in a
40 world without biology (Maier-Reimer et al. 1996) and the global climate would be much warmer by default.

41 A key component of the BCP is the biological gravitational pump (BGP). The BGP is the process by which large and/or dense
42 aggregates of POC sink due to gravity. Large particles of POC (> 500 μm), also called marine snow, can consist of aggregated
43 phytoplankton cells such as diatoms, different types of aggregates resulting from coagulation processes (Le Moigne, 2019),
44 and zooplankton activity, such as phytoplankton grazing and faecal pellet egestion (Turner, 2015). This mechanism is
45 estimated, through empirical and food web models, to export about 3 to 10 Pg of carbon per year below the euphotic zone or
46 100 meters depth depending on the study (Dunne et al., 2005; Henson et al., 2012; Siegel et al., 2014; Bisson et al., 2020). The
47 speed at which surface aggregates sink to the deep ocean depends on their individual sinking rates, which are influenced by
48 their combined morphological (size, porosity, etc.) and chemical properties (ratio of organic versus mineral, mineral type, etc.)
49 (Stemmann et al., 2004 ; Cael et al., 2021 ; Trudnowska et al., 2021 ; Soviadan et al., submitted). Laboratory experiments have
50 estimated that the sinking velocity of marine snow range from a few meters to several hundred meters per day (Shanks and
51 Trent, 1980; Azetsu-Scott and Johnson, 1992; Ploug et al., 2008; Laurenceau-Cornec et al., 2015; Cael et al., 2021) and, in a
52 few cases, from in situ imaging time series (Alldredge and Gotschalk, 1988; Stemmann et al., 2002; Trudnowska et al., 2021;
53 Soviadan et al., 2024). In situ imagery has proven to be a valuable tool for estimating sinking speeds. This can improve our
54 understanding of particle dynamics, which affect the BGP.

55 Another important component of the BCP that can occur concurrently with the BGP, are the particle injection pumps (PIPs).
56 These consist of the export of carbon mediated by plankton migrations or physical vertical movement and can also play a
57 significant role in the ocean's capacity to store carbon. PIPs encompass a variety of mechanisms, temporal-spatial scales, and
58 geographical extent, and can affect all types of particles in the water column. They typically transport particles below the
59 euphotic zone. Depending on the specific injection mechanism, PIPs can reach depths greater than 1000 m (Boyd et al. 2019).

60 The physical processes that make up the PIPs include subduction resulting from the mixed-layer shallowing (referred to as the
61 mixed-layer pump), subduction caused by the large-scale ocean circulation over distances of 100-1000 km (referred to as the
62 large-scale subduction pump), and subduction mediated by mesoscale (10-100 km, few weeks to several months) to
63 submesoscale (100 m to 10 km, hours to days) ocean dynamics (Thomas et al., 2008; McWilliams, 2016).

64 In particular, the influence of mesoscale eddies on particle production, aggregation and export (Stemmann et al., 2008 ; Guidi
65 et al., 2012 ; McGillicuddy, 2016 ; Stuckel et al., 2017) is a very active area of research because these structures are ubiquitous
66 in the global ocean and are the largest source of ocean variability (Stammer, 1997; Wunsch, 1999). For example, spatial
67 patterns of particles, differentiated by size, have been shown to be associated with anticyclonic circulation (Gorsky et al., 2002;
68 Waite et al., 2016). Upwelling at eddy's interfaces can enhance phytoplankton productivity and particle production (Shih et
69 al., 2020) while downwelling, contributes to oblique transport of dissolved, and particulate (both sinking and suspended)
70 carbon to depth (Stemmann et al., 2008; Guidi et al., 2012) in a process called the Eddy Subduction Pump (ESP; Omand et al.
71 2015). Vertical transport has been suggested to be increased by sub-mesoscale vertical velocities associated with fronts (Guidi
72 et al., 2007). Understanding the mechanisms associated with physical-biological biogeochemical interaction is challenging due
73 to the transient nature of the underlying processes. Therefore, it is essential to employ multidisciplinary approaches, including
74 in situ observations, to elucidate these intricate phenomena (McGillicuddy, 2016).

75 This work is based on the deployment of a new prototype of BGC Argo float (part of the Argo international program:
76 <https://argo.ucsd.edu>) equipped with an Underwater Vision Profiler 6 (UVP6; Picheral et al., 2022) and several physical-
77 biogeochemical sensors in the Southeast Atlantic Ocean. The float was deployed in the Cape Basin, a region southwest of
78 Africa, known for its intense eddy activity, which is mainly controlled by a complex interaction between the Benguela
79 Upwelling, the Agulhas Current System and the South Atlantic Current (Richardson et al., 2003; Boebel et al., 2003). The
80 float was recovered after one year of operation and the collected images were analyzed and classified into plankton categories
81 and morphological types of marine snow (Trudnowska et al., 2022). Hydrological and particle data collected by the float were
82 then combined with satellite altimetry to identify frontal structures and mesoscale eddies (Chaigneau et al., 2009; Laxenaire et
83 al., 2018; 2019; 2020; 2024). Based on recurrent observations of marine snow concentration “hot spots” at mesopelagic depth
84 during the productive season, we discuss the role of horizontal and vertical circulation at fronts on marine snow production
85 and export to the deep sea.

86 **2 Material and Methods**

87 **1.1 Observing strategy**

88 During the SO283 cruise, a BGC Argo float (WMO: 6903095) was deployed, from the RV Sonne, on April 14, 2021, in a
89 cyclonic eddy in the southeastern region of the Atlantic Ocean, near the Benguela upwelling system at 33.0978°S and

90 13.8673°E (Fig. 1.A). The float remained within the eddy for about 5 months. During this period, the eddy merged with another
91 cyclone (Baudena et al., 2023), until it disappeared from satellite altimetry maps probably due to subduction (Ioannou et al.,
92 2022). A detailed analysis of this timeframe of the dataset is provided in Baudena et al., (2023). It then sampled different
93 mesoscale features within the region, and after a sampling period of about 1.5 years, it was retrieved by the S.A. Agulhas II
94 on September 19, 2022. During its deployment, the float completed a total of 183 profiles, the majority of which were acquired
95 from the surface down to 600- or 1000-meter depth.

96 **1.2 Environmental data**

97 The float was equipped with several sensors to quantify seawater properties along the water column. The float was
98 instrumented with pressure (DRUCK_2900PSIA, SN: 11587115), temperature and salinity sensors (SBE41CP_V7.2.5, SN:
99 13100) to measure the hydrological water properties. The biogeochemical properties were measured with oxygen
100 (AANDERAA_OPTODE_4330, SN: 3489), fluorescence and backscattering (700 nm) sensors (ECO_FLBB_2K, SN: 6310).
101 All the BGC Argo data that were used in this work, are made freely available by the International Argo Program
102 (<https://fleetmonitoring.euro-argo.eu/float/6903095>). Before analysis, some derived variables were calculated based on a
103 Python implementation of the Gibbs SeaWater (GSW) Oceanographic Toolbox of TEOS-10 (<http://www.teos-10.org/>). Firstly,
104 Absolute Salinity (SA) was computed from Practical Salinity (PSAL) and pressure (dbar) measurements and Conservative
105 Temperature (CT, °C) was computed from in-situ Temperature (T, °C). These two variables were then used to calculate the
106 Potential Density (kg.m^{-3}) with a reference pressure of 0 dbar (Roquet et al., 2015). Regarding the oxygen parameter, the
107 Apparent Oxygen Utilization (AOU, $\mu\text{mol.kg}^{-3}$) was computed as the difference between the oxygen concentration expected
108 at equilibrium with air and the in-situ oxygen concentrations. The expected oxygen concentration was computed from
109 solubility coefficients derived from the data of Benson and Krause (1984), as fitted by Garcia and Gordon (1992). Finally, the
110 mixed layer depth (MLD), which is the upper part of the water column where salinity, temperature, and density remain
111 vertically constant, was detected following De Boyer Montégut (2004). A reference value for density was taken at 5 dbar and
112 the water column was considered to be mixed until the depth at which density deviates from this reference by more than 0.03
113 kg.m^{-3}

114 **1.2 Living and non-living particle data**

115 **1.1.1 Small phytoplanktonic and bulk particles**

116 To estimate chlorophyll-a concentrations emitted by phytoplanktonic cells, the float was equipped with a fluorescence sensor
117 (ECO_FLBB_2K, SN: 6310). The backscattering (700 nm) sensor (ECO_FLBB_2K, SN: 6310) was used to quantify the
118 amount of all particles (including detritus and phytoplankton). The backscattering coefficient signal (*bbp*) was decomposed to
119 extract the signal of small particles (*bbsr*) from the raw signal which also contained spikes triggered by rare large aggregates
120 passing in the flow field. This was done by applying the method proposed by Briggs et al., 2020 (see supplementary materials)

121 that decomposes the backscattering signal into its baseline (as a proxy of small particles, *bbsr*) and intermittent pulses (as
122 proxy of larger aggregates). The *bbsr* signal represented the distribution of particles between 5 to 20 μm .

123 **1.2.2 Underwater Vision Profiler 6 (UVP6-LP)**

124 The float was also equipped with an in-situ camera, the Underwater Vision Profiler 6 Low-Power (UVP6-LP, SN: 000101)
125 specifically designed to be deployed on autonomous platforms. The UVP6 detects and measures the size (from 0.102 to 16.40
126 mm in Equivalent Spherical Diameter, ESD) of zooplankton and various organic/biogenic matter such as marine snow and
127 fecal pellets. Thanks to the float recovery, images of objects $>500 \mu\text{m}$ could be retrieved as well and therefore, taxonomic
128 identification of macrozooplankton and large particle classification could be conducted on the Ecotaxa platform
129 (<http://ecotaxa.obs-vlfr.fr>). Taxonomic classification was initially assisted by a CNN (Convolutional Neural Network)
130 algorithm to extract descriptive features from the images. From these, the taxonomic group of each image was predicted using
131 a Random Forest algorithm. Then, living organisms' predictions have all been manually validated by taxonomic experts. All
132 the images used during this work can be found here: <https://ecotaxa.obs-vlfr.fr/prj/8801>. A more detailed description of the
133 UVP6-LP can be found in Picheral et al., 2022.

134 **1.2.3 A broad size classification of particles (MiP and MaP)**

135 To conduct a community analysis of marine snow and examine their spatio-temporal distribution, we applied a rough size
136 classification on raw size- spectra data ($>100 \mu\text{m}$) provided by the UVP6 (without any plankton identification). In this case
137 the assumption was made that zooplankton represents only a small fraction of objects sampled by the UVP6 (14.5% of images)
138 compared to particles (85.5%). Hence, we consider its contribution as neglectable for this purpose. Then, all size-spectra were
139 divided into two sub-classes: MiP (Micrometric Particles) and MaP (Macroscopic Particles). MiP concentrations were obtained
140 by integrating the concentrations overall size classes between 0.1- and 0.5-mm. MaP concentrations were computed exactly in
141 the same way but considering all size classes between 0.5- and 16-mm. The 0.5 mm threshold was used as detrital aggregates
142 $> 0.5 \text{ mm}$ are considered marine snow (i.e., aggregates, Alldredge and Gotschalk, 1988) and was chosen for visualization
143 purposes. However, the count/size measurements of the objects seen by the UVP6 contain zooplanktons and it is not possible,
144 from the images, to determine whether an object smaller than 0.5 mm is a living organism or detritus due to the limited
145 resolution. As a result, the MiP and MaP signals could be influenced by zooplankton abundances. However, the proportion of
146 living organisms to the total particle counts (ESD $> 500\mu\text{m}$) are usually smaller than 10% (Stemmann and Boss, 2012).

147 Organic carbon content of MiPs and MaPs was calculated assuming that particle mass can be estimated using an empirically
148 derived relationship for marine aggregates (Alldredge, 1998; Kriest, 2002 reference 2a of Table 1). Assuming a
149 carbon:nitrogen ratio of 106:16, this yields an expression for the carbon content of a particle in a given size class characterized
150 by its diameter ESD (in cm). Moreover, this formula is dedicated to estimate POC content of miscellaneous marine snow,
151 including components such as fecal pellets. Multiplying the carbon content with the particle number in this size class (in

152 particles.m⁻³), and integrating over the MiP and MaP size classes, respectively, we obtain the total POC content (mgC.m⁻³) for
153 MiPs and MaPs.

154 Our study suggests the presence of vertical velocities within the water column which could significantly influence the marine
155 snow distribution (MiPs and MaPs) at depth. The literature provides various methods for estimating POC fluxes from imaging
156 devices. However, these approaches are based on particle size, sinking speed, and carbon content relationships which do not
157 include the influence of physical processes such as water masses vertical movement. Therefore, a simple POC fluxes estimates
158 from particle size would not accurately represent the actual fluxes in our study area. Furthermore, we couldn't disentangle the
159 contributions of particle sinking speeds from the vertical displacement of the water mass. Given these limitations, we chose
160 not to provide flux estimates.

161 The raw data corresponding to this section can be found on the Ecopart platform (<https://ecopart.obs-vlfr.fr>, project:
162 uvp6_sn000101lp_2021_WMO6903095_recovery).

163 **1.2.4 Unsupervised morphological classification of marine snow**

164 To better characterize the marine snow dynamics, an unsupervised classification method was used, following the previous
165 study on particle dynamics in the Arctic Ocean (Trudnowska et al., 2021). This provides information on particle size, shape,
166 gray level, and heterogeneity. This method allows one to classify rapidly and efficiently particle images in objective categories.
167 In summary, firstly, zooplankton and detrital particle images were separated, by manual validation and treated independently.
168 After this separation, a PCA was performed on morphological traits of the detrital particle images. Those specific traits
169 represented their size (e.g., area, perimeter), shade intensity (e.g., mean/median gray level), shape (e.g., symmetry, elongation),
170 and structure (i.e., homogeneity or heterogeneity, mostly based on the variability in gray level). To obtain a normal distribution
171 for each variable, extreme values (in that they were below or above the first and 95th percentile) were removed and each
172 variable was transformed by the Yeo-Johnson transformation (Yeo, 2000). This PCA led to the creation of a morphospace in
173 which each particle image can be located based on their morphological features. Then, a K-means clustering was performed
174 on this new morphospace using the first five principal components. The number of clusters, “k”, was set to four. This specific
175 number, after several simulations, was chosen because it conducted the best partitioning with four clearly different groups of
176 particle morphology.

177 Finally, the concentration (nb.m⁻³) of each morphotype was computed by multiplying the number of particles found in each
178 cluster and depth bin by the volume sampled by the UVP6. To study their spatio-temporal distributions, group concentrations
179 were interpolated according to depth and time with a resolution of 5 meters and one day respectively.

180 Since some groups in the morphospace partially overlap (Fig. 5.B), potentially affecting the quality of the classification, a
181 further selection process was implemented. This involved calculating the Euclidean distance between individual particle
182 images and their respective cluster centers. Subsequently, for each group, the first quartile of the Euclidean distance distribution

183 was computed, and only individuals with a distance smaller than the first quartile were included in the selection. The
184 concentrations of the different morphotypes shown in figure 6 correspond to those of these 'exclusive members'. Objects with
185 a too large distance (out of the first quartile) were not included in the further analysis.

186 **1.2.5 Selection of profiles corresponding to deep massive exports**

187 To characterize in an objective way significant changes in the deep marine snow spatio-temporal distribution, the Sequential
188 T-test Analysis of Regime Shifts (STARS) method was used (Rodionov, 2004). This method, based on the Student's t-test²,
189 analyses a dataset in a sequential manner. It compares each new observation with all the entries in the current 'regime' or group.
190 If an entry significantly deviates from the average of that regime, it is marked as a potential 'shift point'. The algorithm then
191 tests whether this detected shift is persistent over time. To characterize significant changes in the water column, marine snow
192 concentrations were integrated, for each UVP6 profile, between 150 and 600 meters. Then, profiles detected in each significant
193 'shift' were selected and considered as belonging to (or 'inside') those features in marine snow distribution (see Fig. S1).
194 Afterward, to compare the aggregates distribution outside and inside each feature, profiles one month before and one month
195 after each feature were selected and merged, providing the mean of particle concentrations 'outside' each feature. The same
196 protocol was applied to study the morphotype proportions according to depth. The latter were computed in four depth layers,
197 between 0-100, 100-300, 300-600 and 600-1000 meters to see the evolution of the morphotypes relative abundance overall the
198 water column.

199 **1.2.6 Eddy subduction detection**

200 To compare our findings with the literature, we applied the algorithm proposed by Llorc et al., 2018 to detect ESP events from
201 AOU and spiciness anomalies derived from BGC-Argo float data. Spiciness was defined as in Flament, 2002 and allows
202 differentiating water masses with distinct thermohaline properties but with similar density. Then, we compared each profile's
203 3-bin smoothed values to a 20-bin average to detect anomalies for both AOU and spiciness. An event was classified as
204 subduction-driven only if AOU and spiciness anomalies occurred at the same depth, which helped differentiate subduction
205 effects from horizontal mixing. Thresholds of AOU anomaly $< -8 \mu\text{mol/kg}$ and spiciness < -0.05 were set to detect these kinds
206 of events. Finally, we compared the ESP occurrence with the export features spatial distribution detected with the STARS
207 method. We also considered calculating vertical velocities according to Siegelman et al. (2020), but the temporal resolution of
208 our data was not sufficient to enable this (pers. communication L. Siegelman).

209 **1.3 Satellite data and the TOEddies algorithm**

210 To identify mesoscale eddies, we implemented the TOEddies algorithm (The Ocean Eddy Detection and Tracking Algorithm,
211 Laxenaire et al., 2024). TOEddies is based on the identification of mesoscale eddies as closed contours of Sea Surface Height
212 (SSH) surrounding an extremum. This relies on the principle that in a geostrophic balance, SSH isolines align with current
213 streamlines. As a result, a maximum (minimum) SSH that is surrounded by a closed circulation is classified as an anticyclonic

214 (cyclonic) eddy. To track the eddies over time, the algorithm takes advantage of the fact that daily eddy displacements are
215 small compared to their dimensions, resulting in overlapping areas between successive days. This methodology allows the
216 derivation of trajectories and the detection of events where eddies merge or split, providing a mechanism for tracing the origin
217 of sampled water masses which is a critical component for the objectives of this study .

218 For the purposes of this study, the TOEddies algorithm was applied to the Absolute Dynamic Topography (ADT, a proxy for
219 SSH) and its associated with geostrophic currents. These 1/4 gridded daily maps are produced by Ssalto/Duacs and distributed
220 by the Copernicus Marine Environment Monitoring Service (<http://marine.copernicus.eu/>) in the version released in April 2018
221 (DT18; Pujol et al., 2016; Ballarotta et al., 2019). Each identified eddy was characterized by two radii associated to the two
222 eddy boundaries defined in TOEddies: the outermost contour (R_{out}), and the contour with the maximum averaged geostrophic
223 velocities ($R_{V_{max}}$ and associated velocity V_{max}).

224 Eddies identified by the algorithm were collocated with float profiles (Chaigneau et al., 2011; Laxenaire et al., 2019; 2020).
225 This allows us to categorize the profiles according to whether they sampled a cyclone, an anticyclone, a region outside of the
226 influence of mesoscale eddies, or an area at the interface of two eddies. The application of TOEddies to ADT maps, coupled
227 with the collocation of detected eddies with Argo profiles, has proven to be a successful combination for exploring eddy
228 dynamics in the southeast Atlantic (Laxenaire et al., 2019, 2020; Ioannou et al., 2022; Baudena et al., 2023).

229 **1.4 Lagrangian diagnostics**

230 Several Lagrangian diagnostics have been computed at the location of each profile using satellite-derived currents and
231 environmental variables. First, for each station (i.e., profile location), a region was defined as representative of the water parcel
232 sampled by the float. In this study, this region was a circular neighborhood with a radius r of 0.1° around each profile location.
233 This distance allowed us to smooth the satellite uncertainties and has been used in previous studies (Chambault et al., 2019;
234 Baudena et al., 2021; Ser-Giacomi et al., 2021; Fabri-Ruiz et al., 2023). This circular shape was then filled with virtual particles
235 (nearly 300) separated by 0.01° . Then, for each virtual particle, a given Lagrangian diagnostic was computed (detailed below).
236 This resulted in about 300 values for each sampling station. These have been averaged, leading to a value of a given Lagrangian
237 diagnostic for each profile. The velocity field we used have been derived from both altimetry and delayed-time model
238 assimilation data and includes both the geostrophic and the Ekman components (Copernicus CMEMS product MULTIOBS
239 GLO PHY REP 015 004-TDS). It has been used backward in time to advect each virtual particle (within the representative
240 water parcel) from the profile day until an advective time (τ). Different τ values were used, ranging from 5 to 45 days. Hence,
241 for each profile, each diagnostic has been calculated using different advective times. The first diagnostic we implemented was
242 the Finite-Time Lyapunov Exponent (FTLE, days⁻¹; Shadden et al., 2005). By construction, intense FTLE values (typically
243 disposed in filament shapes) are found at the edge between two water masses that have been widely separated in the preceding
244 days. As these two water masses come from distant locations, they are likely to share different hydrological characteristics,
245 such as temperature, primary production or biological activity (d'Ovidio et al., 2010; Haller, 2015; Lehahn et al., 2018). For
246 these reasons, FTLE is useful to identify oceanic fronts and can be considered as proxies for water masses convergence and

247 thus, possibly, associated vertical downwelling (McWilliams, 2016). FTLEs were computed as in Shadden et al., (2005), with
248 an initial separation of 0.1° . We implemented as a second diagnostic the Lagrangian chlorophyll-a ($\text{mg}\cdot\text{m}^{-3}$), which is the mean
249 chlorophyll content calculated along the backward virtual particle trajectory. This diagnostic determines whether the seawater
250 parcel sampled at a profile location was rich in chlorophyll in the preceding days. For the chlorophyll, we used the delayed-
251 time satellite product “OCEANCOLOUR GLO BGC L4 MY 009 104-TDS” provided by CMEMS Copernicus website (0.25°
252 resolution, provided daily).

253 **2 Results**

254 **2.1 Circulation and water mass spatio-temporal distribution**

255 The lateral variability in thermohaline properties (Fig. 2) is driven by mesoscale eddies and submesoscale features, which carry
256 distinct signatures and interact dynamically, creating spatio-temporal heterogeneity in water masses. Visual inspection of the
257 TOEddies algorithm results, coupled with analysis of hydrological data provided important information about the history and
258 origin of the water masses sampled by the float. In the following, we separate the life history of the float trajectory in different
259 periods. During April to October 2021 (fall and winter), the float was trapped within a cyclonic eddy shed from the southern
260 Benguela upwelling front (Baudena et al., 2023, preprint). During this period, temperature, salinity, and density were relatively
261 stable. Figure 2 shows that the MLD varied between near-surface depths and 200 m. Analysis of the AOU time series shows
262 predominantly weak positive or even negative values only above the MLD (Fig. 2.F). Regarding the FTLE time series, values
263 remained low compared to the entire time series (less than 0.25 days^{-1}) except around August 2021 when the targeted eddy
264 merged with another Benguela Upwelling cyclone (0.45 days^{-1}). Overall, the float remained near the center of the cyclonic
265 eddy, which explains the low FTLE values. After the merging, the float continued to move within the new cyclonic structure.
266 This cyclonic eddy merged again (in early October 2021) with an Agulhas cyclone that formed along the Agulhas Bank, the
267 southern shelf-edge of Africa (Penven et al., 2001; Lutjeharms et al., 2003). This type of cyclone originates from the southern
268 African continental slope from barotropic instabilities and enters the ocean interior at the northern edge of the Agulhas Current
269 Retroflection (Duncombe Rae, 1991) with very different hydrographic characteristics (warmer and saltier water masses,
270 Giulivi and Gordon, 2006) compared with the Benguela upwelling cyclones.

271 After exiting the cyclone, the float remained within its periphery. In mid-October, the float was at the interface between the
272 cyclone and an anticyclonic eddy. Then, the float moved southward until May 2022. The water column was more stratified
273 and characterized by a shallower MLD (typical for spring and summer). During this period, two phases of the life history of
274 the float can be identified. During the first phase, warmer and saltier waters were observed between 200 and 800 m depth.
275 These waters clearly originate from Agulhas Current water masses, very likely originating from an injection in the region of
276 the Agulhas rings generated at the Agulhas Current Retroflection (Laxenaire et al., 2018). The second phase is characterized
277 by colder and fresher water masses. Indeed, between January and March 2022, the float crossed the Subantarctic front and

278 continued to move southward along the edge of an Agulhas ring, a relatively old Agulhas cyclone, as well as a Subantarctic
279 Front cyclone. Finally, in April 2022, the float passed next to another Subantarctic Front cyclone, which could explain the
280 colder and less salty water masses during this period. Moreover, specific patterns in the AOU and the density time series are
281 also observed during the transition between these two phases. Indeed, the AOU time series shows smaller values (close to 0
282 $\mu\text{mol}\cdot\text{m}^{-3}$) at depths between 200 and 1000 m. The latter are also associated with important horizontal isopycnal variations
283 (steep slopes), reaching depths close to 900 m and coinciding with high FTLE values (above 0.45 days^{-1}).

284 The final period spans May to September 2022 and is marked by three high-intensity mesoscale features that influence the
285 water column down to about 800 to 1000 m depth. These features are characterized by a deeper MLD and the presence of
286 much warmer and saltier water masses all over the water column. The AOU time series shows a strong signal during this
287 period, with negative values observed at depths around 800 m. This period was also characterized by intense FTLE values
288 throughout. The TOEddies analysis showed that the float profiled different cyclones and anticyclones during this period.

289 In summary, during its deployment, the float sampled water masses with significantly different hydrological characteristics
290 and from multiple geographical zones. At this stage, one of the main results to keep in mind is that the float sampled interface
291 zones between anticyclonic and cyclonic structure. Overall, these observations highlight the dynamic nature of the study area,
292 characterized by contrasting water mass properties and their temporal variations throughout the year.

293 **2.2 Spatio-temporal distribution of marine snow during the survey**

294 From April to October 2021 (Fall and Winter), surface chlorophyll-a concentrations and the *bbsr* coefficient remained
295 relatively low (Fig. 2.E.F). Afterwards, a significant change occurred between the end of October 2021 and May 2022 (Spring
296 and Summer). This period coincided with the seasonal production of phytoplankton, as evident in the chlorophyll-a
297 concentration time series. Also, a noticeable increase in the *bbsr* coefficient indicates greater concentrations of small particles
298 in the surface (Fig. 2.E). Moving forward to the period between May and September 2022, there was a noticeable decline in
299 chlorophyll-a concentration. Consequently, weaker concentrations were observed at the surface, and the *bbsr* coefficient was
300 also reduced. In general, the spatio-temporal dynamics of MiP and MaP exhibit notable differences (Fig. 3). MiPs were
301 generally more abundant than MaPs, ranging between $1.5\text{-}7.5 \text{ part}\cdot\text{L}^{-1}$, while MaP concentrations ranged from 0 to 1.6
302 $\text{part}\cdot\text{L}^{-1}$ (Fig. 3). Both types of particles displayed higher mean concentrations above the MLD than below. MiP were
303 consistently present throughout the float deployment, with a slightly higher abundance observed between October 2021 and
304 May 2022. Conversely, the distribution pattern of MaPs differed. Their concentration was relatively low from the beginning
305 of the time series until October 2021. Subsequently, their surface abundance significantly increased during the phytoplankton
306 production period between the end of October 2021 and May 2022. Overall, these observations highlight the distinct spatio-
307 temporal dynamics of MiP and MaP. A key result in the marine snow spatial distribution is that three different "columns" of
308 increased particle concentration (in particular MaPs) were observed between the surface down to 600 meters. These features

309 lasted for approximately a month. The first one took place between October 8 and 23, 2021, the second one occurred from
310 November 25 to December 22, 2021, and finally, the last one spanned approximately between March 3 and April 28, 2022.

311 **2.3 Spatio-temporal distribution of MaP morphological groups during the survey**

312 The unsupervised clustering method led to the identification of four morphotypes distinguished by their size, circularity,
313 brightness, and homogeneity (Fig. 5.A.B). The first morphotype was characterized by small, dark, and predominantly circular
314 particles. The second morphotype comprised elongated objects with varying degrees of brightness. The third morphotype
315 consisted of bright, fluffy, and diverse marine snow particles. The fourth morphotype encompassed larger marine snow
316 particles, often with the form of aggregated structures with some heterogeneity. All the identified morphotypes were
317 predominantly found in the surface layer. Specifically, the elongated particles (Fig. 6.B) exhibited a distinct concentration
318 increase from late September 2021, maintaining a stable abundance until early May 2022. Before and after this period, their
319 presence was considerably smaller. Additionally, these elongated particles displayed a strong positive correlation with
320 chlorophyll-a concentration in the surface layer (0-100m), as evidenced by a significant Spearman correlation coefficient of
321 0.65 (p-value = $9.3 \cdot 10^{-22}$, Fig. S3). In contrast, the other three morphotypes (small, bright, and aggregates, Fig. 6.A.C.D)
322 exhibited different dynamics. They were present in all three MaP features described above, whereas the elongated particles
323 did not appear to be extensively involved. The dense aggregates morphotype (purple in Fig. 5.C) is the most abundant during
324 these three features (Fig. 6.A-C).

325 **2.4 Vertical distribution of particle community composition inside and outside massive export features**

326 Here we analyze the distribution of the four morphotypes in the water column during the three export features (Fig. 5.D).
327 Indeed, a shift is observed in their relative proportion between the surface and the layers below. Specifically, the abundance
328 of small particles (salmon pink in Fig. 5.D) and dense aggregates (purple) increases, while the proportion of elongated and
329 bright morphotypes decreases. For example, in column 3, the proportion of small morphotypes incremented from 12% to 23%
330 and from 25% to 47% in dense aggregates. Furthermore, the distribution of morphotypes within each export feature did not
331 change considerably, except perhaps in the case of column 2.

332 **2.5 The eddy dynamic context**

333 The first and the second export feature occurred at the boundary between a cyclonic and an anticyclonic eddy (Fig. 1. B.C).
334 This region was therefore characterized by very intense submesoscale frontal dynamics. During the second feature (Fig. 1. C),
335 the position of the cyclone did not change significantly. The float entered the cyclone but remained close to its $R_{V_{max}}$ boundary
336 and thus within the submesoscale frontal region of the cyclone edge. Indeed, the eddy frontal regions extend over an area of
337 10-20 km across the region of eddy maximum azimuthal velocity (i.e., across $R_{V_{max}}$) as shown in Barabinot et al., (2023). This
338 second feature ended when the float was expelled from the cyclone and began to be advected southward, leaving the frontal

339 region. The third export occurred when the float was advected around the southern edge of a large anticyclone (Fig. 1.D), again
340 a submesoscale frontal region.

341 **2.6 Impact of the three features on the upper 600m water column**

342 Figure 4 clearly illustrates the high abundance of particulate carbon associated with the three export events, with their influence
343 extending down to 600 m depth. The abundance increased by a factor of 2-3 (with a factor of more than 7 during the first
344 feature) compared to periods when the Argo float was moving ‘outside’ these frontal regions. An average increase in MiP POC
345 of about 25% is also observed for the first and the second features. Importantly, the three features occurred during the surface
346 production period and do not show a signature in smaller particle abundances (as indicated by the absence of such a pattern in
347 fluorescence and *bbsr*, Fig. 2.D.E). In particular, MiP and MaP abundances between 100 and 1000 m were significantly
348 correlated with intense FTLE values (Spearman’s rank correlation coefficient of 0.4, p-value = 4.10^{-4} and 0.49, p-value =
349 $1.3.10^{-5}$ respectively, Fig. S4-S5). Mean MiP abundance, at this depth, was also significantly correlated with low AOU values
350 (coefficient correlation of -0.59, p-value = $1.6.10^{-8}$, Fig. S6).

351 **3 Discussion**

352 **3.1 Drivers of marine snow production in the surface layer**

353 The analysis of the chlorophyll-a time series helped to characterize the seasonality of primary production in our study area. In
354 particular, from the end of October 2021 to May 2022 (spanning spring and summer), there was a significant increase in surface
355 layer chlorophyll-a concentrations (Fig. 2.D). This observation is consistent with the existing knowledge on the seasonality of
356 phytoplankton in the southern part of the Atlantic Ocean (Thomalla et al., 2011) and led us to consider this period as the
357 productive period.

358 Regarding the spatiotemporal distribution of MiP and MaP (Fig. 3.B), the abundance of MaP (i.e. aggregates) in the surface
359 layer (0-100m) was significantly correlated with the surface Lagrangian chlorophyll-a 15 days backward (see Fig. S2) and
360 high FTLE, indicating a strong biophysical coupling via several synergistic mechanisms (enhanced primary production,
361 coagulation, transport). Ocean eddies, especially cyclones, have the potential to enhance primary production by upwelling
362 nutrient-rich water from deeper layers to the surface (Benitez-Nelson et al., 2007; Ascani et al., 2013; Cornec et al., 2021).
363 This leads to the biomass accumulation at the edges of cyclones due to water mass divergence (water mass flow from the
364 center to the cyclone periphery), resulting in aggregate formation between submesoscale structures (Lima, 2002). Eddies can
365 also move phytoplankton patches through eddy stirring or trapping (McGillicuddy, 2016), leading to the accumulation of
366 organic matter at the eddy boundaries (Fig. 7.1). This implies that actively growing phytoplankton transported by the water
367 body in the previous days could have contributed to increase the abundance of MaPs by aggregation of organic matter and
368 biological activity. Among the MaP, large particles classified as elongated type were mostly found at the surface and they were
369 the best correlated with surface chlorophyll-a. Their origin is difficult to determine. Their filamentous morphology suggests a

370 resemblance to chain-forming diatom colonies. The average size of particles classified under the 'elongated' morphotype is
371 approximately 820 μm ($\pm 96 \mu\text{m}$). Given their size and the study area, it's likely that some of these particles could include
372 colonies of *Chaetoceros sp.*, which are known to form filamentous structures and to dominate phytoplanktonic blooms during
373 the austral summer (Laubscher et al., 1993). They could also be Euphausiid fecal pellets, however, this kind of organisms was
374 not observed at the surface by the UVP6 which could be attributed to their potential avoidance behavior, making their
375 identification challenging. However, given their size ($>500 \mu\text{m}$), it is unlikely that they are copepod fecal pellets, most of
376 which are smaller than 200 μm (Møller et al., 2011). The other categories of MaPs are also abundant and could be the result
377 of the aggregation into larger particles by biophysical coagulation or trophic activities. Coagulation is responsible for the
378 production of large particles when both particle concentrations and stickiness are high. Additionally, a heterogeneous particle
379 size distribution enhances coagulation, as smaller particles have a higher probability of colliding with larger particles (Hunt,
380 1982; McCave, 1984; Jackson, 1990). Through this mechanism, particle encounter rates are enhanced by Brownian motion,
381 shear and/or differential settling resulting in the formation of a single, larger particle (Jackson, 1990; Stemmann et al., 2004)
382 on a timescale of a few days, as already suggested in the Southern Ocean (Jouandet et al., 2014). By affecting photosynthesis
383 and water movement, the observed intense mesoscale and submesoscale dynamics, (Fig. 1.B.C.D), could significantly affect
384 particle concentration and the probability of aggregation. The second aggregation mechanism by zooplankton grazing, sloppy
385 feeding (Lampitt et al., 1990) and fecal pellet production (Turner, 2015), occurs at long temporal scales due to the slower
386 growth time of zooplankton. Our observation strategy with a float cannot rule this aggregation mechanism out. However, it
387 seems that typical mesozooplankton fecal pellets (a few hundred μm) were not observed in abundance in, at least, three of the
388 four morphotypes. We haven't also observed a clear increase in zooplankton abundance during the three particle distribution
389 events. However, a slight increase in copepod abundance was noted during the first and third features within the first 100
390 meters (see Fig. S7). In our case, it is more likely that physical coagulation had a greater influence on aggregate formation,
391 however, we cannot rule out trophic biological aggregation. In fact, MaP were present at the surface only during the period of
392 maximum chlorophyll-a concentration and were associated with intense FTLE values (greater than 0.45 days^{-1}), which can be
393 used as a proxy of water masses convergence (i.e. frontal zones as in Prants, 2013; Hernández-Carrasco et al., 2018). In other
394 words, MaP concentrations may have been enhanced due to the combination of two important factors for coagulation according
395 to the model of Jackson (1990), increased shear associated with high hydrodynamics at front and enhanced phytoplankton
396 biomass.

397 **3.2 Coupling between massive export of large aggregates and regional ocean dynamics**

398 Analysis of the spatio-temporal distribution of particles has revealed three regions of enhanced concentration of particles at
399 depth, suggesting that vertical export of organic matter occurred in these areas during the productive season. These were
400 characterized by intense MaP and MiP abundances extending vertically from the surface to depths of about 600 m. These
401 export regions were associated with high FTLE values suggesting frontogenesis-driven mechanisms during which there could
402 be a strong coupling between gravitational sinking of particles and intensified physical vertical velocities.

403 **3.2.1 A submesoscale frontogenesis-driven mechanism**

404 The abundance of particles such as MaP and MiP below the MLD (100-600m) was positively correlated with the surface
405 Lagrangian FTLE as well as for the small, bright and aggregated morphotypes. Large FTLE values can identify convergence
406 of water masses with different hydrological properties, creating intense density gradients. It is known that intense velocity and
407 density gradients arise in correspondence with mesoscale (geostrophic) and submesoscale (ageostrophic) frontogenesis, e.g. at
408 the edge of mesoscale features (Freilich and Mahadevan, 2021). At such fronts upper-ocean waters converge and subduct
409 beneath the mixed layer into the stratified pycnocline (e.g. Omand et al. 2015) or also in deeper layers (e.g. Llort et al., 2018).
410 These regions are typically associated with significant vertical velocities (up to 20 m/day). Frontal patterns, in the potential
411 density time series, are clearly seen extending into the ocean interior (Fig. 2.C) and are also found to correspond to the three
412 intense export features. During these features, the signal reached about 1000 m. All of them were located at the periphery of
413 mesoscale eddies (Fig. 1. B.C.D), where the vertical velocity is expected to be higher (Thomas et al., 2008; Freilich and
414 Mahadevan, 2019). Unfortunately, it was not possible to calculate vertical velocities from the data provided by the BGC Argo
415 profiler.

416 Previous studies in a similar mesoscale physical context have shown that mesoscale activity can result in the intrusion of small
417 POM-rich water masses into the mesopelagic layers (Omand et al., 2015; Llort et al., 2018). In our study, the three features
418 described, occurred from the MLD to a depth of about 600 m or deeper (i.e. over a large part of the water column), whereas
419 the subduction described in Llort et al. (2018) occurred well below the MLD in the mesopelagic in depth layers thickness of
420 about 50-100 m. We applied the Llort et al. (2018) algorithm to identify ESP events across all profiles. Only 28 profiles were
421 classified as ESP events (see Figure 1.A, yellow dots). Of these, seven were located near export features described in this
422 study. However, increases in *bbsr*, chlorophyll-a, MiP, and MaP were not consistently observed across these ESP events.
423 Furthermore, the ESP events were generally less than 100 meters thick, whereas the export features we identified extended
424 through much of the water column. These findings suggest that while some export features may be linked to ESP events, the
425 ESP alone does not appear to be a fundamental trigger for these features. This suggests that we are describing a slightly
426 different mechanism compared to Omand et al. (2015) and Llort et al. (2018) responsible for the accumulation of organic
427 matter at depth, but also one related to mesoscale and submesoscale processes. This highlights the fact that the influence of
428 these physical mechanisms is a challenging area of research.

429 **3.2.2 The key role of the gravitational carbon pump and the MLD**

430 Historically, particle size has been considered as the primary factor influencing settling velocity (Guidi et al., 2008). However,
431 with advances in imaging systems, it has become increasingly clear that particle morphology has a significant effect on settling
432 velocities (Iversen and Lampitt, 2020; Cael et al., 2021; Williams and Giering, 2022). This process supports the idea that larger
433 (large ESD, size characteristic) and more compact (non-porous, morphological property) particles will sink faster. In this study,
434 direct estimates of settling particle velocity (e.g. export plume methodology; Stemmann et al., 2002; Briggs et al., 2020;

435 Trudnowska et al., 2021) could not be computed due to the non-completely Lagrangian nature of the float. However, it is
436 possible to assume that the morphotypes identified in this work have different sinking velocities with the highest for
437 small/dense and dark aggregate morphotypes (which dominate in the deepest water column, Fig. 5.D) and the lowest for the
438 elongated morphotypes because they are only found at the surface (Fig. 5.B). In addition, the particles with the higher
439 velocities should be rapidly exported to depth, so they should spend less time in the upper water column than particles with
440 the lowest sinking velocity. In other words, the latter will be more exposed to remineralization.

441 Furthermore, the analysis of the morphotype distribution during the three export features showed a shift in the group
442 proportions between the surface layer (0-100m, which is approximately the mean depth of the MLD, all profiles included) and
443 deeper layers (100-1000m). This shift favored small and dense aggregate groups (in terms of proportion) between these two
444 layers. These morphotypes probably have the highest sinking speed (Soviadan et al., 2024). This supports the idea that the
445 MLD could act as a physical barrier (Hosoda et al., 2010) and only sinking particles were able to cross it. This conclusion is
446 also supported by the fact that, in most profiles, only MiP and especially MaP are located below the MLD, while small labile
447 and refractory particles (*bbsr*) and chlorophyll-containing particles were rarely found below the MLD. Among the MaP, the
448 sinking explanation is valid for three morphotypes (small particles, bright and dense aggregates), but not for the elongated
449 types that we hypothesized to be chain-forming diatom colonies (*Chaetoceros sp.*). This result further emphasizes the critical
450 importance of considering morphology and not just particle size when analyzing the size of particles in marine snow dynamics
451 and when calculating vertical fluxes using only allometric relationships.

452 Another result is that features 1 and 3 show minimal changes in morphotype proportions between layer depths. In fact, it would
453 be expected that the relative proportion of each morphotype would vary with depth due to their presumed different settling
454 rates. It is possible that the morphotypes do not have different settling rates and settle at similar rates. Alternatively, there may
455 be some other mechanism at work that is significantly more important than settling velocity and is responsible for transporting
456 particles to deeper regions, which will be discussed below.

457 **3.2.3 Possible coupling with vertical velocities**

458 During the three described features, MiP abundance between 100 and 1000 meters was significantly correlated with low AOU
459 values. AOU is a proxy for the age of water masses (Sarmiento, 2006), with lower AOU values indicating that the water masses
460 had a more recent contact with the surface. The significant negative correlation between AOU and 100-1000 m MiP abundance
461 suggests a physical downward transport leading to the formation of these features. In addition, we know from the eddy
462 detection algorithm that each export feature was detected in the frontal region separating two adjacent eddies of opposite
463 polarity. Mesoscale activity is known to play an important role in the vertical distribution of water masses.

464 In addition, surface frontal regions develop ageostrophic secondary circulations (Lévy et al., 2018) that lead to intense vertical
465 velocities, which can be stronger at the edges of cyclonic structures and can be on the order of 100 m d⁻¹ or more (Mahadevan

466 & Archer, 2000; Mahadevan et al., 2016; McWilliams, 2016; Freilich & Mahadevan, 2019; Siegelman et al., 2020; Capó et
467 al., 2021; Tarry et al., 2021). This is further supported by several studies that show that the presence of mesoscale eddies
468 greatly enhances the vertical transport of water properties (Omand et al., 2015, Llord et al., 2018, Couespel et al., 2024). In the
469 study region, mesoscale ocean dynamics are particularly active, with eddies generated by the Agulhas Current (the Agulhas
470 rings), the Agulhas Bank (the Agulhas lee cyclones), the Benguela upwelling, and subantarctic front cyclones. All can influence
471 the water column to depths of up to 1600 meters (Schmid et al., 2003). While these dynamics are known to exist, their impact
472 on the vertical exchange of properties through the water column remains to be assessed. However, a recent study (Siegelman
473 et al., 2020) has shown that such vertical velocities are enhanced below the MLD, which acts as a buffer for them, by relatively
474 deep submesoscale fronts. This result may explain why only large particles (i.e., MiP, MaP, and morphotypes) involved in the
475 gravitational pump and capable of crossing the physical barrier represented by the MLD are entrained in this process. However,
476 we lack information on the 3D context of the water mass, both in terms of currents and biogeochemical properties, which
477 makes it impossible to determine what happened at depth before the float passed. Consequently, it's impossible to rule out the
478 action of lateral advection on the mechanism described in this study. Nevertheless, the strong correlation between the described
479 events, the FTLE, and the positions of the eddies suggests a significant link to vertical rather than lateral advection. In addition,
480 previous studies have shown that frontal structures identified by Lyapunov Exponents ridges at the surface can persist in the
481 water column (Bettencourt et al., 2012), corroborating our findings. The hypothesis that the gravitational pump may be
482 associated with physical processes related to mesoscale activity has already been proposed by Guidi et al. (2007). The authors
483 found that the natural gravitational settling of particles combined with the associated vertical velocities of the water masses
484 triggered the export of particles into the deep Atlantic. Such a physical mechanism associated with the gravitational pump
485 would be a key process of carbon export to the deep ocean observed in our study.

486 **4 Conclusion**

487 As described in the conceptual schematic (Fig. 7), mesoscale frontal dynamics between cyclones and anticyclones seem to
488 have a profound effect on particle distribution down to 600 m depth. We propose that particle concentration at these locations
489 is enhanced by increased primary production and/or horizontal convergence induced by frontal activity or trapping. As a result,
490 coagulation processes may have been enhanced, with the ultimate result being the formation of larger aggregates. These
491 particles could have sunk below the MLD, in particular the large and/or dense ones, due to their higher sinking velocities. The
492 consistently observed vertical distribution of particles from the surface to a depth of 600 m suggests that their downward
493 transport is extremely rapid. We propose that such features result from the combination of the relatively large sinking speed
494 of such particles (likely due to their great density) and the enhanced vertical motion of the water induced by submesoscale
495 frontal dynamics, in particular below the MLD. If such a phenomenon is influenced by deeper mesoscale structures, it is likely
496 to extend into deeper layers. Such vertical transport is an integral part of the physical particle injection pump, particularly a
497 unique frontal subduction pump, characterized by intense vertical velocities that might materialize in intense frontal regions.

498 However, the relatively coarse temporal resolution of our dataset did not enable us to calculate the according vertical velocities,
499 and we hence could not disentangle the gravitational and subduction pump in more detail.

500 Our study suggests that small-scale ocean dynamics represent an efficient particle injection pump that can enhance the
501 efficiency of the biological pump by increasing the depth of carbon transport. It is crucial to note that the explicit mechanisms
502 underlying these features are not fully defined due to the temporal and spatial limitations imposed by the Argo float's lack of
503 resolution. Additionally, the submesoscale nature of these features introduces high variability in both space and time. This
504 study underscores the significance of implementing repeated sampling campaigns or the use of gliders equipped with UVP6
505 and further sensors (e.g. microstructure) and focusing on the interface zones between eddies. Such studies would help to
506 validate our proposed mechanism and to disentangle the relative contribution of the various PIPs processes (such as ESP). In
507 particular, focus on such studies needs to be put on resolving the water movements (e.g. the vertical velocities) to enable the
508 separation of the passive sinking and vertical translocation of particles. Since mesoscale and submesoscale structures are
509 ubiquitous in the ocean, it would also be interesting to quantify the influence of this type of process on the overall carbon
510 budget and to determine the extent to which it contributes to carbon sequestration in the deep ocean, information that is crucial
511 in the context of global change.

512 **5 Author contribution**

513 A.A., R.K.; SS and L.S.: designed the study

514 A.A.: conducted data analysis, interpreted results, drafted the manuscript, under guidance of RK and LS

515 AB and RL.: supported the study by environmental background data analysis, revised manuscript.

516 R.K. and S.S.: contributed to the conception of the study, revised manuscript.

517 R.K.: coordinated the recapture of the float

518 L.S.: contributed to the conception and design of the study, supervised the analysis, substantively revised the manuscript.

519 **6 Competing interests**

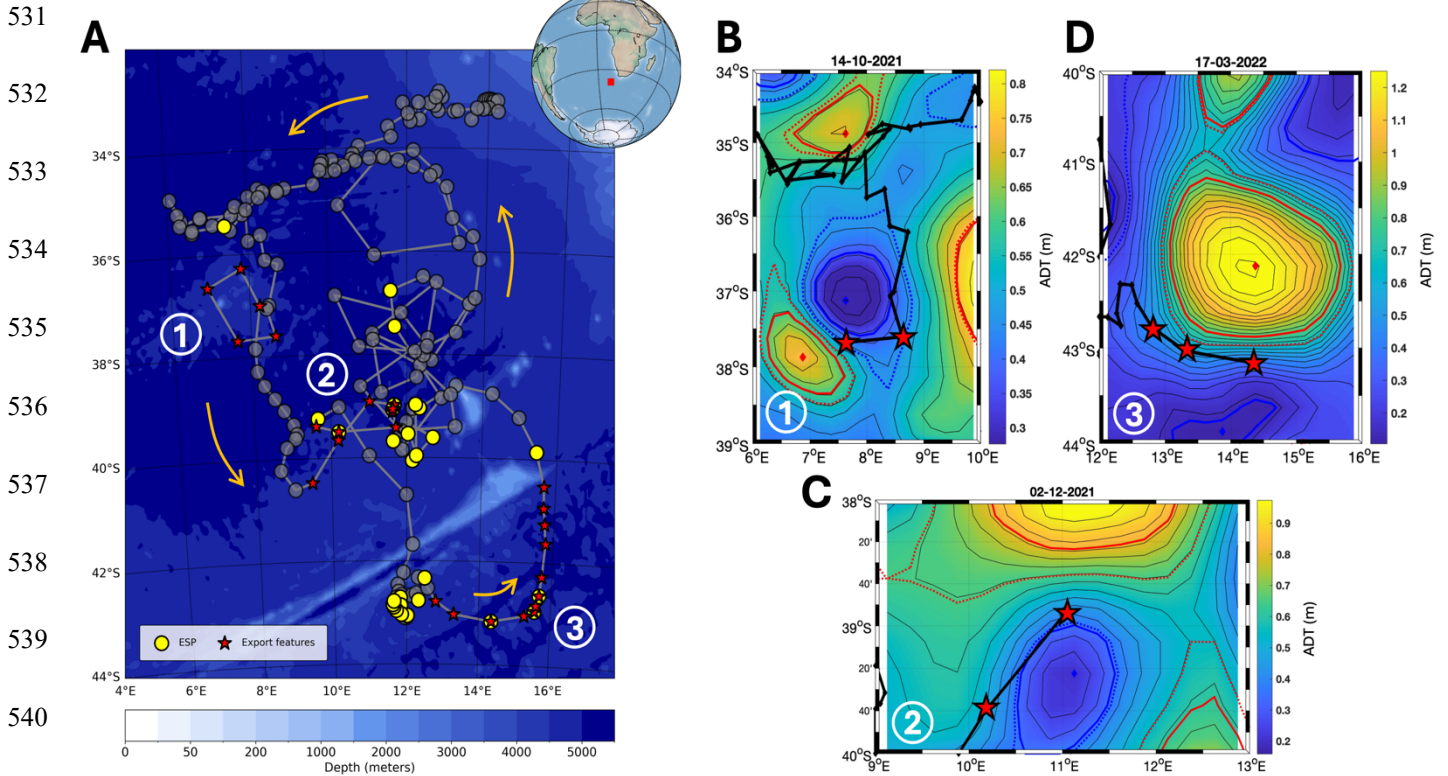
520 The authors declare that they have no conflict of interest.

521 **7 Acknowledgments**

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530 Figures



542 **Figure 1: (A) Float trajectory (thick gray line) during its entire deployment from April 2021 to September 2022 in the South-East**
543 **Atlantic Ocean. Orange arrows indicate the direction of the float trajectory. Stars highlight export features described in our study**
544 **(1 to 3 in panels B, C and D). Yellow dots indicate Eddy Subduction Pump (ESP) events (defined as in Llort et al., 2018). Shaded**
545 **gray dots indicate profiles during which no export features were detected. The background map is the bathymetry of the study zone.**
546 **(B), (C) and (D) panels show ADT field snapshots with the float trajectory (thick black line) during each export feature. Cyclones**
547 **and anticyclones are associated with blue and red colors, respectively. Diamonds show eddies centroid. Thick solid lines correspond**
548 **to eddies maximum speed. Thin solid lines correspond to eddies outer limit definition. Dashed lines to eddies outer limit definition.**

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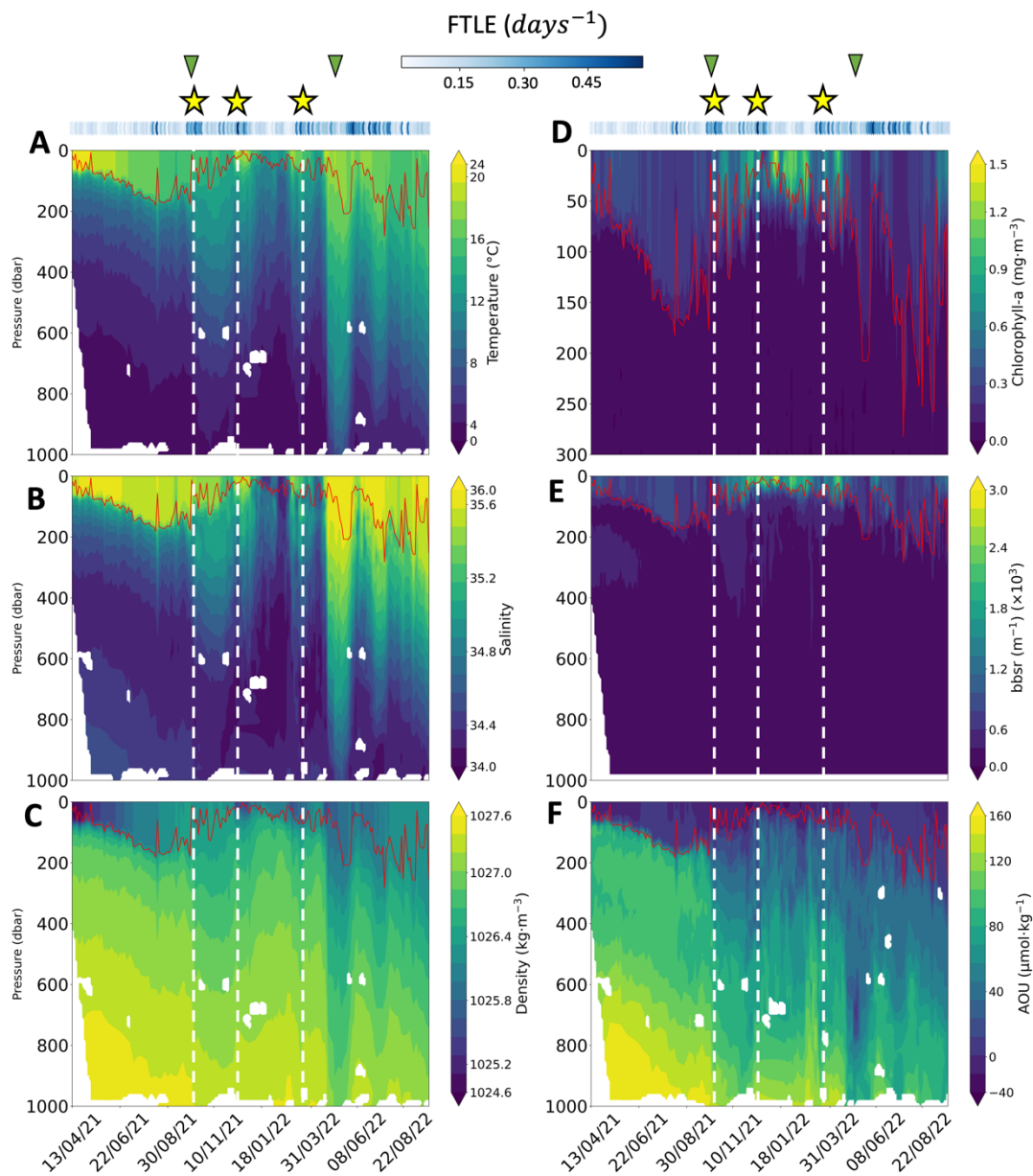


Figure 2: Hydrographic and biogeochemical properties as a function of time and depth along the float trajectory (1.5 years, from April 2021 to September 2022). The panels show (A) temperature, (B) salinity, (C) potential density, (D) chlorophyll-a concentration, (E) log₁₀ of 700 nm optical backscatter bbsr, (F) Apparent Oxygen Utilization (AOU). The red solid line in each panel shows the mixed layer depth (MLD). The white dashed lines and the yellow stars show the location of intense exports of particles. The green triangles indicate the start and the end of the production period. Blue dots on top of the panel show the mean five days backward FTLE (days⁻¹) for each profile location.

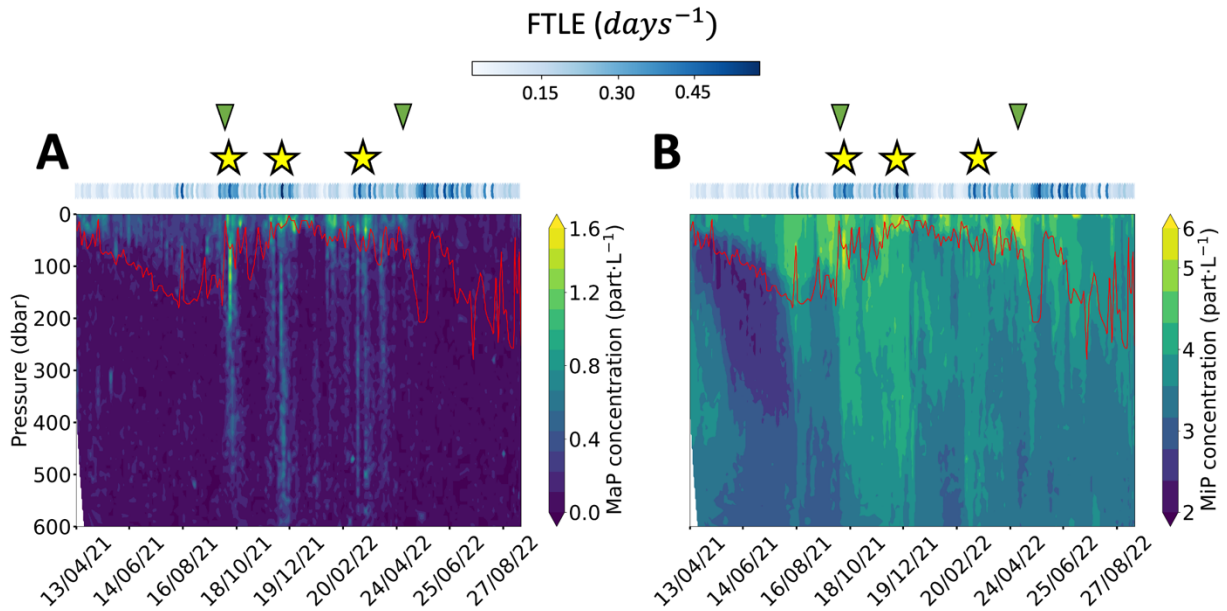


Figure 3: Particles spatio-temporal distribution. The panels show, (A) MiP (Micrometric Particles $0.1 < \text{ESD} < 0.5 \text{ mm}$) concentrations, (B) MaP (Macrometric Particles $0.6 < \text{ESD} < 16 \text{ mm}$) concentrations. Both concentrations were log transformed. Red solid line represents the MLD. Yellow stars show the location of intense exports of particles. Green triangles give the start and the end of the production period. Blue dots on top of the panels show five days backward FTLE (days^{-1}) for each profile location.

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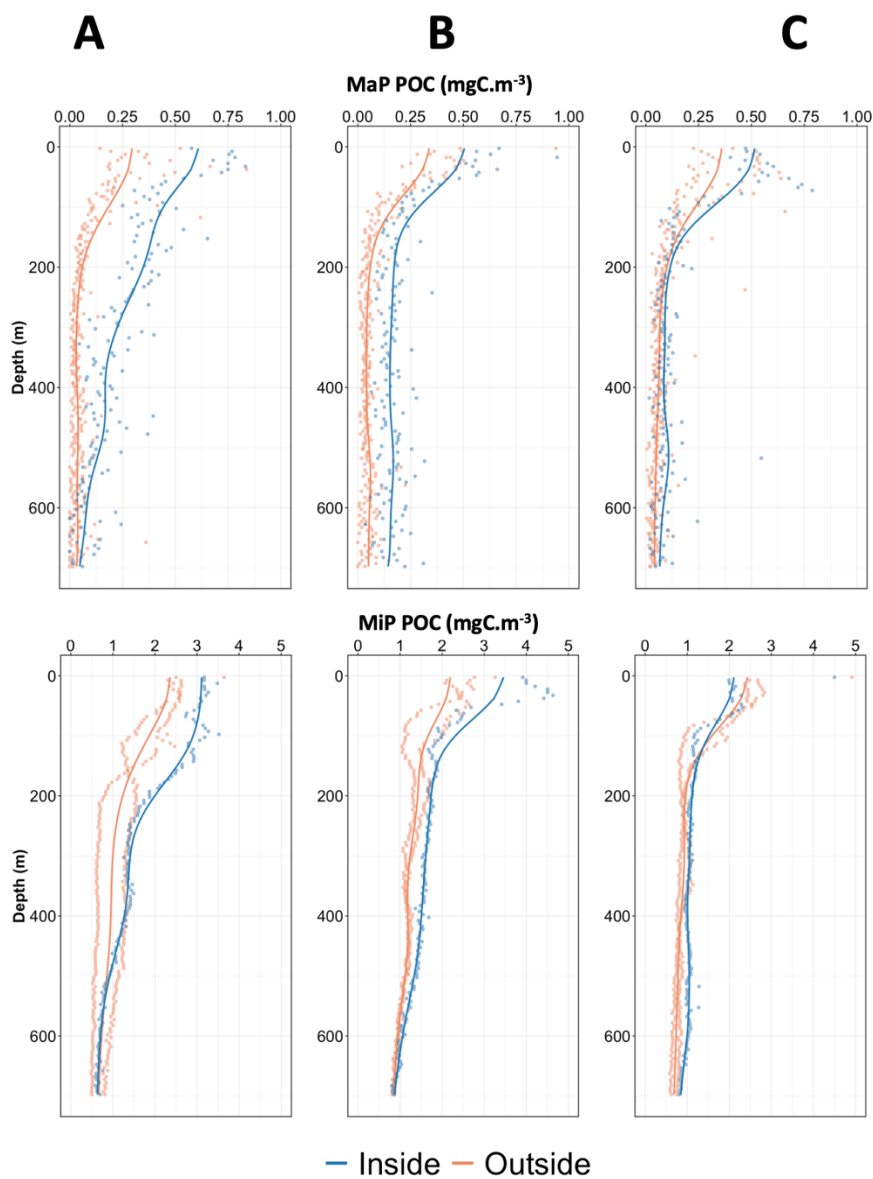
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Figure 4: Comparison of MiP POC (top panels) and MaP POC (bottom panels) in the water column both outside and inside each export feature. The panels show, (A) the first export feature (01-10-2021 – 17/10/2021), (B) the second one (01-12-2021 – 19-12-2021) and (C) the last one (01/03/2022 – 28/03/2022). The dots on the graph represent the data averaged over 5-meter bins. The solid lines are a moving average of the 5-meter bins data. The orange signal corresponds to the average of profiles recorded one month prior to and after each feature (outside), while the blue signal corresponds to the average profiles recorded during each feature (inside).

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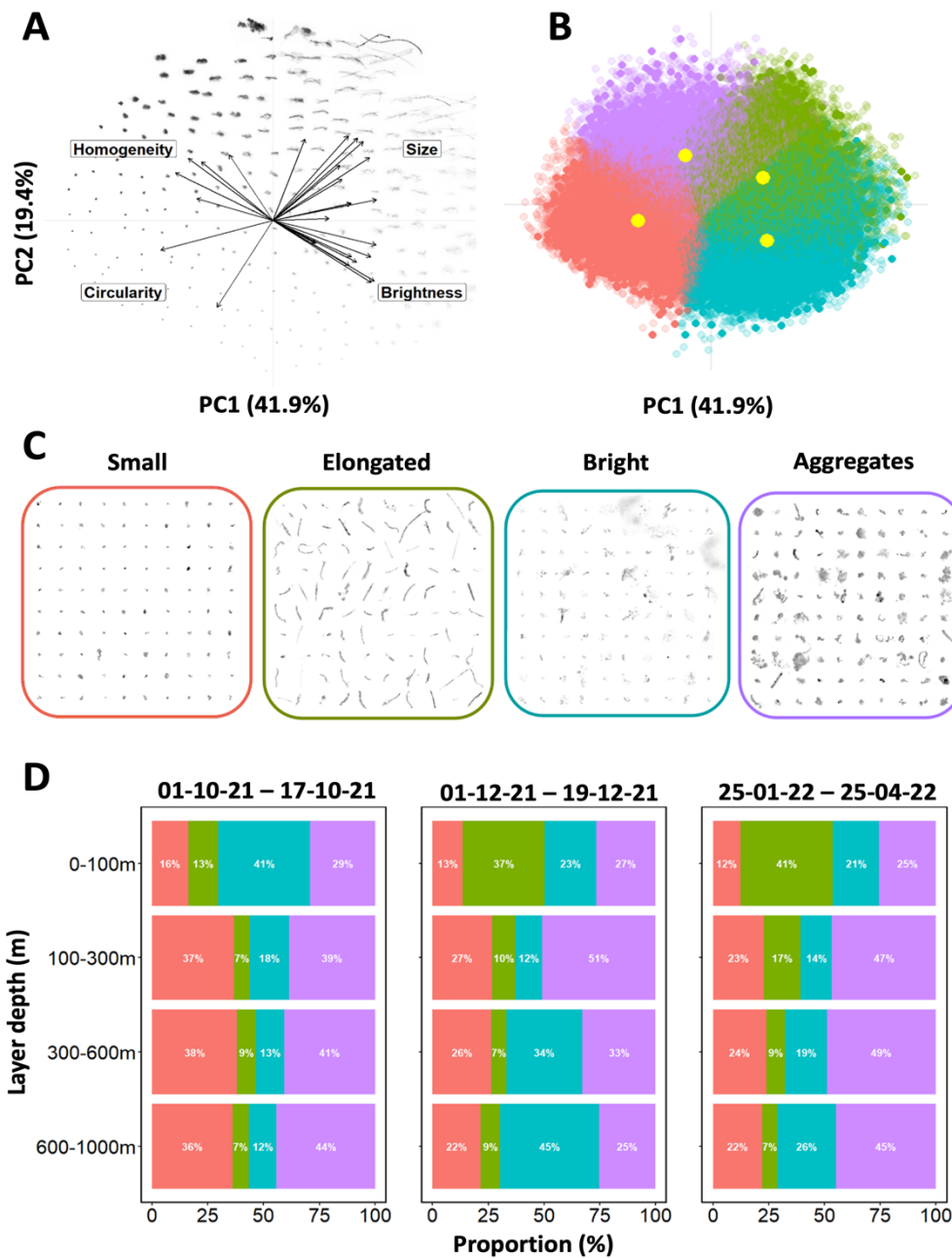
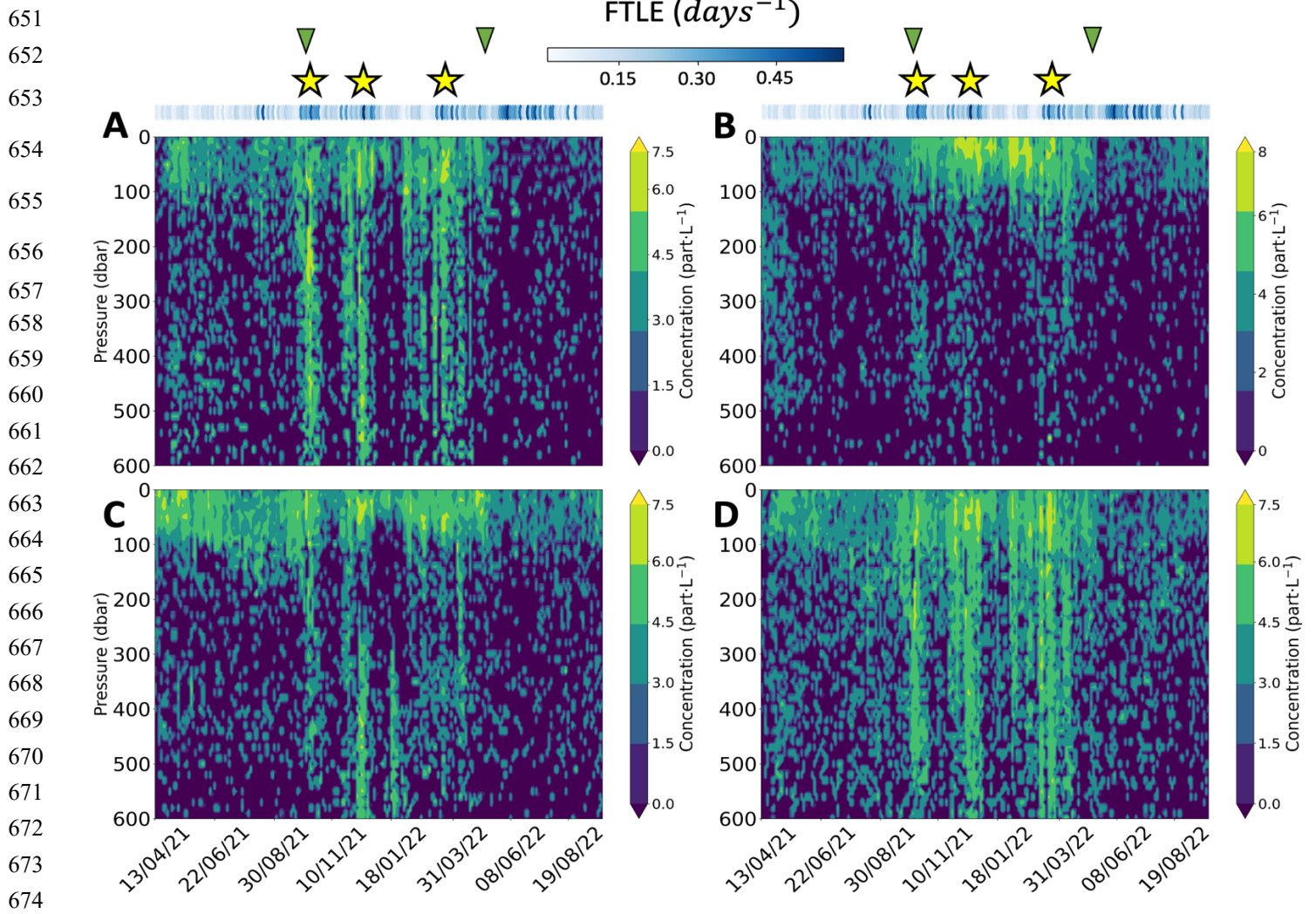


Figure 5: Results of PCA/K-means clustering on morphological traits of particles. Panels show, (A) the distribution of particle images in the morphospace built by PCA, (B) the K-means clustering classification where each point represents an image, and each cluster is colored independently. The yellow dots represent the center of each cluster. The most transparent dots represent images not retained in the analysis, (C) Representative subset of each morphotype and (D) the proportion (%) of each group according to depth layers during the three export features observed in the morphotypes spatio-temporal distribution. The color code is the same for (B), (C) and (D).



675 **Figure 6: Morphotypes spatio-temporal distribution of exclusive members. The panels show log transformed concentrations**
676 **($part.L^{-1}$) of (A) Small, (B) Elongated, (C) Bright and (D) Aggregates morphotypes. Yellow stars and green triangles have the same**
677 **meaning as in the Figure 2**

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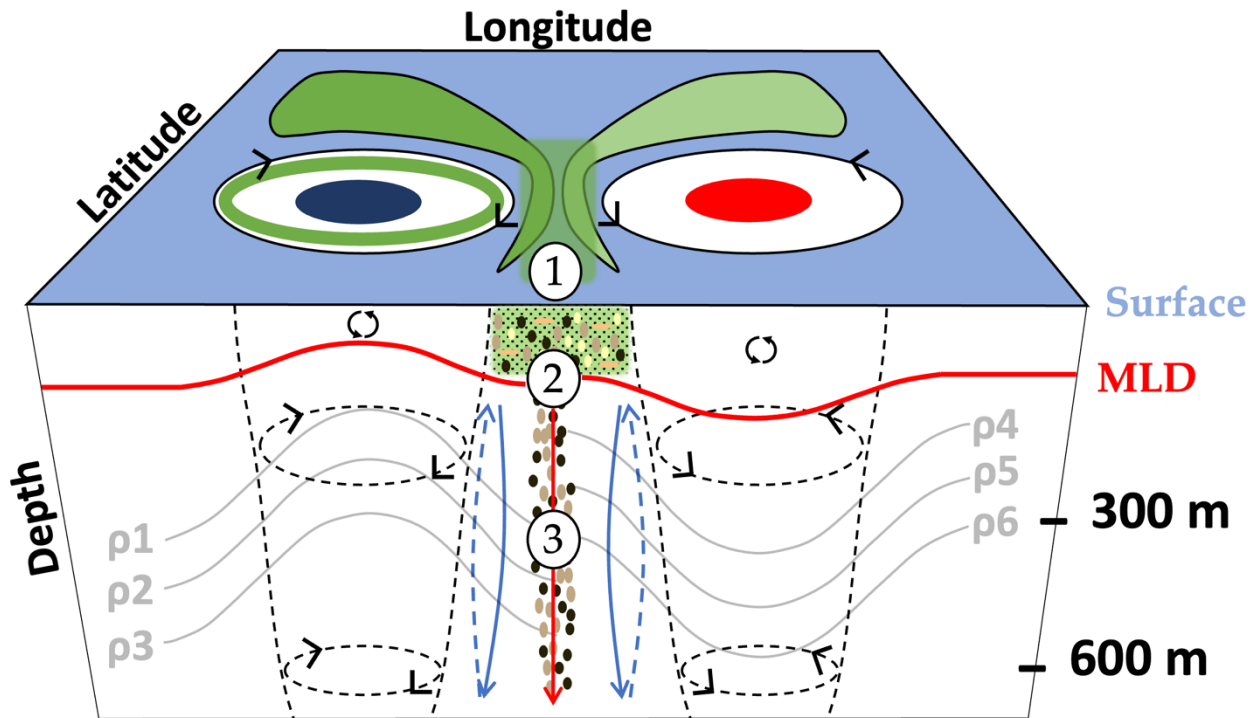


Figure 7: Schematic view of the proposed mechanism for the deep observed accumulation of particulate carbon in the mesoscale context of the study. (1) Aggregation and coagulation of surface organic matter (green shapes around eddies), facilitated by eddy trapping or stirring. The green circle in the cyclone represents the accumulation of POM at its periphery (resulting from the divergence of the water masses) (2) Influence of the Gravitational Carbon Pump (represented by the red vertical arrow) that transporting selected marine snow types with sufficient downward speed beneath the Mixed Layer Depth (MLD). (3) Coupling with a frontogenesis mechanism inducing enhanced physical vertical speeds (represented by blue arrows), particularly below the MLD and in interface zones between mesoscale structures. The coupling between (1), (2) and (3) can lead to the transport of particles down to significant depths (600 meters in our study). Black arrows in the MLD represent the physical mixing.

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