Evolution of biogeochemical Properties Inside Poleward Undercurrent Eddies in the Southeast Pacific Ocean

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Abstract. Oceanic eddies are ubiquitous features of the circulation thought to be involved in transporting water mass properties over long distances from their source region. Among these is a particular type with a core within the thermocline with little surface expression. Despite their significance, their role in the ocean circulation remains largely undocumented from observations. This study characterizes the variations in internal biogeochemistry, disparities with external properties, and processes influencing the dissolved oxygen budget of Poleward undercurrent eddies (Puddies) during their transit to oceanic waters. Employing a high-resolution coupled simulation of the Southeast Pacific, we document biogeochemical properties and processes associated with the nitrogen cycle inside Puddies and contrast them with those of the surrounding environment. Our findings reveal that Puddies capture a biogeochemical signal contingent upon their formation location along the coast, particularly associated with the core of the Peru-Chile Undercurrent at the core of the Oxygen Minimum Zone (OMZ). While permeability at the periphery facilitates exchange with external waters, thereby modulating the original properties, the core signal retains negative oxygen (O_2) anomalies and positive anomalies of other biogeochemical tracers. These anomalous conditions result in tracer values exceeding the 90th percentile of their distribution in the open ocean, in contrast to the formation zones, where anomalies only surpass the 50th percentile. This indicates that Puddies may play a role in modulating the average properties of the open ocean. Suboxic ($O_2 < 20$ μM) cores are prevalent near the coast but decrease in abundance with distance from shore, giving way to a predominance of hypoxic (20 μM $< O_2 <$ 45 μM) cores (predominating at 60% in the open sea), suggesting core ventilation during transit. The principal mechanism governing O_2 input into, or output from the eddy core entails lateral and vertical advection, with vertical mixing supplying O_2 to a lesser extent. Biological activity consumes O_2 inside Puddies for around 6 to 12 months, especially intensely for the first 100 days, thus facilitating the persistence of low O_2 conditions and extending the lifetime of biogeochemical anomalies within the core (up to 800 km offshore). The ammonium and nitrite deplete earlier

42 in the eddy core with a decay rate greater than the nitrate and nitrous oxide, while these are accumulating in
43 open sea (up to 16% and 100% higher than mean state, respectively). Our results suggest that southern regions
44 of the southeast Pacific OMZ undergo greater deoxygenation and nutrient enrichment due to Puddies compared
45 to northern regions. However, the combination of various physical conditions can generate zones with more
46 pronounced changes in the nitrite (subsurface water masses due to interactions with the Puddies, such as at
47 30ºS. The maximum contribution of NO_2^-) takes place in particular along this latitude, with a 460% increase
48 compared to the mean state, near the coastal zone.

49 In summary, Puddies formed along the Chilean coast capture distinct biogeochemical "signatures" depending
50 on where they form. In the north, minimal ventilation fosters suboxic conditions and denitrification –leading
51 to deficits of nitrate (NO_3^-) and nitrous oxide (N_2O) but high NO_2^- and ammonium (NH_4^+)– whereas central
52 and southern subregions show increased NO_3^- and higher N_2O. Moreover, cross-shore exchange between
53 Equatorial Subsurface Water and Subantarctic Water further amplifies this variability, giving rise to eddies
54 with diverse nutrient and oxygen properties as they move offshore.

55

1 Introduction

57 Oxygen plays a fundamental role for life in the ocean, and numerous processes regulate its concentration in
58 the water column. In subsurface waters (100-800 m depth), oxygen concentrations (O_2) decrease significantly
59 due to the decomposition of organic matter and limited ventilation, leading to the formation of oxygen
60 minimum zones (OMZ) in eastern boundary upwelling systems (EBUS; Wyrtki, 1962; Helly & Levin, 2004;
61 Karstensen et al., 2008; Paulmier & Ruiz-Pino, 2009; Stramma et al., 2010). Under these conditions of low
62 oxygen in the subsurface (i.e. dissolved O_2 less than 20 μM), heterotrophic metabolic processes are
63 important, dominated by activity of bacteria and archaea, resulting in significant shifts in biogeochemical
64 cycles (Lam et al., 2009; Paulmier & Ruiz-Pino, 2009; Wright et al., 2012).

65 The nitrogen cycle in the oceans involves various chemical species with different oxidation states. Outside
66 the OMZ, where conditions are oxygenated, dinitrogen (N_2) is transformed into ammonium (NH_4^+), nitrite
67 (NO_2^-), and nitrate (NO_3^-) through nitrification, with nitrous oxide (N_2O) produced as a byproduct. However,
68 within the OMZ, where O_2 is depleted, nitrate becomes the primary oxidant, triggering denitrification. In this
69 process, nitrate is reduced to gaseous forms (N_2 and N_2O), which can then be released into the atmosphere.
70 This process has implications for primary production, carbon sequestration, and the release of N_2O into the
71 atmosphere, a potent greenhouse gas (Goreau et al., 1980; Mantoura et al., 1993; Sarmiento & Gruber, 2006;
72 Lam et al., 2009; Paulmier & Ruiz-Pino, 2009; Wright et al., 2012).

73 The southeast Pacific Ocean is the site of one of the most extensive and shallow OMZs (Paulmier & Ruiz-
74 Pino, 2009), where even anoxic conditions can be observed (Ulloa et al., 2012). Several authors have
75 determined the vertical and zonal (offshore) extent of the OMZ, which exhibits significant seasonal
76 variability, modulated both meridionally by subsurface currents towards the pole, and zonally by mesoscale
77 processes (jets, eddies, fronts, filaments, etc.; Bettencourt et al., 2015; Chaigneau et al., 2011; Grados et al.,
78 2016; Hormazabal et al., 2013; Morales et al., 2012; Stramma et al., 2013; Vergara et al., 2016; Pizarro-Koch

79 et al., 2019). These processes result in changes in water mass properties, and together contribute up to a 25%

80 reduction in O_2 volume during spring (Pizarro-Koch et al., 2019).

81 Furthermore, future projections suggest the expansion of these O_2 depleted zones through global warming

82 (Matear & Hirst, 2003; Stramma et al., 2010; Oschlies et al., 2018) although uncertainties remain (Almendra

83 et al., 2024). The increase in sea surface temperature will affect O_2 solubility, and enhanced water column

84 stratification will impact a range of biological processes that influence O_2 concentrations (Couespel et al.,

85 2019; Keeling et al., 2010; Matear & Hirst, 2003; Oschlies et al., 2018; Schmidtko et al., 2017). In addition,

86 various mechanisms can potentially modify ventilation processes, leading to changes in subsurface water

87 properties. While in current generation climate models, the changes in mean circulation either in the tropics

88 or the high-latitudes, mediated by diapycnal mixing, are invoked to explain the ventilation process (Pitcher et

89 al., 2021), regional modeling studies highlight the importance of mesoscale dynamics, such as mesoscale

90 eddies and zonal jets, in expanding and ventilating oceanic zones with oxygen deficits (Bettencourt et al.,

91 2015; Auger et al., 2021; Calil, 2023). The regional models also provide a more realistic representation of the

92 OMZs than the climate models that do not resolve sub to mesoscale dynamics. This is why understanding the

93 role of mesoscale dynamics on the O_2 and carbon cycles in EBUS has been a key focus of research in recent

94 years.

95 'Poleward undercurrent eddies' (Puddies) are types of subsurface or intrathermocline eddies characterized by

96 coherent anticyclonic lenticular shaped vortices with cores located within the pycnocline and relatively

97 homogenous interior waters (Dugan et al., 1982; McWilliams, 1985; Kostianoy and Belkin, 1989). Puddies

98 originate in the EBUS (Frenger et al., 2018) due to the interaction of the poleward-flowing current with the

99 continental slope, generating submesoscale instabilities with anticyclonic vorticity, subsequently forming

100 these characteristic mesoscale structures (Hormazabal et al., 2013; Combes et al., 2015, Molemaker et al.,

101 2015; Thomsen et al., 2016; Contreras et al., 2019). These eddies represent 30-55% of the anticyclone eddies

102 originating in the EBUS (Pegliasco et al., 2015; Combes et al., 2015) with cores that are warmer, saltier, O_2-

103 depleted, and nutrient-enriched relative to surrounding waters (Collins et al., 2013; Hormazabal et al., 2013;

104 Morales et al., 2012; Johnson and McTaggart, 2010). Therefore, Puddies can play a crucial role in

105 transporting these water properties hundreds or thousands of kilometers offshore to subtropical gyres,

106 potentially contributing to the expansion of the OMZ beyond the coastal region (Frenger et al., 2018).

107 Observations of low O_2 events in open ocean regions provide support for this idea (Lukas and Santiago-

108 Mandujano, 2001; Johnson and McTaggart, 2010; Cornejo-D'Ottone, 2016; Schütte et al., 2016b; Stramma et

109 al., 2013, 2014; Karstensen et al., 2015), with further evidence of biogeochemical processes typically

110 observed only in the OMZ, such as N_2O production (Cornejo-D'Otonne et al., 2016; Arévalo-Martínez et al.,

111 2016; Grundle et al., 2017) and nitrogen loss through denitrification (Altabet et al., 2012; Löscher et al.,

112 2015). Additionally, the observed O_2 utilization rates within the eddy cores range from 0.29 to 44 nmol O_2 L$^-$

113 ^{1} d^{-1}, which is up to 3 to 5 times higher than in the surrounding waters (Cornejo-D'Ottone et al., 2016;

114 Karstensen et al., 2015). There is evidence of harboring microbial communities and metabolisms associated

115 with low-oxygen environments that persist even when the eddies enter highly oxygenated waters, a

116 phenomenon known as the "stewpot effect" (Löscher et al., 2015; Frenger et al., 2018).

The Southeast Pacific (SEP) is characterized by extensive subsurface mesoscale eddy activity with radii ranging from ~25 to ~50 km and cores of ~500 m of vertical extent (Chaigneau et al., 2009; Hormazabal et al., 2013; Combes et al., 2015, Frenger et al., 2018). They transport a total volume of approximately 1 Sv (1 Sv = ~1x10^6 m^3 s^{-1}) westward with an average velocity of ~2 km d^{-1} (Hormazabal et al., 2013). The cores of these eddies exhibit homogenous salinity profiles (>34.5) and low O$_2$ concentrations (< 1.0 mL L^{-1}), linking them to Equatorial Subsurface Water (ESSW) transported poleward by the Peru-Chile Undercurrent (PCUC; Hormazabal, 2004; Colas et al., 2012; Hormazabal et al., 2013). Generally, the low values of O$_2$ in subsurface eddies is related to higher concentrations of nitrate, phosphate, and silicate (Czeschel et al., 2015). However, under suboxic conditions (O$_2$ < 20 μM), the prevailing anaerobic metabolism is denitrification, where nitrate is utilized as an electron acceptor, leading to increased production of NO$_2^-$ and N$_2$O (Goreau et al., 1980; Mantoura et al., 1993; Lam et al., 2009; Wright et al., 2012). Within these eddies, various biogeochemical processes coexist that are highly sensitive to O$_2$ variations, while physical processes modulate biogeochemical patterns through vertical and lateral mixing, submesoscale stirring, or mass exchange with water masses from different origins through turbulent advection (José et al., 2017; Kartensen et al., 2017; Loveccio et al., 2022).

This complexity of processes involved during the life cycle of a Puddy, along with the lack of continuous in situ measurements, limits our understanding of nutrient recycling throughout their lifetime, and the balance between processes controlling the rate of change of O$_2$ and nutrients. In the present study, we aim to characterize the internal biogeochemistry of eddies formed under various low-oxygen conditions in the SEP. We analyze the physical and biogeochemical factors influencing the variability in the lifespan of elements trapped within the Puddies, with a particular focus on those related to the nitrogen cycle, as they travel across the OMZ towards better-ventilated oceanic waters. Specifically, we document the evolution of water mass properties and processes inside Puddies with contrasting initial O$_2$ concentrations (suboxic versus hypoxic) to evaluate their role in maintaining the OMZ. Additionally, we aim to address knowledge gaps in the biogeochemical dynamics of this type of eddy, stemming from the lack of observational data, particularly in the SEP. To quantify the changes Puddies undergo due to their complex dynamics, we use a regional coupled biogeochemical model simulation.

Our approach involves a robust statistical analysis of contrasting water mass properties inside and outside the Puddies. First, we characterize the initial biogeochemical signal from their formation to assess how, and to what extent, the biogeochemical properties of Puddy' cores vary across different regions of the SEP. Second, we quantify how these properties influence the subsurface waters through which Puddies travel, evaluating the balance of processes involved.

The structure of this study is as follows: Section 2 details the model and methods used for the identification and characterization of Puddies. Section 3 describes the biogeochemical characterization inside and outside the Puddies, changes in the O$_2$ budget, and variations in biogeochemical properties from the coastal to oceanic zones. Section 4 discusses the results, and Section 5 presents the main conclusions and future projections.

2 Methods

2.1 Regional biogeochemical coupled model

We used a high-resolution, coupled physical-biogeochemical model simulation of the SEP that considers the main processes involved in the transformation of the water masses relevant to the OMZ variability and the dynamics of the Peru-Chile Undercurrent (PCUC). This current plays a significant role in generating Puddies and in the southward extension of the OMZ in the Peru-Chile EBUS.

The physical dynamics was simulated using the Regional Ocean Modelling System (ROMS), a regional ocean circulation model that solves the primitive equations with free surface and sigma coordinates (Shchepetkin and McWilliams 2005; 2009). ROMS was coupled with the biogeochemical model BioEBUS, specifically developed for Eastern Boundary Upwelling Systems (EBUS) and based on the nitrogen cycle using $N_2P_2Z_2D_2$ model formulation (Koné et al., 2005; Gutknecht et al., 2013a). We adopted the same configuration as specified in several other studies in the region (Dewitte et al., 2012; Vergara et al., 2016; Pizarro-Koch et al., 2019). The model has a spatial resolution of 1/12°, 37 vertical levels. 3-day mean outputs are used, which is suitable for resolving mesoscale features. The overall domain covers the latitudinal range of 12°N to 40°S from the coast to 95°W, although the present study focuses on latitudes off the coast of Chile between 20°S and 40°S (Figure 1a). The simulated period was from 2000 to 2008.
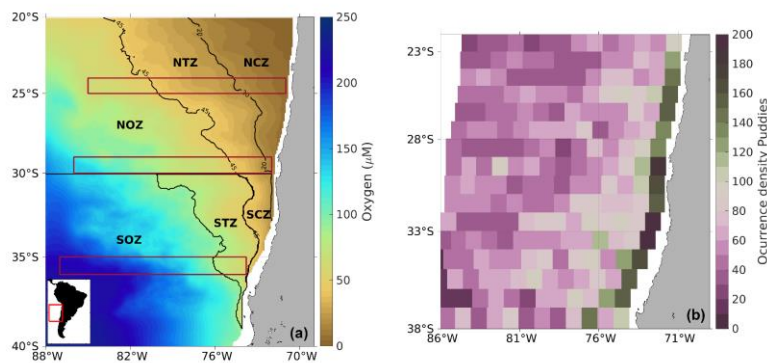
Figure 1. (a) Modeled dissolved O_2 climatology off the Chilean coast, and (b) spatial distribution of the occurrence density of Puddies identified over the nine-year period. Oxygen was considered as being in the isopycnal layer 26.6 kg m^{-3} representative of the OMZ core (defined with S$_{core}$ layer; see Section 2.2). The study area covers 20 - 40°S and from the coast to 88°W. The contours used to subdivide regions are based on biogeochemical differences among water masses (see details in Section 2.2). Northern Coastal Zone (NCZ) is delimited by the suboxic zone limit (O_2 = 20 μM); Northern Transition Zone (NTZ) and Southern Coastal Zone (SCZ) separate to 30°S and the traditional OMZ limit (O_2 = 1mL L^{-1} or ~ 45 μM), Northern Oceanic Zone (NOZ) with O_2 > 45 μM to northern 30°S; Southern Transition Zone (STZ) delimited with oxygen contours of 45 μM < O_2 < 90 μM and Southern Oceanic Zone (SOZ) with 90 μM < O_2, both southern 30°S. Red boxes enclosed the zonal bands taken for made the

Comentado [1]: Figure 1 was modified following the recommendations and it now only includes two panels allowing for a bigger size and font. The new figure 1a displays the limits of the new domains (6 regions)

181 **average compounds by Puddies to 25ºS (from 71ºW to 85ºW), 30ºS (72ºW to 86ºW) and 36ºS (74ºW to 87ºW; see**

182 **Sections 2.6.2 and 3.4). (Right box) Occurrence density (colormap) is quantified by the total number of Puddies**

183 **identified in each 1°x1° area for each snapshot (Δt = 3 days), with the possibility that the same eddy may be**

184 **counted more than once if remaining in the same area. Numbers refer to the total occurrence density by region**

185 **(see details in Section 2.5).**

186

187 The model uses atmospheric momentum forcing data from NCEP-NCAR statistically downscaled based on

188 the QuickSCAT satellite data (see Goubanova et al. (2011) for details). Latent heat flux and other variables –

189 for estimating other air-sea fluxes– such as air temperature and humidity are provided by monthly

190 climatology with a resolution of 1° x 1° from COADS (da Silva et al., 1994). The boundary conditions for

191 temperature, salinity, and horizontal velocity were provided by the SODA 1.4.2 reanalysis (Smith et al.,

192 1992). The BioEBUS model consists of 12 compartments interacting through advection-diffusion equations

193 and source-minus-sink (SMS) processes. The considered components include inorganic dissolved nutrients

194 (NO_3^-, NO_2^-, and NH_4^+), large and small phytoplankton ("small" representing nanophytoplankton; mainly

195 small flagellates between 2 and 20 µm and "large" representing microphytoplankton; mainly diatoms

196 between 20 and 200 µm), large and small zooplankton ("small" representing microzooplankton; mainly

197 heterotrophic ciliates between 20 and 200 µm, and "large" mesozooplankton; mainly copepods between 200

198 µm and 2 mm), and detritus (small and large). Dissolved organic nitrogen (DON) was considered following

199 the formulation of Dadou et al. (2001, 2004) and Huret et al. (2005), O_2 including its ocean-atmosphere

200 interaction according to Peña et al. (2010) and Yakushev et al. (2007), and the production of N_2O using the

201 parameterization of Suntharalingam et al. (2000, 2012). The boundary and initial conditions for the BioEBUS

202 model were obtained from the CARS2006 climatology (CSIRO Atlas of Regional Seas) for O_2 and NO_3^-,

203 with constant vertical profiles adopted for NH_4^+, NO_2^-, and dissolved organic nitrogen (DON) (based on

204 Koné et al. (2005)). The estimated phytoplankton biomass comes from the model. Detailed information on

205 simulation and validation of the physical model (ROMS) is given by Dewitte et al. (2012) and Vergara et al.

206 (2017). The parameter configuration of BioEBUS is the same as that used in Montes et al. (2014).

207 The time rate of change of the concentration of each component is governed by the advection-diffusion

208 equation (see Gutknecht et al., 2013a). For instance, the O_2 balance is given by

209
$$\frac{\partial O_2}{\partial t} = -\nabla \cdot (\vec{u} O_2) + K_H \nabla^2 O_2 + \frac{\partial}{\partial z}\left(K_z \frac{\partial O_2}{\partial z}\right) + SMS(O_2) \tag{1}$$

210 where $\vec{u} = (u, v, w)$ represents the fluid velocity, with components u for zonal, v for meridional, and w for

211 vertical. The first term on the right-hand side represents the advection (ADV = $-\nabla \cdot (\vec{u} O_2)$), which is a

212 scalar, but can also be decomposed in the sum of zonal (XADV = $-u\frac{\partial O_2}{\partial x}$), meridional (YADV = $-v\frac{\partial O_2}{\partial y}$),

213 and vertical (VADV = $-w\frac{\partial O_2}{\partial z}$) components. The second and third terms correspond to horizontal (HMIX)

214 and vertical (VMIX) diffusion, where K_H is the horizontal eddy diffusion coefficient (set to 100 m² s ⁻¹ in this

215 version of the model), and K_z is the turbulent diffusion coefficient calculated using the K-profile

216 parameterization mixing scheme (Large et al., 1994). The last term $SMS(O_2)$ represents the effect of sources

217 and sinks associated with biogeochemical processes. For O_2, the source process is primary production, and
218 sink processes include remineralization, nitrification, and zooplankton excretion (Peña et al., 2010).

2.2 Characterization of the study area

Comentado [2]: we have reduced the number of biogeochemical zones or study areas and the method has been expanded

220 The study area extends from 20º to 40ºS and from the Chilean coast to 88ºW. In this region the OMZ core
221 ($O_2 < 45$ μM or ~ 1 mL/L) is centered at a density surface of $\sigma_\theta = 26.6$ kg m^{-3} (S_{core}) following as reference
222 the core of ESSW near coastal zones, which is similar to Pizarro-Koch et al., (2019; see Section 2.2). S_{core}
223 depth varies, being shallow in the coastal area and deeper in the oceanic region (Table 1). Near the slope, a
224 deepening in S_{core} is observed north of 30°S, where the slope is narrower whereas south of 30°S, it widens.

225 All variables were interpolated from the original sigma vertical coordinate to depth at 5-meter intervals from
226 800 m to the surface. In the model, there are 28 vertical levels spanning ~1000 m depth to the surface and 9
227 vertical levels for depths >1000 m (Figure S1). Regions were selected for averaging tracers and rates, which
228 was based on the characteristic water masses in the region, resulting in domains with irregular shapes (see
229 Figure 1a). The water masses that were considered include primarily the Subantarctic Water (SAAW; also
230 called East-southern Pacific Intermediate Water (ESPIW), characterized here by 11.5°C, 33.8) south of 30°S,
231 where the OMZ is predominantly hypoxic ($O_2 < 45$ μM; as described by Naqvi et al., 2010, and Pizarro-Koch
232 et al., 2019) and significantly narrower. The biogeochemistry of SAAW differs notably from that of
233 Subtropical Water (STW; 20°C, 35.2) north of 30°S, which features a zonally broader OMZ characterized by
234 suboxic conditions ($O_2 < 20$ μM, Figure 2; following Wright et al., 2012), particularly in oxygen,
235 ammonium, and nitrite.

Comentado [3]: Figure S1 clarify the number of sigma levels contained in the first 1000 m

Comentado [4]: This part was modified to clearly detail the criteria used to delineate the study areas.

236 The separation of coastal, transitional, and oceanic zones considered the dominance of Equatorial Subsurface
237 Water (ESSW; 12.5°C, 34.9) in the subsurface waters and its increasing oxygenation farther from the coast
238 (Silva et al., 2009). Given the importance of ESSW in defining the study areas and as the primary water
239 source enclosed in the Puddies, the isopycnal surface associated with the ESSW and OMZ core was used as a
240 reference. Specifically, we focused on the isopycnal with a density of 26.6 kg m^{-3}, corresponding to the
241 reference OMZ core in this model (Pizarro-Koch et al., 2019), which was used in part of our statistical
242 analysis.

243 We thus came up with 6 subregions: Northern Coastal Zone (NCZ; suboxic conditions); Northern Transition
244 Zone (NTZ; hypoxic conditions); Northern Oceanic Zone (NOZ; with 45 μM $< O_2$); Southern Oceanic Zone
245 (SOZ; with 90 μM $< O_2$); Southern Transition Zone (STZ with 45 μM $< O_2 < 90$ μM) and Southern Coastal
246 Zone (SCZ; hypoxic conditions, Figure 1a).

Figure 2. Diagram showing the averages of conservative temperature, absolute salinity, and biogeochemical tracers (in color) for the six study zones (see Figure 1a). The biogeochemical tracers include oxygen (column 1), ammonium (column 2), nitrate (column 3), nitrite (column 4), and nitrous oxide (column 5). From top to bottom the region's names are : Northern Coastal Zone (NCZ); Northern Transition Zone (NTZ); Northern Oceanic Zone (NOZ); Southern Oceanic Zone (SOZ); Southern Transition Zone (STZ) and Southern Coastal Zone (SCZ). The zones' selection is based on the characteristic water masses in the region, primarily the SAAW (Subantarctic Water) south of 30°S, whose biogeochemistry differs significantly from the STW (Subtropical Water) north of 30°S, particularly in oxygen, ammonium, and nitrite. The separation of the coastal, transitional, and oceanic zones considered the dominance of the ESSW in the subsurface waters and its oxygenation away from the coast.

Within the first ~100 km off the coast, the formation zone for Puddies was identified, where a large number of surface and subsurface eddies are typically generated (e.g., Chaigneau et al., 2009) as shown by the occurrence density Puddies (Figure 1b green strip). We considered the total number of Puddies's profiles with a grid box of approximately 1° by 1° in order to characterize the biogeochemical properties of the source water that the Puddies eventually enclose upon formation (see Section 2.6.1).

2.3 Definition of "mean state" and mesoscale contribution

To estimate the physical and biogeochemical perturbations from the mean field associated with the eddies, we use a Reynolds decomposition, which for the field of NO$_3^-$ concentration is written as follows in Eq. (2):

$$NO_3(x,y,z,t) = <NO_3>_{9-year} + NO_3'(x,y,z,t) \qquad (2)$$

where $<NO_3>_{9-year}(x,y,z)$ is the "mean state" of NO$_3^-$ calculated as an overall mean across 9 years simulated between the period 2000-2008. Fluctuations of this "mean state" thus consider the large intraseasonal and seasonal variability and are denoted as $NO_3'(x,y,z,t)$. Similarly, for the other variables, $<S>_{9-year}, <NO_2>_{9-year}$, etc., denoted the "mean state", whereas S´, NO$_2$´ etc., correspond to anomalies, which includes eddy fluctuations and changes associated with annual and interannual variability. The averages anomalies were denoted as $<S'>, <NO_2'>$, etc., This decomposition method was used for all variables analyzed in each selected subregion (Figure 1a). To evaluate the impacts of the Puddies on the

273   various fields, we used an algorithm to identify subsurface eddies (See details in Section 2.5) and then

274   compared the perturbed fields inside the Puddies with the total field. This latter procedure is further

275   explained in section 2.6.

276   **2.4 Calculation of AOU, ΔNO_3^- and ΔN_2O**

277   The apparent oxygen utilization (AOU), NO_3^- production (ΔNO_3^-), and N_2O production (ΔN_2O) provide an

278   estimate of how much has been produced/consumed by biological processes since the water mass was formed

279   in terms of oxygen, nitrate, and nitrous oxide respectively. These estimates are associated with the time the

280   water mass has spent without coming into contact with the ocean surface or being ventilated.

281   The AOU calculation was derived from the García & Gordon (1992) algorithm, based on the O_2 saturation

282   concentration at any temperature and salinity,):

283
$$AOU = [O_2]_{sat} - [O_2] \qquad (3)$$

284   where $[O_2]_{sat}$ is the oxygen saturation and was calculated based on TEOS-10 (using the Gibbs-SeaWater

285   oceanographic toolbox) (https://www.teos-10.org/software.htm), for $[O_2]$ we used the modeled oxygen. The

286   N_2O production (ΔN_2O) was calculated using the Gruber & Sarmiento (2002)'s methodology and the

287   following relationship, Eq. (4):

288
$$\Delta N_2O = [N_2O] - [N_2O]_{sat} \qquad (4)$$

289   where $[N_2O]_{sat}$ is the nitrous oxide saturation calculated from to modeled temperature and salinity, for $[N_2O]$

290   we used the modeled nitrous oxide. NO_3^- production (ΔNO_3^-) is defined as follows,

291
$$\Delta NO_3^- = [NO_3^-] - [NO_3^-]_{preformed} \qquad (5)$$

292   where $[NO_3^-]$ is the modeled nitrate. The value of $[NO_3^-]_{preformed}$ in subsurface waters considered for the

293   above calculation was that of Equatorial Subsurface Water (ESSW), except in SOZ where the value for

294   Antarctic Subsurface Water (SAAW) was taken from Llanillo et al. (2012). The assessment of the modeled

295   O_2, NO_3^- and surface NO_3^- is provided in Appendix.

296

297   **2.5 Puddy Identification**

298   For the identification of Puddies, the algorithm proposed by Faghmous et al. (2015) was adapted to deal with

299   subsurface eddies that have a weak dynamical signature at the surface of the ocean. The original algorithm is

300   based on the presence of local extreme values of sea level anomalies (SLA) (minimum in the case of cyclonic

301   eddies and maximum in the case of anticyclonic eddies, considering a neighborhood defined a priori around

302   it). Because the SLA signal from subsurface eddies may be rather weak or absent, the present study used

303   anomalies in the layer thickness (δh) defined as the difference between the depths of the density surfaces

304 S_{upper} = 26.0 kg m^{-3} and S_{lower} = 26.9 kg m^{-3}. Thus, positive anomalies ($\delta h > 0$) indicate the presence of

305 subsurface anticyclonic eddies due to their convex shape (for our case, Puddies). When δh is at its maximum

306 (δh_{max}), the largest closed contour around the geographical location of δh_{max} is considered as the edge of the

307 eddy, as δh_{max} is associated with the center of the eddy and the points contained within the eddy edge are the

308 body of the eddy (Figure S2a; Faghmous et al., 2015). Starting from δh_{max}, a gradual decrease of 0.1 m was

309 used to establish the size and amplitude of the eddy. Only eddies that reached a minimum horizontal area of

310 30 grid points (A_{min}~1.95x10^9 m², equivalent to a radius of ~ 25 km) were considered, as eddies below this

311 threshold are not well identified (reducing the total of selected Puddies by 30%). Additionally, only eddies

312 with a radius not exceeding 150 km (~32 pixels in diameter) were included, as larger eddies are also not well

313 detected, with at most three closed-contour structures per snapshot being discarded. This also helps

314 distinguish eddies in coastal regions from other processes, such as coastal trapped waves or upwelling events

315 which occur on larger spatial scales.

316 Eddy identification was performed using 3-day averages across the entire period. Subsequently, all δh_{max}

317 positions were classified by subregion and in 1°x1° cells for their enumeration (Figure 1b) and for

318 characterizing the average properties of these Puddies along the coast (see Section 2.6.1; statistical analyses

319 are shown in section 3).

320 **2.6 Compound Formation**

321 **2.6.1 Average Puddies Profiles**

322 To understand the typical conditions within Puddies identified in the formation zone and each subregion,

323 average profiles were constructed as follows: i) all eddy centers (i.e., δh_{max} positions) were classified in

324 1°x1° grid cells along the coast and also within the regions defined in Figure 1a, ii) for each eddy center,

325 vertical profiles were extracted between the density surfaces S_{upper} and S_{lower} for all variables, in each

326 corresponding region, iii) then, these profiles were time-averaged to obtain typical profiles for each variable.

327 For the different regions, the values associated with the S_{core} are shown (Section 3.2) to emphasize changes in

328 the ESSW core. The analysis of these results is presented in sections 3.1 and 3.2.

329 **2.6.2 Average zonal compound**

330 Based on the identification of eddies over a 9-year period, different latitude bands (25°S, 30°S, and 36°S,

331 Figure 1a) were selected to create a composite constructed from 3D Puddies, considering all the δh_{max} values

332 identified within 1°x1° areas. For these Puddies, we estimated characteristics within the entire eddy volume

333 as follows: i) for each δh_{max} (Puddy center), a mask of the entire volume was created; ii) the area mask was

334 calculated to identify the edge using the Faghmous et al. (2015)'s algorithm, which was found to be most

335 accurate approach (Figure S3; see sensitivity analysis in the Supplementary Material); iii) this mask was

336 applied across all depths (at 5-meter intervals), creating an irregular cylinder between S_{upper} and S_{lower}; iv)

337 from the total volume enclosed by the cylinder, an average vertical profile was obtained at each time step for

338 each variable (see an example of vertical Puddy characterization in Figures S2b-e).

> **Comentado [5]:** Following the reviewer's recommendation, we conducted a more robust analysis by considering all Puddies identified at each time step (t = 3 days) over a 9-year period across the three selected latitudes. Figures 8–11 and Table 4 summarize the findings.

339 A total of 862 Puddies (δh_{max} values) were accounted for in the 25°S zonal band, 810 in the 30°S band, and

340 658 in the 36°S band. Additionally, for each latitude, biogeochemical variables averaged over the 9-year

341 period, representing the mean state (defined in Section 2.3), were used to calculate an average profile

342 associated with a 1°x1° area. Anomalies were then calculated as the difference between these two profiles.

343 The results of this statistical analysis and the subsurface modifications caused by Puddies are presented in

344 Section 3.4.

345 **2.7 Calculation of percentiles**

346 To assess the significance of the internal contribution of Puddies relative to the mean state (defined in

347 Section 2.3), we employed a bootstrap method, which involved randomly sampling more than 200 positions

348 in each region and deriving diagnostics. A total of 92 random time steps were selected, and for each time

349 step, 1,000 latitudes and 1,000 longitudes were generated within the domain. These positions were then

350 filtered for each region. The total number of random positions found per region was as follows: 1,246 in

351 NCZ, 1,474 in NTZ, 3,509 in NOZ, 6,808 in SOZ, 521 in STZ, and 235 in SCZ (Table S2).

352 For each obtained position, biogeochemical properties were extracted at the S_{core}. This approach generated an

353 ensemble of values, allowing us to infer the 50th, 75th, and 90th percentiles (P50, P75, P90) used to provide

354 an estimate of significance levels.

355

356 **3 Results**

357 **3.1 Contrasting biogeochemical characteristics inside and outside the Puddies in the formation zone**

358 The region within the first ~100 km off the coast was considered a formation zone for Puddies where a large

359 number of surface and subsurface eddies are typically generated (e.g., Chaigneau et al., 2009; Figure 1b,

360 green strip). Approximately 1° of latitude x 1° longitude boxes were selected along the coast to characterize

361 the biogeochemical properties of the source water that the Puddies eventually enclose upon formation (see

362 Section 2.6.1).

363 Over the 9-year study period in the simulated study region (Figure 1a), an average of approximately 14

364 Puddies were observed at each time step, resulting in a total of ~15,340 Puddy profiles (defined as the

365 vertical profile associated with the δh_{max}) identified (see Section 2.5). If the same eddy remained within the

366 same 1°x1° grid area, it was counted multiple times (using a 3-day time step) until the center of the eddy

367 moved to an adjacent 1°x1° grid. The area with the highest density of identified Puddies profiles was

368 concentrated in the coastal region (2,548), within the first ~100 km from shore, with the maximum

369 abundance noted between 29° – 35°S (Figure 1b). To assess the impact of Puddies along the coastal strip, we

370 evaluated the mean distribution of several variables (salinity, O_2, NO_3^-, NO_2^-, NH_4^+, and N_2O) in areas of

371 approximately 1°x1° along the coast from 20°S to 38°S and between the isopycnal surfaces S_{upper} and S_{lower}

372 that define the OMZ core in the model (see details in Section 2.6.1). Then, we calculated the mean profiles of

373 these variables in the center of the Puddies observed in each discrete coastal area (1°x1°) and estimated

374 anomalies of the profiles concerning the general mean profile of the corresponding box (Figures 3, see also

375 Figure S4 in the supplementary material).

376 Meridional changes in water properties along the coastal strip impact the initial properties of the Puddies. In

377 the northern sector (between 20°S and 30°S), the waters are warmer, more saline, and have lower O_2 (Figures

378 3a, 3d), with higher concentrations of NO_2^- and NH_4^+ (Figures 3j and 3m). In contrast, towards the south

379 (south of 30°S), these characteristics generally show the opposite tendency, consistent with the water

380 properties observed within Puddy cores. However, NO_3^- and N_2O evidence maximum levels in the central

381 region (near 30°S) (Figures 3g and 3p), where eddies with the highest N_2O concentrations are also observed.

382 Oxygen levels were higher at the upper and lower limits of the OMZ (i.e., near $\sigma_\theta = 26.3$ kg m^{-3} and $\sigma_\theta = 26.7$

383 kg m^{-3}) and remained relatively low in the OMZ core ($\sigma_\theta \sim 26.5$ kg m^{-3}). Both NH_4^+ and NO_2^- anomalies

384 generated by the Puddies showed maximum values in the upper limit of the eddy cores (near $\sigma_\theta = 26.3$ kg m^{-3}

385 ; Figures 3k, 3n) and were fairly uniform along the coastal strip, except between 22° - 24ºS and the north-

386 central region, which showed slightly higher anomalies (Figures 3k). South of 33°S, in the narrowest part of

387 the OMZ, the largest anomalies in O_2, NO_3^- and N_2O are observed (Figures 3e, 3h, 3q), accompanied by a

388 higher standard deviation (Figures 3f, 3i, 3r).

389
390
391 **3.2 Biogeochemical characteristics inside the offshore Puddies**

Comentado [6]: This section was reorganized to improve the clarity of its content.

392 From the total of 15,340 Puddies profiles, statistics over the 6 subregions defined in Section 2.2 (see also

393 Figure 1a) are performed, which is synthesized in Tables 1 to 3. Table 1 provides statistics associated with

394 general characteristics of the subregion, Table 2 presents statistics on ESSW properties, while Table 3

395 focuses on Puddies' characteristics.

396

397 **Table 1.** General characteristics of the study subregions. The S_{upper} layer refers to $\sigma_\theta = 26.0$ kg m^{-3}, the S_{core} layer

398 refers to $\sigma_\theta = 26.6$ kg m^{-3} and the S_{lower} layer corresponds to $\sigma_\theta = 26.9$ kg m^{-3}. Their average depth was indicated

399 with (±) representing the errors estimated based on a bootstrap method (see Methods). Mean thickness was

400 defined as the distance between the S_{upper} and S_{lower} isopycnal layers.

Comentado [7]: Table 1 was modified. The number of pixels refers to the area which is now expressed in km2 for clarity.

Regions	Area (km²)	Depth S_{upper} (m)	Depth S_{core} (m)	Depth S_{lower} (m)	Mean thickness (m)
NCZ	449 550	108±2	267±3	466±4	360
NTZ	655 300	149±3	277±2	449±2	300
NOZ	1 220 800	188±3	305±3	456±3	270

SOZ	1 808 100	176±9	289±10	439±10	260
STZ	359 760	151±3	278±3	451±3	300
SCZ	113 600	99±3	256±2	454±4	355

3.2.1 Oxygen and salinity relationship in ESSW

An evaluation of the relationship between average salinity ($< S >_{9-year}$, as a conservative variable) and average oxygen ($< O_2 >_{9-year}$) and average AOU ($< AOU >_{9-year}$) was conducted for each subregion (Table 2). This analysis was performed using the 26.6 kg m^{-3}, where the ESSW core was observed (see Section 2.2).

Each water mass acquires characteristics through physical and biogeochemical processes, producing particular relationships between the physicochemical variables. Low O_2 waters are closely related to relatively salty ESSW waters. In our study region, this water mass is located between two low-salinity and relatively well-ventilated water masses (i.e., SAAW above and AIWW below). Thus, salinity and O_2 show a linear inverse correlation between the upper and lower oxyclines that delimit the OMZ. Nevertheless, the occurrence of biogeochemical processes can disrupt this relationship. Therefore, it is useful to quantify which regions show these nonlinear biogeochemical processes in the context of the hypothesis that a linear relationship between O_2 and salinity corresponds to an aging of the water mass due to lack of ventilation. A nonlinear relationship would imply the presence of other processes, such as denitrification. Linear regression was performed between absolute salinity, O_2, and AOU on the S_{core} surface, where AOU provides a measure of the apparent O_2 consumption since the ESSW formation (Table 2).

Table 2. **Linear regression between average AOU (μM, $< AOU >_{9-year}$) and average salinity (g kg^{-1}, $< S >_{9-year}$), and between average oxygen (μM, $< O_2 >_{9-year}$) and $< S >_{9-year}$ within each subregions in the S_{core} layer (σ_θ = 26.6 kg m^{-3}). Linear correlation coefficient (R²) provides a measure of how well $< AOU >_{9-year}$ and $< O_2 >_{9-year}$ are accounted for by a linear model where mean absolute salinity is considered a predictor. Error in the parameters' estimate is provided.**

Regions	$< AOU >_{9-year} = a \times < S >_{9-year} + b$			$< O_2 >_{9-year} = a' \times < S >_{9-year} + b'$		
	R²	**a**	**b**	**R²**	**a'**	**b'**
NCZ	0.88	112.5±0.57	-3664.6±21	0.92	-142±0.6	4963.5±20.1

NTZ	0.85	199.2±1	-6685.2±33.5	0.88	-229±0.9	7998.6±33.4
NOZ	0.96	380.3±0.6	-12908±20.3	0.97	-412±0.6	14281±20.4
SOZ	0.75	409.3±1.6	-13893±55.6	0.78	-445.2±1.6	15410±55.6
STZ	0.95	294.5±1	-9989.3±36.2	0.96	-327.1±1	11396±36
SCZ	0.98	200.8±0.7	-6737±25.2	0.99	-232±0.7	8097±25.6

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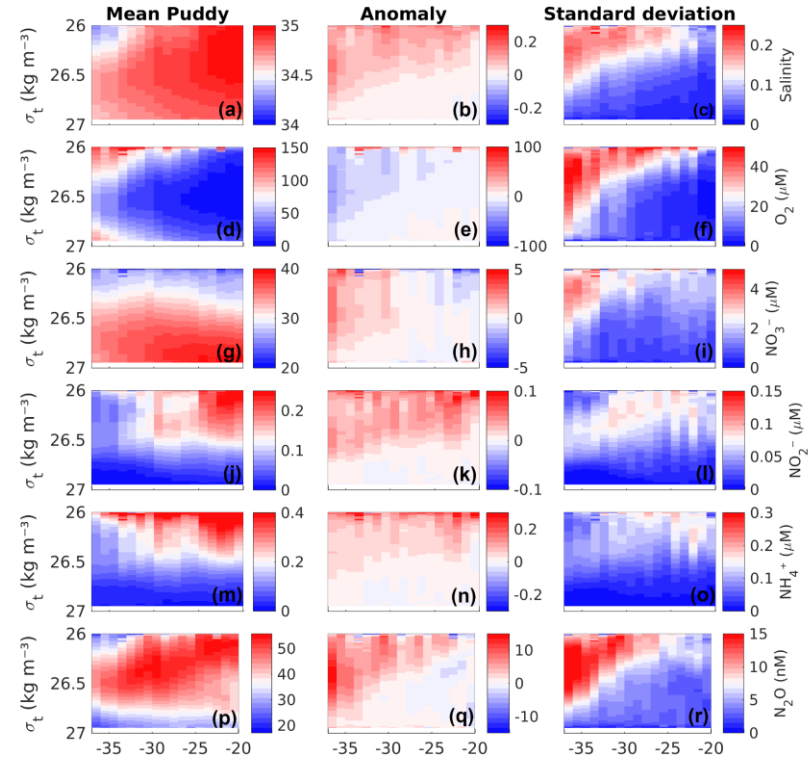
Figure 3. Composite mean vertical profiles (left column), their anomalies relative to the long-term mean (middle column) and the standard deviation of the anomalies (right column) associated with biogeochemical features within the center of the Puddies over the first ~100 km from the slope where there are higher occurrence Puddies (strip in green in Figure 1b). From top to bottom: (a-c) absolute salinity (g kg^{-1}), (d-f) O_2, (g-i) NO_3^-, (j-l) NO_2^-, (m-o) NH_4^+, and (p-r) N_2O. Eddies' mean profiles were obtained by calculating the mean of total profiles identified

436 Oxygen and AOU exhibited a strong linear relationship with absolute salinity ($R^2 > 0.85$) in regions where
437 there is a greater contribution from ESSW (NCZ, NTZ, NOZ, STZ, and SCZ). The slope values ranged from
438 112.5 to 380 for AOU and 142 to 412 for O_2 fit. In contrast, the SOZ exhibited a weaker linear relationship
439 ($R^2 < 0.80$), likely due to the mixing properties of SAAW and AAIW with ESSW (Figure 2, Table S1). SCZ
440 ($R^2 > 0.98$) showed the strongest relationship in the coastal zone, which decreased in NCZ ($R^2 < 0.96$) where
441 denitrification processes have been recorded and there is an evident high value of AOU and a nitrate
442 deficiency (Figures 4a, 4b; Tables 2 and S1). In the northern region, the linear fit improves as it approaches
443 the oceanic zone (NOZ) ($R^2 > 0.96$), indicating a strong presence of the ESSW and a reduced influence from
444 either this biological process or mixing with another water mass.

445

446 **3.2.2 Conditions of Suboxia and Hypoxia in the Oceanic Puddies**

447 We assessed the number of Puddies exhibiting suboxia and hypoxia in each region by identifying the
448 predominant type of low-oxygen cores in coastal, transition, and oceanic zones. The main results are
449 presented in Table 3. The percentage of Puddies exhibiting hypoxia ($O_2 < 45$ μM) and suboxia ($O_2 < 20$ μM)
450 was determined by classifying the range of O_2 concentrations observed in the center of the eddies. The
451 presence of Puddies with these characteristics in the more remote regions was quantified (referred to as NOZ
452 and SOZ in Table 3).

453

454 **Table 3. Percentage of total identified Puddies showing suboxic ($O_2 < 20$ μM) and hypoxic (20 μM < O_2**
455 **< 45 μM) cores within each region. Total profiles indicated the Puddy profiles identified over the entire**
456 **study period. Mean thickness shown the distance between S$_{upper}$ ($\sigma_0 = 26.0$ kg m^{-3}) and S$_{lower}$ ($\sigma_0 = 26.9$**
457 **kg m^{-3}) and δh is the average anomaly thickness generated due to the passage of Puddies in that region**
458 **(i.e. composite δh anomaly).**

459

Regions	Total profiles	Mean thickness (m)	δh (m)	Suboxic cores (%)	Hypoxic cores (%)
NCZ	2,295	475	115	100	0
NTZ	2,114	320	20	70	30

NOZ	3223	325	55	15	66
SOZ	4781	475	215	<1	9
STZ	1,941	540	240	9	60
SCZ	986	550	195	30	70

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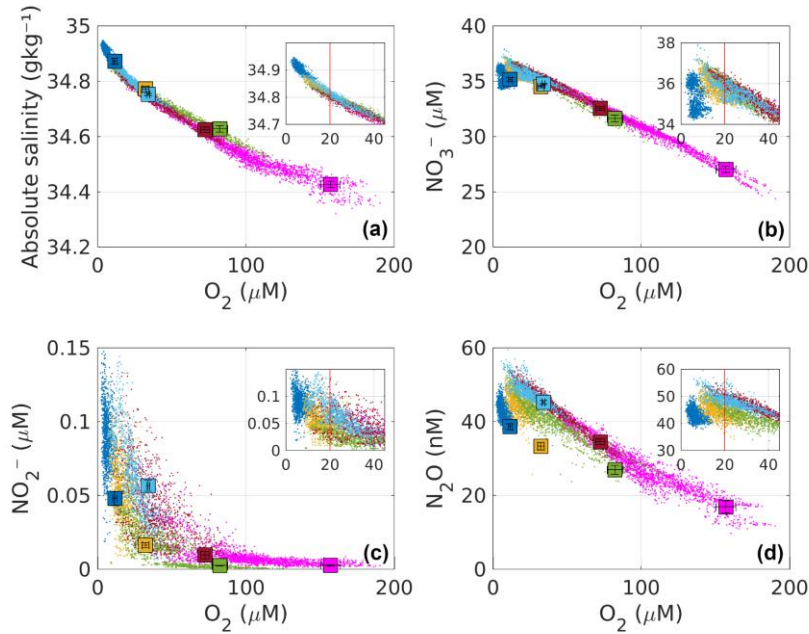


Figure 4. Relationship between mean O_2 concentration and (a) absolute salinity, (b) NO_3^-, (c) NO_2^-, and (d) N_2O at the S_{core} layer for all identified Puddies. The dots represent the core properties of Puddies (in the S_{core}) of all Puddies identified over a 9-years period, at each timestep. The color indicates the subregion (see Section 2.6.1), which was compared to the mean state value (colored squares, Section 2.3). A positive oxygen gradient is observed from coastal regions (NCZ - dark blue; SCZ - light blue), followed by transition zones (NTZ - yellow; STZ - brown) to the oceanic regions (NOZ - green; SOZ - magenta). Error bars inside the squares correspond to the standard deviation of biogeochemical values within S_{core} for each subregion. The smaller box shows a magnified view of the larger box for hypoxic (20 μM < O_2 < 45 μM) and suboxic (1 μM < O_2 < 20 μM) conditions to highlight . The red line indicates the threshold of O_2 = 20 μM.

473

3.2.3 Differences between biogeochemical properties inside and outside Puddies

To understand the biogeochemical impacts of eddies in oceanic waters, the tracers' values found in the core
of the Puddies were compared with the "mean conditions" (Figure S5) of each region in S_{core}. The presence of
Puddies manifests a physical change in the mean thickness by the isopycnal layers perturbation during the
passage of Puddies, which manifests itself with the average anomaly thickness (δh), different in each
subregion (Table 3) and biogeochemical changes with greater contrast observed away from the coast in the
south (Figure 4). Values of $< AOU' >, < \Delta NO_3' >$ and $< \Delta N_2O' >$ observed inside the Puddies were higher
than $< AOU >_{9-year}, < \Delta NO_3 >_{9-year}$ and $< \Delta N_2O >_{9-year}$ observed outside (Figure 4, 5, 6; Table S1,
S2) confirming that eddies maintain hypoxic or suboxic cores that impact regions farther offshore, as shown
in the Section 3.2.2 (Table 3).

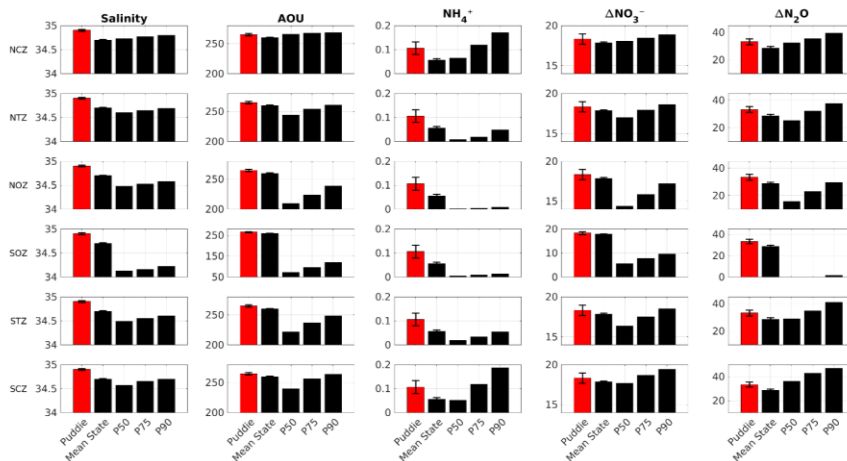



Figure 5. **Comparison between the average value associated with all Puddies (red color), the mean state, and the
50th, 75th, and 90th percentiles (black color, P50, P75, P90 respectively) for absolute salinity (g kg⁻¹), AOU, NH₄⁺,
ΔNO₃⁻ (μM), and ΔN₂O (nM) in each region (see Section 2.4). The profiles for calculating the percentiles are based
on a distribution between 235 to 6800 values - according to the size of the region - obtained from random
resampling using Monte Carlo's method (see Section 2.7). The averages were calculated for the S_{core} layer (see
Methods) . The errorbar indicates the standard deviation for Puddies and for the mean state (see also Tables S1
and S2 for complementary information).**

On the other hand, the asymptotic behavior of NO_2^- was similar to that of NH_4^+ (not show), occurring when
$O_2 < 45$ μM (NCZ, NTZ, and SCZ) and tending towards undetectable in regions where $O_2 > 45$ μM (Figure
4c). In SCZ, Puddies with higher concentrations of N_2O than in NCZ (which has suboxic conditions) and
NTZ (with hypoxic conditions) can be observed (Figure 4d, Table S1).

Comentado [9]: We have added a new figure with the
percentiles information (new Figure 5) and the Table
was moved to the Supplementary material (Table S2).

496 In general in the NCZ and SCZ, Puddies maintain the same average salinity, exhibited an increment of 0.5 -

497 0.7 μM ΔNO_3^- (+2.5 – 4 %), 0.01 up to 0.05 μM NH_4^+ similar to NO_2^- (+12.5 – 83 %), and 3 – 4.5 nM ΔN_2O

498 (+9 – 16 %) associated with an increase of 5 – 9 μM AOU (+2 – 4 %) higher than the mean state (Figures 4

499 and 5; more details, see Table S1). These anomalies were greater than the 50th percentile (P50) for ΔNO_3^-

500 and ΔN_2O and close to the 75th percentile (P75) for AOU and NH_4^+ with salinity exceeding P90 (Figure 5),

501 indicating a significant elevation of biogeochemical elements in the coastal zones due to Puddies compared

502 to the mean state. Offshore, the contrast with the mean state was greater, particularly in the SOZ, reaching

503 100% for NH_4^+, 43% for ΔNO_3^-, 215% for ΔN_2O, 45% for AOU, and 0.3 g kg^{-1} for salinity. These values

504 exceed the P90 (Table S2). Similarly, in the NOZ and STZ, only NH_4^+ exceeded P90, while the rest remained

505 at P75. In NTZ, the AOU and ΔN_2O had values close to or greater than P75, while NH_4^+ and ΔNO_3^- exceeded

506 P90 (Figure 5). The perturbations to the mean state contributed by Puddies in the open sea are more

507 significant than near the coast, although salinity and biogeochemical tracers decrease as the core becomes

508 more oxygenated offshore.

509 The AOU/ΔNO_3^- ratio allows us to quantify the remineralization of organic matter through aerobic processes,

510 which is determined by the Redfield ratio ($R_{N/O}$; 16/138 = 0.11; Redfield et al., 1963). Changes in this

511 relationship indicate the presence of other biological processes that contribute/consume nitrogen in a system,

512 such as nitrogen fixation (ΔNO_3^- /AOU > $R_{N/O}$) and denitrification (ΔNO_3^- /AOU < $R_{N/O}$). On the other hand,

513 the ΔN_2O/AOU ratio provides a measure of N_2O accumulation, so that a high ΔN_2O/AOU is associated with

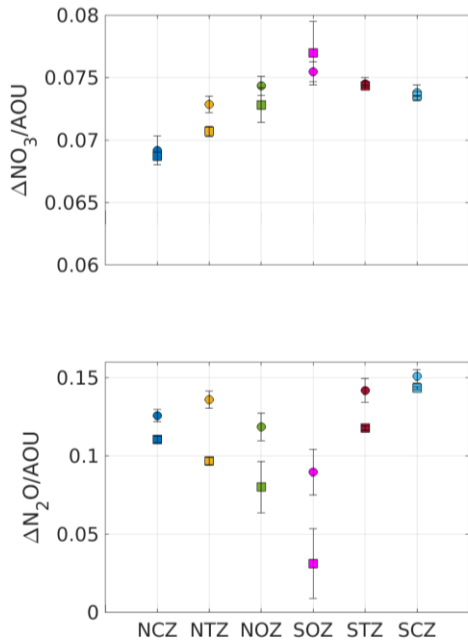
514 the denitrification process (Sarmiento & Gruber, 2006).

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Figure 6. Mean ratios for composite Puddies and mean conditions within each region. (Upper panel) Ratios of ΔNO_3^-/AOU. Note that values are smaller than the Redfield ratio ($R_{N/O} = 0.11$). (Lower panel) Ratios of ΔN_2O/AOU. Values of composite Puddies are indicated with a circle while values of the mean state conditions are indicated with a square. Values are for the S_{core} layer (see Methods). Color code is similar to that of Figure 4. The error bar indicates half the standard deviation calculated from the relationship between ΔNO_3^-/AOU and ΔN_2O/AOU within the S_{core} for each subregion .

We observed a ΔNO_3^- /AOU ratio lower than $R_{N/O}$, inside and outside the Puddies (Figure 6, upper box), indicating a deficit of NO_3^- and high O_2 consumption due to the elevated remineralization in subsurface waters. The ratio is higher in the suboxic region (NCZ) with an AOU:ΔNO_3^- = 15:1, while in the other regions this signal of old and poorly ventilated waters also extends, albeit in different proportions (Table S1). When $\frac{<\Delta NO_3'>}{<AOU'>} < \frac{<\Delta NO_3>_{9-year}}{<AOU>_{9-year}}$, it must be the case that $< AOU' >$ greater than $< AOU >_{9-year}$ or $< \Delta NO_3' >$ is less than $< \Delta NO_3 >_{9-year}$. Since the second assumption is not met, it is true that $< AOU' >$ is greater than $< AOU >_{9-year}$ (Table S1). However, in regions NTZ and NOZ, $\frac{<\Delta NO_3'>}{<AOU'>} > \frac{<\Delta NO_3>_{9-year}}{<AOU>_{9-year}}$, indicating that $< \Delta NO_3' >$ greater than $< \Delta NO_3 >_{9-year}$ or $< AOU' >$ less than $< AOU >_{9-year}$. Given that $< AOU' >$ greater than $< AOU >_{9-year}$, it must have occurred that $< \Delta NO_3' >$ is greater than $< \Delta NO_3 >_{9-year}$, so the production of NO_3^- was greater in the Puddies found in these regions compared to others (Table S1). On the other hand, it holds that $\frac{<\Delta N_2O'>}{<AOU'>} > \frac{<\Delta N_2O>_{9-year}}{<AOU>_{9-year}}$. Since $< AOU' >$ greater than $< AOU >_{9-year}$, it also follows that $< \Delta N_2O' >$ greater than $< \Delta N_2O >_{9-year}$, therefore the production of N_2O was proportionally larger than O_2 consumption in the Puddies (Figure 6, lower box; Table S1). Note that although in SCZ and STZ the eddies exhibited the highest values of $\frac{<\Delta N_2O'>}{<AOU'>}$, $\frac{<\Delta N_2O>_{9-year}}{<AOU>_{9-year}}$ was also high (Figure 6). Additionally, the variability of physicochemical conditions in the core increased with distance from the coast and oxygenation.

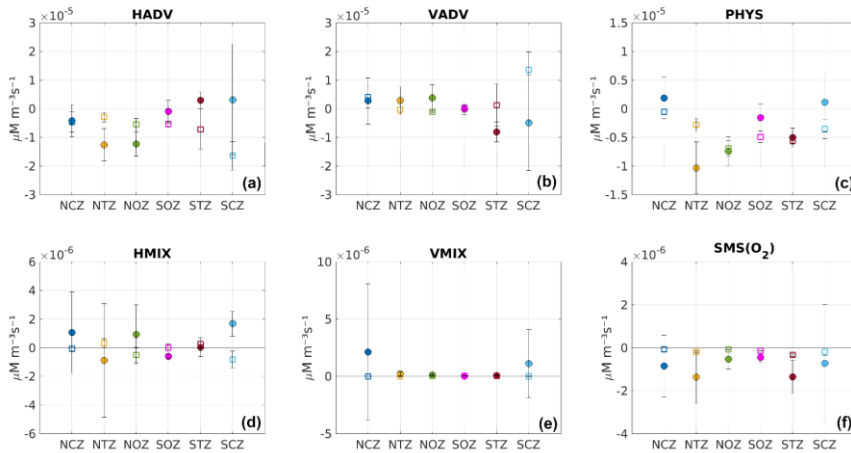
To sum up, according to our model results, Puddies generate significant changes for the mean conditions observed in all regions; particularly large differences were found in AOU and ΔN_2O in SOZ. In contrast, the differences in ΔNO_3^- and AOU were not significant in the coastal regions (NCZ and SCZ).

3.3 Oxygen Budget in the Puddies

The processes that contribute to the modulation of the total O_2 content are represented in the advection-diffusion equation (Eq. 1, Section 2.1). One part of the equation is associated with O_2 changes due to physical processes (referred to as *PHYS*), and another part is related to the production/consumption of O_2 through biogeochemical processes (*SMS*), so we can write $\frac{\partial O_2}{\partial t} = PHYS + SMS$. PHYS comprises horizontal advective processes (HADV = XADV + YADV), horizontal mixing (HMIX) in the *x-y* plane, vertical advection (VADV), and vertical mixing (VMIX) in the *z*-direction so that PHYS = HADV + VADV + HMIX + VMIX. Note that HMIX and VMIX are mainly related to small-scale (subgrid-scale processes) mixing (e.g., Pizarro-Koch et al., 2019). On the other hand, the SMS (source minus sink processes of O_2) includes

Comentado [10]: We improved this figure as part of the reviewers' recommendations. The information that was previously shown in this figure (formerly Figure 4) has been synthesized into the current Figure 5.

550 primary production, remineralization, nitrification, and zooplankton excretion (SMS = PP + Rem + Nitrif +
551 Exc).

552 We analyzed the contribution of each component of the equation to the O_2 balance in the center of the
553 Puddies, dividing the contributions above and below the S_{core} (Figure 7). This was motivated by the fact that
554 there is a significant variance in the upper part of the eddy cores, which is also associated with a large
555 skewness (Figure S6). This indicates a marked vertical variability in the probability density function of the
556 different terms involved in the O_2 balance in the upper part of the eddy cores, probably induced by vertical
557 mixing. Positive (negative) values indicate O_2 increasing/production (decreasing/consumption). In general,
558 we observed that the contribution of PHYS was negative, mainly in the lower part of the eddy, while only
559 NCZ and SCZ positive values dominated at the top, although they were weak, indicating O_2 increasing
560 within the core (Figure 7c). On the other hand, O_2 consumption through SMS (maximum in the transition
561 zones NTZ and STZ) occurred in the upper part of the Puddies (Figure 7f). This proves that elevated
562 biological activity is maintained in the eddies far from shore, with higher intensity in younger eddies but
563 weakening in eddies that reach regions very distant from the coast (NOZ and SOZ). Although the SMS
564 fluxes are of the order $O(10^{-6})$, one order of magnitude lower than the PHYS, small changes in O_2 due to
565 SMS can also result in a sharp local spatial gradient in O_2 that induces strong changes in the advection of O_2.
566 This could significantly impact on the behavior of biogeochemical components that are highly sensitive to
567 minimal changes in O_2 concentration, especially under hypoxic or suboxic conditions.

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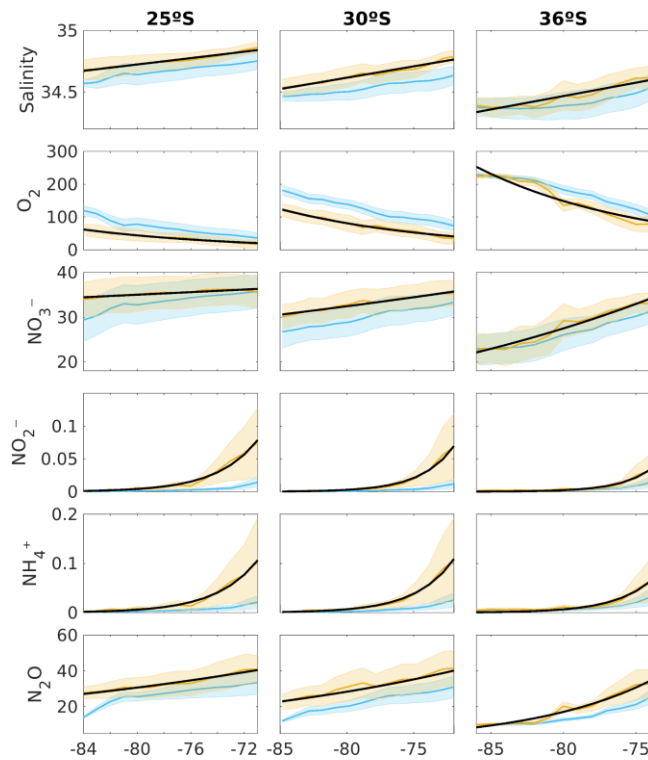
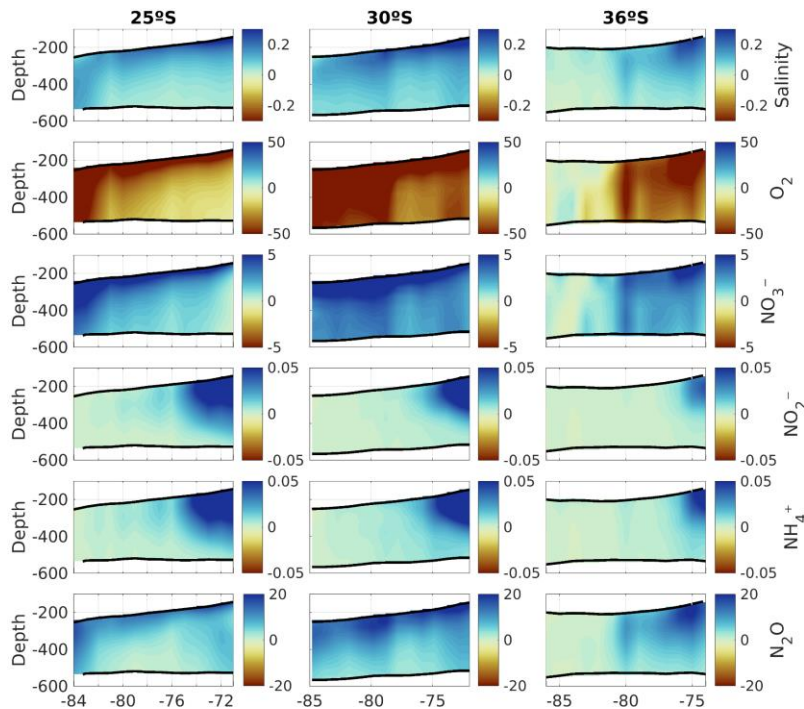
569 **Figure 7. Mean terms involved in the O_2 budget (see equation 1). The different terms were temporally averaged**
570 **inside the eddies in each subregion. PHYS is the sum of physical processes, which encompasses horizontal**
571 **advection (HADV = XADV + YADV), vertical advection (VADV), horizontal mixing (HMIX), and vertical mixing**
572 **(VMIX). The biogeochemical processes are included as sources minus sinks (SMS) processes impacting O_2. In**
573 **particular, SMS includes the O_2 fluxes by primary production, nitrification, remineralization, and excretion of the**
574 **zooplankton. Positive (negative) values indicate processes contributing to increasing (depleting) O_2 inside the**

575 **eddy. (a) HADV (b) VADV, (c) PHYS, (d) HMIX, (e) VMIX, and (f) SMS. The averaging was carried out by**
576 **dividing the composite Puddy profile (see Section 2.6.1) into two parts: above (fill circles) and below (squares) the**
577 **26.5 kg/m³ isopycnal surface. This division was based on the marked vertical variability observed in the**
578 **probability density function, as indicated by the variance and skewness (Figure S6). The vertical bars represent**
579 **standard deviations of the O₂ budget terms within S_{core} for each subregion.**

580 The advection components ($O(10^{-5})$) can be interpreted as the ability to maintain O₂ at the center of the eddy
581 during the eddy's displacement. They dominate the O₂ budget compared to mixing processes ($O(10^{-6})$)
582 involving diffusion of O₂ (Figures 7a, 7b). The lateral fluxes (HADV) showed O₂ leakage (HADV < 0) from
583 the core mainly in the northern eddies but not in the southern eddies (HADV > 0), where O₂ influx to the
584 core was evident (Figure 7a). Assuming vertical oxygen advection dominates over shear-induced oxygen
585 transport, in the northern regions, VADV > 0 dominates in the upper part of the Puddies, indicating O₂ input.
586 In contrast, in the southern regions, this pattern is reversed. In coastal zones, vertical advective processes
587 become significant, with VADV > 0, highlighting the greater O₂ input in SCZ (Figure 7b).

588

589 **Figure 8. (orange line) Average biogeochemical properties of the total volume of Puddies identified in the zonal**
590 **bands corresponding to the latitudes of 25°S (left), 30°S (middle), and 36°S (right), and (blue line) the mean state**
591 **associated with that volume . In order from top to bottom: absolute salinity (g kg⁻¹), oxygen, nitrate, nitrite,**
592 **ammonium (μM) and nitrous oxide (nM). The x-axis shows the longitude in degrees west. At 25ºS, 30ºS and 36°S**
593 **862, 810 and 658 Puddies profiles were considered, respectively. The shading indicates the standard deviation**
594 **amongst the Puddies. The black line stands for the result of an exponential model of the form y = Ae⁻ᵏˣ that**

595   provides the decay rate of mean biogeochemical properties as the distance from the coastal zone (see Table 4 for
596   values of *k* for both mean state and Puddies).

598
599   **Figure 9. Puddies composite anomalies for tracers along three zonal bands at different latitudes (25°S - left, 30°S -**
600   **middle and 36°S - right). In order from top to bottom: absolute salinity (g kg^{-1}), oxygen, nitrate, nitrite,**
601   **ammonium (μM) and nitrous oxide (nM). Anomalies are only shown between the isopycnals layers S$_{upper}$ and**
602   **S$_{lower}$ (black contours). The *x*-axis shows the longitude in degrees. The number of Puddies used for the composites**
603   **is identical to that used for Figure 8.**
604

605   Vertical mixing fluxes were positive in newly formed eddies (mainly in coastal regions), while lateral
606   diffusion fluxes showed high variability in magnitude and direction (Figures 7d, 7e).

607

608   **3.4 Subsurface water band changes by Puddies**

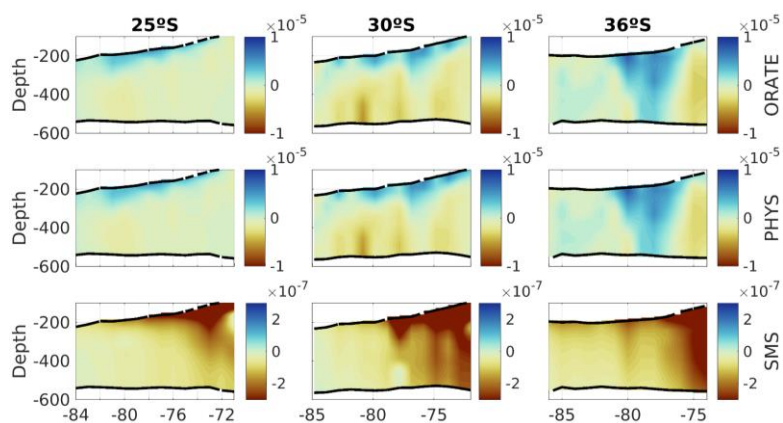
> **Comentado [11]:** This change was made due to a modification in the methodology, the study cases were removed.

609   In this section, a robust approach was used to demonstrate the effect of Puddies on the mean state through the
610   modification of biogeochemical properties, vertical structure, and the contribution of various processes to
611   changes in the subsurface water band delimited by the density surfaces S$_{upper}$ and S$_{lower}$ across different
612   latitudes (25°S, 30°S, and 36°S) during their interaction. All Puddies identified in the three latitudinal bands
613   over the 9-year period were used to build a composite by extracting properties in x-y-z dimensions to obtain
614   the average zonal variables associated with Puddies (details in Section 2.6.2).

We compared the characteristics acquired by Puddies in the subsurface band corresponding to 25°S, 30°S, and 36°S with the mean state of the same volume (Figure 8). First, we observed a decrease in salinity farther from the coast, which indicates the intrusion of external waters distinct from the ESSW. At 25°S, Puddies farther from the coast retain saltier water with higher nitrate concentrations (16% higher than mean state) and lower oxygen levels (49% less than mean state) than those at 30°S (12% increase in NO_3^- and 33% decrease in O_2) and 36°S (it finishes completely mixed). Decay rates in Puddies at 30°S are higher than the mean state, except for NO_3^- and N_2O, while at 36°S, only N_2O exhibits a lower decay rate in Puddies (Table 4). At 25°S, the opposite is observed, with lower decay rates in Puddies except for NH_4^+ and NO_3^-. However, the biogeochemical concentrations in both Puddies and the mean state gradually decrease southward. Puddies' contributions are generally higher at 30°S, as shown by anomalies highlighting low O_2 and high NO_3^- and N_2O concentrations (Figure 9). At 25°S, Puddies input more NH_4^+ and NO_2^- (~400% higher than the mean state) in the subsurface band near the coastal zone, while in the oceanic zone, NO_3^- and N_2O (~200% more than the mean state) are the primary contributions, alongside waters with low O_2. The maximum contribution of NO_2^- occurred at 30ºS, with a 460% increase compared to the mean state near the coastal zone. At 36°S, Puddies show increased contributions in the transition zones, unlike at other latitudes, with salinity, NO_2^-, and NO_3^- maintaining high concentrations up to 76°W. N_2O also exhibits higher contributions from Puddies at 36°S, particularly in the near-coastal (29% higher than the mean state) and transitional zones. NH_4^+ and NO_2^- concentrations are highest near the formation zones at all three latitudes and decrease sharply in the transitional zones or at the beginning of the oceanic zone. In the northern regions, where the OMZ is broader, and there is less differentiation between water masses, in contrast, farther south, the SAAW erodes the OMZ, making it narrower and causing more abrupt biogeochemical changes between the coastal and transition zones.

Additionally, the dynamics associated with each latitude could drive different changes. The net oxygen budget, referred to as O-RATE in Figure 10, shows that in the upper parts of the eddies, there is always a positive oxygen contribution into the Puddies, with ventilation increasing in the southern eddies within the transitional zone, as seen at 36°S. Oxygen primarily enters through physical processes, with horizontal and vertical advection (HADV and VADV) being dominant (Figure 11). Oxygen depletion in Puddies is also influenced by advective processes, which allow the inflow of less oxygenated waters, ventilating the cores primarily in the middle and lower parts of the eddies (30°S band) or distributed between the S_{upper} and S_{lower} layers in the near-coastal zone (36°S band). Oceanic regions (up to ~800 km offshore) in the 30°S and 36°S bands show intensified SMS activity (e.g., ammonification, zooplankton excretion, and nitrification; Figures 10 and 11). To estimate the time Puddies take to cover a certain distance (i.e., 100 km (~1°)), we could consider a propagation speed of ~2 km/day similar to surface eddies (Chaigneau et al., 2009; Hormazabal et al., 2013). Accordingly, it would take them approximately 50 days to travel that distance. Then, the observed SMS < 0 in the oceanic zone at 30ºS remained in the Puddies for about a year.

650

651

652 Figure 10. Same as figure 9 but for the main terms of the O₂ budget: (top panels) the rate of change of oxygen,
653 (middle panels) the sum of all physical processes, and (bottom panels) sources minus sinks (SMS) of
654 biogeochemical processes.

655

656 Table 4. Estimates of the decay rate of tracers along 25°S, 30°S and 36°S for mean state and anomalous conditions
657 within Puddies. The decay rate derived from an exponential fit of the form $y = Ae^{-kx}$, where x represents the
658 distance from the coast in km and y is the concentration of the biogeochemical tracer. k is the decay rate and A the
659 tracer concentration in the coastal strip (1°x1°). A zonal extent of 1,445 km was used at 25°S and 30°S, while at
660 36°S we used 1,334 km (i.e. same range of longitude as in Figure 8). Values of k are statistically significant at the
661 95% confidence level.

Comentado [12]: Table 6 changed to Table 4

662

Variable	Decay rate (k) using exponential fit $y = Ae^{-kx}$					
	Puddies (25ºS)	**Mean state (25ºS)**	**Puddies (30ºS)**	**Mean state (30ºS)**	**Puddies (36ºS)**	**Mean state (36ºS)**
Salinity	3.35×10^{-6}	3.38×10^{-6}	4.8×10^{-6}	3.5×10^{-6}	5.7×10^{-6}	3.3×10^{-6}
NO₃⁻	4×10^{-5}	1×10^{-4}	1×10^{-4}	1.6×10^{-4}	3.2×10^{-4}	2.6×10^{-4}
NO₂⁻	3×10^{-3}	3×10^{-3}	4×10^{-3}	3×10^{-3}	4×0^{-3}	3×10^{-3}
NH₄⁺	3×10^{-3}	2×10^{-3}	3.1×10^{-3}	2.8×10^{-3}	3×10^{-3}	2×10^{-3}
O₂	-7.6×10^{-4}	-8×10^{-4}	-7.7×10^{-4}	-6×10^{-4}	-7.9×10^{-4}	-5×10^{-4}
N₂O	3×10^{-4}	4×10^{-4}	4×10^{-4}	5×10^{-4}	1×10^{-3}	8×10^{-4}

663

At 30°S and 36°S, SMS < 0 extends into the lower parts of the eddies near the coastal zone more intensely (~100 - 150 days), potentially prolonging the lifespan of NO_2^- and NH_4^+. Furthermore, lower oxygen concentrations intrude through HADV and VADV, particularly at 36°S.

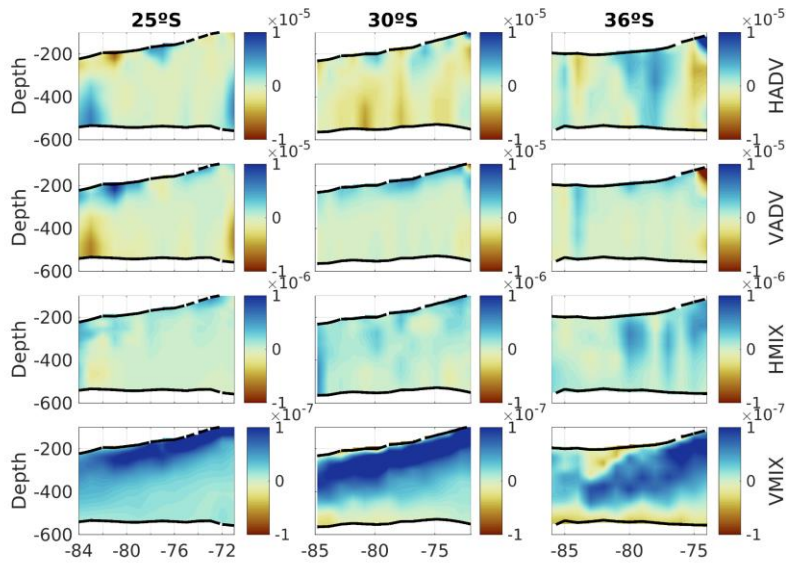



Figure 11. Same as figure 10 but for the various contributions of PHYS (see Eq. 1). from top to bottom: Horizontal advection (HADV), vertical advection (VADV), horizontal mixing (HMIX), vertical mixing (VMIX).

4 Discussion

Several studies have reported *in situ* subsurface eddies with similar biogeochemical characteristics to those observed in the present study (Stramma et al., 2013; Stramma et al., 2014; Cornejo D'Ottone et al., 2016; Arévalo-Martínez et al., 2016; Grundle et al., 2017; Hormazabal et al., 2013; Kartensen et al., 2017). However, studies focused on a detailed recycling of bioelements within these eddies are scarce. While recent studies have used high-resolution coupled models to describe and quantify more complex processes involved in the O_2, nutrient, or organic matter balance within eddies (José et al., 2017; Frenger et al., 2018; Loveccio et al., 2022), the agents generating natural variability in the lifespan of these bioelements associated with the nitrogen cycle during their trajectory from the OMZ to oceanic waters, have not been analyzed in detail.

In this work, a robust statistical analysis was conducted considering all Puddies identified over a 9-year period using two approaches. In the first approach, we characterized the biogeochemical signal of the source water inside the Puddies. Subsequently, we analyzed the eddy cores, focusing on the average Puddies' profiles (using δh_{max}; see Section 2.6.1) and presented the values in the isopycnal layer of 26.6 kg m^{-3} to

assess how and to what extent the biogeochemical properties of the Puddies' cores differ across various regions of the SEP from their formation zone (results in Sections 3.1, 3.2, and 3.3).

In the second approach, we considered the entire volume of the Puddies to characterize their average conditions and quantify how these properties modify the intrathermocline band where the Puddies travel— from the coastal zone, through the transition zone, and into the oceanic zone (see Section 3.4). Additionally, we evaluated the balance of processes involved in the interaction of the Puddies along their trajectory (details in Sections 3.3 and 3.4). This analysis allowed us to identify differences in the impact of Puddies at different latitudes and gain a deeper understanding of the processes involved.

4.1 Biogeochemical anomalies in Puddies from their formation

Subsurface anticyclonic eddies appear to be formed by separating the Peru-Chile Undercurrent from the slope (e.g., Molemaker et al., 2015; Thomsen et al., 2016; Contreras et al., 2019). Here, we observed a higher recurrence of Puddies in specific sectors, namely, between 29º-35ºS (Figure 1b), related to the widening of the continental shelf. This change in topography may lead to greater separation of the PCUC from the slope, creating favorable conditions for the generation of Puddies, as observed by Chaigneau et al. (2009). Puddies appear to originate from instabilities forced in the bottom boundary layer at the upper continental slope where the core of the PCUC interacts with the sea bottom (Contreras et al., 2019), and where the core of the OMZ is observed. This water, trapped within the Puddies, is characterized by positive NH_4^+, NO_3^-, NO_2^- and N_2O anomalies and very low O_2 that vary with latitude, as described in Section 3.1. However, unlike O_2 and salinity, which exhibit a more uniform gradient along the coast, several other biogeochemical components have more irregular spatial distributions depending on whether conditions are hypoxic or suboxic.

In the northern part of the coastal zone, limited ventilation creates an environment with suboxic conditions and denitrification, resulting in NO_3^- and N_2O deficits, and NO_2^- and NH_4^+ enrichment. In contrast, the central coastal waters exhibit increased NO_3^-, with the southern part showing higher N_2O concentrations. Additionally, as the formation of Puddies is associated with cross-shore velocities – exchanging nutrients between the continental shelf and open sea (Thompsen et al., 2015) – the mixture of ESSW and SAAW waters, also affected by the southward reduction in the contribution of ESSW (Figure 2; Silva et al., 2009), enhances the biogeochemical variability of the Puddies generated along the Chilean coast (Figure 3).

In summary, Puddies formed along the Chilean coast capture distinct biogeochemical "signatures" depending on where they form. In the north, minimal ventilation fosters suboxic conditions and denitrification –leading to deficits of NO_3^- and N_2O but high NO_2^- and NH_4^+– whereas central and southern subregions show increased NO_3^- and higher N_2O. Moreover, cross-shore exchange between ESSW and SAAW further amplifies this variability, giving rise to eddies with diverse nutrient and oxygen properties as they move offshore.

4.2 Persistence of Biogeochemical Anomalies Away from the Coast

In each subregion (Figure 1a), the Puddies exhibited distinct biogeochemical configurations, as summarized in Figures 4, 5, and 6 (results in Section 3.2). The dominance of SAAW in the southern regions explains the largest number of hypoxic Puddies containing higher O_2 concentrations and lower levels of NO_3^-, NH_4^+, NO_2^-, and N_2O compared to Puddies farther north, where suboxic cores are more prevalent (Silva et al., 2009). Consequently, Puddies that capture a larger fraction of ESSW during their formation exhibit biogeochemical contributions closer to the P75 (Figure 5, Table S2) and show a higher O_2 deficit than the mean state. This suggests that the southern regions are experiencing greater deoxygenation and nutrient enrichment due to the influence of Puddies compared to the northern regions, where the OMZ is much broader.

When estimating the percentage of core distributions exhibiting hypoxia and suboxia, the results showed that hypoxic cores predominantly occur in oceanic waters (Table 2). In general, as we move away from the Chilean coast, biogeochemical element concentrations decrease significantly, though the magnitude of the decrease varies by element (Figure 4). Although Puddies share common characteristics within each region, some variability is observed. This reflects the variety of drivers - such as kinetic and potential energy, vorticity and other dynamics - as well as the differences in the properties of the source water it encloses, its trajectory (potentially interacting with different external water masses), and the physical and biogeochemical processes occurring within it during its lifespan. These factors can enhance or diminish the Puddy's ability to transport properties far from its formation zone.

However, the results indicate an effective transport of these properties to oceanic regions, where values exceed the P90. In contrast, for the transition zones (NTZ and STZ), only AOU, salinity, and NH_4^+ exceed the P90, while ΔN_2O and ΔNO_3^- are closer to the P75. This regional difference clearly demonstrates that the perturbations to the mean state caused by Puddies are more significant in the open ocean than near the coast (Figures 4 and 5; Table S1).

4.3 Changes in the Biogeochemistry of Subsurface Water Masses by the Puddies

Our results showed changes from the coastal to oceanic zones across three latitudes, where a decrease in dissolved inorganic nitrogen compounds, along with a salinity decay rate, confirmed that Puddies age and mix with external waters as they move into the oceanic zone (Figure 8; Table 4). Similar patterns were observed by José et al. (2017) in the upwelling system off Peru, Frenger et al. (2018) across the main EBUS, and Loveccio et al. (2022) in the Northern Canary upwelling system. This offshore change suggests that Puddies have relatively permeable boundaries, but the level of coherence and isolation within the Puddy core can significantly influence the lifespan of compounds enclosed in it. The macronutrient behavior observed was consistent with Frenger et al. (2018), though in our case, N_2O —despite its minimal concentrations— exhibited a pattern similar to other macronutrients, such as NO_3^- (Figure 8). Decay rates for NO_2^- and NH_4^+ were faster than those for NO_3^- and N_2O (Table 4).

757 Nitrate showed higher concentrations compared to other nitrogen compounds. Additionally, as long as NH_4^+

758 and NO_2^- are present (Figures 4, 8, and 9), nitrification can replenish the NO_3^- pool in subsurface waters

759 where photosynthesis does not consume it. In addition, N_2O production depends on $[NH_4^+]$, $[NO_2^-]$, and $[O_2]$

760 levels and the nitrification and denitrification processes. According to the model parameterization (for more

761 details, see Gutknecht et al., 2013a), the maximum N_2O production occurs when $O_2 = 1$ μM, with $SMS(N_2O)$

762 $= \alpha(\text{Nitrif}) + \beta(\text{Nitrif})$ (α, β constant), whereas when O_2 is high or $O_2 < 1$ μM, the N_2O production decreased

763 because $SMS(N_2O) \rightarrow \alpha(\text{Nitrif})$. On one hand, N_2O production diminishes as NO_2^- and NH_4^+ availability

764 declines, as observed in the open sea; on the other hand, in coastal zones, denitrification rapidly depletes

765 these compounds until N_2O production ceases at oxygen concentrations below 1 μM. Since the model does

766 not account for N_2O consumption by biological processes (via denitrification or fixation) but only through

767 atmospheric exchange, the Puddies act as a source of N_2O as they move offshore and the observed N_2O

768 decrease within Puddies can only result from physical processes facilitating exchange with external waters.

769 Notably, the 30°S zonal band exhibited the largest anomalies in biogeochemical characteristics (Figure 9).

770 Along this band, the high occurrence of Puddies, including those formed at or south of this latitude, is

771 significant due to the characteristic northwest trajectory of eddies. This could explain the high nutrient

772 concentrations there (Figure 3). Newly formed Puddies must be supported by dissolved organic nitrogen

773 from the source water with higher O_2 consumption (*SMS*) during the first 100-150 days, as Loveccio et al.

774 (2022) proposed. Mixing with external waters (Figure 8) is driven by physical processes, particularly

775 advection (HADV and VADV, Figures 10 and 11). Compared to the other two latitudes, higher O_2

776 consumption (SMS < 0) at 30°S suggests higher local nutrient production through remineralization (i.e.,

777 more organic material is being broken down), potentially extending the lifespan of NO_2^- and NH_4^+, necessary

778 for the ΔN_2O and ΔNO_3^-, activity that remained in the Puddies for about a year around 800 km offshore.

779 Biological activity sustains low-oxygen cores for longer periods, preserving original conditions even with O_2

780 < 20 μM in the cores, where denitrification continues while the edges ventilate. Additionally, horizontal

781 advective processes further reduce oxygen levels in the lower part of the eddy by allowing the intrusion of

782 low-oxygen waters, contrasting with observations at 25°S and 36°S.

783 This combination of conditions suggests that regions of significant interaction with Puddies can transform the

784 biogeochemistry of the subsurface layer in meaningful ways. Both approaches used to characterize Puddies

785 provide valuable insights into how and to what extent these Puddies evolve, driving changes in the

786 intrathermocline from their formation to their dispersion across the SEP.

787 **4.4 Advantages and Disadvantages of the Model for Low Oxygen Conditions**

788 We now discuss the limitations of the model formulation in accounting for the transition between the two

789 oxygen regimes (hypoxic versus suboxic) and its implication for Puddies life cycle. AOU:NO_3^- ratios of

790 250:30 (up to 20:1) have been documented in the Atlantic from *in situ* monitoring of NO_3^- within mode water

791 eddies (Kartensen et al., 2017) and in eddy cores with NO_3^- < 25 μM at O_2 < 5 μM in the SEP (Stramma et

792 al., 2013). The eddies modeled here showed AOU values similar to those found by Karstensen et al. (2017)

793 in the eastern tropical North Atlantic, although NO_3^- was overestimated by 3 - 5 μM leading to an

794   AOU:ΔNO_3^- ratio of 5:1 (Figures 4b and 6 - upper box; Stramma et al., 2013). Suboxic Puddies build up

795   NO_2^-, although the modeled maximum concentration appears underestimated compared to previously

796   reported *in situ* data (Stramma et al., 2013; Cornejo et al., 2012; Cornejo-D'Ottone et al., 2016).

797   Consequently, the relationship between NO_2^- and ΔN_2O in the northern zone also showed underestimation.

798   At the modeled N_2O maximum (>30 nM, Figure 6), field data shows NO_2^- values >1 μM (Cornejo et al.,

799   2012), while the modeled NO_2^- maximum reaches 0.15 μM (Figures 4 and 5). Comparing our results with

800   eddies monitored in the SEP, the N_2O concentrations observed in open ocean eddies agree with those

801   measured by Cornejo-D'Otonne et al. (2016; Figure 4d, S5) in an eddy originated near the coast off

802   Concepcion (~37°S, south zone), although there are differences of up to 20 nM with the eddy reported by

803   Arévalo-Martínez et al. (2016; Figure 4d, S5) off northern Chile. These results suggest a better representation

804   of biogeochemical processes by the model in a hypoxic than suboxic environment.

805   Biogeochemical components are challenging to model due to the numerous physical, biogeochemical, and

806   biological processes involved. Specifically, under hypoxic or suboxic conditions, the nitrogen cycle is more

807   complex due to additional processes that occur within a narrow O_2 range, increasing the system's sensitivity.

808   Processes removing nitrogen from the system, such as denitrification, also generate intermediate products

809   such as N_2O and NO_2^- (e.g., denitrification, NO_3^- reduction). Denitrification is a complex process to

810   parameterize, involving a range of steps for each nitrogen component and various rates of decomposition of

811   particulate (large and small) and dissolved material. However, despite the attempt to consider these processes

812   realistically, the model remains an approximation but reasonably represents the involved processes, primarily

813   within the intrathermocline band (see Appendix). In the suboxic zone, while the model underestimated O_2,

814   NO_3^- remained overestimated, but in the subsurface band associated with the OMZ core, the model

815   represented the lowest biases in O_2 and nitrogen evaluated with climatological observations (see Appendix).

816   This allowed us to present a robust statistical analysis of biogeochemical properties inside and outside the

817   Puddies. Despite the difficulty in simulating realistically sharp mean gradients in water mass properties

818   (Pizarro-Koth et al., 2019), the model did highlight typical features, such as NO_3^- consumption and

819   production of NO_2^- and N_2O, processes that persist within Puddies far from their origin within the OMZ.

820

821   **5 Conclusions**

822   Using a high-resolution coupled simulation of the SEP, we characterized the biogeochemical changes within

823   Puddies, their differences with the external properties, and the processes involved in the O_2 balance during

824   their transport to oceanic waters. The model resolved eddy dynamics and biogeochemical processes related to

825   the nitrogen cycle, including characteristic EBUS processes such as denitrification. This methodology

826   allowed us to statistically approximate the biogeochemical changes occurring within these Puddies, quantify

827   the modifications to water bodies along their paths, and identify the dominant mechanisms regulating

828   compound concentrations from the formation zone to hundreds of kilometers offshore.

829   During formation, Puddies capture a biogeochemical signal that varies depending on their origin, which is

830   associated with the core of the Peru-Chile Undercurrent. Peripheral permeability enables exchange with

external waters, modulating the original signature. However, the core signal retains characteristic negative O_2 anomalies and positive anomalies for other biogeochemical tracers. These disturbances may cause average properties to exceed the 90th percentile (P90) in the open ocean, in contrast to the formation zone, where values remain above the 50th percentile (P50). While a high percentage of Puddies near the coast exhibit suboxic cores (all in the north and 70% in central-south Chile), the proportion decreases with distance from the coast, where hypoxic cores become predominant (60% in the STZ and NOZ). This suggests core ventilation during their trajectory, as indicated by an estimate of the salinity decay rate as a function of latitude.

The dominant mechanism for O_2 exchange in the eddy core is lateral and vertical advection, with vertical mixing contributing two orders of magnitude less. O_2 consumption through biological activity (SMS) was maintained inside the Puddies (around 6 to 12 months) up to the oceanic zones (e.g., at 30°S the O_2 consumption was maintained up to ~800 km from the coast), enabling the persistence of low O_2 conditions in the core despite peripheral ventilation. This persistence supports processes such as denitrification, which occur under hypoxic or suboxic conditions within the OMZ, and can extend into areas far beyond the OMZ, sustained in core niches with $O_2 < 20$ μM. The SCZ and STZ experience significant deoxygenation and nutrient enrichment due to Puddies formed with larger anomalies. At 30°S, a combination of factors significantly impacts the intrathermocline biogeochemistry due to Puddies transiting this latitude. The maximum contribution of NO_2^- occurred at 30ºS, with a 460% increase compared to the mean state, near the coastal zone. Clearly, the formation of Puddies is a critical process in extending the OMZ boundaries at its southern edge. Additionally, the interplay of physical conditions can generate regions with substantial subsurface water mass changes due to interactions with Puddies.

Biogeochemical tracers exhibit varying lifespans depending on their original concentrations, as well as their demand and production rates. Ammonium (NH_4^+) and nitrite (NO_2^-) tend to decline first, whose concentration was maximum in the coastal zone (300-400% higher than mean state), with high decay rates with distance from the coast, while other components decrease more slowly and persist longer. Despite being produced in low concentrations, N_2O is retained in Puddies farther from the coast, serving as a proxy for denitrification in the source water and contributing to the subsurface reservoir of this greenhouse gas in the open ocean (up to ~100% higher than the mean state). Characterizing Puddies provides valuable insights into how they evolve and drive intrathermocline changes from their formation to dispersion across the SEP. Beyond offering insights into the biogeochemical dynamics of Puddies, this study's findings can also help guide *in situ* monitoring, particularly in remote areas where unusual biogeochemical signals may indicate the presence of a Puddy.

Higher-resolution models enable better characterization of mixing processes involved in eddy core ventilation and the exchange of properties with external waters through submesoscale dynamics (Brannigan et al. 2017). Coupling with more complex biogeochemical models will help quantify the effects of additional SMS processes within Puddies not included in this study. This is planned for future research. Validation and supplementary statistics through further observations in the study area are also recommended to deepen our understanding of coupled processes in surface and subsurface eddies.

869

Appendix: model assessment

871

A.1 Data

Observed climatological O_2 and NO_3^- fields were taken from the CSIRO Atlas of Regional Seas (CARS2009; www.marine.csiro.au/~dunn/cars2009/) for the biogeochemical model assessment, which has a spatial resolution of 0.5 degrees and a monthly mean resolution. The model validation was performed over the first 800 m. The vertical resolution of the data set is 10 meters to the first 300 m, 25 meters to 500 m, and 50 meters down to 800m.

A.2 Surface Nitrate

The model simulates low NO_3^- (< 2 μM) in general, except in the areas near the coast and in the southwest where concentrations reached 8 μM (Fig. A1a). The observed concentrations were higher, particularly in the south (Fig. A1b). Overall, the model underestimated NO_3^- concentrations in most of the domain, although the differences with observations remain relatively small, ranging between 0 - 4 μM south of 30ºS and between 0-2 μM north of 30ºS (Figs. A1a, A1c). Adjacent to the coast between 25º-35ºS, the model overestimates concentrations by ~7 μM (Fig. A1c). In general, differences were minimal over most of the study area, and it can therefore be considered that the model fairly well represents surface NO_3^-.

Figure A1. Spatial distribution of mean surface NO_3^-. (a) ROMS-BioEBUS simulation, (b) CARS climatology, and (c) BIAS (model - observations). Units are μM.

889

A.3 Oxygen and nitrate on the isopycnal layers

The comparison between observations and model is here done over different density layers S_{upper}, S_{lower} and S_{core} (Figures A2, A3, A4). The model captures the principal characteristics of O_2 and NO_3^-, displaying a similar structure and latitudinal and zonal gradients. Compared with observed data, lower O_2 concentrations and higher NO_3^- concentrations were predicted near the coast and north of 30ºS associated with the meridional changes of the offshore extension of the OMZ.

896 In the S_{upper} surface, observations reveal discontinuous areas with lower O_2 concentrations north of 25ºS (O_2

897 <100 μM), between 30 - 31ºS and 35 - 36ºS (O_2 <150 μM). The model mostly underestimated these O_2

898 concentrations by 40 μM north of 30ºS, by around 20 μM between 30 - 35ºS, and overestimated them by 20

899 μM between 35 - 38ºS near the slope, but performed better south of 35º S offshore. For NO_3^-, observations

900 indicated very low concentrations mainly along the coast between 23 - 35ºS (<10 μM), with an increase

901 to >15 μM in the oceanic region. Therefore, the model overestimated concentrations in the coastal zone (>10

902 μM) and in the northern oceanic zone (4 - 8 μM, Figures A2).

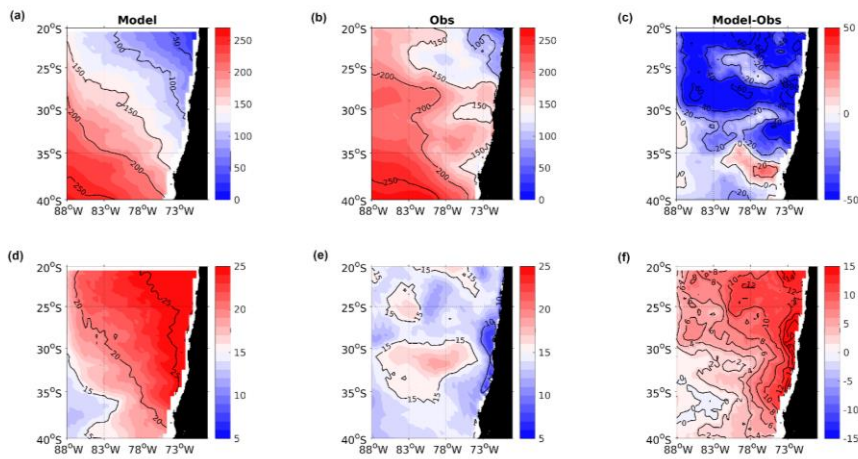
903 Regarding the S_{core} layer, the model performed better in the northern region, underestimating O_2

904 concentrations between 0 - 10 μM. Off the coast, the bias ranged from -10 to 10 μM. However, south of 30º

905 S, between 75 - 80ºW, the model overestimated O_2 concentrations by over 40 μM, whereas west of 82ºW, the

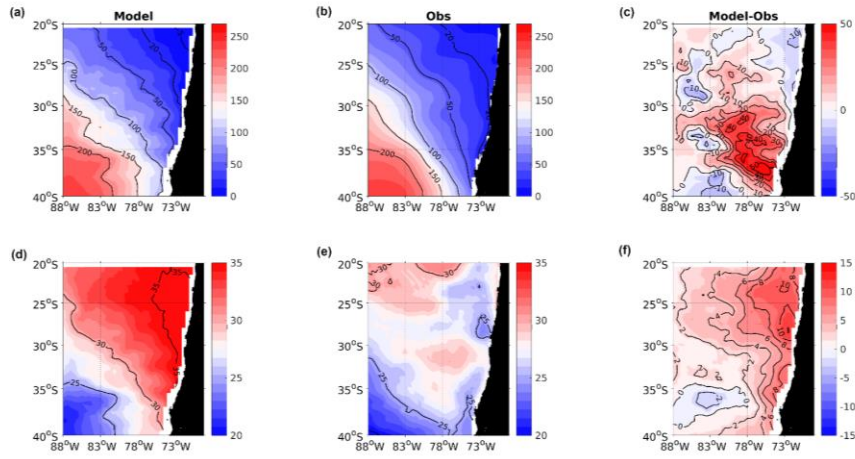
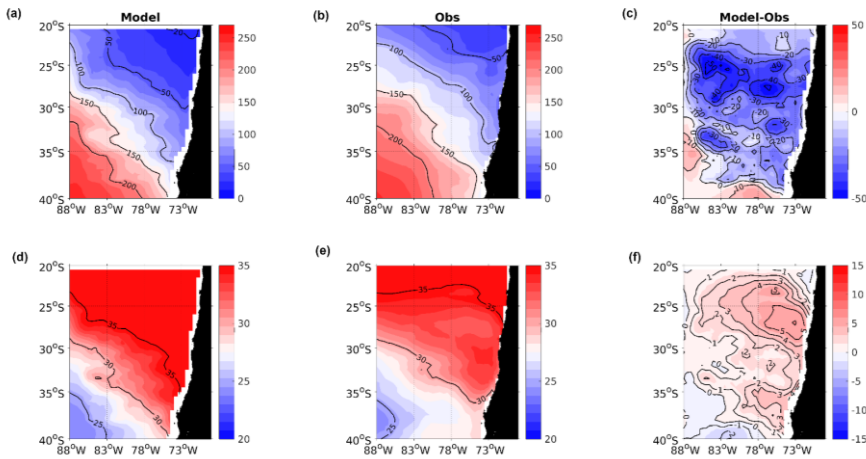
906 bias varied between -10 to 10 μM. Nitrate concentration is overestimated by the model in the coastal region

907 with concentrations exceeding 6 - 8 μM, particularly in the northern oceanic area (2 - 4 μM). The model is

908 more realistic in terms of NO_3^- in the region west of 78ºW and south of 30ºS (Figure A3).

909

910 **Figure A2. (top panels, a-c) Mean O_2 and (bottom panels, d - f) mean NO_3^- concentration in the isopycnal layer**

911 **S_{upper} = 26.0 kg m⁻³ from the ROMS-BioEBUS simulation (left), the CARS climatology (middle), and the BIAS**

912 **(right). Units are μM..**

913
914 **Figure A3. Same as Figure A2 but for the isopycnal layer S_{core} = 26.6 kg m⁻³.**

915
916 **Figure A4. Same as Figure A2 but for the isopycnal layer S_{lower} = 26.9 kg m⁻³.**

917 In the S_{lower} layer, the model simulates in general lower O_2 concentrations than observations north of 30ºS ,
918 underestimating by between 10 - 40 μM. This bias is smaller south of 30º S (10 - 30 μM) and in the
919 southwest (0 - 10 μM). The model realistically simulates NO_3^-, with deviations from observations ranging
920 from -2 to 5 μM and with the greatest overestimation occurring in the region where $O_2 < 50$ μM (Figure A4).

921

922 **A.4 Vertical Structure**

923 The comparison between model and observations is done along zonal sections at 25ºS, 30ºS, and 35ºS
924 (Figures A5, A6). Along the latitudinal gradient, the contour of 50 µM shows that the OMZ narrows towards
925 the south. Observations evidence an elongated low-oxygen tongue in subsurface waters that is more
926 pronounced than in the model simulations, along with an intrusion of oxygenated waters both at the surface
927 and at depth (~600 m), enclosing the low-oxygen water with a marked oxycline (Figure A5). The oxyclines
928 showed a greater bias, with the model tending to underestimate the observed data, particularly in the lower
929 oxycline with an underestimation of up to 60 µM. In the subsurface layer between 200 - 400 m, the model
930 better represents O_2 levels, especially at 25 - 30ºS where differences ranged from 0 - 10 µM (Figure A5c,
931 A5f). At 35ºS, there is an overestimation (40 µM) between 75-80ºW low 200 - 300 m depth (Figure A5i).

932

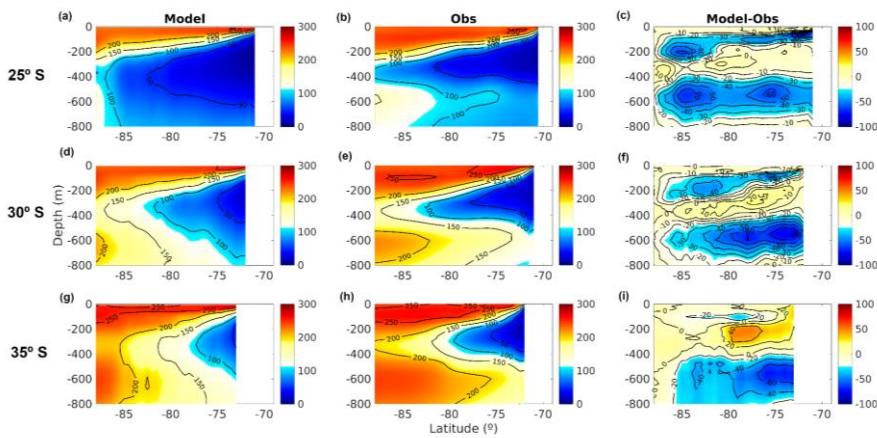
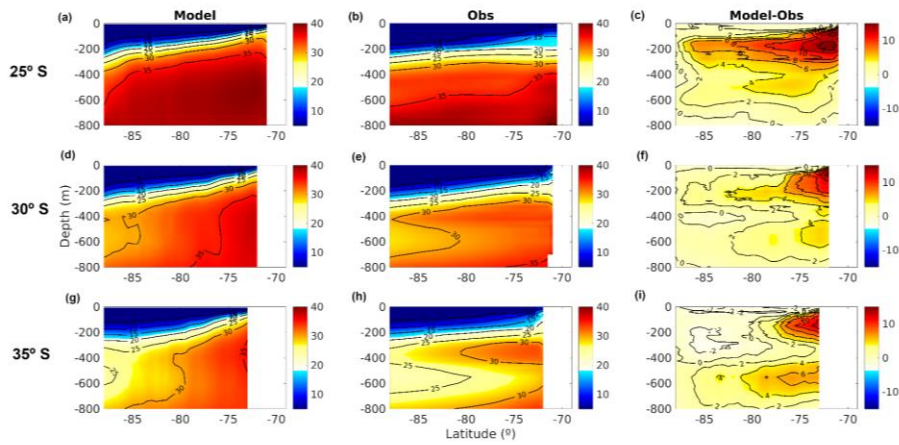



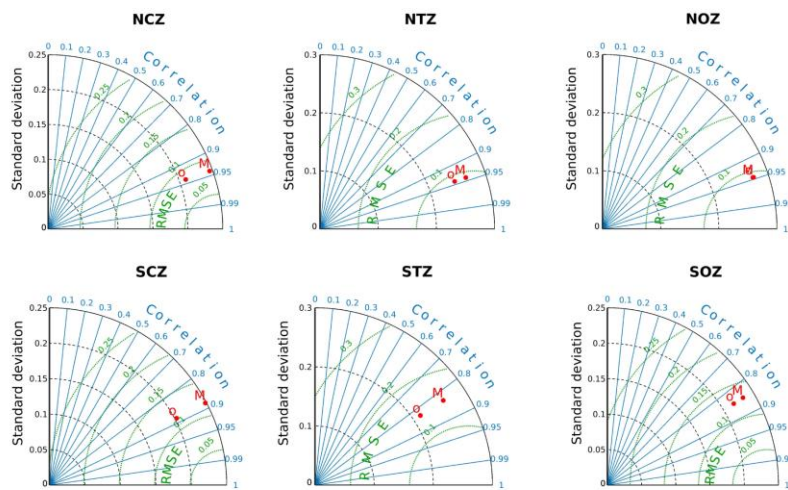
Figure A5. Zonal section of mean O_2 concentration at (a - c) 25ºS, (d - e) 30ºS, and (f - h) 35ºS. (a, d, g) from the ROMS-BioEBUS simulation (left boxes), CARS climatology (middle boxes), and BIAS (right boxes). Units are µM.

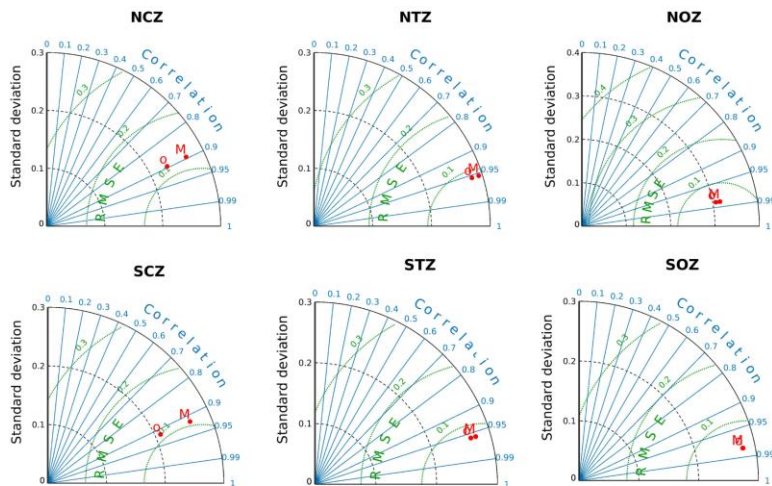
936 Along 25ºS the model simulates higher subsurface NO_3^- concentrations near the coast compared to
937 observations, showing differences of up to 15 µM. Below 400 m of depth, overestimations range from 0 - 4
938 µM (Figure A6a, A6b, A6c). These differences decrease towards the south; at 30ºS and 35ºS, the most
939 significant differences extend from the coast to 76ºW and below -300 m (overestimations of 8 - 12 µM),
940 whereas elsewhere, the differences remain between 0 - 4 µM. Subsurface NO_3^- is underestimated by 2 µM by
941 the model at 35ºW and west of 80ºW (Figures A6f, A6i).

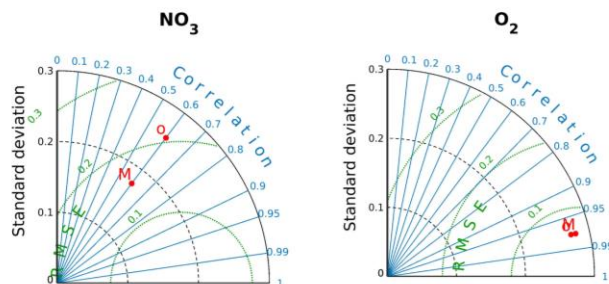
942 Taylor diagrams synthesize the agreement between model and observations for the annual mean O_2 and NO_3^-
943 in each of the subregions integrated in the upper 800 m of the water column (Figures A7, A8). Estimates of
944 standard deviation, correlation, and RMSE reveal that the current model configuration is generally in
945 reasonable agreement with observations, primarily in the subsurface layer where most of the properties of
946 Puddies were computed (Figure A9). Therefore, there is confidence in using the model for the
947 biogeochemical characterization of these mesoscale processes.

948

949 **Figure A6. Same as Figure A5 but for mean NO₃⁻ concentration.**

950

951

952 Figure A7. Taylor diagram for mean O_2 concentrations over the six subregions (Figure 1a) and within the first
953 800m. M is for the model while O is for the CARS climatology. The X-Y axis refers to the standard deviation
954 (black lines), correlations in the radial axis (blue lines) and RMSE is indicated by curved lines (green). Region's
955 names are: Northern Coastal Zone (NCZ); Northern Transition Zone (NTZ); Northern Oceanic Zone (NOZ);
956 Southern Oceanic Zone (SOZ); Southern Transition Zone (STZ) and Southern Coastal Zone (SCZ).

957

958

959 **Figure A8. Same as figure A7 but for mean NO₃⁻ concentration.**

960

961 **Figure A9. Taylor diagram for mean NO₃⁻ and O₂ concentrations over the entire S_core volume. Details are similar**
962 **to those in Figures A7 and A8.**

963 **Code availability**

964 ROMS model code is available at http://www.croco-ocean.org. All input data set and configuration of our
965 ROMS/BIOEBUS simulations are described in section and in the references therein. This work was granted
966 access to the HPC resources of CALMIP supercomputing center at the Toulouse University under the
967 allocations 2023-1044 and 2024-1044.

968 **Author contributions**

LOC, OP, MC and BD designed the study. BD performed the simulation. LOC made the assessment, eddy identification and statistical analysis of the model outputs. OP supervised the project. LOC interpreted the results and wrote the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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