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Editors of Biogeosciences

Dear Editors,

I am pleased to send the manuscript entitled "**BIOGEOCHEMICAL CHARACTERISTICS OF A LONG-LIVED ANTICYCLONIC EDDY IN THE EASTERN SOUTH PACIFIC OCEAN**" by Marcela Cornejo, Luis Bravo, Marcel Ramos, Oscar Pizarro, Johannes Karstensen, Mauricio Gallegos, Marco Correa-Ramirez, Nelson Silva, Laura Farias and Lee Karp-Boss. The manuscript was revised by two reviewers, who made several comments and suggestions about the presentation of results and figures, as well as about the English.

We have taken into account most of the suggestions from both reviewers and We included them in the manuscript. The English was re-reviewed by a native English colleague. All the changes we made in the paper have been included in a document below with a detailed point by point.

We are deeply grateful to the reviewers, who with their comments and suggestions have helped to strengthen and improve the manuscript.

I look forward to hearing from you.

Yours sincerely,

Marcela Cornejo-D'Ottone
(Email: marcela.cornejo@ucv.cl)

DETAILED CHANGES AT THE MANUSCRIPT

We thank the reviewers for their time and constructive comments. We carefully read each of the comments and addressed them as stated below:

About the comments made by Reviewer #2:

1. The manuscript was re-reviewed and re-edited by a colleague, who is a native English speaker, Dr. John Dolan.
2. All the mistakes and non-scientific terms noticed by Reviewer #2 have been corrected in the text.
3. We revised the abstract and expanded it to improve the summary of the results.
4. The information about eddy polarities and their properties were included in the introduction and We are explicit about that our eddy was an anticyclonic eddy throughout the manuscript.
5. The characteristics of the waters transported by cyclonic eddies were included in the introduction.
6. The name of the stations were changed from E03 to 094-A in order to uniform the name as the Tara Oceans stations.
7. The table and its caption was modified as suggested by the reviewer.

8. We put the label a) b) c), etc, in a white box, in order to make them easily to see.
9. The climatological mean was added to Figure 2.
10. We corrected the terms "stisopycnales" by "sigma-t isopicnals" and "isocline" by "isolines"
11. The caption in figure 6 was changed in order to be clearer.
12. In figure 7, the lines of isopicnals were reviewed and changed.
13. We defined ESP (Eastern South Pacific) in the abstract.
14. The asked references in the introduction were included.
15. The acknowledgement to AVISO was included in the corresponding section.
16. We corrected the citation of the mentioned figures in the text.
17. The information of the use of a 1°x1° grid was included in the method section.
18. We were more specific when we talk about the low oxygen concentrations detected in the middle of the ocean by Silva et al. (2009). We revised the phrase and re-written to better explain it.

About the comments made by Reviewer#3:

1. About the hotspot of denitrification inside the eddy, the reviewer raises a valid concern. The proxies that we measured in it suggest the presence of active denitrification. However, as the reviewer says, is only one sampled profile in this eddy so We had the precaution to say that, and that this issue needs to have further studies. In the same sense, about the rates of change in biogeochemical properties we referred to the calculations as 'back of the envelope' type calculations and cautioned in the text that they should be taken with a grain of salt. We were very careful to specify that our calculations are rough and we need more studies in order to estimate more precisely these rates.
2. We added the standard deviation of replicate samples for nitrite and N_2O values. In the case of nitrite, the standard deviations are very low, so it is difficult to see them in the figure.
3. We were more explicit about that with our data we can not include mixing in our calculations.

4. The first paragraph of the introduction was modified in order to separate the ideas.
5. We added information in the introduction about the description and characteristics of water masses in the region which is source of water for the mesoscale eddies.
6. We added a description of sample collection in the methods.
7. We included the reference about the glider track in the methods.
8. We included the data from E02 (now station 093) in the figure 1e.
9. We included the caption of figure 6b.

Biogeochemical characteristics of a Long-lived anticyclonic eddy in the eastern South Pacific Ocean

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ABSTRACT

~~Eastern boundary upwelling systems are characterized by high productivity that often leads to subsurface hypoxia on the shelf.~~ Mesoscale eddies are important, frequent, and persistent features of the circulation in ~~these regions~~the eastern South Pacific (ESP) Ocean, transporting physical, chemical and biological properties from the productive shelves to the open ocean. ~~In~~Some of these eddies exhibit subsurface hypoxic or suboxic conditions and may serve as important hotspots for nitrogen loss, but little is known about oxygen consumption rates and nitrogen transformation processes associated with these eddies. In the austral fall of 2011, during the Tara Oceans expedition, ~~a subsurface layer (200-400 m) in which the concentration of oxygen was very low (<2 μmol kg^{-1} of O_2) was observed in the eastern South Pacific, ~900 km offshore (30°S, 81°W). Satellite altimetry combined with CTD observations associated the local oxygen anomaly with~~ an intrathermocline, anticyclonic, mesoscale eddy with a ~~diameter of about 150 km.~~ suboxic (<2 μmol kg^{-1} of O_2), subsurface layer (200-400 m) was detected ~900 km off the Chilean shore (30°S, 81°W). The ~~eddy contained~~core of the eddy's suboxic layer had a temperature-salinity signature characteristic of Equatorial Subsurface Water (ESSW) that at this latitude is normally restricted to an area near the coast. ~~Undersaturation~~Measurements of nitrogen species within the eddy revealed undersaturation (below 44%) of nitrous oxide (N_2O) and nitrite accumulation (> 0.5 μM~~) gave evidence for~~), suggesting that active denitrification occurred in this water mass. ~~Based on~~Using satellite altimetry, we ~~tracked~~were able to track the eddy back to its region of formation on the coast of central Chile (36.1°S, 74.6°W). ~~We estimate that the eddy formed in April 2010.~~ Field studies conducted ~~on the~~in Chilean shelf ~~in June~~

~~2010~~waters close to the time of eddy formation provided ~~approximate information on~~ estimates of initial O_2 and N_2O concentrations of ~~‘~~the ESSW source ~~water’~~water in the ~~region at~~eddy. By the time of ~~eddy formation. Concentrations~~its offshore sighting, concentrations of both O_2 and N_2O in the subsurface oxygen minimum zone (OMZ) of the ~~offshore~~ eddy were lower than ~~its surroundings or~~ concentrations in surrounding water and ‘source water’ on the shelf, ~~suggesting~~indicating that these chemical species were consumed as the eddy moved offshore. Estimates of apparent oxygen utilization rates at the OMZ of the eddy ranged from 0.29 to 44 nmol L^{-1} d^{-1} and the rate of N_2O consumption was 3.92 nmol L^{-1} d^{-1}. ~~Our~~These results show that mesoscale eddies affect open-ocean biogeochemistry in the ESP not only ~~transport~~by transporting physical and chemical properties ~~of the ESSW~~ from the coast to the ocean interior~~,~~ but also ~~export and transform biogeochemical properties, creating suboxic environments in the oligotrophic region of the eastern South Pacific. Suboxic water masses that are advected by eddies act as hotspots for~~during advection, local biological consumption of oxygen within an eddy further generates conditions favorable to denitrification and loss of fixed nitrogen from the system.

INTRODUCTION

Mesoscale eddies play a major role in vertical and horizontal transport of heat, salts and other physical, chemical and biological constituents~~.~~ (Chelton et al., 2007; Chaigneau et al., 2008, 2009). In the eastern South Pacific (ESP) Ocean, mesoscale eddies frequently form in the coastal transition zone off central Chile due to the instability of the alongshore currents ~~in the coastal region~~ (Hormazábal et al., 2013; Morales et al., 2010, 2012). These eddies transport water for long distances and over several months across biogeographic boundaries, from the productive Humboldt (Peru-Chile) Current to adjacent oligotrophic waters of the subtropical gyre (Pizarro et al., 2006). While cyclonic eddies transport surface waters and are seen as negative anomalies by altimetry data, anticyclonic eddies, including the Intrathermocline eddies (ITE) are deeper and transport low oxygen and salty subsurface waters from the Equatorial Subsurface Waters (ESSW) (Chaigneau et al., 2011).

Although eddies have been considered a net loss of nutrients from the coastal zone (Gruber, 2011), they constitute a nutrient source in the open ocean that stimulates production in oligotrophic regions (McGillicuddy et al., 1998). In addition ~~to transporting nutrients~~, eddies introduce spatial heterogeneity in productivity, community structure and particle flux, as has been observed in the Sargasso Sea (McGillicuddy et al., 1998; Sweeney et al., 2003). Impacts of eddies on biogeochemical processes are of particular interest for coastal transition zones of eastern boundary currents, where oxygen minimum zones (OMZs) and eddies interact (Altabet et al., 2012; Stramma et al., 2013). Open-ocean eddies associated with subsurface hypoxic or suboxic conditions have been observed in both the eastern tropical Atlantic and eastern tropical Pacific (e.g., Lukas and Santiago-Mandujano 2001;

Stramma et al., 2014; Karstensen et al., 2015). High surface productivity~~ and~~, downward particle flux and oxygen respiration, combined with sluggish exchange between the eddy interior and surrounding waters, have been proposed as mechanisms leading to the formation of "dead zones" observed within anticyclonic-mode water eddies (Karstensen et al., 2015). Oxygen consumption rates within an eddy can be 3 to 5 times higher than in the surrounding oligotrophic water (Karstensen et al., 2015). Eddies containing hypoxic or suboxic water can become hotspots for nitrogen cycling, including biogenic production of N_2 and loss of fixed nitrogen from the system (Altabet et al., 2012; Stramma et al., 2013). ~~Recent observations on eddies formed~~ Recently, Stramma et al. (2013) suggested that in the eastern tropical Pacific Ocean, ~~off Peru, suggest that~~ coastal mode water eddies are ~~regions~~zones of active loss of fixed nitrogen ~~loss, whereas the contribution of eddies generated in the open ocean to~~while nitrogen loss ~~in this region~~ associated with older, open ocean mode water eddies is ~~negligible (Stramma et al., 2013).~~considerably lower .

In eastern boundary subtropical upwelling ~~zones~~systems with a pronounced subsurface OMZ, such as in the ESP, eddies may play an important role in transporting OMZ waters and their microbial communities to the open ocean. The OMZ in the upwelling region of the ESP is associated with Equatorial Subsurface Water (ESSW~~), originating in~~) that has been transported poleward, from the Pacific Ocean equatorial belt~~ and transported poleward~~, along the coast with the Peru-Chile undercurrent. The ESSW is characterized by high salinity and nutrient concentrations, low oxygen concentrations and an active, bacterially mediated nitrogen cycling, including production and consumption of the greenhouse gas nitrous oxide (N_2O). ~~Intense nitrification, denitrification and nitrous oxide (N_2O) production (Codispoti~~

~~and Christensen, 1985)~~Intense nitrification, denitrification and nitrous oxide (N_2O) production associated with ESSW is generally confined to a narrow coastal band and contributes to net nitrogen loss in this region (Lam and Kuypers, 2011).

Intriguing questions about the role of coastally generated eddies abound: What biogeochemical transformations occur as this volume of water is advected offshore? Do concentrations of dissolved oxygen decrease, increase or remain the same? If changes in dissolved oxygen concentrations occur during transport, what are other biogeochemical consequences in both surface and subsurface layers? Here, we present results ~~of~~from a study on the physical and chemical characteristics of a single anticyclonic eddy observed ~900 km offshore, off central Chile. We tracked ~~it~~the eddy back to its region of formation and examined changes in concentration of oxygen and nitrogen species from the time it left the coast to the time it was sampled in the oligotrophic ocean.

METHODS

Hydrography and nitrogen data

Hydrographic data and water samples for analyses of nutrients, N_2O and surface δ^{15}N-POM were collected along a transect from Valparaíso, Chile (33°S, 71.6° W) to Easter Island (28.2° S, 107.4° W) during the Tara Oceans Expedition (~~16~~11 – 31 March 2011, Fig. 1; Karsenti et al., 2011). Sampling consisted of 11 vertical profiles using a Sea-Bird ~~911equipped~~911 equipped with an oxygen sensor (SBE43, sampling rate 24 Hz; Picheral et al., 2014). ~~Unfortunately~~Due to logistical constraints, the oxygen sensor could not be calibrated on board. It was calibrated at the start of the expedition (July 2009) and a year later (August 2010 during a stopover in Cape Town, South Africa). A third calibration was conducted in September 2011 (during a stopover in Papeete). The sensor showed mean drifts of 0.101 (August 2010) and 0.405 µmol kg^{-1} (September 2011), ~~respectively,~~ between successive calibrations. Because oxygen calibrations could not be done routinely, post-cruise validation of oxygen data included comparison of raw oxygen measurements with WOA13 climatology (Garcia et al., 2014) as described by Roullier et al. (2014). For the ESP transect, absolute differences between measured dissolved oxygen (SBE 43) and climatology for the upper 500 m of the water column averaged 9.1 µmol kg^{-1} (0.03 – 24.47 µmol kg^{-1}) for oceanic stations and 16.7 µmol kg^{-1} (0.06 – 36.24 µmol kg^{-1}) for the coastal stations. Below 850m, absolute differences between in situ measurements and climatology averaged 6.62 µmol kg^{-1} (0.81 – 19.08 µmol kg^{-1}).

Discrete water samples for N_2O (in triplicate) and nutrient (in duplicate) analyses were obtained from a rosette equipped with ~~12~~10 L Niskin bottles. Samples were collected at 0, 50, 100, 150, 200, 250, 300, 400, 500, and 900 m. N_2O samples (~~20mL)~~20 mL) were taken after the inorganic carbon samples, using a tygon tubing to avoid bubble formation. Samples were fixed with 50 µL of saturated mercuric chloride and stored in the dark. N_2O concentrations were determined onshore using a gas chromatograph equipped with an electron capture detector (ECD), following a headspace technique (McAullife, 1971). A four-point calibration curve was determined with air (0.32 ppm) and N_2O standards of 0.1, 0.5 and 1 ppm (Scotty gas mixture; Air Liquid Co.).

Nutrient samples (NO_3^-, NO_2^- and PO_4^{-3}) were collected by filtering seawater (GF/F 0.7 µm filters); filtrates were stored at -20°C until analysis onshore. Concentrations of NO_3^-, NO_2^- and PO_4^{-3} were measured using a Seal Analytical AA3 AutoAnalyzer (Grasshoff et al., 1983).

Eddy identification and tracking

Presence and position of mesoscale eddies in the region was determined by analyzing weekly maps of anomalies in sea level and geostrophic velocities from the multi-satellite AVISO product (Ssalto/Duacs, ~~http://www.aviso.oceanobs.com/duacs/),~~http://www.aviso.oceanobs.com/duacs/), from April 2010 to September 2011. This gridded, multi-satellite altimeter product provides spatial resolution of 1/3° and allows resolution of eddies with an e-folding scale > 40 km (Chaigneau et al., 2011; Chelton et al., 2011). ~~Detection of an eddy and subsequent tracking back to its region of origin used the Okubo-Weiss (W) parameter~~For eddy tracking, we used the Okubo-Weiss parameter method (W), which evaluates the relative dominance of strain and vorticity (Chelton et al., 2007; Okubo, 1970; Sangrà et al., 2009; Weiss, 1991)~~, which evaluates the relative dominance of strain and vorticity:~~:

$$W = S_n^2 + S_s^2 - \omega^2 \quad (1)$$

With

$$S_n = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}; \quad (2)$$

$$S_s = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}; \quad (3)$$

$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}; \quad (4)$$

where, S_n and S_s are the normal and shear components of strain, respectively, and ω is the relative vorticity.

This approach ~~associated~~confirmed that the water mass sampled in station ~~E03~~094-A (30°S, 81°W; TARA_20110316T1152Z_999_EVENT_CAST; http://doi.pangaea.de/10.1594/PANGAEA.836473; Fig. ~~1)~~1a) was associated with an eddy. The path of this eddy was reconstructed from its time of origin (28 April 2010) to the time of its decay (29 June 2011) by tracing the eddy center (~~approximate position of~~i.e., the ~~center of the~~region with highest vorticity~~ region~~) in successive geostrophic fields.

Vertical hydrographic profiles obtained from ~~the E03~~ station ~~(sampled~~ 094-A (within the identified eddy) were compared with~~ available~~ vertical profiles of temperature, salinity and dissolved oxygen concentration collected during other studies in the area and with nearby Argo buoy profiles and climatological information from WOA13 data (Garcia et al., 2014). Data available for the nearest grid (1° x 1°) to station ~~E03~~094-A were used in this analysis.

Glider information at the origin of the eddy

To characterize the properties of water ~~close to~~near the time and location of eddy formation we used temperature, salinity and oxygen data from a cross-shore transect (73.0 – 74.8° W, 36.5° S) conducted with a Slocum glider (Teledyne Technologies) in June 2010~~.~~ (Pizarro et al., 2015). The data covered an area that extended to within 160 km from the presumed starting point of the eddy based on satellite backtracking. The glider was

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equipped with an optical oxygen sensor (Aanderaa Data Instrument oxygen Optode model 3830). Oxygen sensor calibrations are routinely done at the Physical Oceanography Laboratory, Universidad de Concepción, with a two-point calibration ~~curve~~ (0% and 100% of oxygen saturation). Details of the sensor and the physical principles involved in the measurements are described in Körtzinger et al. (2005) and Uchida et al. (2008).

RESULTS AND DISCUSSION

Hydrography

A vertical section of temperature, salinity and oxygen, measured along the transect from Valparaíso (33.4° S, 71.6° W) to Easter Island (27.08° S, 109.3° W) in March 2011 provides regional context (Fig. ~~1).~~1b, 1c, 1d,respectively). A subsurface oxygen minimum layer (with dissolved oxygen concentration as low as 1.17 µmol O_2 kg^{-1}) was detected at station ~~E03~~094-A, 922 km offshore (30°S, 81°W, Fig. 1d). Dissolved oxygen concentrations observed at ~~E03~~094-A are anomalous given that at this latitude the boundary of the OMZ (defined as O_2< 44.6 µmol kg^{-1}) ~~at this latitude is typically located closer to shore (~ 600 km from shoreline), while~~and its core (defined as O_2< 22.3 µmol kg^{-1}) ~~is confined to a thin subsurface layer that does~~do not ~~normally stretch~~typically extend beyond ~600 km and ~500 km from ~~shore~~the shoreline, respectively (Silva et al., 2009). Suboxic conditions (O_2< 10 µmol kg^{-1}), are thought to be confined to the shelf region and were reported only in some bottom waters over the continental shelf (Farías, 2003). Climatological data indicate that ~~the~~ subsurface ~~layer at~~ water in the vicinity of station ~~E03 region~~094-A is typically oxygenated (Fig. 1e). According to ~~this~~above classification of dissolved oxygen concentrations, the OMZ observed at station ~~E03~~094-A has its upper and lower boundaries at depths of 164 and 536 m, respectively, while suboxic conditions were observed between 174 m and 421 m (66% of the OMZ).

The low-oxygen water mass was associated with higher salinities (34.60 – 34.66) compared to ~~background~~surrounding water (Fig. 1c) and climatology for this region (34.15 – 34.36, for the years 1965 - 2012). Historical data from previous cruises conducted along the P06-WOCE transect (32.5° S) or north of the study region (e.g., 28°S, Scorpio; ~~Silva et al., 2009~~Silva et al., 2009; 27°S, CIMAR 5 cruise ~~Fuenzalida et al., 2006)~~Fuenzalida et al., 2006) do not show such ~~extreme~~anomalies in physical and chemical conditions at this longitude (Fig. 2a and 2b). The presence of the anomalous salinity signature observed in this study is supported by an independent Argo float that profiled in the vicinity of ~~E03~~094-A (33.86º S, 79.84º W) during the Tara Oceans' sampling period (Fig. 2).

Vertical profiles of salinity and temperature anomalies at ~~E03 show a warm and salty core centered between 230 and 270 m, accompanied by the dome and bowl shapes of the upper and lower thermocline, respectively (Fig. 3). This feature is characteristic of an intrathermocline, anticyclonic eddy (ITE, Xiu and Chai 2011; Chaigneau et al., 2011; Hormazábal et al., 2013). Positive sea-level anomalies (SLA) and associated geostrophic currents further indicate that station E03~~094-A show a warm and salty core centered between 230 and 270 m, accompanied by the dome and bowl shapes of the upper and lower thermocline, respectively (Fig. 3). This feature is characteristic of an intrathermocline, anticyclonic eddy (ITE, Xiu and Chai 2011; Chaigneau et al., 2011; Hormazábal et al., 2013). Positive sea-level anomalies (SLA) and associated geostrophic currents further indicate that station 094-A was located close to the center of a mesoscale anticyclonic eddy (~ 150 km in diameter), centered at 33.45°S, 80.85°W (Fig. 4).

Reconstruction of this mesoscale eddy suggests that it was formed nearin the coastal transition zone off Concepción (36.09° S, 74.21° W), in the coastal transition zone, approximately 315 d prior to our sampling at station 094-A, and advected northwest at a mean velocity of 2.4 cm s^{-1} , approx. 2 Km d^{-1} (Fig. 4). Reconstruction of the eddy's velocity and direction agrees well with previously reported trajectories of eddies in the area (Chaigneau, 2005).

OMZ evolution in the eddy

In the ESP, eddies could frequently transport suboxic water from the coastal OMZ to oceanic regions. (Hormazábal et al., 2013). Low-oxygen water masses ($O_2 < <$ 44.6 µM) have been detected in the middle of the South Pacific Ocean (2000 km offshore at 28°S; Silva et al., 2009), but their associationat the time the authors did not associated these water masses with mesoscale eddies has been speculative.. In the North Pacific Ocean, low concentrations of dissolved oxygen in the subsurface open ocean have been previously described in association with anticyclonic mesoscale eddies (Altabet et al., 2012; Chaigneau et al., 2011; Johnson and McTaggart, 2010; Lukas and Santiago-Mandujano, 2001), and could result fromhave been attributed to low-oxygen source waters (Lukas and Santiago-Mandujano, 2001) or fromto local consumption asduring the transport of an eddy is being transported (Karstensen et al., 2015).

To ~~approximate the evolution~~estimate temporal changes in concentrations of dissolved oxygen in the subsurface layer of ~~the~~our sampled eddy, we used underwater glider measurements, collected in June 2010, at 36.5˚S / 74° W (120 km from shore~~) during June 2010.~~). This is the estimated location of the eddy one month after its formation~~. The distribution~~ and oxygen concentrations of source water are in agreement with those reported for other ITEs in the same region (Hormazábal et al. 2013). Glider measurements of dissolved oxygen ~~measured by the glider~~ showed a well-developed OMZ (O_2< 44.6 µM; Fig. 5) between 104 and 352 m, with a suboxic layer located between 135 and 226 m. We refer to these values as the eddy's ~~initial~~'initial' subsurface oxygen concentrations. Dissolved oxygen concentrations were then compared along isopycnals between the estimated location of the eddy's origin and its offshore location at station ~~E03~~094-A (Fig. 6). By the time the eddy reached its offshore location, the OMZ in the eddy was deeper and thicker (located between 164 and 537 m) than the OMZ measured in the coastal transition zone, and the lowest dissolved oxygen concentration decreased from 7.34 µmol kg^{-1} at 173 m to 1.17 µmol kg^{-1} at a depth of 338 m. The suboxic layer of the eddy in the open-ocean ~~eddy~~ was located between 174 and 422 m,~~ a layer~~ almost three times thicker than the suboxic layer of the "source water" (Fig. 6). This suggests that the observed OMZ offshore ~~OMZ~~ is a result of both ~~the transport~~advection of low-oxygen coastal water by an eddy and continuing biological consumption ~~as the eddy moved offshore~~during its transport. Estimated oxygen consumption rate in the OMZ of the eddy ranged from 0.29 to 44 nmol O_2 L^{-1} d^{-1} (~0.1 - 15 µmol O_2 L^{-1} yr^{-1}) in the core of the eddy (Fig. 6), which is quite high compared to previously reported oxygen consumption rates in other OMZs in this depth range (Karstensen et al., 2008). Considering the eddy's area (20 × 10^3 km^2~~), a~~; transport of ESSW of ~1.38 Sv) and the thickness of the layer with dissolved oxygen concentrations < 44.6 µM (373 m), an oxygen deficit of 12.2 Tg ~~of O_2~~ is expected in the ~~whole~~ subsurface eddy's layer. This calculation is likely to underestimate the oxygen deficit since mixing with surrounding oxygen-rich water has not been taken into account here. If the whole ~~oxygen~~ sub-saturated oxygen layer ~~(from ~80 to 1000m)~~ of the eddy is considered~~,~~ (from ~80 to 1000m), the estimated oxygen deficit transported to the oceanic region is even larger. ~~Although~~While this crude, back-of-the-envelope calculation of oxygen deficit should be taken with a grain of salt, it highlights the significant influence of eddies on OMZs in the open ocean. When the eddy dissipates, the oxygen deficit in the subsurface layer will be redistributed and will contribute to the overall oxygen budget of the ESP OMZ region.

The area of the 'birth' of the studied eddy (~36°S) has been identified as a hotspot of eddy generation (Hormazábal et al., 2013), with~ 5-7 ~~ITE eddies~~ITEs that can reach a diameter > 100 km being formed every year. If the eddy studied here is representative of eddies generated in the OMZ ~~between 31° and 36° S~~ of the eastern boundary of the Pacific Ocean, between 31° and 36° S, advection of and continued respiration within oxygen-deficient waters could produce a deficit as high as 60 – 85 Tg O_2 yr^{-1} within the oceanic region.

Subsurface biogeochemical implications of the eddy

OMZ regions of eastern boundary current systems are considered important with respect to the nitrogen cycle. ~~They~~These are areas where nitrogen is lost due to denitrification and anammox, and are often associated with buildup of nitrite (NO_2^-; Lam and Kuypers, 2011).

~~Much of~~ Water masses with these features can be advected and the processes enhanced offshore as indicated by the observed accumulation of high subsurface NO_2^- in anticyclonic coastal eddies (Stramma et al., 2013).

Off the Chilean coast, elevated NO_2^- concentrations are generally found within~~In the present study, initial oxygen concentrations in the OMZ of the eddy were low enough to support high denitrification and anammox and, consequently, the accumulation of NO_2^-. Previous measurements from the area of the eddy's origin show that nitrite concentrations in hypoxic waters (<7 µmol O_2 kg^{-1}) are <0.1 µM (Cornejo and Farías, 2012b). As an eddy is transported offshore, oxygen is consumed and conditions become favorable for denitrification. In the coastal water off Chile, elevated NO_2^- concentrations are generally found in~~ the core of the OMZ (Cornejo and Farías, 2012a; Silva et al., 2009). Previous studies conducted in the region of the eddy's formation show that nitrite concentrations in hypoxic waters (< 7 µmol O_2 kg^{-1}) are < 0.1 µM (Cornejo and Farías, 2012b). In the present study, initial oxygen concentrations in the OMZ of the eddy were low enough to support high denitrification and anammox and, consequently, the accumulation of NO_2^-. ~~In this study, the vertical distribution of NO_2^- in station E03 (oligotrophic ocean) shows a buildup of this nitrogen species, forming a subsurface NO_2^- maximum (up to 0.56 µM) at a depth of 250 m (Fig. 1f). The increase in NO_2^- concentration corresponds to a NO_3^- deficit of -13.90 µM (Fig. 6) when compared~~ The vertical distribution of NO_2^- in station 094-A (oligotrophic ocean) shows a subsurface NO_2^- maximum (up to 0.56 µM) at a depth of 250 m (Fig. 1f). The apparent buildup of NO_2^- concentration within the eddy corresponds to a NO_3^- deficit (N*) of -13.90 µM (Fig. 6) relative to surrounding water (determined from the deviation of the

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NO_3^-:PO_4^{-3} molar ratio from the Redfield ratio according with ~~Deutsch et al., 2001)~~Deutsch et al., 2001), suggesting that conditions in the eddy's anoxic zone were favorable for denitrification. A subsurface water mass with low oxygen concentrations and marked nitrate deficit has been previously observed in the oligotrophic, oceanic water of the EPS, during the Scorpio cruise (Fig. 7, Silva et al., 2009), but other nitrogen species indicative of denitrification were not measured, and tools to link this water mass to eddy activity were not well developed at that time.

Another indication of ~~an~~the existence of anaerobic ~~environment~~conditions within the OMZ of the eddy is the presence of a N_2O consumption layer. This greenhouse gas is produced by nitrification and denitrification under hypoxic conditions and consumed by denitrification under suboxic conditions (< 8 µM of O_2; Bonin et al., 1989). The vertical distribution of N_2O in the eddy (station ~~E03~~094-A) shows a double peak with a supersaturation at the upper and lower boundaries of the subsurface OMZ (up to 224%) and subsaturation (44%) in the upper region of the OMZ core (Fig. 1e), suggesting that both production and consumption of N_2O occurred in the eddy. Layers depleted in N_2O have been previously observed in different OMZs in coastal environments where denitrification takes place (Cornejo and Farías, 2012a). To ~~our~~the best of our knowledge, this is the first reported N_2O consumption layer in oceanic subsurface waters of the South Pacific Ocean.

Oxygen concentrations in the ~~eddy's generation region~~area where the eddy was formed are often too high to support significant N_2O consumption ~~(Cornejo and Farías, 2012b; Cornejo et al., 2014).~~(Cornejo and Farías, 2012b; Cornejo et al., 2015). Thus N_2O is being accumulated alongshore in the coastal OMZ (up to 25 nM) and consumed only in bottom waters associated with suboxic conditions. ~~Taking~~In the absence of direct measurements of N_2O concentrations at the time of eddy formation, we use the mean coastal N_2O concentrations (22.68 ± 2.99 nM) from three previous cruises (FIP; Cornejo et al., 2015) observed at the isopycnal σ_t = 26.56 kg m^{-3}~~, corresponding to~~ (depth with N_2O undersaturation~~,~~ at station 094-A) as the ~~starting point during the eddy's generation, we~~ 'initial' concentration of N_2O in the eddy. We estimated a ~~N_2O~~ consumption rate of 3.92 nmol N_2O L^{-1} d^{-1} during the time the eddy was ~~moving~~advected offshore. This N_2O consumption rate is half of those reported from incubation experiments conducted at the upper (shallower) boundary of the OMZ off Perú (8.16 nmol L^{-1} d^{-1}; Dalsgaard et al., 2012). Higher rates might have occurred in the center of the eddy, where more active denitrification ~~should be~~is expected. Furthermore, ~~unlike incubation experiments, estimates of in situ~~it is likely that we have underestimated N_2O ~~consumption are affected by diffusion from the~~ production since mixing with upper and lower layers ~~with~~ that are supersaturated with respect to N_2O ~~supersaturation, resulting in underestimation of the N_2O reduction.~~, was not taken into account in our calculation.

Although N_2O was sampled from discrete depths, the thickness of the N_2O consumption layer can be estimated considering that N_2O consumption does not occur at dissolved oxygen concentrations > 8 µM (Bonin et al., 1989). ~~At~~Within the eddy, this layer was 60 m thick (210 – 270 m) meaning that net consumption was at least ~ 0.15 Gg N_2O during the offshore transfer. This N_2O consumption represents only 14% of the N_2O accumulation estimated above and below the consumption layer, ~~meaning~~suggesting that the eddy provided a net supply of ~0.85 Gg of N_2O to the oceanic region. ~~Regardless of the N_2O~~

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Observing both production ~~or~~and consumption of N_2O in the eddy~~, the occurrence of both means a~~ signifies net nitrogen loss, with possible impacts on even global nitrogen and N_2O balances.

This study provides ~~further indication~~new evidence that anticyclonic mesoscale eddies play important roles in the biogeochemistry of the ESP (Altabet et al., 2012; Stramma et al., 2013). Previous studies have shown that ~~coastal~~ mesoscale eddies ~~provide~~act as hotspots for microbially mediated nitrogen loss via denitrification in coastal water; here we show that open-ocean anticyclonic eddies can play a similar role in parts of the ocean that are far removed from productive coastal waters and their associated OMZs.

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This article is contribution number ZZZ of Tara Oceans.

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Table 1.~~Hydrographic information~~ Sources of hydrographic data used ~~during~~in this study. The name, location, and distance ~~of~~between the nearest location of the measurements and station ~~from the station E03~~094-A are ~~also~~ reported ~~(this profile corresponds to a cast done near station TARA_094,labelTARA_20110316T1152Z_999)~~.

~~Cruise~~**Name of the program**	**Year**	**Station**	~~**Latitude**~~ ~~**[ºS]**~~**Location**	~~**Longitude**~~ ~~**[ºW**~~**Distance to 094-A [km]**	~~**Distanceto E03**~~ ~~**[km]**~~**Kind of data**
P06E (WOCE)[1]	1992, 2003 2010	24	32.52° S/80.64°W	93.1~~80.64~~	Profile~~93.1~~
Biosope[2]	2004	STB19	33.04° S/81.18°W	23.8~~81.18~~	Profile~~23.8~~
~~TARA Oceans[3]~~	~~2011~~	~~E03~~	~~33.2471~~	~~81.1267~~	~~0~~
Float ~~ARGO[4]~~ARGO[3]	2011	---	33.86° S/79.84°W	137.3~~79.84~~	Float~~137.3~~
WOA13[2]	Climatology	~~13604~~13237	33.50° S/81.50°W	~~81.50~~41.7	~~44.2~~

[1] http://www.nodc.noaa.gov/woce

[2] ~~source~~[2] source: http://www.nodc.noaa.gov/OC5/indprod.html

[3] ~~http://doi.pangaea.de/10.1594/PANGAEA.836473~~

[4] ~~source: http://www.coriolis.eu.org~~

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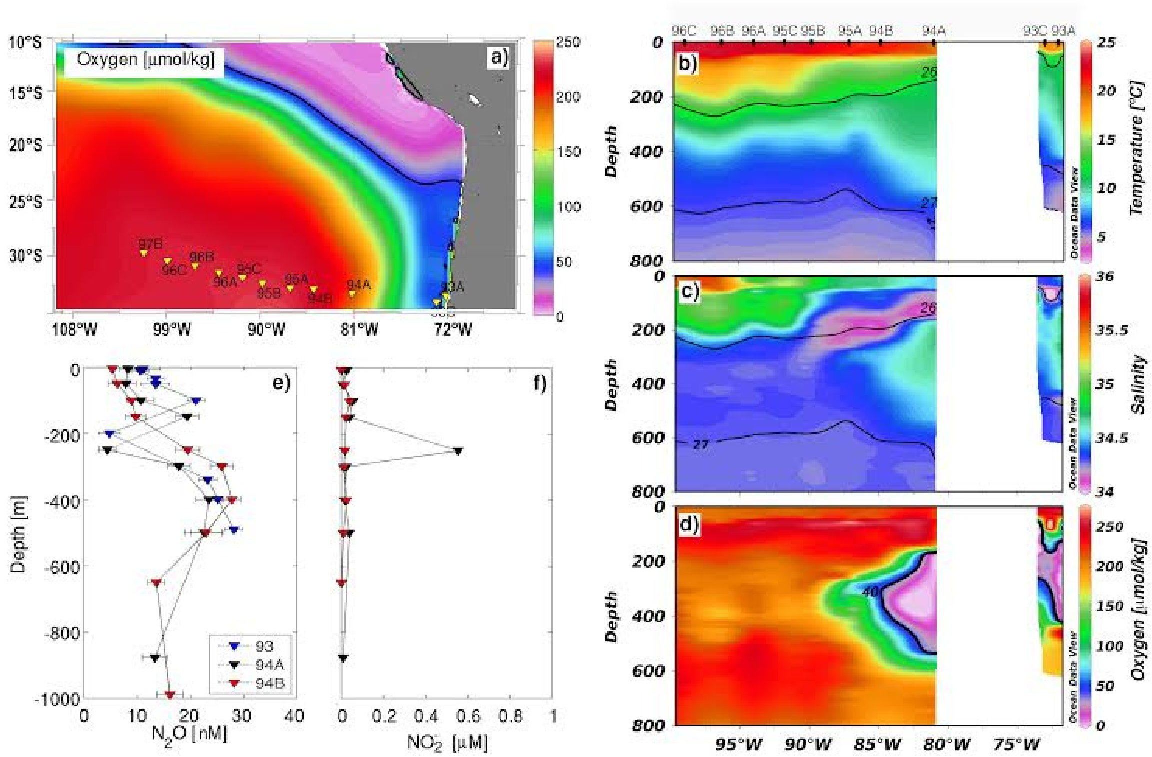

Figure 1. a) Climatology of dissolved oxygen distributions (µmol kg^{-1}) at a depth of 200 m in the eastern South Pacific Ocean. Yellow triangles indicate locations of stations during the Tara Oceans cruise. Vertical distributions of b) temperature (°C) c) salinity and d) dissolved oxygen along the transect of the Tara Ocean cruise, from coastal water off Chile to the open ocean. Black lines in b) and c) indicate the 26.0 and 27.0 kg m^{-3}σ_t isopycnals. Black line in d) indicates the isoclines of 40 µmol kg^{-1} of dissolved oxygen. e) Vertical distribution of N_2O at Tara stations 093 (34.0° S / 73.0°W, blue triangles; TARA_20110312T1637Z_093_EVENT_CAST), 094-A (33.2 °S / 81.1°W, black triangles; TARA_20110316T1152Z_999_EVENT_CAST) and 094-B (32.8°S / 84.8°W, red triangles; TARA_20110317T1815Z_999_EVENT_CAST). f) Vertical distribution of NO_2^- at Tara stations, 094-A (black triangles) and 094-B (red triangles). For a complete detail of the Tara CTD cast please refer to (Picheral et al., 2014)**.**

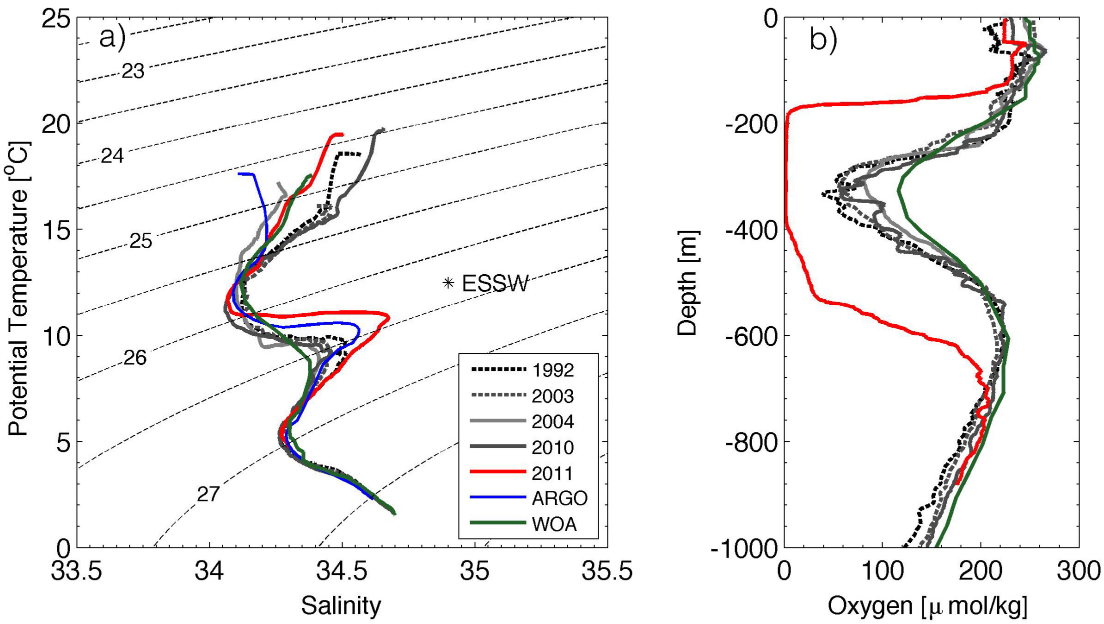

Figure 2.a) T-S diagram from various sampling programs in the study area; b) Dissolved oxygen profiles at Tara station 094-A (red line) and stations in its vicinity from cruises conducted on 1992 (black dashed line), 2003 (gray dashed line), 2010 (thick gray line) and 2004 (thin gray line); from Argo buoys (blue line, without oxygen), and the WOA 2013 climatology (green line). More detail on data sources are provided in Table 1.

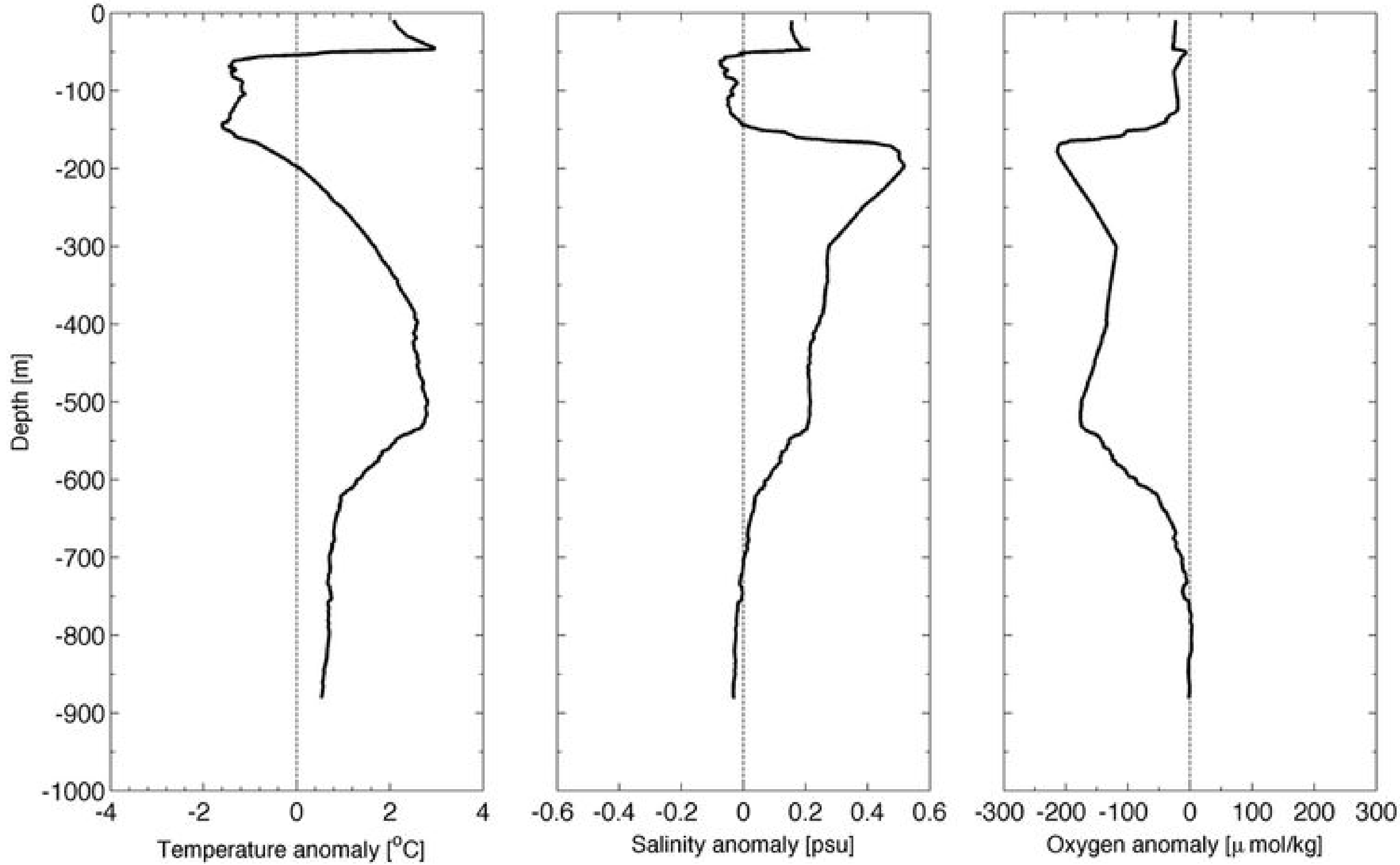

Figure 3. Vertical anomalies of: a) temperature (°C), b) Salinity, c) dissolved oxygen (μmol kg^{-1}) in station 094-A compared with WOA 2013 climatology (range of years for climatology).

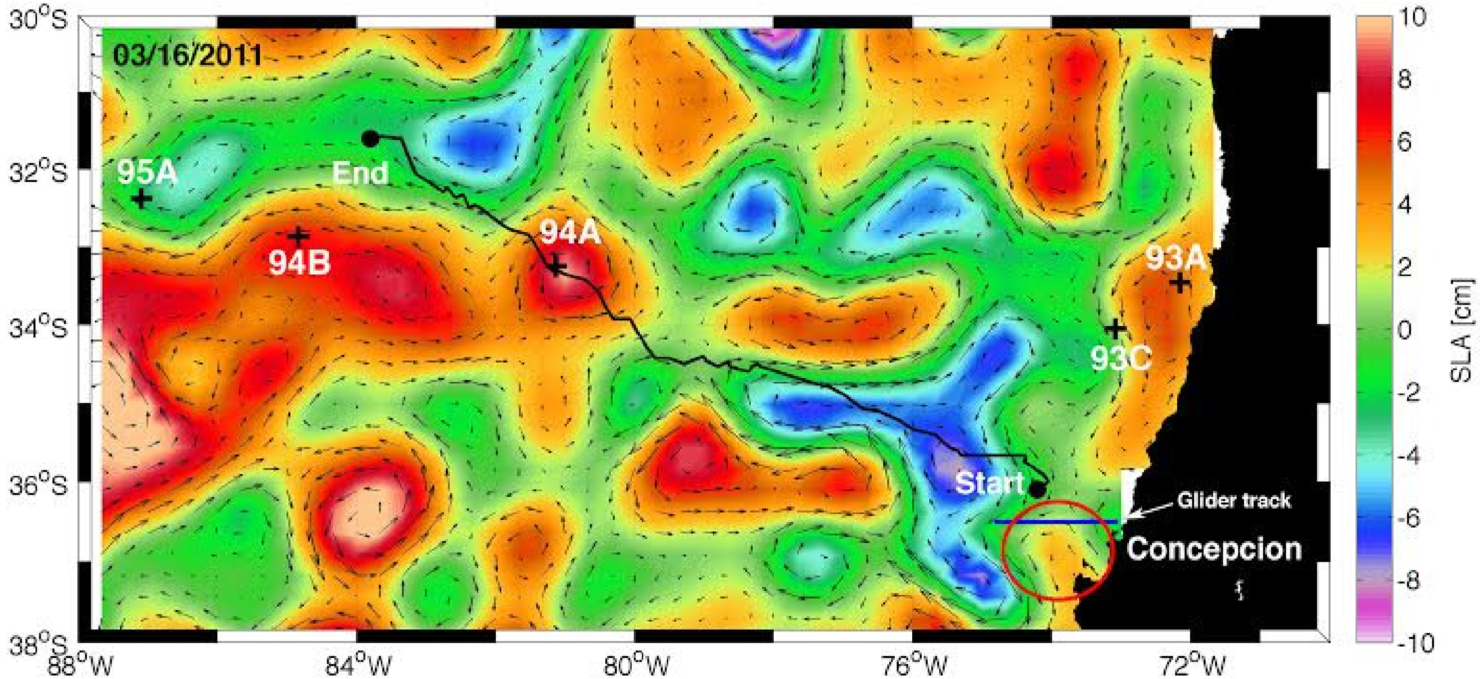

Figure 4. Sea surface hight from satellite data at the time of sampling in Tara station 094-A (March 2011). The position of the sampling stations (black crosses) and estimated eddy trajectory (black line) with start and end locations (black circles) of the trajectory are also indicated. The red circle off Concepción (36°S) shows the probable eddy generation zone

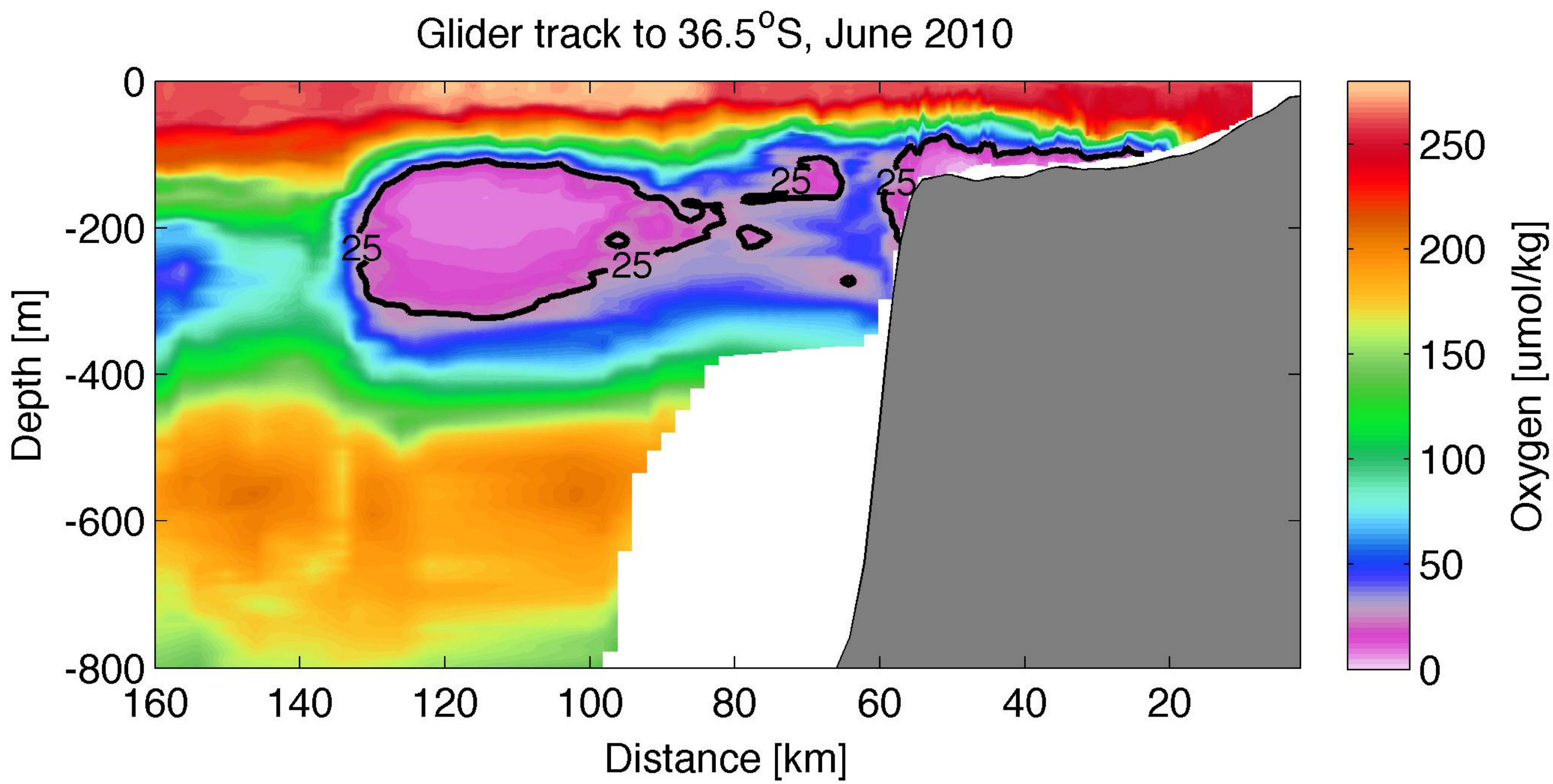

Figure 5.Vertical distributions of dissolved oxygen (µmol kg^{-1}) in a cross-shore section at 36.5°S near the time of eddy formation (June 2010). Black line indicates the isoline of 25 µmol kg^{-1}.

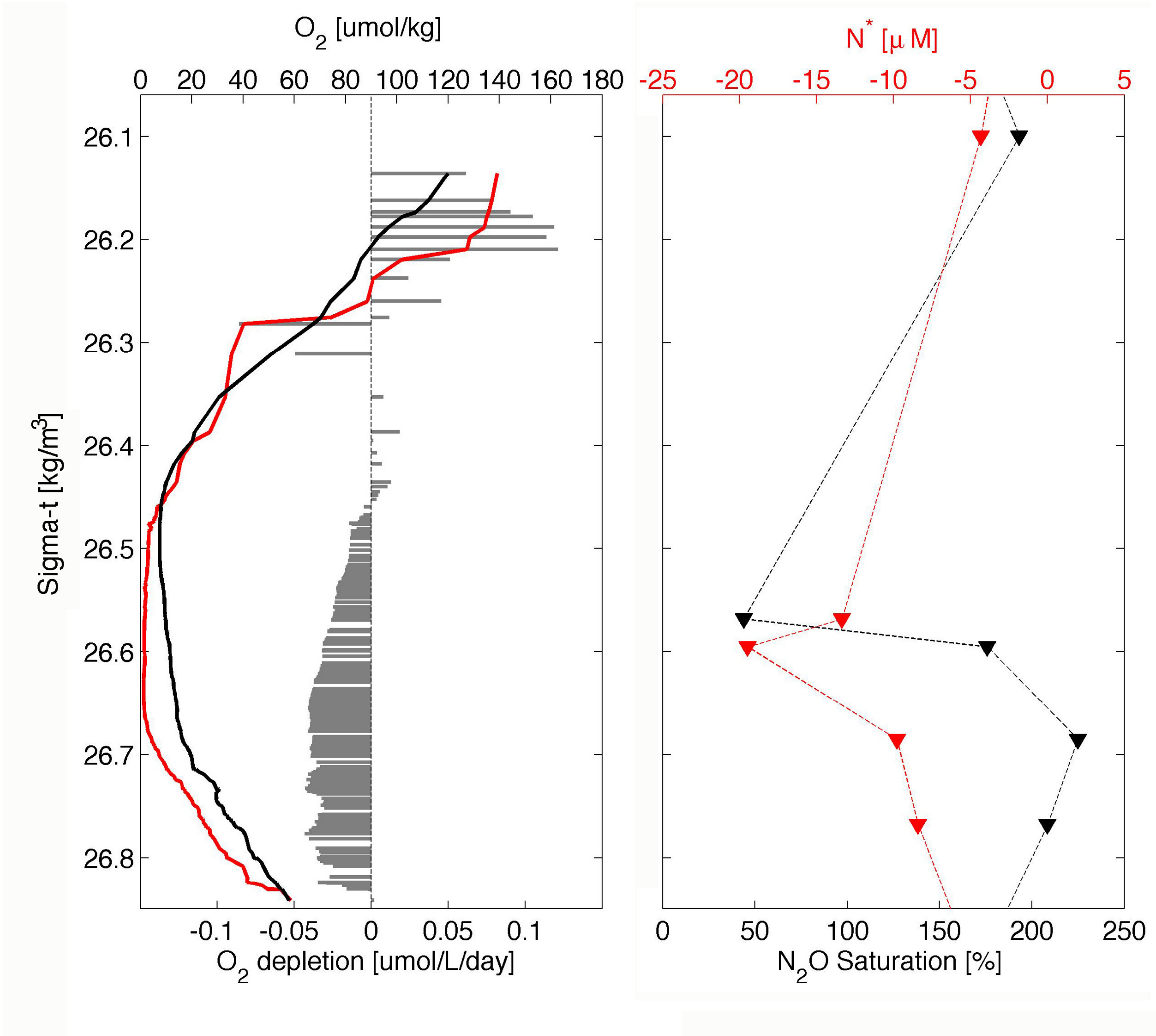

Figure 6. a) Vertical distribution of Oxygen as a function of sigma-t at Tara station 094-A (within the eddy) in March 2011 (red line) and at the coast in June 2010 (black line). Estimated O_2 depletion rates are shown as gray bars, where the vertical dotted line marks zero O_2 consumption rate. b) Vertical distributions of Nitrate deficit (N*) and Nitrous oxide saturation (black triangles and line) as a function of sigma-t within the eddy at station 094-A.

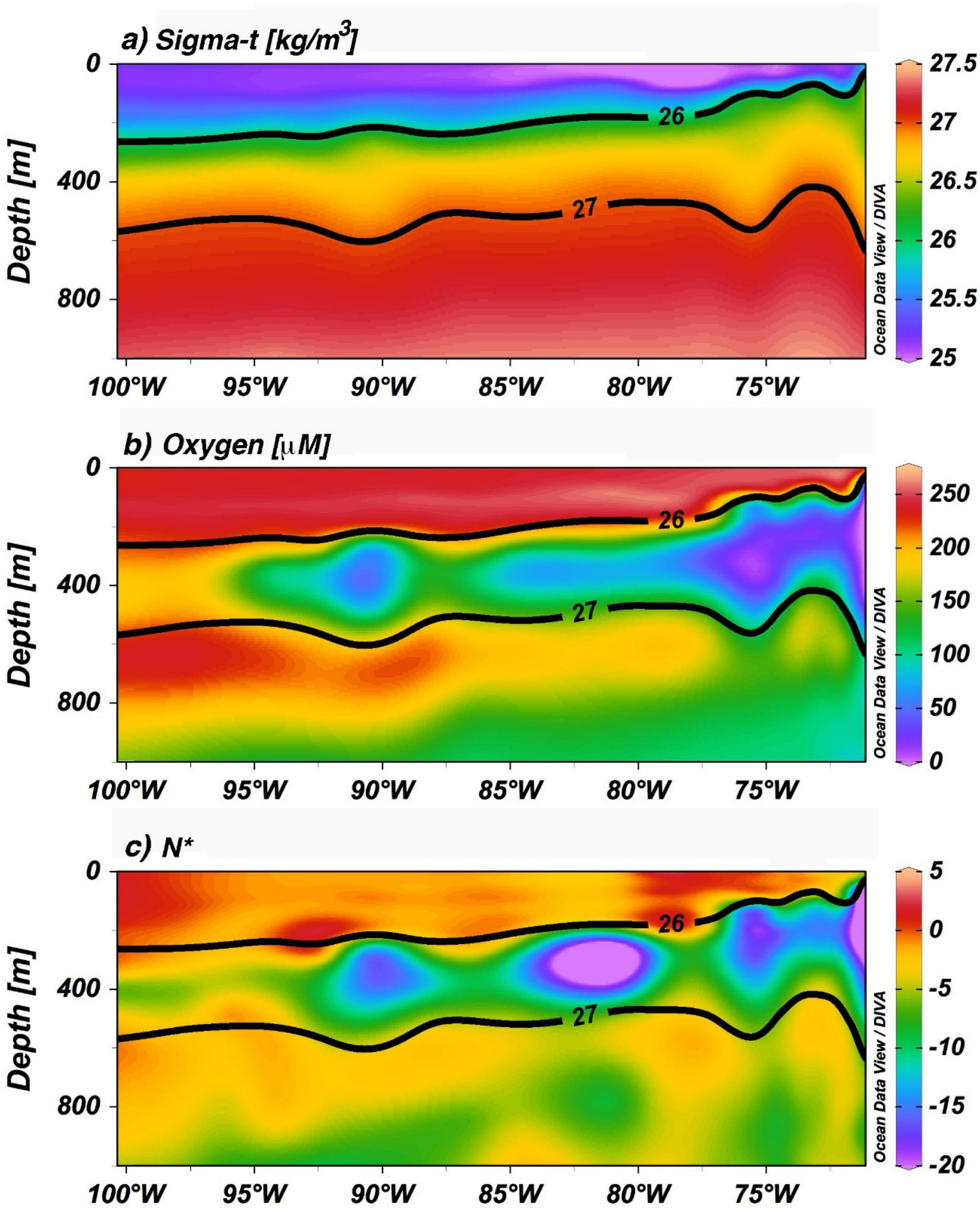

Figure 7. Vertical distributions of sigma-t, dissolved oxygen and nitrate deficit (N*; according to Deutsch et al., 2001) in a cross-shore transect along 28°S in the Eastern Southern Pacific Ocean (72° to 100° S) during Scorpio cruise (June 1967). Black lines refer to sigma-t of 26 and 27 kg m^{-3}.

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