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## Maintaining of the Eastern South Pacific Oxygen Minimum Zone (OMZ) off Chile

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[1] Processes regulating OMZs persistence in the oxygenated ocean remain poorly understood. Four cruises (21°–30°S) and fixed-point monitoring (36°S) between 2000 and 2002 using techniques adapted to O<sub>2</sub> conditions as low as 1 μM allow a preliminary analysis of the entire Chilean OMZ structure. A shallow OMZ is observed in the three studied areas, although its structure differs. Off northern and central Chile, the OMZ is a permanent feature, more pronounced at the coast than further offshore. On the shelf, it forms in spring and erodes in fall. A conceptual model of two intermittent active or passive phases (intense or low biogeochemical O<sub>2</sub> consumption) is proposed as a key mechanism for the local OMZ maintaining. The highest O<sub>2</sub> consumptions are paradoxically favoured at the oxycline when the OMZ is less intense as offshore and on the shelf in spring and fall, suggesting a control by O<sub>2</sub> availability of the OMZ remineralization. **Citation:** Paulmier, A., D. Ruiz-Pino, V. Garçon, and L. Farías (2006), Maintaining of the Eastern South Pacific Oxygen Minimum Zone (OMZ) off Chile, *Geophys. Res. Lett.*, *33*, L20601, doi:10.1029/2006GL026801.

### 1. Introduction

[2] Oxygen minimum zones (OMZs) are subsurface suboxic layers, several hundred meters deep, which in the generally oxygenated present-day ocean can potentially be considered as persistent traces of the primitive anoxic ocean. OMZs in the open ocean are found in the Eastern Tropical North Pacific (ETNP), in the Arabian Sea (AS) and off Peru [Anderson *et al.*, 1982]. They have been studied mainly for their fundamental role in the global nitrogen cycle through the processes of denitrification and nitrification [Anderson *et al.*, 1982], and the Anammox reactions [Thamdrup *et al.*, 2006]. However, the oxygen distribution in OMZs is poorly characterized, and the root causes of their existence and persistence remain an open question.

[3] The Eastern South Pacific (ESP) OMZ, one of the most extended OMZs (cf map of hypoxia [Kamykowski and Zentara, 1990; Helly and Levin, 2004]), is today a permanent feature covering the areas offshore Equator, Peru and Chile (Figure 1). Little is known about the structure and variability of the southernmost component, the Chilean OMZ. Morales *et al.* [1999] studied the OMZ off northern

Chile focusing on the variability of the 40 μM O<sub>2</sub> isoline; Escribano *et al.* [2004] concentrated their study on waters presenting O<sub>2</sub> contents higher than 40 μM. Both studies dealt only with the upper ocean (0–100 m) only. The entire Chilean OMZ thickness has not yet been documented. O<sub>2</sub> concentrations can go lower than 40 μM, reaching O<sub>2</sub><10 μM as in Peru, and can extend down to 400 m depth [Anderson *et al.*, 1982]. The Chilean OMZ exhibits variability on the interannual scale: a deepening (50–100 m) of the 40 μM O<sub>2</sub> isoline has been observed during El Niño periods, associated with coastally-trapped Kelvin waves and a reduction in upwelling activity [Morales *et al.*, 1999; Ulloa *et al.*, 2001]. On the seasonal scale, only one study reports a marked seasonal variability in O<sub>2</sub> distribution, on the continental shelf (36°S, Concepción Bay), with low O<sub>2</sub> of 10 μM in summer and one order of magnitude higher in fall-winter [Graco *et al.*, 2001; Graco, 2002; Graco *et al.*, 2006]. The possible dynamical and biogeochemical mechanisms contributing to the maintaining of the OMZ remain poorly understood. The existence of the ESP OMZ regionally depends on advection of low-O<sub>2</sub> (<40–80 μM) waters from the equator by the Peru-Chile Undercurrent (PCU) [Strub *et al.*, 1998]. The role of the intense productivity (9 gC/m<sup>2</sup>/d [Daneri *et al.*, 2000]), 20 times higher than the oceanic average, leading to a strong subsurface organic matter degradation, may drive an intense O<sub>2</sub> consumption [Reid, 1965] and be an important contributor to the OMZ maintaining. Our objective is to analyze the biogeochemical role of O<sub>2</sub> consumption on the maintaining of the local Chilean OMZ. To do this, the OMZ changes in intensity, depth and thickness will be determined in coastal and open areas *a priori* subject to different productivities and dynamical regimes.

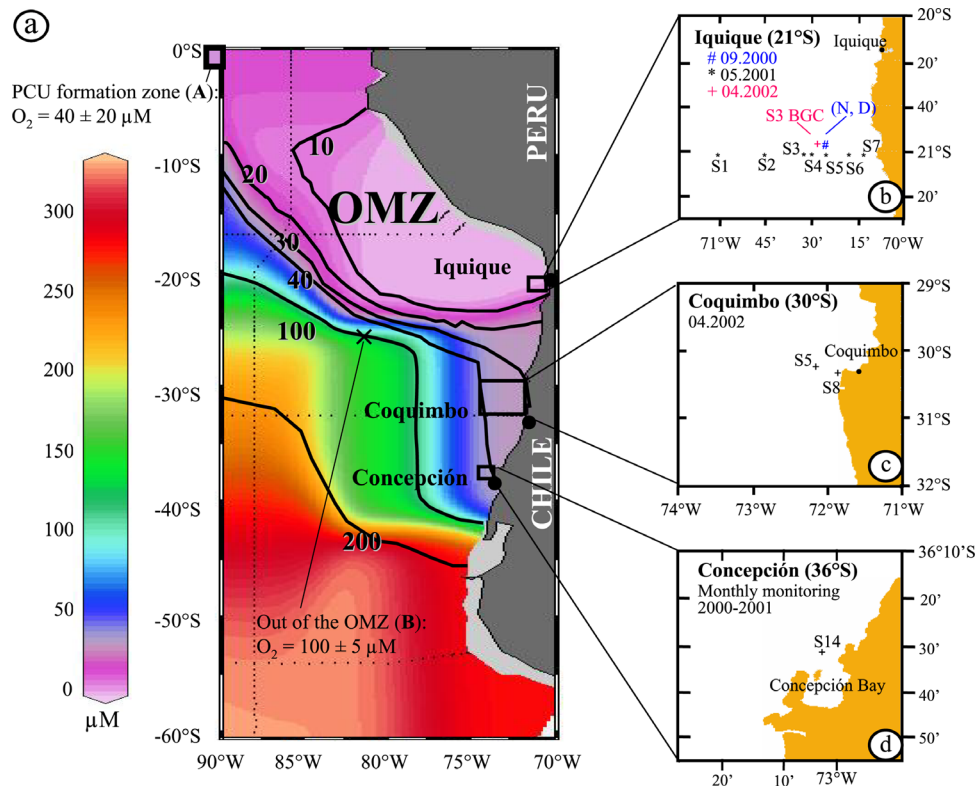
### 2. Methodology

[4] To capture the strong O<sub>2</sub> gradients (variations of 200 μM over 20–30 m) and to cover the entire OMZ, a high vertical resolution sampling, every 5–10 m between 0 and 110 m and every 20–100 m below 110 m, has been carried out. The OMZ off Chile was sampled during different non El Niño periods between 2000 and 2002, and at 3 sites (in the North: Iquique, 21°S; in the Center: Coquimbo, 30°S; on the shelf, Concepción, 36°S). Four cruises off the continental shelf at 21°S and 30°S (Figures 1b and 1c) allowed a description of different biogeochemical and dynamical regimes: e.g. a higher primary production (between 0.5–20 mgC/m<sup>2</sup>/d [Daneri *et al.*, 2000]) and a deeper PCU [Strub *et al.*, 1998] in the Center than in the North. A monthly monitoring at a fixed station at 36°S outside of an enclosed bay (Figure 1d) for nearly one year

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**Figure 1.** (a) O<sub>2</sub> distribution at 250 m depth (1992–95 WOCE data, dotted lines). Sampling sites and stations depths: (b) 21°S at Iquique (80–1880 m); (c) 30°S at Coquimbo (700–4000 m); (d) 36°S at Concepción (down to 60 m).

from September 2000 to May 2001 allowed a documentation of the seasonal variability.

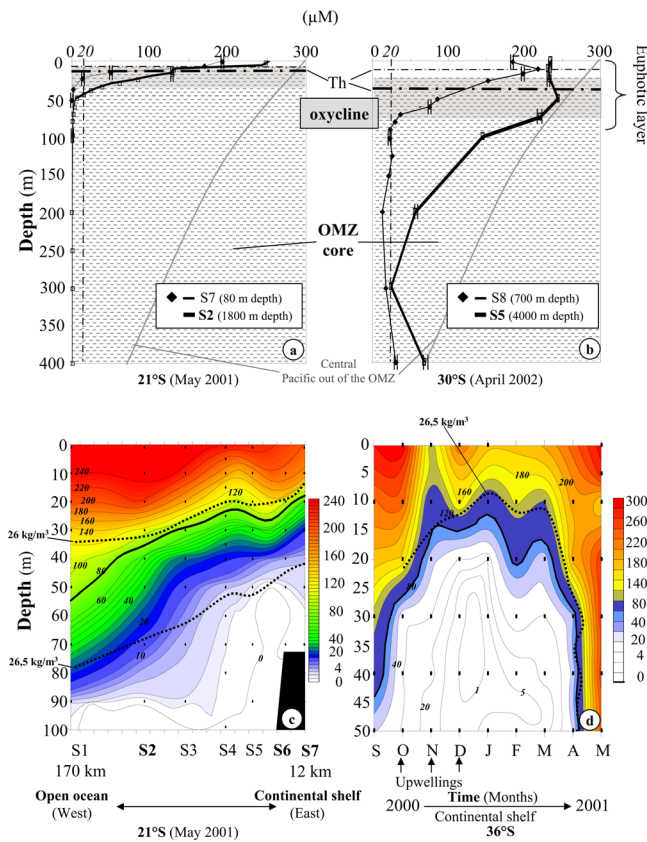
[5] The samples were analyzed according to the Winckler method, improved and adapted to low concentration detection ( $O_2 < 40 \mu\text{M}$ ) by the PROFC following *Broenckow and Cline* [1969]. Avoiding any interference with  $\text{NO}_2^-$  by  $\text{NaN}_3$  addition, the precision over the whole set (154) of samples ranges between 0.5 and  $1 \mu\text{M}$  [Paulmier, 2005]. The obtained reproducibility over 77 duplicates is  $1.8 \mu\text{M}$ , in agreement with the WOCE Operation Manual [World Ocean Circulation Experiment, 1994] recommendations.

[6] To obtain estimates of O<sub>2</sub> consumption contributions within the OMZ, we performed a water mass analysis based on an inversion method [Maamaatuaiahutapu et al., 1992] to determine mixing proportions between the source water types present in the area between 0 and 1000 m (STW-Surface Tropical, SAW-Surface Antarctic, ESSW-Equatorial Subsurface, AIW-Antarctic Intermediate Waters). The measured O<sub>2</sub> concentrations can be expressed as the sum of a contribution due to mixing processes called  $O_{2\text{mixing}}$ , and a remaining contribution or residual called  $\Delta O_2$  due only to biogeochemical processes. This hydrological model is usually applied regionally and the  $\Delta O_2$  corresponds to the integrated biogeochemical effect during history of mixing between the theoretical source water types up to the considered hydrographic station. To compare the biogeochemical effect on O<sub>2</sub> of the OMZ communities at each sampled profile, we chose to apply locally our method to infer a local biogeochemical residual within the OMZ and in particular at the oxycline level. This implies a minor effect of the local horizontal mixing and advection which does not

significantly affect the vertical O<sub>2</sub> mixing [Paulmier, 2005]. The biogeochemical residuals can be interpreted as the in situ O<sub>2</sub> consumption or production of the OMZ communities for each location, depth and period.

### 3. Results

[7] A new criterion to characterize and analyze the entire OMZ changes between 21°S and 30°S, from the shelf to offshore (21°S) and at the seasonal scale (36°S) is defined (Figure 2) from all O<sub>2</sub> profiles. This criterion can be defined due to the high vertical resolution and the improved precision (40 times higher) over previous studies on the Chilean OMZ [Escribano et al., 2004]. The O<sub>2</sub> data set collected off Chile shows an OMZ structure off the shelf:  $O_2 < 20 \mu\text{M}$  starting at 140 m depth, with a thickness of  $\sim 220$  m at 21°S and 30°S (Figures 2a, 2b, and 2c). This structure has an upper O<sub>2</sub> gradient (oxycline), a core and a lower O<sub>2</sub> gradient. The oxycline, with an upper limit defined by the level where  $O_2 < 4\%$  of O<sub>2</sub> surface is intense ( $> 1 \mu\text{M/m}$ : up to  $10 \mu\text{M/m}$  at 21°S, Figure 2a),  $\sim 10$  times more than a classical O<sub>2</sub> minimum outside of the OMZ. The oxycline exhibits a  $\sim 200 \mu\text{M}$  O<sub>2</sub> decrease over tens of meters, i.e., an O<sub>2</sub> continuum from oxic ( $> 200 \mu\text{M}$ ) to suboxic ( $< 20 \mu\text{M}$ ) conditions associated with a strong stratification ( $0.5 \text{ kg/m}^3$  increase over  $\sim 40$  m between 26 and  $26.5 \text{ kg/m}^3$  isopycnals, Figure 2c). The oxycline is close to the sea surface (5–200 m), and can thus intercept the euphotic layer between 60 and 120 m (Figures 2a and 2b). The OMZ core is defined by a central part with  $O_2 < 20 \mu\text{M}$  over a 100–320 m thickness. The O<sub>2</sub> concentrations in the



**Figure 2.** (a, b) O<sub>2</sub> profiles at 21°S and 30°S for four representative stations far and near the coast (S2-S7 and S5-S8). Th = thermocline depth. O<sub>2</sub> vertical sections, (c) along an East-West gradient and (d) versus time. Points indicate sampling locations. October (O) and December (D) correspond to year 2001.

core are among the weakest found in the global ocean [Helly and Levin, 2004], reaching the detection limit ( $<1 \mu\text{M}$  at 21°S, Figure 2a). The OMZ core is always located below the thermocline (by more than 25 m: Figures 2a and 2b) and below the  $26.5 \text{ kg/m}^3$  isopycnal (by more than 5 m: Figures 2c and 2d). These physical characteristics tend to indicate that the upper boundary of the core is delimited by the intense isopycnal mixing with the surface oxygenated waters. The lower O<sub>2</sub> gradient, an order of magnitude less intense ( $\sim +0.3 \mu\text{M/m}$ ) than the oxycline, is delimited above by the core and below by the depth where the O<sub>2</sub> slope changes significantly (slope break  $>0.1 \mu\text{M/m}$ ). Consequently, the lower O<sub>2</sub> gradient may extend from 300 to 800 m depth, and the total OMZ layer from 5 to 800 m.

[8] This OMZ structure, observed at the two sampled sites at 21°S and 30°S (Figures 2a and 2b), corresponds to a permanent structure off northern and central Chile. The core at 30°S (Figure 2b) is located below 100 m (S8) and 300 m (S5), i.e., 75 and 250 m deeper than at 21°S in S7 and S2 (Figure 2a). This observation confirms the southward deepening of the  $40 \mu\text{M}$  O<sub>2</sub> isoline between 18° and 24°S [Morales *et al.*, 1999],  $\sim 500 \text{ km}$  more in the North. The OMZ is between 50 and 200 m thinner at 30°S than at 21°S. The core minima ( $10\text{--}20 \mu\text{M}$ ) and the oxycline ( $\sim 1\text{--}1.25 \mu\text{M/m}$ ) at 30°S are 2–3 and 3–4 times less intense than at 21°S,

respectively. At 21°S, the core (white, Figure 2c) is truncated by the continental shelf without change in its intensity. The continental slope induces a 30–40 m core shoaling following the  $20 \mu\text{M}$  O<sub>2</sub> isoline. This shoaling is not constant, sharp (40 m) between S1 and S3 and slow (10 m) between S3 and S7. The reduction towards the coast of the vertical distance between the  $200 \mu\text{M}$  and  $20 \mu\text{M}$  O<sub>2</sub> isolines, the upper and lower oxycline limits, yields an oxycline intensification of 40% corresponding to a higher stratification.

[9] At 36°S on the shelf, the OMZ becomes established in austral spring-summer (October to March) with O<sub>2</sub> concentrations lower than  $20 \mu\text{M}$  from 20 to 50 m of depth (Figure 2d). The OMZ starts to settle in spring during the high upwelling activity period [Ahumada *et al.*, 1983]. In fall (April-May), the  $180 \mu\text{M}$  O<sub>2</sub> isoline extends from the surface to the bottom, indicative of a homogenized and reoxygenated water column with a complete OMZ destruction, confirming previous observations in the same area [Graco, 2002].

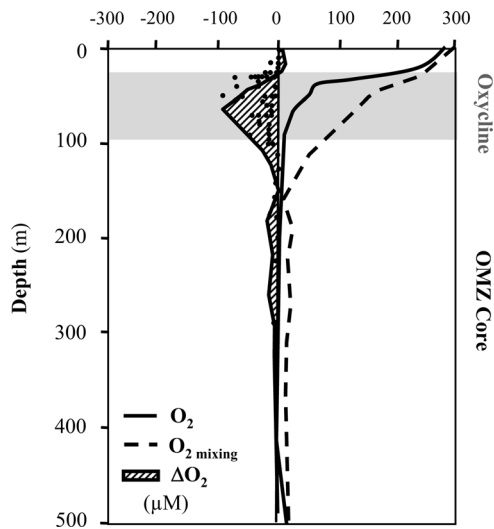
[10] Off northern and central Chile, the OMZ is shallower and more intense at 21°S and the coast than at 30°S and offshore. On the shelf at 36°S, the setting is distinct and a seasonal suboxia develops: the OMZ forms in spring, gets established in summer, and is destroyed at the end of fall. Despite these modulations, the OMZ structure has been observed in all the three studied areas off the coast of Chile.

#### 4. Discussion

[11] After having characterized the vertical extension of the Chilean OMZ, we examine the possible causes of its maintaining. In a “classical” O<sub>2</sub> minimum, typical of all intermediate waters of the world ocean [Wyrki, 1962], both biogeochemical and dynamical processes contribute. Considering the relatively small area documented by our data ( $<2\%$  of the ESP surface, Figure 1), we will focus here on the local O<sub>2</sub> contributions. Results of the hydrological method applied locally to each profile provide the  $\Delta\text{O}_2 = \text{O}_2 - \text{O}_{2\text{mixing}}$  (Figure 3) residuals associated with the biogeochemical contributions. In all profiles, the computed  $\Delta\text{O}_2$  are negative, indicating a O<sub>2</sub> consumption. The comparison between O<sub>2</sub> and O<sub>2mixing</sub> profiles suggests that the core and oxycline would be  $10\text{--}20 \mu\text{M}$  lower and 3 times less intense without this O<sub>2</sub> consumption, respectively.

[12] This consumption does not take place uniformly over the OMZ depth, but has peaks ( $|\Delta\text{O}_2|_{\text{max}}$ ) in the oxycline on average three times more intense than in the OMZ core, with a biogeochemical contribution which can reach  $100 \mu\text{M}$  (Figure 3). Because of this strong O<sub>2</sub> consumption and the potential ventilation effect from the oxygenated surface layers, the oxycline can be regarded as the local engine maintaining the OMZ. On the cross-shore transect and time-series, the peaks  $|\Delta\text{O}_2|_{\text{max}}$  offshore, in October and April (between 22 and  $101 \mu\text{M}$ ) are 5 and 9 times higher than at the coast and in summer, respectively (Figure 4). To analyze the role of these  $|\Delta\text{O}_2|_{\text{max}}$  variations on the OMZ changes, we propose a conceptual model with two phases, passive and active. A passive (active) phase corresponds to an OMZ whose  $|\Delta\text{O}_2|_{\text{max}}$  is lower (larger) than  $20 \mu\text{M}$  at the oxycline. This threshold of  $20 \mu\text{M}$



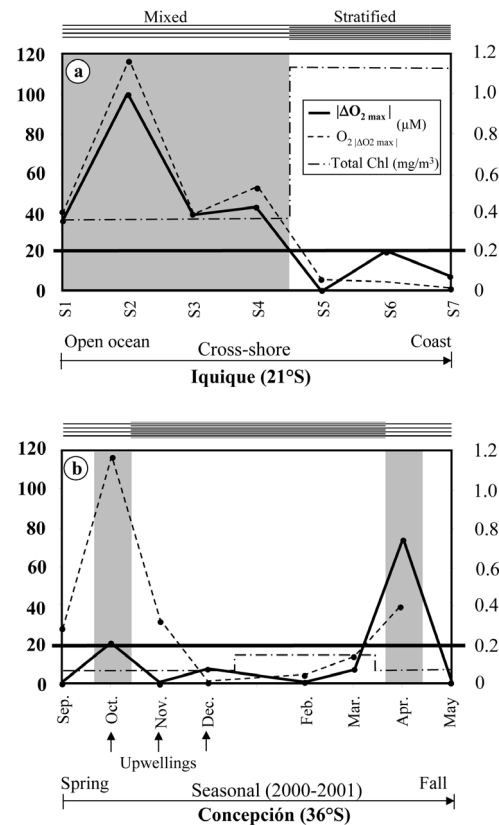


**Figure 3.**  $O_2$ ,  $O_{2\text{mixing}}$  and  $\Delta O_2$  profiles evaluated from the hydrological method for an illustrative station (S2). Points represent the  $\Delta O_2$  values for samples of all cruises. Errors on  $O_{2\text{mixing}}$  and  $\Delta O_2$  are  $< 2$  and  $4 \mu\text{M}$ , respectively [Paulmier, 2005].

corresponds to the  $O_2$  consumption associated with the most intense remineralization estimated in the oxygenated ocean [Rivkin and Legendre, 2001], calculated for a mean annual primary production off Chile of  $2.6 \text{ gC/m}^2/\text{d}$  [Daneri et al., 2000]. The OMZ is active offshore (Figure 4a) where the oxycline associated with a lower stratification is less intense than at the coast (Figure 2c). On the shelf, the OMZ is active in spring and fall (Figure 4b) when the OMZ is formed during the upwelling period and destroyed at the beginning of the strong winter overturning (Figure 2d). To understand the regional and temporal OMZ differences, the alternation of active and passive phases is not sufficient. The spatial and seasonal changes in mixing, rather than in the  $O_2$  consumption at the oxycline, contribute to the intensification, establishment and destruction of the OMZ. The OMZ in regions in the North and at the coast (S4-S7 at  $21^\circ\text{S}$ ; S8 at  $30^\circ\text{S}$ ) is under the stronger influence of the less-oxygenated STW, while the Center and offshore (S1-S3 at  $21^\circ\text{S}$ ; S5 at  $30^\circ\text{S}$ ) feel the stronger influence of the more-oxygenated SAW [Paulmier, 2005]. In addition, the PCU and upwelling advection of less-oxygenated waters (STW and ESSW, respectively) are higher in the North and at the coast than in the Center and offshore [Strub et al., 1998]. Consequently, the northern and coastal parts of the OMZ should be more intense and dynamically-maintained than the Centre and offshore parts of the OMZ. At  $36^\circ\text{S}$  on the shelf, the OMZ should also be more pre-formed and dynamically-maintained in spring and summer during upwelling favourable periods.

[13] Why is this local  $O_2$  consumption at the oxycline both intermittent and up to 5 times more intense than in the oxygenated ocean? On one hand,  $O_2$  consumption is classically related to biomass. However here, the OMZ activity (Figure 4) is associated with  $O_2$  availability (oxycline less intense offshore; OMZ not yet formed in spring or eroded in fall: Figures 2c and 2d). During the active phases,  $O_2$  is provided by mixing of oxygenated surface layers ( $O_2 > 30 -$

$40 \mu\text{M}$ ). The sea surface biomass is then 3 times lower than at the coast and in summer (passive conditions: Figure 4). The high  $O_2$  consumption would agree with a non-local “productivity-driven” denitrification in the OMZ on a paleoceanographic scale [De Pol-Holz et al., 2006], and rather suggests an “oxygen-driven” activity of both remineralization and denitrification in the OMZ. Only a small occurrence of an active phase (35% of the sampling: Figure 4) - which by high  $O_2$  consumption would induce a shift to a passive phase (a less-oxygenated oxycline) - should be enough to maintain the OMZ. Then the changes in productivity level and distribution do not directly affect the changes in  $O_2$  consumption, and thus in the local OMZ maintaining. On the other hand, the oxycline has a well-lit  $O_2$  continuum going from oxic ( $> 200 \mu\text{M}$  near the surface) to suboxic ( $< 20 \mu\text{M}$  near the core) concentrations with sufficient high stratification (Figure 2) and shifts between the passive (suboxic) and active (oxic) phases. These unique conditions allow a potential co-existence of anaerobic/aerobic (e.g. denitrification/nitrification) and photic/aphotic (e.g. phototrophy/heterotrophy) processes. The high  $O_2$  consumption found at the oxycline is in agreement with previous experimental work, showing that remineralization with alternation of oxic and anoxic conditions could be  $\sim 10$  times more efficient than in oxic conditions only [Sun et al., 2002].



**Figure 4.** (a) Cross-shore and (b) seasonal variations, for maximal  $O_2$  consumptions ( $|\Delta O_2|_{\text{max}}$ ) and  $O_2$  at  $|\Delta O_2|_{\text{max}}$  depth in the oxycline, mean surface chlorophyll from SeaWiFS climatology and stratification intensity.  $O_2$   $|\Delta O_2|_{\text{max}}$  in May ( $225 \mu\text{M}$ ) is not reported because of the complete OMZ destruction. Biogeochemical OMZ activity is defined by  $|\Delta O_2|_{\text{max}} > 20 \mu\text{M}$  (grey background).

[14] Despite the fact that oxycline  $O_2$  consumption is vital in maintaining such an intense  $O_2$  minimum, another essential factor in the ESP OMZ formation is the  $O_2$  deficit preformation by the PCU. Because the PCU is confined to within 40 km of the coast [Strub *et al.*, 1998], while the OMZ extends 2000 km further offshore (Figure 1), we can here infer a rough estimate of the PCU influence on the OMZ maintaining off Chile only for regions close to the coast. Consider a typical  $O_2$  profile from our data set, with concentrations lower than  $20 \mu\text{M}$  in the core. This Chilean OMZ characteristic profile is compared with a historical  $O_2$  profile, from the South Eastern Pacific zone outside the OMZ, with  $O_2 = 100 \pm 5 \mu\text{M}$  at the OMZ core depth of between 200 and 400 m (B, Figure 1). We make the assumption that  $O_2$  concentrations of water masses advected by the PCU correspond to those upstream close to the PCU formation zone, i.e.  $40 \pm 20 \mu\text{M}$  (A, Figure 1). The mean PCU contribution is then  $100 \pm 5 - 40 \pm 20 = 60 \pm 25 \mu\text{M}$ . Compared to the total OMZ  $O_2$  deficit ( $100 - 20 = 80 \mu\text{M}$ ), the PCU then accounts for  $\sim 75\%$  of the OMZ. The remaining contribution of 25% must be due to the local  $O_2$  consumption through the intense remineralization discussed above. Thus the local biogeochemical effect is significant in understanding the existence of the Chilean OMZ, complementary to the important regional role of the PCU, which may also control the OMZ vertical position and thickness.

## 5. Conclusion

[15] The Chilean OMZ structure, between 5 and 800 m depth, is maintained everywhere off the shelf with an intense oxycline ( $>1 \mu\text{M}/\text{m}$ ) and minimum concentrations reaching  $O_2 < 1 \mu\text{M}$  in the OMZ core. The maintaining of the OMZ requires a local high remineralization at the oxycline ("activity"), 3 times more intense than in the OMZ core. This activity, associated with the remineralization process, leads us to consider the oxycline as the OMZ "engine". Without this remineralization of up to 5 times higher than in the oxygenated areas, a "classical"  $O_2$  minimum would form rather than an OMZ. The OMZ activity requires a minimal oxygenation ( $O_2 > 30\text{--}40 \mu\text{M}$ ) which can occur only in the oxycline. Consequently, the remineralization is thought to be more sensitive to  $O_2$  availability than to surface biomass, suggesting an "oxygen-driven" remineralization. This strong OMZ remineralization should be further explored, considering the oxycline oxic/suboxic/well-lit specificity which allows a possible co-existence of aerobic/anaerobic and photic/aphotic processes, usually occurring at different depths. Despite its persistence off northern and central Chile, the OMZ is shallower and stronger at the coast and  $21^\circ\text{S}$  than offshore and at  $30^\circ\text{S}$ . Off southern Chile, on the shelf, a seasonal suboxia develops: it is formed in austral spring by upwelling and destroyed at the end of fall by winter overturning. The highest  $O_2$  consumption occurs preferentially offshore, in spring and fall, during periods of weak stratification (weaker oxycline), and then shifts to passivity (lower  $O_2$  consumption). The OMZ maintaining cannot be due only to the activity. Another prerequisite, not detailed here, is regional dynamical transport by the PCU of  $O_2$ -depleted waters; this dynamically pre-formed OMZ gets intensified by the local biogeochemical  $O_2$  consumption.

[16] Both climatic and environmental anthropogenic perturbations in the coming decades will likely drive OMZ changes. It is therefore urgent to characterize the structure of all OMZs, evaluate their extension and analyze the details of their chemical and ecosystem nature and dynamics. The adapted sampling and ultra low- $O_2$  technique used to capture the Chilean OMZ structure could support future OMZs study strategies.

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