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Modeling the seasonal cycle of the oxygen minimum zone over the continental shelf off Concepción, Chile (36.5° S)

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Abstract

We analyze the seasonal dynamics of oxygen concentrations in the southernmost part of the Eastern South Pacific oxygen minimum zone (ESP's OMZ), offshore of Concepción, Chile ($\sim 37^\circ$ S). We use data from a time series over the continental shelf off Concepción, as well as other hydrographic data and measurements from moored instruments and ocean gliders to evaluate temporal and spatial variability in this region. We identify two extreme modes (winter and summer) that characterize the seasonal variability. A simple model that account for the main physical and biological processes that influences the oxygen concentration was developed. According to our results, the seasonal variability of the dissolved oxygen in the study region is mainly driven by lateral (advective and diffusive) transport that connect the waters over the shelf with poorly oxygenated water from the slope, which is in turn, advected southward by the Peru-Chile Undercurrent.

1 Introduction

One of the key features that give structure and shape to life in the marine environments is oxygen concentration, determining metabolic and physiological processes; especially where oceanographic conditions set low oxygen concentrations in subsurface waters and minimal changes in available oxygen drives drastic biological changes. These oceanic regions of low oxygen, known as oxygen minimum zones (OMZs) are located in areas such as closed basins or eastern boundary systems where upwelling feeds high biomass production and remineralization. OMZs are defined as zones of the water column where dissolved oxygen (DO) concentrations fall below $20 \mu\text{M}$, although levels can drop below $1 \mu\text{M}$ in the core of certain OMZs (Paulmier and Ruiz-Pino, 2009). These areas play a central role in the biogeochemical cycle of nitrogen, due to enhanced nitrification and intense denitrification, which produces gaseous nitrogen species such as N_2 and N_2O (Codispoti et al., 2001). Thus, OMZs are commonly

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nitrogen deficient with respect to phosphorus, and the N : P ratio falls below the Redfield ratio (Tyrrell, 1999). OMZs have a high environmental impact due to the release of large amounts of greenhouse gases, mainly carbon dioxide, nitrous oxide and methane (Paulmier and Ruiz-Pino, 2009), and the production of reduced chemical species, e.g. Fe(II) and Cu(I), which stimulates photosynthesis (Richards et al., 1965). Furthermore, low DO concentrations determine the existence of benthonic communities adapted to anoxia (Graco et al., 2006), like the sulfur-oxidant giant bacteria *Thioploca* (Gallardo, 1977).

The OMZs located in the Eastern South Pacific Ocean (ESP), offshore Ecuador, Peru and Chile, is in one of the most productive regions of the world ocean (Daneri et al., 2000; Carr, 2001), sustaining one of the world's most important fishing industries (Escribano and Schneider, 2007). This area expands from 0 to 37° S, covering $2 \pm 1 \times 10^6 \text{ km}^3$ (Fuenzalida et al., 2009), and is characterized by a very shallow and steep oxycline, marking a transition from oxic to anoxic conditions in about ~ 30 m (Farías et al., 2007). The high primary productivity and associated bacterial remineralization are closely related to the circulation regime, producing different characteristics in distinct zones of the ESP. While in Peru and Northern Chile (equatorward of ~ 24° S), the OMZ is present throughout the year, off Concepción (~ 36.5° S) the OMZ displays a marked seasonality, with a shallower and more intense OMZ in summertime (Paulmier et al., 2006). This temporal variability is mainly related to the rising of nutrient-rich waters driven by wind patterns that are favorable to upwelling (mainly SW winds) during the spring-summer (Daneri et al., 2000). The upwelling regime ensures a high supply of nitrate and other nutrients that enhance both primary productivity and bacterial activity (Vargas et al., 2007). However, the seasonal variability of the OMZ is also related to other processes that modify alongshore and cross-shore advection and stratification of the water column. In particular, the high insolation and consequent increase in temperature of the water near the surface during summer, and the riverine fresh water discharge during winter (Sobarzo et al., 2007). Furthermore, southward advection of Equatorial Subsurface Water (ESSW) plays an important role, carrying

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poorly oxygenated waters ($< 1 \text{ ml l}^{-1}$) via the Peru-Chile Undercurrent (PCU) off Peru-Chile (Silva and Neshyba, 1979). In fact, it has been shown that ESSW reaches 42° S , preserving 50 % of its mass at this latitude (Silva et al., 2009). Alternatively, the structure and variability of the ESP's OMZ may be strongly linked to regional and global climatic systems. Global models project an overall decrease in oceanic DO concentrations (Joos et al., 2003; Shaffer et al., 2009), and an intensification of the OMZs (Shaffer et al., 2009). In fact, slight intensification and expansion of the ESP's OMZ have been observed over the past decades, possibly due to changes in ocean circulation (Shaffer et al., 2000; Stramma et al., 2008).

The mechanism of coastal upwelling driven by winds along western continental margins is a well-known phenomenon (Lentz, 1992), characterized by the rise of nutrient rich and poor oxygenated subsurface waters in response to equator-ward winds. It is widely held that upwelled water directly enhances productivity by supplying nutrients; thereafter, the remineralization of the organic matter produced (and consequent bacterial oxygen utilization), along with poor ventilation, sets the suboxic conditions in coastal upwelling regions (Helly and Levin, 2004). However, the underlying upwelling-productivity-oxygen depletion mechanism has not yet been clearly explained, and relies on complex physical and biogeochemical processes that work together to drive suboxia or anoxia. For example, iron concentrations have been shown to have a potential role determining the extent of the productivity in some coastal upwelling areas of the Pacific Ocean (Bruland and Rue, 2001; Hutchins et al., 2002), which is important since iron has a direct influence on marine bacterial activity (Ussher et al., 2004). Cuevas et al. (2004) showed that bacterial production off Concepción accounts for up to 22 % of the total primary production during the upwelling season, with marked seasonal variation in their growth. Farías et al. (2009) evaluated primary production in the area, differentiating between photo- (bacterial and phytoplankton) and chemo- (bacterial) autotrophy. These authors found that chemoautotrophic production accounts for a large part ($\sim 50\%$) of total production, which is relevant since chemolithotrophic

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activity (nitrification and ammonium oxidation) are enhanced at low DO concentrations, despite being aerobic processes (Ward et al., 1989; Schubert et al., 2006).

The modeling of oceanographic processes is a valuable tool for studying marine environments, making generalizations based on discrete observations, and predicting future states. Surprisingly, few efforts have been made to model OMZs in coastal upwelling environments (Peña et al., 2010). Even scarcer are attempts to model oxygen dynamics in the ocean (e.g., Thomas et al., 1990; Steiner et al., 2007). Here, we present a simple numerical model that analyze the seasonal cycle of the DO concentration over the continental shelf off Concepción (36.5° S), as well as a brief description of the spatial and temporal behaviors of oxygen concentrations within the ESP's OMZ.

2 Study area and hydrographic measurements

The study area is located in the Eastern South Pacific off Central Chile (Fig. 1), including a time-series station, called Station 18 (36.5° S; 73.1° W). This station is located on the continental shelf at 20 km from the coast, and the bottom depth is about 90 m. The shelf width varies from 25 km (south) to 60 km (north) in this region, with a shelf break near 150 m depth (Sobarzo and Djurfeldt, 2004). This time series was typically sampled once a month, depending on weather conditions. A second, shorter time series station (station 40) was used to estimate the zonal oxygen transport due to horizontal advection and diffusion. This station is located over the slope, 40.4 km westward from station 18, at the same latitude (Fig. 1).

Nutrients, temperature, salinity and oxygen data acquired for the COPAS center (<http://copas.udec.cl/eng/research/serie/>), cover nine years of CTD casts. For the CTD data, a SeaBird 19 plus equipped with a SBE 43 oxygen sensor was used. Oxygen measurements were calibrated using the Winkler method. Nutrients were determined from samples taken during the CTD casts, following the procedure described in Sect. 2.2.1 of Farías et al. (2009).

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During years 2010 and 2011, high resolution transects were taken using a deep ocean Slocum Glider, rated for 1000 m depth with CTD. The glider was additionally equipped with an Aanderaa Optode oxygen sensor. Transects were carried out from the coast to 75° W along 36.5° S.

5 Monthly temperature and salinity CTD data from Station 18 were used to force the model, as well as the initial DO concentration and the oxygen measurements to perform model validation. In order to construct an annual series, temperature and salinity where monthly averaged, and then interpolated using a cubic spline method to obtain daily time series at each depth. The conversions of in-situ temperature into conserva-
10 tive temperature and of practical salinity (in P.S.U.) into absolute salinity, as well as the Brunt-Väisälä frequency calculation, were performed using the Thermodynamic Equation of Seawater – 2010 (www.TEOS-10.org).

Current velocity at Station 18 was measured with a moored 300 kHz ADCP (RDI Instruments) installed near the bottom at 86 m. The time series extent from January
15 2009 to October 2010, from these data we built a one day time step annual series that was extended throughout our modeling period.

Daily wind data gridded with a $0.25^\circ \times 0.25^\circ$ resolution was extracted from the ASCAT database (ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/MWF/L3/ASCAT/). Wind
20 data from 2008 (considered representative of a typical annual wind pattern) was selected as input for the model. To avoid synoptic and other high frequency variability, wind data was low-pass filtered applying a 30 moving average.

3 Oxygen seasonal variability and spatial distribution

Temporal oxygen distribution, derived from COPAS time series station 18 (Fig. 2) shows a distinctive seasonal pattern, which has been described and analyzed (see for in-
25 stance, Morales and Lange, 2004; Ulloa and Pantoja, 2009, and references therein). These researchers found that summer conditions are characterized by a very shallow and steep oxycline and a DO concentration threshold (20 μM) that reaches less than

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20 m depth. Winter, on the other hand, has a deeper and less steep oxycline, which reaches the OMZ threshold at 70–80 m. Despite the high mixing during winter, bottom layers remain suboxic throughout the year. According to Sobarzo et al. (2007), off Central Chile, coastal upwelling is forced by seasonally variable winds along the coast, competing with two other seasonal processes that also modify the vertical density stratification of the water column. These processes drive the mixed layer's heat balance which is dominated by solar radiation, with maxima in January, and the fresh water balance, which is dominated by river discharge and precipitation with maxima in June and July. Other studies have also shown that wind-forced processes (like upwelling) has important synoptic variability (3 to 10 days), and are highly influenced by bottom topography, especially shelf shape and submarine canyons (Sobarzo and Djurfeldt, 2004). The monthly averaged data (oxygen, temperature and salinity and meridional wind) for the whole series are shown in Fig. 3, clearly reflect the water column annual pattern and its relationship with the meridional winds.

Regarding the previously described characteristics of DO, temperature and salinity, based on almost ten years of data, we can define two main modes (winter and summer) for the water column in the area; these modes are represented by two typical profiles shown in Fig. 4. The summer mode (Fig. 4a) is characterized by a shallow pycnocline between 5–10 m deep, followed by a uniform layer that extends down to the bottom. Density distribution follows temperature, and the steep pycnocline is caused by the effect of solar radiation on the surface layer, and the effect of cold upwelled water under the pycnocline (cf. Sobarzo et al., 2007). During the summer mode, oxygen is highly correlated with density, which therefore have clines at the same depth, coinciding with a conspicuous peak of ammonium concentration (Fig. 4c), which indicates a layer of high remineralization, and consequently, high oxygen consumption. This overlapping of processes is most likely related to the accumulation of organic matter in the high-stability layer set by the pycnocline. Below this layer, ammonium decreases and nitrate increases, indicating a high nitrification rate, which is also an oxygen-consuming process that is enhanced at low oxygen concentrations. These biological processes, plus

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physical forcings, drive the suboxia beneath the pycnocline over the shelf off Concepción, with anoxic condition during certain periods of the year (Fariás et al., 2005).

Otherwise, winter mode is characterized by a deeper, less steep pycnocline. Density is highly correlated with salinity at the surface, while temperature displays an inversion in the pycnocline layer (Fig. 4b), imposed by negative net surface heat flux, cooling the sea's surface (Sobarzo et al., 2007). During winter, oxygen is also significantly correlated with density, but ammonium concentration remains low throughout the water column, while nitrate increases as oxygen decreases (Fig. 4d). These profiles indicate that remineralization rate is low at any depth, but nitrification remains active in most of the water column. This means that the rate of oxygen consumption in the water column is lower than in summer, one of the factors that may determine the greater DO concentrations commonly observed during winter. Ammonium only increases near the bottom, which suggests that despite high mixing during this season, the accumulation of organic matter near the bottom and the oxygen uptake by the sediments may contribute to maintain a permanent oxygen minimum zone in this layer. The importance of oxygen consumption processes in the ESP's OMZ has been described by Paulmier et al. (2006), who found that the core of the oxycline would be about three times less intense without these processes.

A different view of the seasonality of oxygen distribution can be obtained from the histograms shown in Fig. 5a, b. As expected, during summer DO concentrations lie largely below 25 μM . During winter, oxygen concentrations are much more homogeneous and show a bi-modal behavior, with one peak at low values (bottom layer), and another peak around 200 μM . This distribution can be explained by analyzing Fig. 5c, d. Oxygen-temperature plots show similar patterns during both seasons (Fig. 5c), with greater dispersion during summertime, and the lowest oxygen concentrations grouped around the lowest temperatures, signaling cold upwelled waters. However, there are two distinct behaviors related to salinity. During summer, oxygen displays a linear relationship to salinity (Fig. 5d), while during winter there are two different trends throughout the water column. First, low salinity waters at the surface have a near constant

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oxygen concentration around 200 μM ; and second, the rest of the water column has an oxygen-salinity slope similar to the summer salinity plot, with an inflection point for all winter casts around 20 m depth. These results suggest that the upper layer is highly influenced by freshwater discharges from the Bio-Bio and Itata rivers, which are highly oxygenated. In fact, Sobarzo et al. (2007) found that river runoff dominates the surface waters during winter, and is a stabilizing force that winds are not able to break, since energy from buoyancy influx (10 to 35 mW m^{-2}) largely exceed the mixing energy provided by winds ($< 0.1 \text{ mW m}^{-2}$).

Zonal transects of oxygen and density obtained by gliders at the same latitude as Station 18 (Fig. 6) show that the OMZ persists throughout the year, but that the position of the low-oxygen layer undergoes seasonal changes. During winter the OMZ is located between 150 m and 400 m, infringing onto the shelf along the upper edge of the slope (Fig. 6a). Near the bottom at Station 18, a horizontal gradient of oxygen is formed, aligned with a density front at the same point (Fig. 6b), that can be seen along the 1026 kg m^{-3} isopycnal. The low density tongue related to river discharge is also observed in the upper right corner of the density transect. During the summer, the OMZ and the pycnocline move over the shelf (Fig. 6c), with the pycnocline bending upwards over the continental shelf (Fig. 6d), due to the influence of the wind forced upwelling. This forms a cold coastal front, with poorly oxygenated waters that can be detected at the surface via satellite within the first 110 km from the coast (Letelier et al., 2009). Several authors have mentioned that the OMZ off Central Chile is closely related to the southward alongshore advection of ESSW by means of the PCU (e.g., Paulmier et al., 2006; Silva et al., 2009), however it must be noted that these observations were made outside the shelf area (see Silva et al., 2009). Furthermore, data from Letelier et al. (2009) shows that oxygen gradient along the coast over the continental shelf is rather small, indicating that the along-shelf net flux is probably small compared to the cross shelf flux. The PCU core is located over the slope, and it is related to the core of larger salinity associated to a larger fraction of ESSW (e.g., Silva et al., 2009). The very low DO concentrations observed over the continental shelf during summer are

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probably related to advection of ESSW from the slope, but local processes occurring over the shelf during summer may also contribute to extend the OMZ over the continental shelf. The relative importance of those processes will be analyzed below using a simple model.

5 In this discussion we separate the temporal variation into two extreme modes (winter and summer), however, it is well known that intermediate seasons (spring and autumn) present their own particular patterns of variation, and cannot merely be considered transitional seasons. Moreover, biological processes that affect marine oxygen concentrations are complex and not yet fully understood. The ecological interactions and
10 temporal scales of such processes, as well as their response to physical and geochemical forcings, are the subject of numerous studies at present. Despite our over simplification, we consider that the summer-winter analysis is useful for understanding the “big picture” of oxygen temporal dynamics over the continental shelf off Concepción.

4 The model

15 4.1 Model description

We developed a simple, non-stationary, 1-D, multilayer numerical model to reproduce oxygen concentrations throughout the water column offshore of Concepción. The model runs on a z -coordinate system. It has a temporal resolution of one day, and a vertical resolution of one meter. We carried out a simulation of one year cycle, considering the two mode behavior discussed in Sect. 2.2, from 1 m to 85 m depth. The
20 oxygen concentration output has units of μM .

The general equation that represents the temporal and spatial variation of oxygen concentration is written as follows:

$$\frac{\partial O_2}{\partial t} + u \frac{\partial O_2}{\partial x} + w_e \frac{\partial O_2}{\partial z} = \frac{\partial}{\partial x} \left(K_h \frac{\partial O_2}{\partial x} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial O_2}{\partial z} \right) + \text{Bio}(z, t) \quad (1)$$

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In this formulation, we consider local effects, and the vertical and zonal advection terms of the total derivative of oxygen concentration. Vertical velocity, w_e , was parameterized according to Pond and Pickard (1983), as the product of the Ekman velocity at the Ekman depth and a shape function, as is described in Signorini et al. (2001), resulting in the vertical and temporal variation of Ekman velocity input. Zonal velocity, u , was extracted from the moored ADCP data, and zonal oxygen gradient was estimated using data from Station 18 and Station 40 time series (Fig. 1). Horizontal mixing was estimated using a horizontal diffusivity term (K_h), which accounts for the horizontal exchange between the continental shelf waters and the adjacent open ocean, and the observed zonal gradient of the oxygen concentration. The value of K_h ($4.8 \times 10^{-7} \text{ cm}^2 \text{ h}^{-1}$) was based on a regional value estimated for the Chilean Coast using satellite altimetry and satellite tracked surface drifters by Chaigneau and Pizarro (2005). Lateral mixing (from u and K_h) was estimated using isopycnal surfaces between continental shelf (Station 18) and the slope (Station 40). Turbulent diffusion (K_z) was estimated using the parameterization of Pacanowski and Philander (1981), which is based on the bulk Richardson number (balance between stabilizing and turbulent forces), calculated with the buoyancy frequency from CTD data and horizontal velocity shear, from ADCP data. Previous works have shown that PCU has a major role transporting ESSW southward along Central Chile Coast (Silva and Neshyba, 1979; Silva et al., 2009). However, meridional oxygen gradients over the shelf appear to be very small (Letelier et al., 2009). Considering these antecedents, we decide to neglect this term in our model. Nevertheless, alongshore advection plays a very significant role in maintaining the offshore OMZ over the slope, which is, in turn, key for the variability observed over the shelf. OMZ over the slope is clearly connected to ESSW and thus it is related with the advection along the slope. As we are using observed variability over the slope, when we consider cross-shore advection, we are indirectly including the along-slope variability. The last term on the right side of Eq. (1) accounts for biological net oxygen production (NOP), i.e. production (through photosynthesis) minus consumption (through aerobic respiration and nitrification). Finding an adequate parameterization of

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5 this term was one of the biggest challenges of our modeling attempt. Previous models have followed different approaches to estimate the influence of biology in oxygen distribution; for example, Steiner et al. (2007) carried out a balance of the sources and sinks of nitrogen (as nitrate and ammonium) in the water column at the Papa Weather Station (North Pacific), and then converts it to NOP using the Redfield ratio. Alternatively, Oguz (2002) estimated NOP in the Black Sea as production (through photosynthesis) minus consumption (through aerobic respiration, nitrification and hydrogen sulfide oxidation), parameterizing each of these terms with their kinetic expressions. Both approximations required knowing several local biological parameters (i.e. reaction rates, respiration rates, excretion rates, etc.) that, in our case, were not available, and are difficult to estimate. In another study, Thomas et al. (1990) used theoretical curves over both depth and time, which accounted for the seasonal and vertical zonation of biological processes.

15 Using photosynthetic production data from Fariás et al. (2009), and data of total oxygen consumption, provided by L. Farias and J. Faúndez (personal communication), we adjusted production and consumption curves for summer and winter (named “Biology one”, Fig. 7a–c). The mathematical expressions for the amplitude of oxygen production (Fig. 7a) variation are:

$$P(z) = 97.08 \cdot e^{-\frac{1}{2}z} \quad (\text{summer})$$
$$P(z) = 6.54 \cdot e^{-\frac{1}{25}z} \quad (\text{winter}) \quad (2)$$

20 and for consumption the adjusted mathematical expressions (Fig. 7b) are:

$$C(z) = -45.00 \cdot e^{-\frac{1}{25}z} \quad (\text{summer})$$
$$C(z) = -10.05 \cdot e^{-\frac{1}{100}z} \quad (\text{winter}) \quad (3)$$

where NOP is equal to the difference between these two expressions (Fig. 7c).

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Thereafter, the temporal variation between these expressions at each depth was calculated by the following expression:

$$\text{Bio}(t, z) = A(z) \cdot \cos\left(\frac{2\pi}{365}t - \xi\right) + J \quad (4)$$

$$A(z) = P_{\max}(z) - C_{\max}(z) \quad (5)$$

where A is the amplitude of the seasonal variation between the two extremes, t is the time expressed in Julian days, ξ is the phase angle, which is set experimentally, and J is a constant equivalent to the average between the two extremes.

As a second NOP construction, we built a theoretical curve (named “Biology two”, Fig. 7d), that has a maximum oxygen production in the surface layer and maximum oxygen consumption in maximum stability layer (H), based on buoyancy frequency profiles. Vertical variation of the NOP is described by the following expression:

$$\text{Bio}(z, t) = \begin{cases} A_s(t) \cdot \sin\left(\frac{\pi z}{H(t)}\right) & \text{if } z < H \\ A_d(t) + \ln(z) & \text{if } z \geq H \end{cases} \quad (6)$$

where A_s and A_d are winter-summer amplitudes in the surface and deep layers, respectively. Both of them possess temporal variation similar to that expressed in Eq. (3), with the implementation of an annual cycle. The amplitudes were estimated from the mentioned data, taking the maximum NOP in summer and the minimum NOP in winter for the surface, and the opposite for depth H .

Upper boundary condition is given by air–sea oxygen exchange, which is accounted by the product of the piston velocity (k_p) and the difference between saturation ($O_{2\text{sat}}$) and in situ oxygen concentrations (Eq. 2).

$$F_a = k_p \frac{(O_{2\text{sat}} - O_2)}{\Delta z} \quad (7)$$

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In order to estimate the piston velocity, four parameterizations were tested (Wanninkhof, 1992; Wanninkhof and McGillis, 1999; Nightingale et al., 2000). Oxygen saturation concentration was determined using the formulae according to García and Gordon (1992).

4.2 Sensitivity tests and model results

In order to test the sensitivity of the model to different parameters and parameterizations, we carried out tests runs which are summarized in Table 1.

DO profiles obtained with different biology setups (Fig. 8a and 8b) shows that during winter the setup with “bio 1” parameterization (A) reproduces the shape of oxygen profile more accurately than the setup with “bio 2” parameterization (B), which tends to exaggerate biological oxygen production over a wide surface layer. More interesting is that, when the model ran without the influence of biological NOP (setup C), the shape of the oxygen profile is preserved, with values slightly higher ($\sim 10\mu\text{M}$) than the setup A. During summer condition, setup B (with “bio 2”) yields a more accurate profile of DO, while “bio 2” exaggerates oxygen consumption. Again, setup C (with $\text{NOP} = 0$) simulates a DO profile very similar to the observed one. These results indicate that, despite the few points used to build “bio 1”, logarithmic decay of NOP seems to be a more accurate description of the biological contribution to the oxygen budget in the water column during winter, compared to the variable shape of NOP described by “bio 2”. The opposite occurs during summer condition, suggesting complete different NOP patterns for both modes. Such difference is expected since conditions during summer, characterized by high primary production and high stratification implies that most of the oxygen produced in the surface is consumed in the layer where organic matter is accumulated (i.e. maximum stability layer). During winter, on the other hand, the lack of stratification implies that organic matter (and oxygen) produced in the surface is consumed along the water column. Otherwise, local biological processes seem to have a limited influence in the budget that set the oxygen vertical distribution, which in turn is determined by physical forcings. This can be explained regarding that both, biological

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oxygen production and consumption processes, are intrinsically coupled, so the contribution of NOP is smaller than the fluxes of oxygen involved in physical processes.

Model setups with different air-sea oxygen flux parameterizations (setups A, D and E) are shown in Fig. 8c, d. No significative differences are seen between these parameterizations, both during winter and summer. As expected, the influence of this term is limited to the surface layer, as can be appreciated by the deviation in the profile yielded by setup F ($k_p = 0$).

Vertical eddy diffusivity variation (Fig. 8e, f, setups A, G and H) also appear to have little influence settling the DO concentration. The average value obtained as described in Sect. 2 ($1.1 \times 10^{-4} \text{ m}^{-2} \text{ s}$, setup A) agree with estimations made in coastal waters (see Table 3 in Charpentier et al., 2010), and gives a profile that has a small variation respect to the profiles obtained with a typical value of K_z ($1 \times 10^{-5} \text{ m}^{-2} \text{ s}$, setup H), and with $K_z = 0$. However, the “saw tooth” pattern of this last plot indicates that the eddy diffusivity has a “softening” effect over DO, associated with short scale mixing.

Influence of vertical advection and lateral mixing are shown in Fig. 8g, h. While profiles with (setup A) and without (setup J) vertical advection show little variation, the absence of lateral mixing (setup I) has a significative impact on the modeled profiles, giving less oxygenated waters both during summer or winter. We consider this result emphasizes the importance of the Peru-Chile Undercurrent, which transports ESSW southward along the slope, and feeds the waters over the shelf.

Figure 9a represents the best fit setup (A). Despite the several uncertainties in the parameterizations used, the Spearman correlation coefficient indicates that the model is able to explain 88.7 % oxygen concentration variance. However, it is worth noting that the correlation coefficient indicates whether or not the analyzed variables have simultaneous coordinated variation, but does not show whether they reach the same value at each depth or time. This withdrawal in magnitude can help understand the improvements needed to be made to the model. We calculated the difference between the modeled and measured oxygen concentration for each depth and time (Fig. 9b). The model represented well about 92 % the oxygen concentration values, with a difference

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of less than 20 μM , and 82 % of the modeled concentrations did not deviate more than 5 μM . Considering the number of parameterizations involved, the temporal and spatial coverage of the inputs included and the limited terms involved in the model, this result is not negligible.

5 Summary and conclusions

In this work, we were able to identify two modes of DO concentration patterns (winter and summer), that describe the seasonal variability of the studied area. This approach allows us to face a simple model in order to identify the factors that drive this seasonality. According to our results, the seasonal variability of the DO over the continental shelf of Concepción, Chile, is mainly driven by lateral (zonal) mixing, which connects this area with the poorly oxygenated ESSW, advected southward by the PCU, that runs alongshore over the slope. Other factors, like biological NOP and vertical mixing (by turbulent diffusion and upwelling/downwelling) have a minor, but not negligible, contribution to the setting of the oxygen temporal and spatial distribution.

From this modeling experience of the southern area of the ESP's OMZ dynamics, we encourage future modeling attempts to include river plume influences and meridional advection in the physics of the model. Also, a better biologically mediated net oxygen production parameterization is needed. Biological processes that affect marine oxygen concentration are complex and not yet fully understood. Ecological interactions and temporal scales of such processes, as well as their response to physical and geochemical forcings, are the subject of further investigations, which would increase our knowledge and allow the adequate assessment of this environment.

To improve the representation of time varying processes, we need to gain access to higher time resolution variable inputs (hydrological and biological). Efforts are being made to validate a regional physical-biogeochemical coupled model (ROMS-PISCES) to represent the dynamics offshore of Concepción. This regional model output will be suitable for implementation in our model, and therefore can be used to study our model

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response in high frequency processes affecting oxygen dynamics and its applications in locations other than Station 18. One of the advantages of simple models, like this used in this work, is that it attempts to represent the complex system that regulates oxygen concentrations in the simplest possible way, with one equation that includes the most important factors, and still obtains satisfactory results, in so far as it explains most of the spatial oxygen distribution.

We would like to emphasize that we do not expect this model to account for every detail of the complex oxygen dynamics described in this work, but it does help to provide direction for future modeling efforts, in order to achieve a better understanding of oxygen concentration behavior.

Acknowledgements. The authors greatly thank Laura Farías and Juan Faúndez for kindly providing photosynthetic production and total oxygen consumption data. This work was supported by COPAS Center, COPAS Sur-Austral Program and the Moore Foundation. J. C. was supported by a Postdoctoral Grant from Chilean Commission for Science and Technology, CONICYT, project no. 3100156. O. P. is grateful for FONDECYT 1121041 Grant.

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Table 1. Description of the different setups used for sensitivity tests. Terms are described in Sect. 4.1.

Term	Setup									
	A	B	C	D	E	F	G	H	I	J
Bio	1	2	0	1	1	1	1	1	1	1
K_p^*	N00	N00	N00	W99	W92	0	N00	N00	N00	N00
K_z (m ⁻² s)	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	0	1×10^{-5}	1.1×10^{-4}	1.1×10^{-4}
u	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
K_h (m ⁻² s)	4800	4800	4800	4800	4800	4800	4800	4800	0	4800
W	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

* Parameterization acronyms as follows: N00: Nightingale et al. (2000), W99: Wanninkhof and McGillis (1999) and W92: Wanninkhof (1992).

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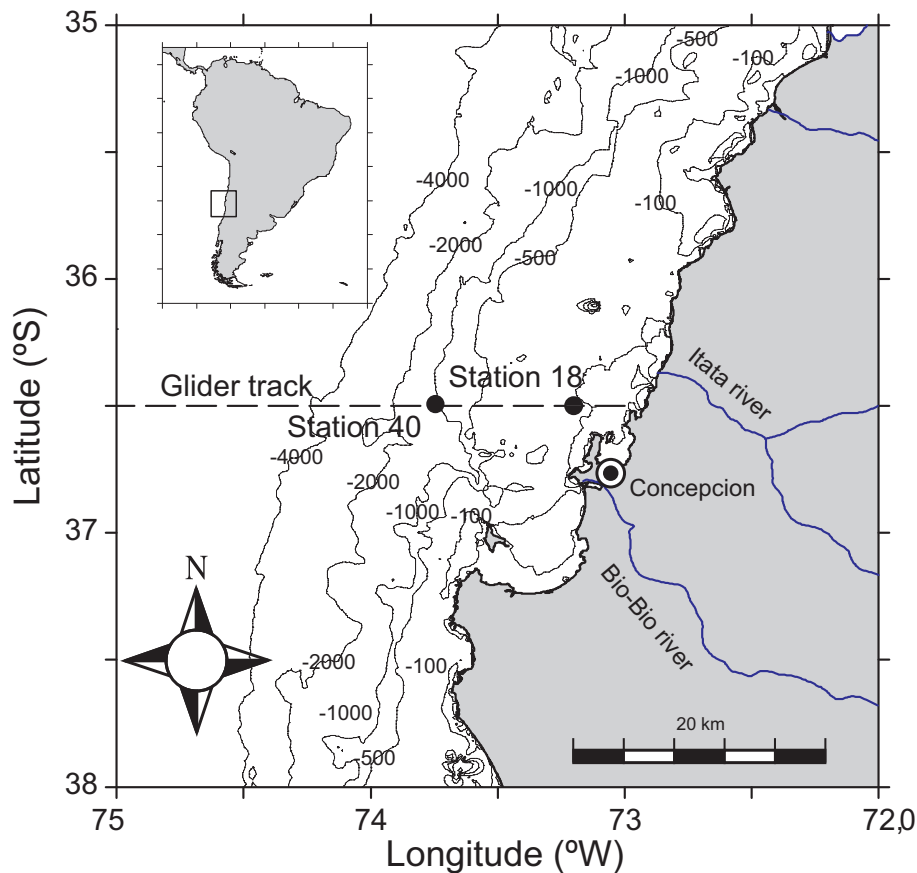


Fig. 1. Study region showing the location of the time series stations 18 and 40 over the continental shelf and slope off Concepción, respectively. The dashed line is the idealized representation of the glider tracks during June 2010 and January 2011.

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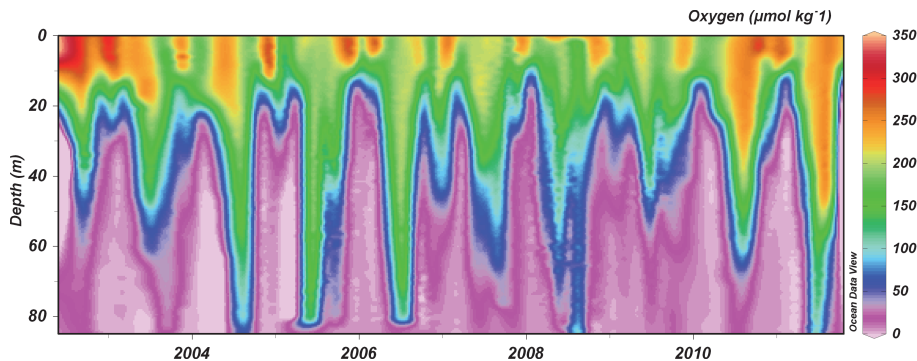


Fig. 2. Dissolved oxygen time series over the continental shelf of Concepción based on monthly data from Station 18.

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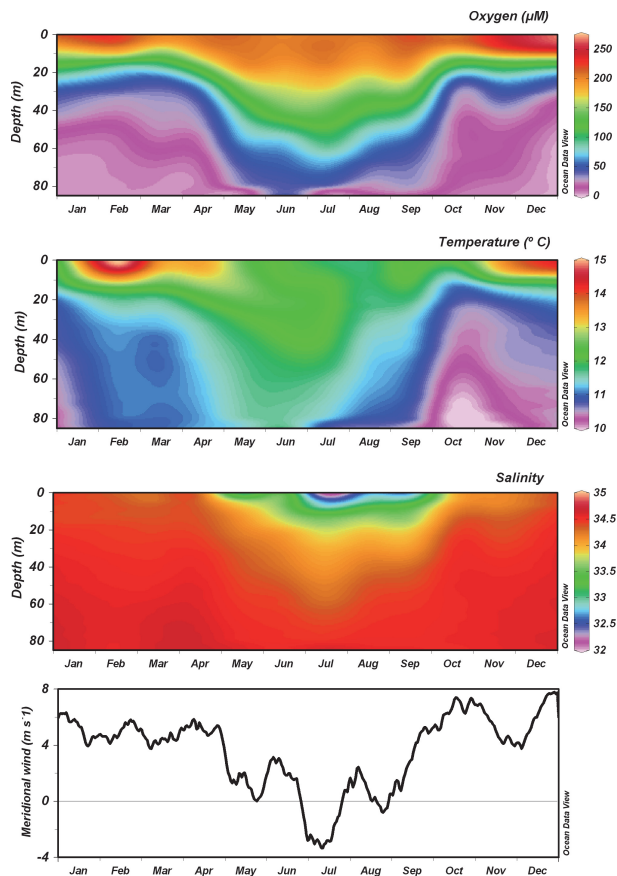


Fig. 3. Annual cycle of DO, temperature and salinity at Station 18. Low-passed (30-day running mean) meridional wind speed for the year 2008 based on daily satellite (ASCAT) data in a grid centred close to station 18 (bottom panel).

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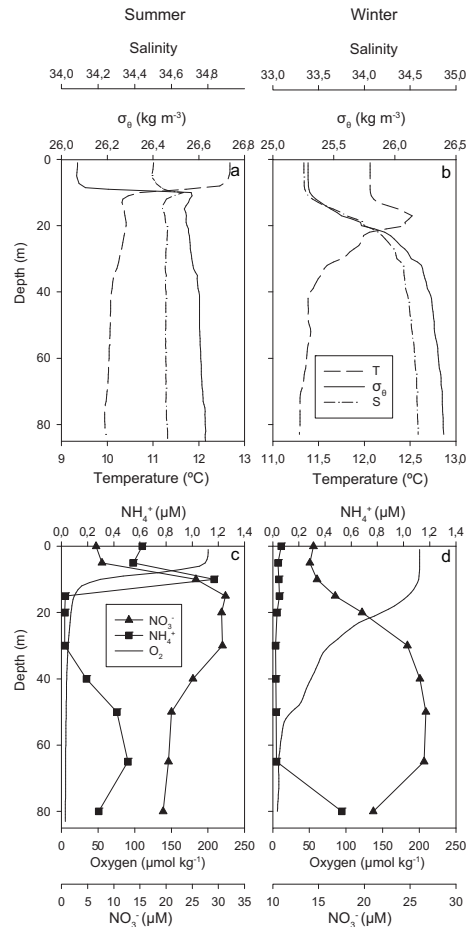


Fig. 4. Typical profiles of salinity, temperature and density (σ_θ) for austral summer (**a**) and winter (**b**) and of ammonium (NH_4), nitrate (NO_3) and DO for austral summer (**c**) and winter (**d**) measured during January 2008 and June 2008, respectively.

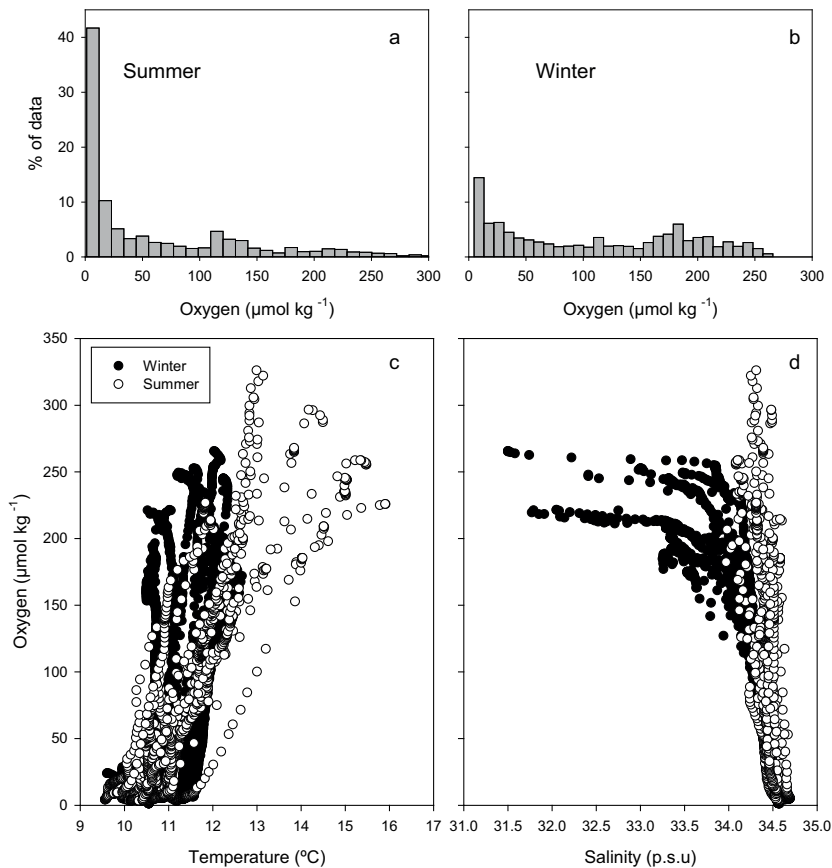


Fig. 5. Histograms of oxygen measurements during the austral summer **(a)** and winter **(b)**. Oxygen versus temperature **(c)** and oxygen versus salinity **(d)** for summer and winter of 2008 (the period used in the model).

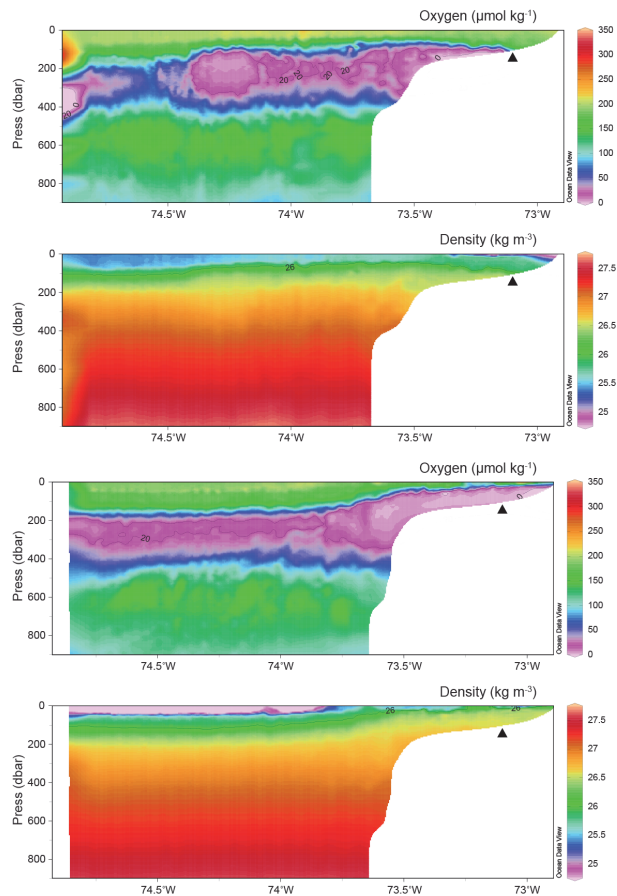


Fig. 6. Dissolved oxygen and density transect along $36^{\circ} 30' S$ off Concepción. The data was obtained using deep Slocum glider during the austral winter (June) of 2010 and the summer (January) of 2011. Note that the glider transects run along Stations 18 and 40. The path of the glider is represented by the dashed line in Fig. 1.

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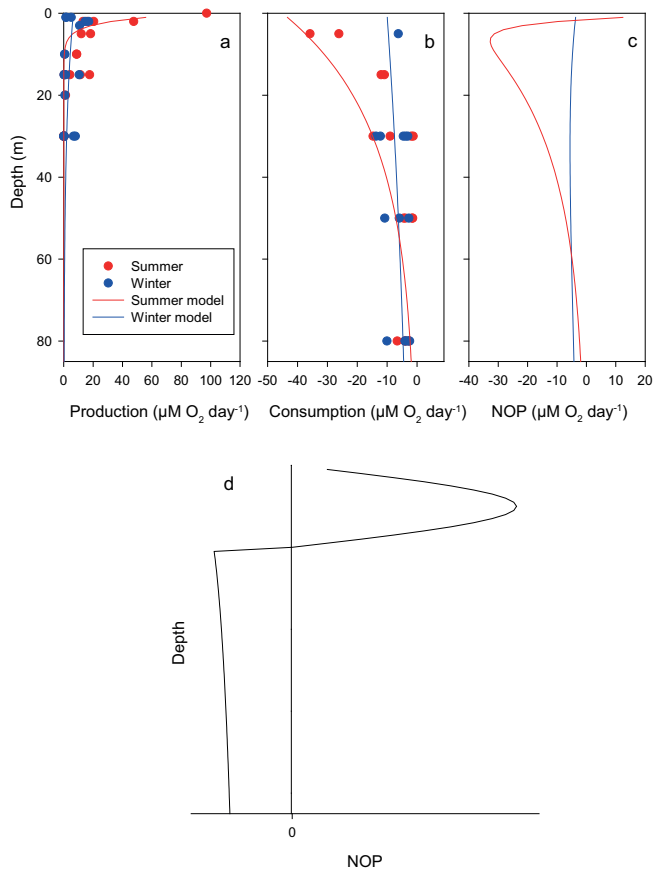


Fig. 7. Adjustment of production (a) and consumption (b) data (filled dots) to produce “bio 1” (c) and theoretical model (d) of NOP (bio 2).

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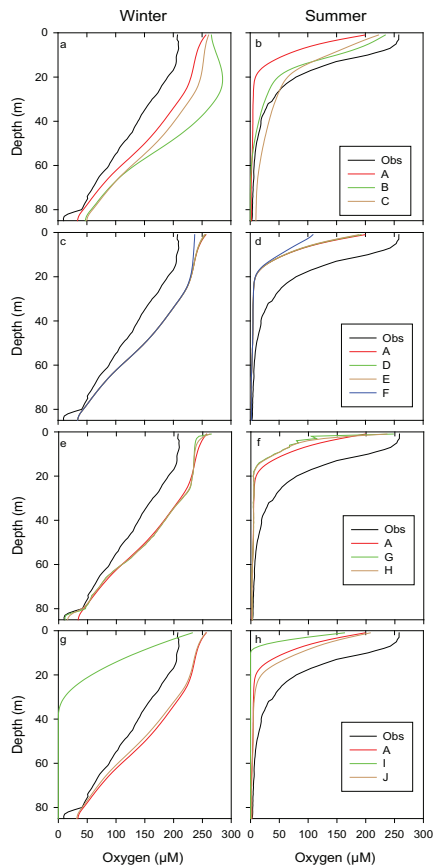


Fig. 8. Sensitivity tests results for the different parameters (uppercase letters) described in Table 1. Each horizontal couple of panels contains results for the same setups in January (summer) and July (winter). Panels show results for different parameterizations of: **(a)** and **(b)**: NOP, **(c)** and **(d)**: air–sea exchange, **(e)** and **(f)**: turbulent diffusion, **(g)** and **(h)**: zonal mixing and vertical advection.

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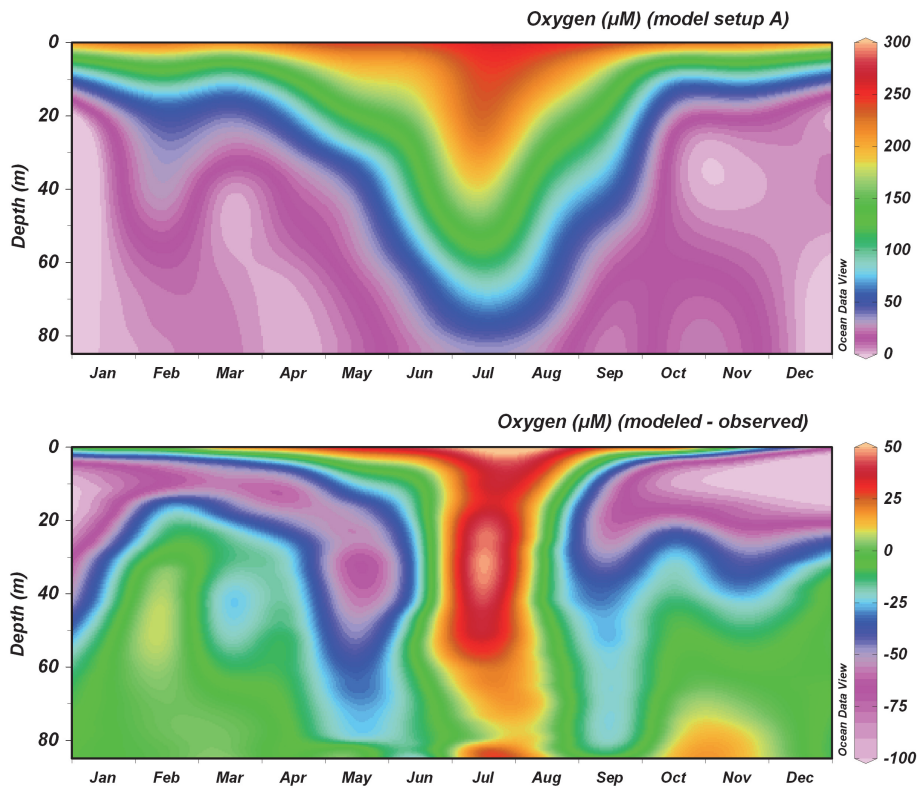


Fig. 9. (a) Model result for the setup A and (b) differences between modeled and observed result (as $\text{DO}_{\text{modeled}} - \text{DO}_{\text{observed}}$).

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