

Supplemental material - DNRA stimulates aerobic microbial processes and restructures the surface planktonic community in the Chilean OMZ

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39 Appendix A Model Validation

40 In this appendix, we provide a comprehensive validation of the model by evaluating
41 its physical and biogeochemical components against climatological datasets, satellite
42 observations, and *in situ* measurements, including glider observations and a fixed-
43 station time series.

44 A.1 Data sources

45 The physical and biogeochemical components of the model are evaluated using a com-
46 bination of climatological datasets, satellite-derived products, and independent *in situ*
47 observations. To analyze Sea Surface Temperature (SST), we used the UK Met Office
48 Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) product from
49 2007 to 2023. It provides daily gap-free analysis of sea surface temperature at a reso-
50 lution of $1/20^\circ$ ([1]).

51 The climatological dataset used is the [2] (CARS 2009). In this study, monthly temper-
52 ature, salinity, oxygen and nitrate climatology were used, on a 0.5° grid, and compared
53 to our control run.

54 Data from the different glider campaigns carried out by the glider group of the Uni-
55 versity of Concepcion were also used to validate our control run configuration ([3]).
56 Teledyne Webb research Electric Slocum gliders version G1 (rated for 1000m depth)
57 were deployed along a recurring transect about 150-180km in length off the coast of
58 Concepcion ($36^\circ 30'S$). The gliders were equipped with optical oxygen sensors (Aan-
59 deraa Data Instrument oxygen optode model 3830) ([3]). The glider transects used
60 are those of June 2010, September 2010, November 2010, January 2011, March 2011,
61 July 2011, March 2012 and December 2012. For these eight transects, we used data
62 on dissolved oxygen, pressure, temperature and salinity.

63 The Station 18 dataset, located off Concepción Bay, was used to compare with outputs
64 from our control simulation of physical and biogeochemical essential ocean variables.
65 This dataset consists of a monthly time series collected on the mid-continental shelf
66 and provides profiles of temperature, salinity, and dissolved oxygen (DO) up to depth
67 of 92 m. Measurements were obtained using conductivity–temperature–depth (CTD)
68 instruments (SBE-25 from 2007 to 2015 and SBE-19 from 2016 to the present). Seawa-
69 ter samples were collected using 10 L Niskin bottles. DO, and nutrients were sampled
70 sequentially at eight depths between the surface and 80 m (approximately 2, 5, 10, 20,
71 30, 50, 65, and 80 m). Triplicate DO samples were collected in iodometric bottles and
72 immediately fixed for further Winkler oxygen analysis. For nutrient analyses (NO_3^- ,
73 NO_2^- , NH_4^+ , and PO_4^{3-}), samples were drawn directly from the Niskin bottle spigot
74 using syringes, filtered through $0.45 \mu\text{M}$ Uptidisc filters, and stored at -20°C ([4]).
75 For this study, data from 2007-2010 and 2016-2020 were analyzed. We used tempera-
76 ture, salinity, and DO data from the CTD, along with nitrate (NO_3^-) concentrations
77 from Niskin bottle samples, from the Station 18 time series.

78 Both climatological database and *in situ* observations (glider, station 18) provide O_2
79 data at low concentration with an estimated uncertainty ranging around $20 \mu\text{M}$.

80 A.2 Validation methodology

81 In surface for the whole study area and period, the SST simulated by the model was
82 evaluated by comparison with the OSTIA satellite data over the period 2007-2023.
83 The model outputs, available every 3 days, were spatially interpolated onto the
84 OSTIA grid using bilinear interpolation to allow a point-to-point comparison. The
85 OSTIA daily data were temporally averaged over a sliding window centered on each
86 model time step to obtain comparable time series without temporal interpolation of
87 the model.

The difference in the mean SST (A1(a)) was obtained by calculating, for each grid point, the difference between the temporal averages for the model’s SST and OSTIA over the period studied, providing an estimate of the average temporal bias. To evaluate the model ability to reproduce temporal variability of the SST, SST anomalies were calculated by subtracting the local temporal mean from each time series. The correlation of the anomalies was then calculated pixel by pixel between the model anomalies and those of OSTIA, using Pearson’s correlation coefficient (A1(b)). Finally, the root mean square error (RMSE) of the anomalies was calculated at each grid point as the square root of the temporal mean of the quadratic differences between simulated and observed anomalies.

On the water column of the entire study area, model temperature, salinity, and dissolved oxygen fields were also compared with the CARS 2009 monthly climatology along the 36°S transect. Model outputs were first averaged for each month over the period 2007–2023 to construct a mean state consistent with the climatological nature of CARS. Both model and CARS fields were interpolated onto a common vertical and horizontal grid along the transect from the coast to 250 km offshore and from the surface to 700 m depth. Differences were then computed as model minus CARS to quantify mean biases in temperature, salinity, and dissolved oxygen. This approach allows for a direct evaluation of the model’s ability to reproduce the large-scale hydrographic and biogeochemical structure represented by the climatology.

Then on specific vertical and cross-shore sections model temperature, salinity, and dissolved oxygen were compared with available glider transects along 36°S between 2010 and 2012. Model outputs were extracted along the glider track and temporally collocated with the observation times. Both datasets were interpolated onto a common vertical and along-track grid to construct longitudinal vertical sections from the surface to 1000 m depth. Differences were computed as model minus glider to quantify biases and to assess agreement in the vertical and along-track structure. This analysis allows for a direct evaluation of the model’s ability to statistically reproduce observed mesoscale and vertical variability sampled by the glider.

Finally, to evaluate model seasonality performance against *in situ* time series observations, vertical profiles from Station 18 were compared with corresponding model outputs over the periods 2007–2010 and 2016–2021 and an extracted profile of the station 18 from the CARS 2009 climatology. Model fields were extracted at the grid point closest to the station location and temporally collocated with the observation times. For each depth level, seasonal and interannual components were separated and the RMS, mean profiles with the standard deviation, and correlation coefficients between the model and the *in situ* data were calculated. Seasons were defined as austral summer (DJF), autumn (MAM), winter (JJA), and spring (SON). Seasonal and interannual statistics were calculated independently to assess the model’s ability to reproduce both the seasonal cycle and the longer-term variability. This analysis was performed for temperature, salinity, dissolved oxygen, and NO_3^- to characterize the model skills throughout the water column.

A.3 Physical component Validation

This section focuses on the validation of the physical components of the model. Comparison with observational datasets indicates that the model reproduces the main spatial and vertical hydrographic structures, providing confidence in its representation of the physical environment.

Figure A1 shows the validation of simulated SST against OSTIA observations over the period 2007–2023. Panel (a) shows the mean difference, indicating cold bias along

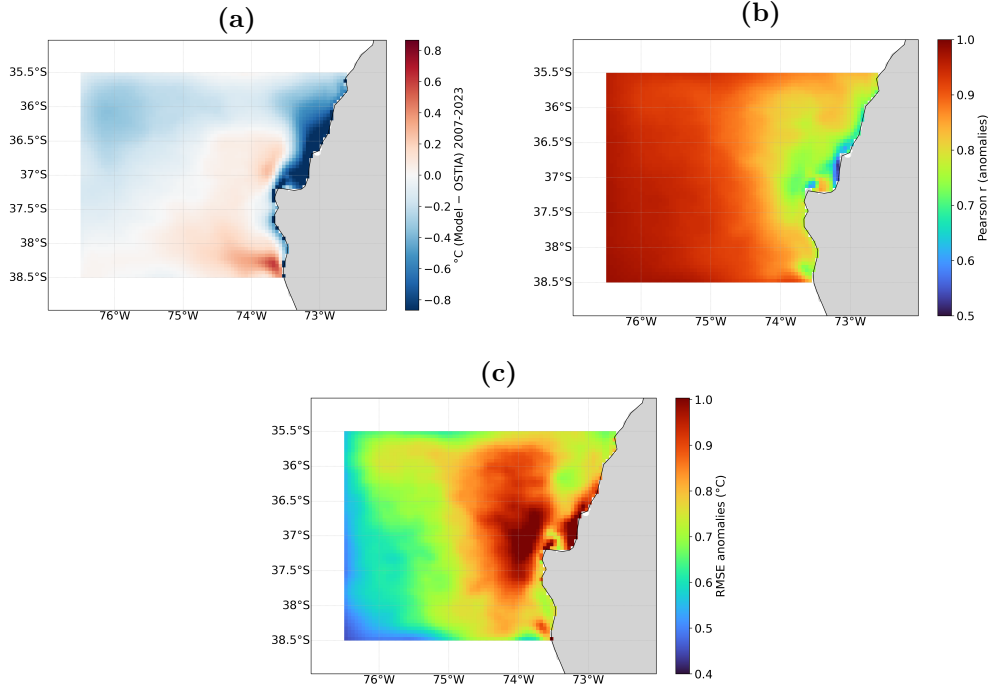


Fig. A1 Comparison between the model sea surface temperature (SST) and the OSTIA SST product, showing (a) the difference in the mean SST over 2007–2023, (b) the correlation of SST anomalies over 2007–2023, and (c) the root-mean-square error (RMSE) of SST anomalies over the same period.

the coast and a warm bias offshore. However, the deviations are below $\pm 0.8^\circ\text{C}$. Panel (b) displays the correlation of SST anomalies, with lower correlation near the coast ($r \approx 0.5 - 0.7$) and higher correlation offshore ($r \approx 1$), demonstrating that the model reproduces temporal variability well in offshore waters. Panel (c) presents the RMSE of SST anomalies always below 1°C , mainly near the coast and in the central study area, but even lower more offshore, consistent with the spatial pattern of mean bias. The surface SST validation indicates that the model captures reasonably well the main spatial patterns and temporal variability along the coast and offshore. We next assess its ability to reproduce vertical hydrographic gradients along the 36°S transect using CARS 2009 climatology.

Vertical transects of temperature and salinity along the 36°S transect compared with the CARS 2009 climatology are presented Figure A2. Panels (a) and (c) show the modeled temperature and salinity on the left and the CARS temperature and salinity on the right, while panels (b) and (d) display the difference between model and climatology. The model successfully reproduces the main vertical structure and offshore-coastal gradients of temperature and salinity. A slight warm bias is observed near the offshore surface for temperature ($\approx 0.2 - 0.4^\circ\text{C}$), and a slight cool bias is present in the coastal region (0–50 km). Salinity differences are minimal, with a small positive bias offshore ($\approx 0.05 - 0.1$ PSU), indicating that the model captures the large-scale mean annual hydrographic structure with reasonable fidelity.

Figure A3 shows the validation of the temperature (panels (a) and (b)) and the salinity (panels (c) and (d)) with on the left the comparison of the water column structure ((a) and (c)) and on the right the difference model - glider ((b) and (d)). The average transect glider value was calculated as the average of the various transects at 36°S (from June, September, and November 2010; January, March, and July 2011; and March and December 2012). The vertical temperature gradient is fairly well

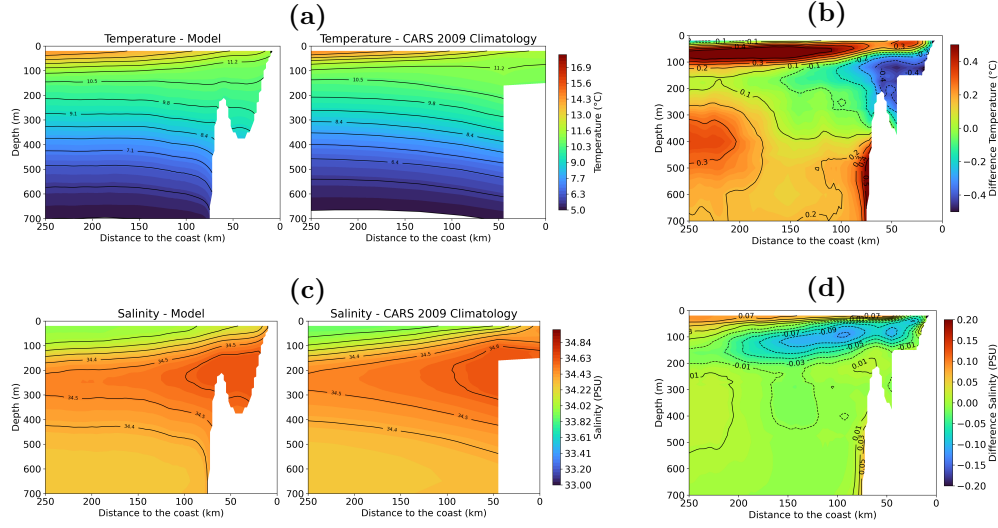


Fig. A2 Comparison of temperature and salinity along the 36°S transect from the coast to 250 km offshore between the CARS 2009 climatology and the control run averaged over 2007-2023. Cross-shore vertical sections of temperature (°C) and salinity (psu) are shown for the model (left) and CARS 2009 (right) in panels (a) and (c), respectively. Panels (b) and (d) show the corresponding differences (model - CARS) in temperature (°C) and salinity (psu) along the same transect, from the surface to 700 m depth.

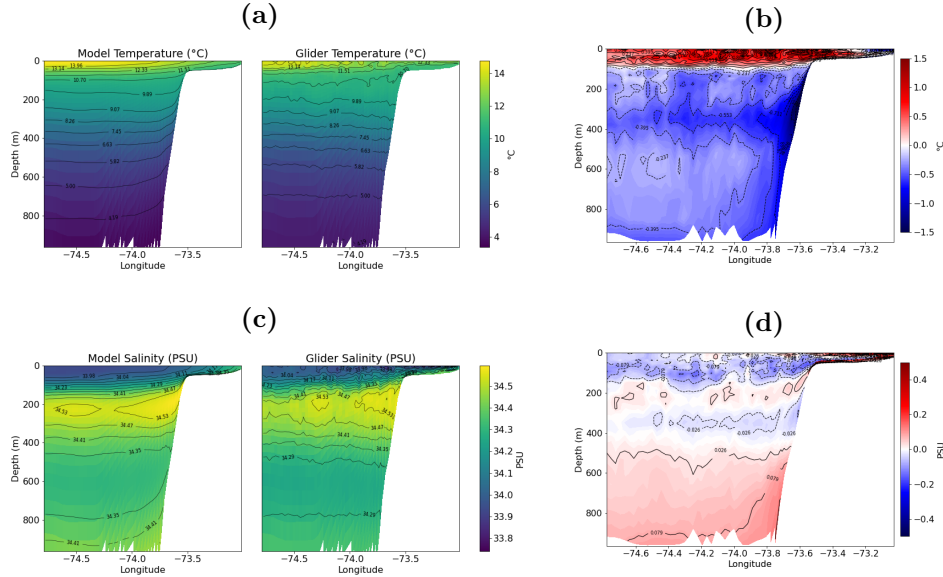


Fig. A3 Comparison of model and glider temperature and salinity along the 36°S transect between 72°W and 74.5°W from the surface to 1000 m depth. Panels (a) and (c) show longitudinal vertical sections of temperature and salinity, respectively, with the model on the left and the glider observations on the right. Panels (b) and (d) display the corresponding differences (model - glider) for temperature and salinity along the same transect.

represented, even though the model is 1.5°C warmer at the surface and 1.5°C cooler at depth. Salinity is also well represented, with differences between the model and the glider transects less than ± 0.1 , except at the surface near the coast where differences of + 0.5 are shown. Furthermore, the contour lines show less variation in the model.

While the CARS transect provides a regional climatological perspective, validation against Station 18 observations allows examination of both seasonal and interannual

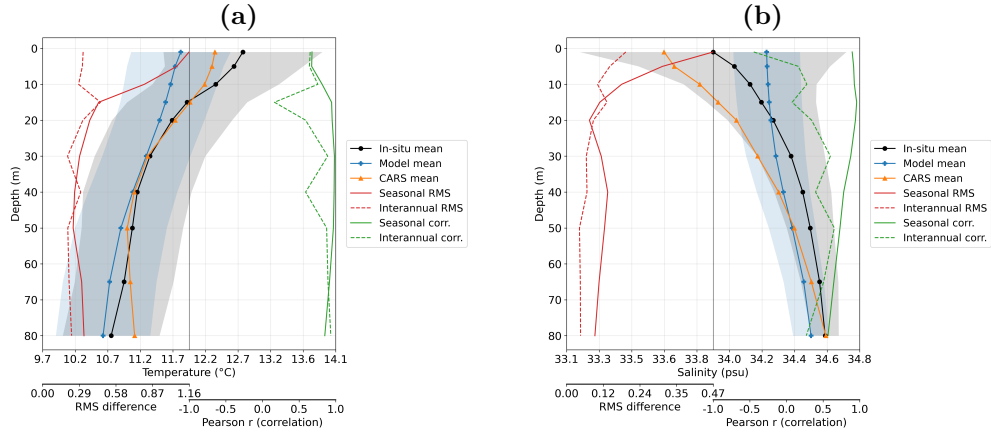


Fig. A4 Vertical profiles comparing *in situ* data at Station 18 with the model and CARS 2009 climatology for 2007–2010 and 2016–2021. Panel (a) shows temperature and panel (b) salinity. Left: seasonal (solid lines) and interannual (dashed lines) root-mean-square differences (RMS) in red; center: mean profiles of the model (blue), *in situ* observations (black) with the standard deviation envelope and CARS 2009 (orange); right: seasonal (solid lines) and interannual (dashed lines) correlation coefficients in green. Profiles summarize both the magnitude of differences and the agreement between model and observations from the surface to 80m depth.

variability at a fixed location. Figure A4 presents vertical profiles of temperature (a) and salinity (b) at Station 18, comparing modeled values (blue) with *in situ* observations (black) and the CARS 2009 climatology (orange). The model reproduces the mean vertical structure accurately, with minor cold bias on the water column, only higher at the surface for temperature ($< 1.5^{\circ}\text{C}$) and small salinity differences (< 0.5). The shaded blue and black areas in panels (a) and (b) represent the standard deviation of the modeled and the *in situ* data of temperature and salinity respectively, illustrating the model and the data temporal variability at each depth. The blue envelope generally encompasses the *in situ* measurements, indicating that the model not only reproduces the mean profiles but also captures the observed range of seasonal and interannual variability. Seasonal RMS is higher near the surface, reflecting stronger variability, while interannual RMS is lower. Seasonal correlations are high (> 0.8) for both temperature and salinity, and interannual correlations remain above 0.5, demonstrating that the model captures both short-term and longer-term variability at this site. The accurate representation of temperature and salinity provides a solid foundation for evaluating the model's performance regarding the biogeochemical processes, including DO and NO_3^- distribution and dynamics.

A.4 Biogeochemical component Validation

This section focuses on the validation of the biogeochemical components of the model.

In Figure A5 vertical oxygen transects and NO_3^- of the model along the 36°S transect are compared with the CARS 2009 climatology. Panels (a) and (c) show the modeled O_2 and NO_3^- on the left and the CARS O_2 and NO_3^- on the right, while panels (b) and (d) display the difference between model and climatology. Panels (a) and (b) show that the model overestimates O_2 by about $40 \mu\text{M}$ at the surface and produces an OMZ with too much oxygen (at approximately $15 \mu\text{M}$). Nevertheless, for NO_3^- , panels (c) and (d) show that the model provides a good representation, with differences between CARS and the model not exceeding $1.5 \mu\text{M}$, and with a nitracline slightly shallower by a few tens of meters.

Finally, Figure A6 shows the validation of the oxygen over the 36°S transect, with panel (a) the comparison between the model and the glider transects and (b) the

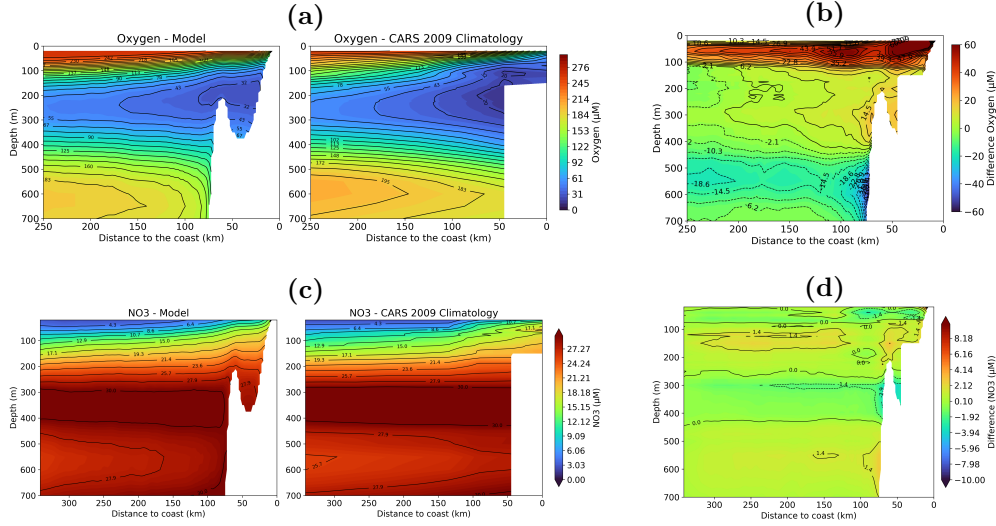


Fig. A5 Comparison of oxygen and nitrate along the 36°S transect from the coast to 250 km offshore between the CARS 2009 climatology and the control run averaged over 2007-2023. Cross-shore vertical sections of oxygen (μMN) and nitrate (μMN) are shown for the model (left) and CARS 2009 (right) in panels (a) and (c), respectively. Panels (b) and (d) show the corresponding differences (model - CARS) in oxygen (μMN) and nitrate (μMN) along the same transect, from the surface to 700 m depth.

206 difference between the model and the gliders transects. Although the model appears
 207 to accurately represent the structure of the water column, it tends to overestimate the
 208 oxygen concentration in the water column, as it was also seen with the glider tran-
 209 sects, particularly between the surface and a depth of 600 meters, where differences
 210 exceed 40 μM . Furthermore, the model underestimates the thickness and intensity of
 211 the OMZ.

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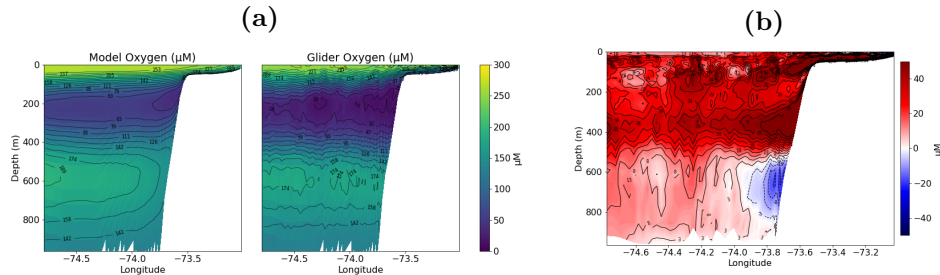


Fig. A6 Comparison of model and glider oxygen along the 36°S transect between 72°W and 74.5°W from the surface to 1000 m depth based on transects from June, September, and November 2010; January, March, and July 2011; and March and December 2012. Panels (a) show longitudinal vertical sections of oxygen with the model on the left and the glider observations on the right. Panel (b) display the corresponding differences (model - glider) for oxygen along the same transect.

213 Finally, Figure A7 presents vertical profiles of O_2 (a) and NO_3^- (b) at Station 18,
 214 comparing modeled values (blue) with *in situ* observations (black) and the CARS 2009
 215 climatology (orange). For O_2 (panel (a)), the mean CARS profiles are in close agree-
 216 ment with the *in situ* observations. However, except at the surface with very good
 217 agreement, the model systematically overestimates oxygen concentrations at depths
 218 of 10 meters or more, although the standard deviation ranges of both datasets over-
 219 lap. Seasonal RMS is higher from 10m to 80m, reflecting stronger variability, while

interannual RMS remains quite low. The model seems to better represent the interannual variability than the seasonal one at station 18. Seasonal correlation is higher (> 0.8) from 15m as the interannual correlation. For NO_3^- (panel (b)), the figure shows that the average *in situ* and model profiles are relatively close at the surface but diverge with depth. The model remains closer to CARS, with NO_3^- values falling between CARS and *in situ* data throughout the water column. The *in situ* data profile shows significantly high variability that neither the model nor CARS captures. This is reflected in the correlation and RMS profiles, and probably associated with very local physical (upwelling, downwelling, mixing) and biogeochemical (water column and sediment coupling) dynamics not taken into account in the simulations.

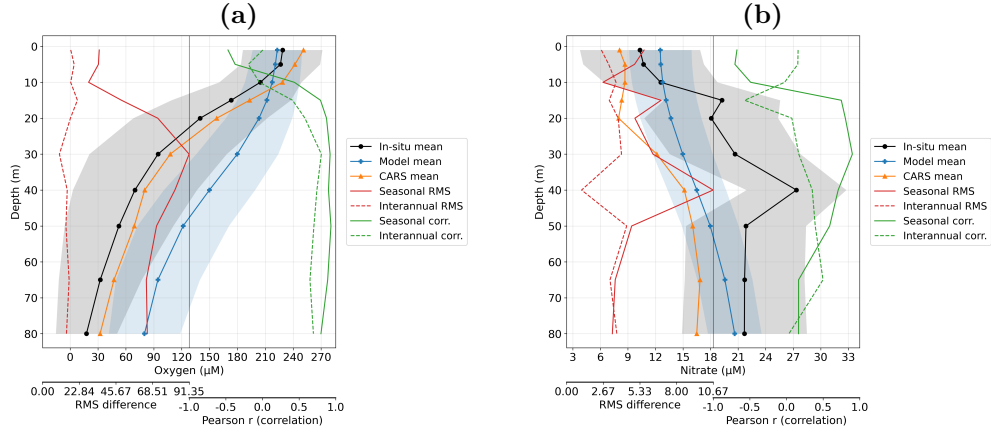


Fig. A7 Vertical profiles comparing *in situ* data at Station 18 with the model for 2007–2010 and 2016–2021. Panel (a) shows oxygen and panel (b) nitrate. Left: seasonal (solid lines) and interannual (dashed lines) root-mean-square differences (RMS) in red; center: mean profiles of the model (blue), *in situ* observations (black) with the standard deviation envelope and CARS 2009 (orange); right: seasonal (solid lines) and interannual (dashed lines) correlation coefficients in green. Profiles summarize both the magnitude of differences and the agreement between model and observations from the surface to 80m depth.

A.5 Overall Model Performance

Overall, the model represents correctly the physical and biogeochemical components of the system across various spatial and temporal scales. SST is well represented, with minimal bias and very good representation offshore. The vertical structure of temperature and salinity is modeled quite realistically both along the 36°S transect and at Station 18, with good representation of interannual and seasonal variability.

For biogeochemical variables (O_2 and NO_3^-), nitrate distributions are generally well represented, even though the model tends to smooth out the seasonal and interannual vertical variations in NO_3^- observed at Station 18 in the *in situ* data. Conversely, oxygen concentrations are systematically overestimated by the model throughout the water column, resulting in a modeled OMZ that is narrower and less intense than observed. Despite this bias, the model still captures the overall vertical structure and the relative variability of oxygen, with minimal DO concentrations reaching values below 25 μM and locally as low as 0 μM in the OMZ core, and then close to the range of O_2 measurements uncertainty in both database and *in situ* observations.

Taken together, these results suggest that, despite some minor discrepancy, the model provides a reliable framework for exploring biogeochemical processes in the region, while also pointing to some limitations in the representation of oxygen dynamics.

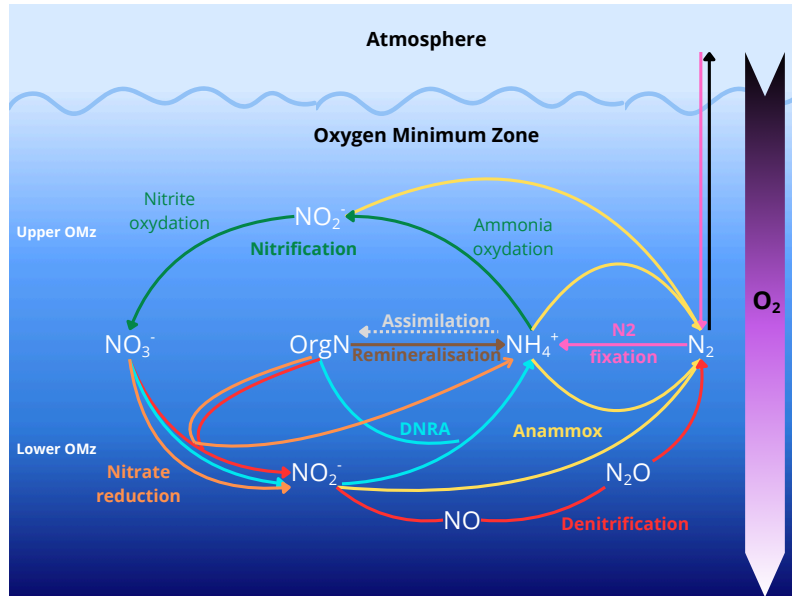


Fig. B1 Updated diagram of nitrogen cycling in the OMZs adapted from [5]

Table B1 Rates of DNRA measured in the OMZ off Peru/Chile from previous studies

Author	Part of the ocean	Date	Stage	Rate
[5]	Peruvian OMZ 25–50 m, inner shelf	April 2005	NH_4^+ production	$0.6 \text{ mmol N m}^{-2} \text{ d}^{-1}$
	Peruvian OMZ 50–94 m, inner shelf			$0.4 \text{ mmol N m}^{-2} \text{ d}^{-1}$
	Peruvian OMZ 25–60 m, mid-shelf			$0.6 \text{ mmol N m}^{-2} \text{ d}^{-1}$
	Peruvian OMZ 60–140 m, mid-shelf			$1.7 \text{ mmol N m}^{-2} \text{ d}^{-1}$
	Peruvian OMZ 25–100 m, offshore			$0.2 \text{ mmol N m}^{-2} \text{ d}^{-1}$
	Peruvian OMZ 100–600 m, offshore			$4.0 \text{ mmol N m}^{-2} \text{ d}^{-1}$
[6]	Station 18, 25 m	12 Sep 2013	NH_4^+ prod. ($NO_3^- \rightarrow NH_4^+$), anoxic	$56.0 \pm 4.0 \text{ nmol L}^{-1} \text{ d}^{-1}$
	Station 18, 85 m		NH_4^+ prod. ($NO_3^- \rightarrow NH_4^+$), anoxic	$49.3 \pm 5.3 \text{ nmol L}^{-1} \text{ d}^{-1}$
	Station 18, 25 m	28 Jan 2014	NH_4^+ prod. (in situ, [O ₂]=91 μM)	$751.2 \pm 81.5 \text{ nmol L}^{-1} \text{ d}^{-1}$
	Station 18, 85 m		NH_4^+ prod. ($NO_3^- \rightarrow NH_4^+$), anoxic	$82.8 \pm 7.3 \text{ nmol L}^{-1} \text{ d}^{-1}$

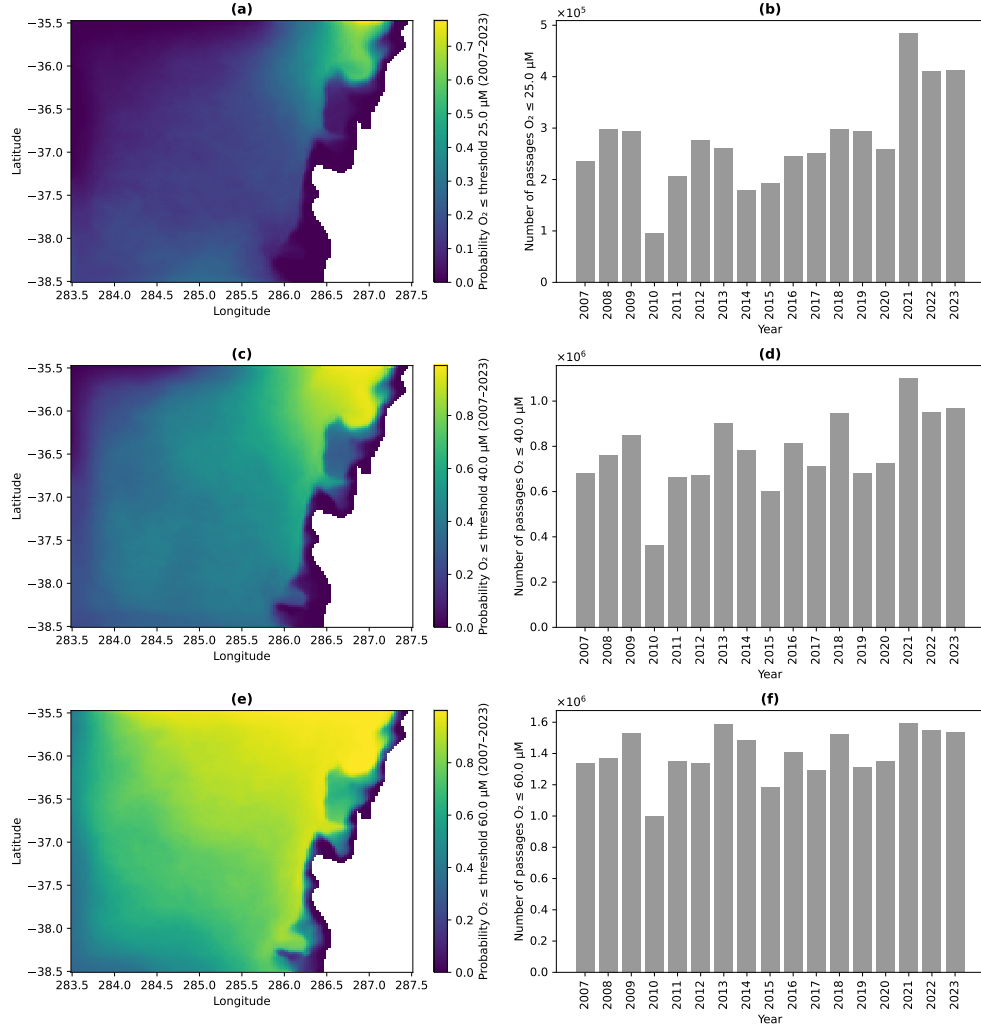


Fig. B2 Spatial and temporal occurrence of hypoxic conditions ($O_2 \leq \text{threshold}$). (a), (c), (e) Probability of oxygen concentration falling below the selected threshold (respectively 25 μM , 45 μM and 60 μM) at each grid cell over all the water column, computed as the ratio between the number of occurrences and the total number of time steps over the study period (2007–2023). (b), (d), (f) Annual number of occurrences of oxygen concentrations below the threshold (respectively 25 μM , 45 μM and 60 μM) over all the water column within the study domain.

Table B2 Overview of the 12 model simulations, combining O_2 threshold for anaerobic processes and DNRA kinetics.

Simulation	O_2 threshold (μM)	DNRA kinetics	DNRA activated
CTRL_25	25	—	No
CTRL_40	40	—	No
CTRL_60	60	—	No
DNRA_25_Vmax/2	25	$V_{max}/2$	Yes
DNRA_25_Vmax	25	V_{max}	Yes
DNRA_25_Vmax*2	25	$2V_{max}$	Yes
DNRA_40_Vmax/2	40	$V_{max}/2$	Yes
DNRA_40_Vmax	40	V_{max}	Yes
DNRA_40_Vmax*2	40	$2V_{max}$	Yes
DNRA_60_Vmax/2	60	$V_{max}/2$	Yes
DNRA_60_Vmax	60	V_{max}	Yes
DNRA_60_Vmax*2	60	$2V_{max}$	Yes

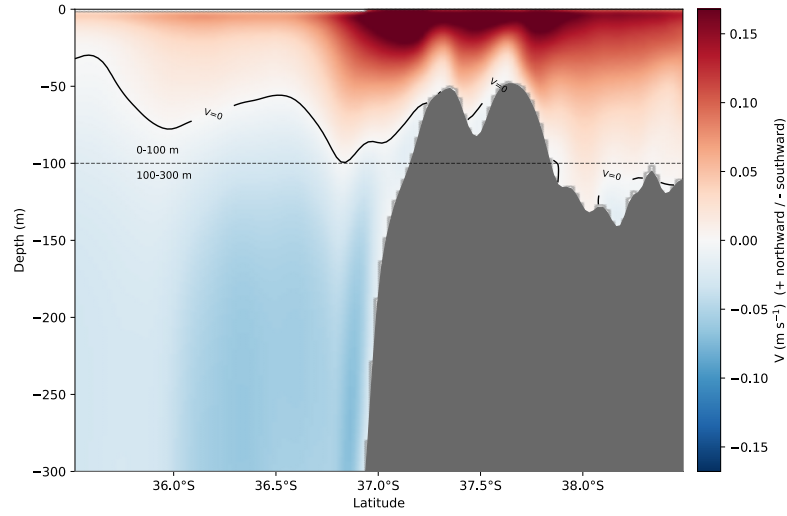


Fig. B3 Meridional cross-section (latitude–depth) of the mean meridional velocity V ($m.s^{-1}$) at $73.7^\circ W$, averaged over the period 2008–2014 (CTRL run). Red colors indicate a northward current ($V \geq 0$) and blue colors indicate a southward current ($V < 0$); the black outline marks the $V = 0$ isoline.

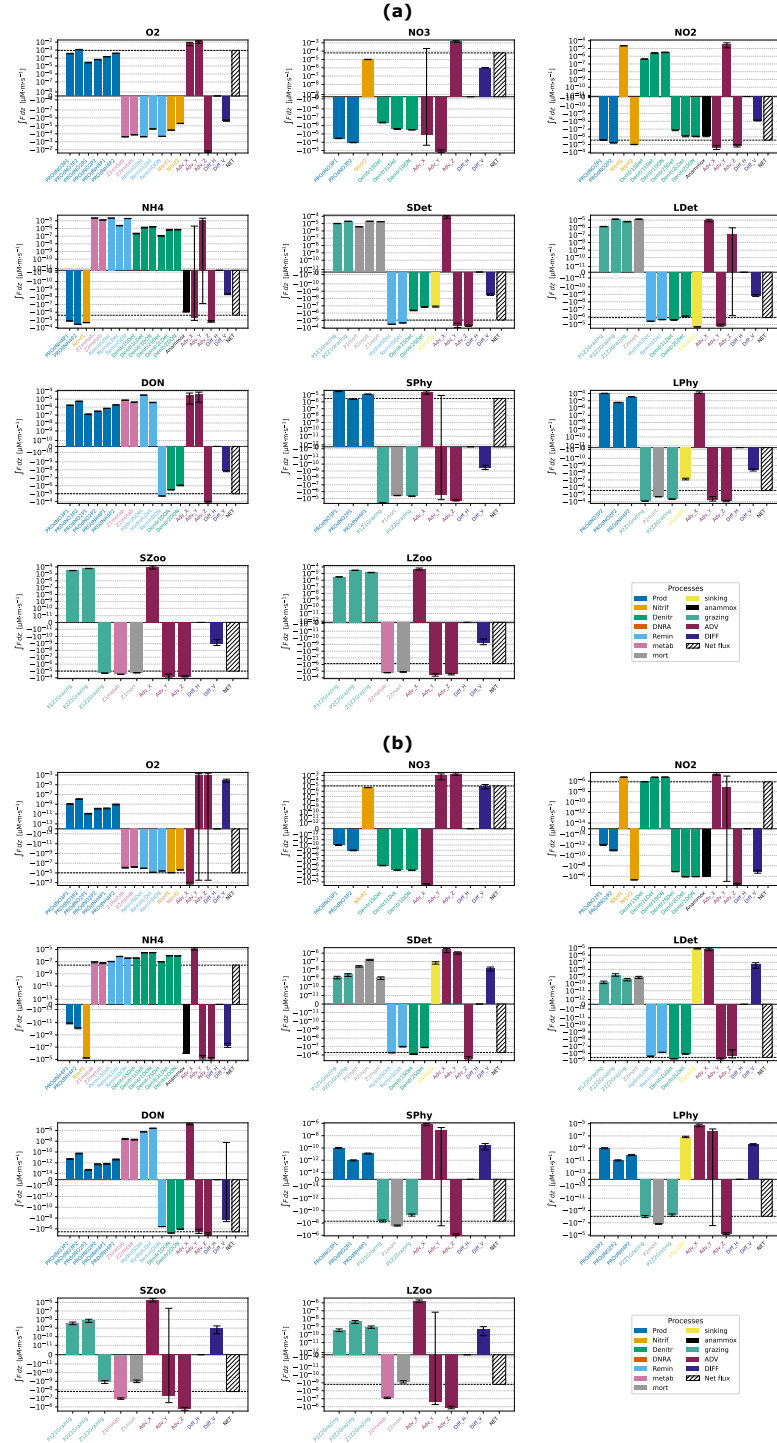


Fig. B4 Vertically integrated biogeochemical budgets at the offshore point lat = -36.0° , lon = -73.7° W). Contributions of individual processes to the net tendency of each tracer are shown for the control run for the upper aerobic layer (0-150 m) (a) anaerobic layer (150-350 m) (b). Bars represent the mean fluxes ($\mu\text{M s}^{-1}$) computed over the 2008–2014 period, while error bars indicate the standard deviation estimated via bootstrap resampling. Colors denote process categories (e.g., biological production, remineralization, nitrification, denitrification, DNRA, anammox, grazing, advection, and diffusion). Positive (negative) values indicate sources (sinks) of the considered tracer. The y-axis is displayed on a symmetric logarithmic scale to emphasize both small and large contributions.

References

- [1] Good, S. *et al.* The current configuration of the ostia system for operational production of foundation sea surface temperature and ice concentration analyses. *Remote Sensing* **12** (2020). URL <https://www.mdpi.com/2072-4292/12/4/720>.
- [2] CSIRO Oceans and Atmosphere. Cars 2009 - csiro atlas of regional seas - world monthly (2015). URL <https://catalogue-imos.aodn.org.au/geonetwork/srv/api/records/d9302a48-57b1-41c2-a0dc-78bd00dd5e4b>.
- [3] Pizarro, O. *et al.* Underwater Glider Observations in the Oxygen Minimum Zone off Central Chile. *Bulletin of the American Meteorological Society* **97**, 1783–1789 (2016). URL <https://journals.ametsoc.org/view/journals/bams/97/10/bams-d-14-00040.1.xml>.
- [4] Farias, L., Quiñonez, R., Tapia, F. & Bibliotecas UdeC. Más de 20 años de monitoreo del sistema de surgencia costera de Chile central. (2021). URL <https://datav.udec.cl/citation?persistentId=doi:10.48665/udec/CMHMEQ>.
- [5] Lam, P. *et al.* Revising the nitrogen cycle in the Peruvian oxygen minimum zone. *Proceedings of the National Academy of Sciences* **106**, 4752–4757 (2009). URL <https://www.pnas.org/doi/abs/10.1073/pnas.0812444106>. Publisher: Proceedings of the National Academy of Sciences.
- [6] Galán, A., Thamdrup, B., Saldías, G. S. & Farías, L. Vertical segregation among pathways mediating nitrogen loss (N₂ and N₂O production) across the oxygen gradient in a coastal upwelling ecosystem. *Biogeosciences* **14**, 4795–4813 (2017). URL <https://bg.copernicus.org/articles/14/4795/2017/>. Publisher: Copernicus GmbH.