Sensitivity of asymmetric Oxygen Minimum Zones to ~~remineralization rate and~~ mixing intensity and stoichiometry in the tropical Pacific using a basin-scale model (OGCM-DMEC V1.~~2~~4)

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Abstract. The tropical Pacific Ocean holds the world's two largest Oxygen Minimum Zones (OMZs), showing a prominent hemispheric asymmetry, with a much stronger and broader OMZ north of the equator. However, many models have difficulties in reproducing the observed asymmetric OMZs in the tropical Pacific. Here, we apply a fully coupled basin-scale model ~~(OGCM-DMEC V1.2)~~ to evaluate the impacts of ~~remineralization rate~~stoichiometry and the intensity of vertical mixing on the dynamics of OMZs in the tropical Pacific. We first utilize observational data of dissolved oxygen (DO~~), dissolved organic nitrogen (DON) and oxygen consumption)~~ to calibrate and validate the basin-scale model. Our model experiments demonstrate that enhanced vertical mixing combined with reduced ~~remineralization rate~~O:C utilization ratio can significantly improve our model capability of reproducing the asymmetric OMZs. Our study shows that DO is more sensitive to biological processes over 200-~~400~~700 m but to physical ~~-~~processes over 400-1000 m. Enhanced vertical mixing ~~not only~~ causes ~~an~~a large increase in ~~DO~~physical supply ~~at mid-depth, but also results~~and a small increase in ~~lower rates of~~ biological consumption ~~in the OMZs, which is associated with redistribution of DON. Our analyses demonstrate that weaker physical supply in the ETNP is the dominant process responsible for the asymmetry of the lower OMZs~~ whereas ~~greater~~ applying a reduced O:C utilization ratio leads to a large decrease in biological consumption~~ to the north plays a larger~~, and a small decrease in physical supply. Our analyses suggest that biological consumption (greater rate to the south) cannot explain the asymmetric feature in the tropical Pacific OMZs, but physical processes (stronger supply to the south) play a major role in regulating the ~~upper~~asymmetry of the tropical Pacific's OMZs. This study also highlights the ~~complex~~ roles of physical ~~supply~~ and biological ~~consumption~~interactions/feedbacks in ~~shaping~~contributing to the ~~asymmetric~~asymmetry of OMZs in the tropical Pacific.

1 Introduction

Photosynthesis and respiration are important processes in all ecosystems on the Earth, with carbon and oxygen being the two main elements. The carbon cycle has garnered much attentions, ~~which made~~with significant ~~progresses~~progress in both the observations and modelling of biological processes (e.g., uptake of CO_2 and respiration), and physical/chemical processes (e.g., carbon fluxes between the atmosphere, land and ocean). However, the oxygen cycle has received much less attention despite its large role in the earth system (Breitburg et al., 2018; Oschlies et al., 2018).

Dissolved oxygen (DO) is a sensitive indicator of physical and biogeochemical processes in the ocean thus a key parameter for understanding the ocean's role in the climate system (Stramma et al., 2010). In addition to photosynthesis and respiration, the distribution of DO in the world's oceans is also regulated by air-sea gas exchange, ocean circulation and ventilation Dissolved oxygen (DO) is a sensitive indicator of physical and biogeochemical processes in the ocean thus a key parameter for understanding the ocean's role in the climate system (Stramma et al., 2010). In addition to photosynthesis and respiration, the distribution of DO in the world's oceans is also regulated by air-sea gas exchange, ocean circulation and ventilation (Bettencourt et al., 2015; Bopp et al., 2002; Levin, 2018). Unlike most dissolved nutrients that display an increase in concentration with depth, DO concentration is generally low at mid-depth of the ocean. The most remarkable feature in the oceanic oxygen dynamics is the so-called Oxygen Minimum Zone (OMZ) that is often present below 200 m in the open oceans (Karstensen et al., 2008; Stramma et al., 2008).

. Previous studies have used the isoline of 20 mmol m^{-3} as the boundary of the OMZ for the estimation of OMZ volume (Bettencourt et al., 2015; Bianchi et al., 2012; Fuenzalida et al., 2009), and also as an up limit to determine the suboxic water (Wright et al., 2012).

The world's two largest OMZs are observed in the Eastern Tropical North Pacific (ETNP) and South Pacific (ETSP), showing a peculiar asymmetric structure across the equator, i.e., a much larger volume of suboxic water (<20 mmol m^{-3}) to the north than to the south (Bettencourt et al., 2015; Paulmier and Ruiz-Pino, 2009). It is known that OMZs are caused by the biological consumption associated with remineralization of organic matter (OM), and weak physical supply of DO due to sluggish subsurface ocean circulation and ventilation (Brandt et al., 2015; Czeschel et al., 2011; Kalvelage et al., 2015). Although there have been a number of observation--based analyses addressing the dynamics of OMZs in the tropical Pacific during the past decade (Czeschel et al., 2012; Garçon et al., 2019; Schmidtko et al., 2017; Stramma et al., 2010), our understanding is uncompleted in terms of limited on the underlying mechanisms that regulate DO dynamics at mid-depth due to the limitation of available data (Oschlies et al., 2018; Stramma et al., 2012).

Large-scale physical-biogeochemical models have become a useful tool to investigate the potential sensitivity of OMZs to climate change (Duteil and Oschlies, 2011; Ward et al., 2018; Williams et al., 2014). However, many models still have some difficulties in reproducing been unable to reproduce the observed patterns of asymmetric OMZs in the tropical Pacific (Cabre et al., 2015; Shigemitsu et al., 2017), which may be due to "unresolved ocean transport processes, unaccounted for variations in respiratory oxygen demand, or missing biogeochemical feedbacks" (Oschlies et al., 2018).(Oschlies et al., 2018). A common problem is that the two asymmetric OMZs merge into one in most models that often overestimate thedue to overestimated OMZ volume of OMZs in the tropical Pacific, which may be related to weaker the regulation of physical supply and/or higher rates of biological consumptionrespiration demand (Cabre et al., 2015; Shigemitsu et al., 2017). Recent studies have also indicated that a realistic representation of circulation and ventilation processes with a high-resolution ocean model is critical to predict the asymmetric OMZs in the tropical Pacific (Berthet et al., 2019; Busecke et al., 2019). ApparentlyHence, it's necessary to carry out model-data integrative studies to improve model capacity of simulating the dynamics of the tropical OMZs, and to better understand -the relative roles of physical and biological processes. Without such process understandings, it is unclear a priori whether simply increasing resolution will render better simulations and predictions.

A basin-scale ocean general circulation model coupled with a dynamic marine ecosystem-carbon model (OGCM-DMEC) was developed for the tropical Pacific (Wang et al., 2008; Wang et al., 2015; Wang et al., 2009b),, which showed capability of reproducing observed spatial and temporal variations of physical, nutrient and carbon fields in the upper ocean. (Wang et al., 2008; Wang et al., 2015; Wang et al., 2009b), and nitrate, iron, POC/detritus and export production below 200 m (Yu et al., 2021). In this study, we conduct model sensitivity experiments and evaluation on responses of mid-depth DO to parameterizations of two relevant processes (i.e., oxygen-restricted remineralization and vertical mixing). We first carry out model calibration and validation using observational data of basin-scale DO and oxygen consumption ratein the water column of the southern tropical Pacific to improve the simulation of OMZs in the tropical Pacific. Then, we use the improved model to evaluate howanalyse the impacts of new parameterizations on biological consumption and physical supply regulate and their relative contributions to the dynamics of mid-depth DO. The objective of this study is to advance our model capacity to simulate the oceanic oxygen cycle, and to identify the mechanisms driving the asymmetric OMZs in the tropical Pacific.

2. Model description

2.1 Ocean physical model

The basin-scale OGCM, a reduced-gravity, primitive-equation, sigma-coordinate model, is coupled to an advective atmospheric model (Murtugudde et al., 1996). There are 20 layers with variable thicknesses in the OGCM. The mixed layer (the upper-most layer) depth is determined by the Chen mixing scheme (Chen et al., 1994), which varies from 10 m to 50 m on the equator. The remaining layers in the euphotic zone are approximately 10 m in thickness. The model domain is between 30ºS and 30ºN, and zonal resolution is 1º. Meridional resolution varies between 0.3º and 0.6º over 15ºS-15ºN (1/3° over 10°S-10ºN), and increases to 2º in the southern and northern "sponge layers" (the 25º-30º bands) where temperature, salinity, and nitrate are gradually relaxed back towards the observed climatological seasonal means from the World Ocean Atlas, 2013 (WOA2013: (Murtugudde et al., 1996). There are 20 layers with variable thicknesses and a total depth of ~1200 m in the OGCM. The mixed layer (the upper-most layer) depth is determined by the Chen mixing scheme (Chen et al., 1994), which varies from 10 m to 50 m on the equator. The remaining layers in the euphotic zone are approximately 10 m in thickness. The vertical resolution is approximately 30-50 m in the core OMZ (at ~300-500 m). The model domain is between 30ºS and 30ºN for the Pacific, and zonal resolution is 1º. Meridional resolution varies between 0.3º and 0.6º over 15ºS-15ºN (1/3° over 10°S-10ºN), and increases to 2º in the southern and northern "sponge layers" (the 25º-30º bands) where temperature, salinity, nutrients and DO are gradually relaxed back towards the observed climatological seasonal means. The model closes the western boundary and no representation of the Indonesian throughflow is included. The boundary conditions of temperature, salinity, nitrate and DO are from the World Ocean Atlas, 2013 (WOA2013: http://www.nodc.noaa.gov/OC5/woa13/pubwoa13.html~~).~~), and boundary condition for dissolved iron is based on limited field data, and given by a linear regression against temperature (see details in Christian et al., 2001). Such model configuration may have a disadvantage for longer simulations and analyses, but has the advantage in reproducing the spatial patterns of most physical and biogeochemical fields.

The model is forced by atmospheric conditions: climatological monthly means of solar radiation and cloudiness, and interannual 6-day means of precipitation and surface wind stress. Precipitation is from ftp://ftp.cdc.noaa.gov/Datasets/gpcp. Wind stresses are from the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996). Air temperature and humidity above the ocean surface are computed by the atmospheric mixed layer model. Initial conditions were obtained from outputs of an interannual hindcast simulation over 1948-~~1978~~2000, which itself is initialized from a 30-year spin up with climatological ~~run with a 30-year spin up.~~forcing, followed by two 40-year interannual simulations. The initial conditions for the ~~climatological~~ spin up are specified from the WOA2013~~.~~, iron concentration for the spin up was initialized from limited field data collected in the tropical Pacific (Johnson et al., 1997). We carry out an interannual simulation for the period of 1978-~~2018~~2010, and analyse the mean states from model ~~output for~~simulations over the period of ~~1981-2000~~1991-2010.

2.2 Ocean biogeochemical model

~~The DMEC model is the main part of the biogeochemical model that is embedded in the basin-scale OGCM.~~ The DMEC model consists of eleven components: small (S) and large (L) sizes of phytoplankton (P_S and P_L), zooplankton (Z_S and Z_L) and detritus (D_S and D_L), dissolved organic nitrogen (DON), ammonium, nitrate, dissolved iron, and DO (Figure 1). Phytoplankton growth is co-limited by nitrogen and iron, which is critical in the tropical Pacific. The model simulates the iron cycle using variable Fe:N ratios, and incorporates atmospheric iron input. All biological components use nitrogen as their unit, ~~and~~ in which sources/sinks are determined by biological and chemical processes in addition to the physical processes (circulation and vertical mixing) that are computed ~~in a manner similar to physical variables~~by the OGCM.

In this model, net community production (NCP) is computed as:

$$-NCP = 6.625(\mu_s P_s + \mu_L P_L - r_s Z_s - r_L Z_L - c_{DON} DON - c_{DS} D_s - c_{DL} D_L) \qquad (1)$$

~~where 6.625 is the C:N ratio, μ the rate of phytoplankton growth, r the rate of zooplankton respiration, c the rates of detritus decomposition and DON remineralization. The equations for biogeochemical processes and model parameters are described in Appendix A and B. There have been changes in some parameters comparing with those in Wang *et al.* (2008), which were~~

~~based on our model calibration and validation for chlorophyll (Wang *et al.*, 2009a), nitrogen cycle (Wang *et al.*, 2009b) and carbon cycle (Wang *et al.*, 2015).~~
where 6.625 is the C:N ratio, μ the rate constant of phytoplankton growth, *r* the rate constant of zooplankton respiration, *c* the rate constants of detritus decomposition and DON remineralization. The equations for biogeochemical processes and model parameters are given in Appendix A and B. There were changes in some parameters comparing with those in Wang et al. (2008), which were based on our model calibration and validation for chlorophyll (Wang et al., 2009a), nitrogen cycle (Wang et al., 2009b) and carbon cycle (Wang et al., 2015).

Recently, we have made further improvements in the parameterizations of detritus decomposition and DON remineralization (eq. B21-B23), which result from the first round of model calibration on DO distribution using WOA2013. In brief, c_{DON} decreases with depth over 100-1000 m, following an exponential function in this study. The differences in the related parameters are given in Appendix C.

2.3 Computation of oxygen sources and sinks

The time evolution of DO is regulated by physical, biological and chemical processes:

$$\frac{\partial O_2}{\partial t} = -u\frac{\partial O_2}{\partial x} - v\frac{\partial O_2}{\partial y} - w\frac{\partial O_2}{\partial z} + O_{mix} - O_{bio} + O_{gas} \quad (2)$$

where *u*, *v*, and *w* are zonal, meridional, and vertical velocity, respectively. O_{mix} is the vertical mixing term that is calculated by three subroutines. Briefly, the first one computes convection to remove instabilities in the water column, and the second one determines the mixed layer depth. The third one computes partial vertical mixing (K_z) between two adjacent layers to relieve gradient Richardson (R_i) number instability, which is calculated as follows:

$$K_z = \left(1 - \left(\frac{Ri}{0.7}\right)^{\lambda}\right)(Ri < 0.7) \quad (3)$$

$$K_z = 0\ (Ri \geq 0.7) \quad (4)$$

where the mixing parameter λ is set to 1. Clearly, partial vertical mixing is the dominant process influencing physical supply of DO in the intermediate waters.

The biological source/sink term O_{bio} is computed as follows:

$$~~-~~O_{bio} = ~~1.3\text{NCP}~~ R_{OC}\text{NCP} \quad (5)$$

where ~~1.3~~R_{OC} is the O:C utilization ratio (set to 1.3 in reference simulation, according to the Redfield ratio~~.~~). Below the euphotic zone, DO concentration is determined by physical supply and biological consumption that results from detritus decomposition and DON remineralization, in which DON remineralization is dominant because DON ~~poor~~pool is several times greater than detritus ~~(Wang *et al.*, 2008)~~(Wang et al., 2008).

The flux of O_2 from the atmosphere to the surface ocean is computed as:

$$O_{gas} = (O_{Sat} - O)K_0 \quad (6)$$

where O_{sat} is the O_2 saturation, a function of temperature and salinity ~~(Weiss, 1970)~~(Weiss, 1970), and K_0 the gas transfer velocity that is a function of wind speed (u_s) and SST according to Wanninkhof (1992):

$$K_0 = 0.31 u_s^2 \sqrt{\frac{Sc}{Sc20}} \sqrt{\frac{S_c}{S_{c20}}} \quad (7)$$

where S_c and S_{c20} are the Schmidt number at SST and 20° C, respectively:

$$S_c = 1953 - 128T + 3.99T^2 - 0.05T^3 \quad (8)$$

3. Model experiments ~~and validation~~

3.1 Evaluation of DO distribution from the reference run

We first evaluate simulated DO for the tropical Pacific Ocean using the outputs from OGCM-DMEC V1.2 (hereafter reference run~~). We focus on model-data comparisons over 200-400 m, 400-700 m and 700-1000 m~~), which use the same set of parameters as Yu et al. (2021). We focus on model-data comparisons over 200-400 m, 400-700 m and 700-1000 m, that broadly represent the upper OMZ, lower OMZ and beneath OMZ, respectively. The WOA2013 data shows a much larger area of suboxic waters (<20 mmol m^{-3}) in the ETNP than in the ETSP over 200-400 m and 400-700 m (Figure 2a and 2c), but no suboxic water over 700-1000 m (Figure 2e). Although the reference run produces two OMZs off the equator over 200-400 m (Figure 2b), the sizes of suboxic water are much larger in the reference run than those in the WOA2013 data. The reference run significantly over-~~estimate~~estimates the size of suboxic water and underestimates DO concentration over 400-700 m (Figure 2d). The difference between WOA2013 and the reference run is small over 700-1000 m, except in the eastern tropical Pacific (Figure 2f). ~~The relative roles of the physics vs. the biogeochemistry in determining the bias are diagnosed further below.~~

3.2 Sensitivity experiments

~~Given~~There have been advances in understanding of oxygen consumption. For example, recent studies have showed that ~~the mid-depth DO concentration is influenced by physical supply and biological consumption,~~O:C utilization ratio varies largely across different basins, e.g., from 0.6 to 2.1 in the Pacific (Moreno et al., 2020; Tanioka and Matsumoto, 2020), and rates of DOM remineralization ~~of DON is the dominant process for~~ or oxygen consumption~~, the underestimated DO~~ are influenced by oxygen level, i.e., a reduction under low DO conditions (Beman et al., 2020; Bertagnolli and Stewart, 2018; Sun et al., 2021). Based on the field data at mid-depth ~~would be a result of overestimation of~~(~350 m) in the Peruvian OMZ (Kalvelage et al., 2015)， we derive a kinetics function between oxygen consumption ~~associated with DON remineralization and/or underestimation of supply. Indeed,~~rate and DO concentration, which yields the ~~reference run over-estimates biological~~

consumption over 100-400 mhalf saturation constant Km being 6.9 and 18.7 mmol m^{-3} (Figure 3). Thus, we apply a By adding this functional form to equation 5, one would get a varying and also reduced DON remineralization constant (50% of the reference run), which leads to a remarkable improvement in simulated DON and consumption. O:C utilization ratio, with lower ratios in in low-DO waters.

The reference run appliesapplied a zero value for background diffusion. However, a previous modelling study has demonstrated that vertical background diffusion iswas an important process for DO supply at mid-depth (Duteil and Oschlies, 2011)(Duteil and Oschlies, 2011). Accordingly, we conduct a few more simulations (Table 1S1) to investigate how reducing remineralization rate and applying different values for verticala reduced O:C utilization ratio (setting Km as 6.9 and 18.7 mmol m^{-3}) and adding background diffusion (setting Kb = 0.1,as 0.3, or25 and 0.5 cm^2 s^{-1}) affect the simulated DO distribution and asymmetricasymmetry of OMZs in the tropical Pacific. ChangingTo eliminate complex interactions and feedbacks, the intensityaddition of verticalbackground diffusion has relatively small influence on vertical distributions of DON and DO consumption in the OMZ (is only applied to the key variables (DO and DON) in this study.

Figure 3).

We then compare simulated DO and WOA2013 climatology data. Figure 4a4 illustrates that based on WOA2013 database, there is a larger volume of suboxic water located north of ~5°N and a smaller volume of suboxic water over 12°S-4°S, which are separated by relatively higher DO (>3020 mmol m^{-3}) water along the equator. Both Cd0.5 run (Figure 4c) and the reference run (Figure 4b) produce much larger volumes of suboxic water that are extend to the equatorial region, and even merge into one. Clearly, thereThere is an improvement in simulated DO with reduced O:C utilization ratio (Figure 4b and 4c) and enhanced vertical mixing (Figure 4d and 4h). Clearly, combination of reduced O:C utilization ratio and enhanced vertical mixing leads to a further improvement in simulated mid-depth DO (Figure 4e, 4f, 4i and 4j). In particular, the combination of a stronger background diffusion (Figure 4d, 4e and 4f). Overall, Cd0.5Kb0.5 is able to capturewith a smaller O:C utilization ratio (i.e., the Km18.7Kb0.5 run) results in the best simulation that reproduces the observed spatial distribution of mid-depth DO, especially the asymmetric feature (i.e., a larger volume of suboxic water to the north but a smaller size of suboxic water to the south), and relatively higher DO (~30-40 mmol m^{-3}) over 2°S-2°N.).

3.3 Model validation

To further evaluate the performance of experiments, threea few statistical measures are applied over 200-400 m, 400-700 m and 700-1000 m in the ETNP (165°W-90°W, 5°-20°N) and ETSP (110°W-80°W, 10°S-3°S). As shown in Table 21, compared towith the reference run, bias, MAE and root mean square error (RMSE–) are reduced in all decrease in the new experimentssimulations, with the smallest values from Cd0.5Kb0Km18.7Kb0.5 run except over 700-1000 m in the ETNP. For example, both ~~MAE~~bias and RMSE ~~are lowest from Cd0.5Kb0~~in the Km18.7Kb0.5 run are smallest over 200-700 m in the ETNP ~~(6.95-16.44 mmol m^{-3})~~(<7.8 and ~~over 200-1000 m in ETSP (3.12-7.59~~10.2 mmol m^{-3}). Many current models show much large RMSE (~20-80 mmol m^{-3}) with respect to observed DO from mixed layer to 1000 m ~~(Cabre *et al.*, 2015; Bao and Li, 2016)~~(Bao and Li, 2016; Cabre et al., 2015). Figure 5 also illustrates that ~~Cd0.5Kb0~~the Km18.7Kb0.5 run produces the best outputs, with the largest correlation coefficients (0.77-0.94) and also the smallest distance to 1 in normalized standard deviation (0.54-1.81 in ETNP and 0.33-1.63 in ETSP).

We also compare the sizes of suboxic water and hypoxic water between model simulations and WOA2013 (Table ~~3~~2). Based on WOA2013,~~ we estimate that the~~ sizes of suboxic water and hypoxic water are 5.97x10^{15} m^3 and 19.98x10^{15} m^3 in the north, and 1.43×10^{15} m^3 and 7.12x10^{15} m^3 in the south, respectively. While ~~the Cd0.5 run (with a~~ reduced ~~remineralization rate) results in~~O:C utilization ratio and enhanced vertical mixing can lead to an improvement in simulated OMZ volume, a significant ~~improvements are~~improvement is obtained with the combination of reduced ~~remineralization~~O:C utilization ratio and enhanced vertical mixing~~ (i.e., with background diffusion).~~. Overall, the Km18.7Kb0.5 simulation has the best performance for reproducing the OMZ ~~volume is Cd0.5Kb0.5 simulation that predicts~~volumes, showing similar volumes for the suboxic water (~~6.61x10^{15}~~5.55x10^{15} m^3 to the north and 1.~~56x10^{15}~~12x10^{15} m^3 to the south) and the hypoxic water (~~19.62x10^{15}~~20.91x10^{15} m^3 and 7.~~13x10^{15}~~39x10^{15} m^3).

We then ~~use cruise data to~~ further validate the modelled DO from the best run (~~Cd0.5Kb0~~Km18.7Kb0.5~~).~~), using the time series of the observed DO data (https://cchdo.ucsd.edu/). Figure 6 ~~shows~~illustrates that the model can generally reproduce the vertical-zonal ~~distribution~~distributions of DO along 10°N and 17°S, spanning from 1989 to 2009, particularly in the eastern tropical Pacific. For example, cruise data from the P04 line during April-May, 1989 show a large area of low DO water spanning from ~200 m to ~800 m (Figure 6a), and our model also predicts low DO water over ~200-700 m (Figure 6b).

4 Model ~~evaluation~~results and discussions

In this section, we further compare the improved model simulations (~~Cd0~~Km18.7, Kb0.5 and ~~Cd0.5Kb0~~Km18.7Kb0.5) with the reference run to diagnose the ~~relative contributions~~influences of improved parameterizations on the distribution of mid-depth DO, and biological consumption and physical supply~~ to the asymmetric OMZs in the tropical Pacific, aiming to identify~~. We then analyse the interactions of physical and biogeochemical processes, and the impacts on the source and sink for the mid-depth DO. In the end, we explore the underlying mechanisms regulating the ~~dynamics of mid-depth DO~~asymmetry of OMZs in the tropical Pacific.

4.1 Changes of mid-depth DO due to reduced remineralization O:C utilization ratio and enhanced vertical mixing

We first compare the changes ofin DO concentrationconcentrations between the three model simulationsimulations over 200-400 m, 400-700 m, and 700-1000 m (Figure 7). Clearly, applying a reduced remineralization rate largelyO:C utilization ratio causes an increase mid-depthof DO in all three layers, with a greaterthe greatest increase (~0-22(>6 mmol m^{-3}) overin the 200-400 m layer (Figure 7a), followed by a modest increase (~03-6 mmol m^{-3}) over 400-700 m (Figure 7d), and a small). Although DO increase (0-3 mmol m^{-3}) overis generally smaller in the 700-1000 m layer (Figure 7h).) than in the 400-700 m layer (Figure 7d), the increase is greater in the north OMZ over 700-1000 m than over 400-700 m. Enhanced vertical mixing -results in a small increase of DO (~2-5 mmol m^{-3}) in DO (<the 10 mmol m^{-3})°S-10°N band over 200-400 m (Figure 7b)), but a large increase ((~5-1215 mmol m^{-3}) in majority of the basin over 400-700 m and 700-1000 m (Figure 7e and 7i). A number of modelling studies have demonstrated that parameterization of vertical mixing has significant impacts on the mean state of DO distributions at

Overall, the mid-depth (Duteil and Oschlies, 2011; Gnanadesikan *et al.*, 2013).DO shows an increase with the combination of a reduced O:C utilization ratio and enhanced vertical mixing (Figure 7c, 7f & 7j). A great increase of DO (>15 mmol m^{-3}) occurs in majority of the basin over 400-700 m, mainly in the central tropical Pacific over 200-400 m, but in a few small areas over 700-1000 m. The spatial pattern and magnitude of DO increase resulting from the combination of reduced O:C utilization ratio and enhanced vertical mixing, have a large similarity to those with reduced O:C utilization ratio for the 200-400 m layer (Figure 7a), but to those under enhanced vertical mixing below 400 m (Figure 7e & 7i). For example, the relative increase of DO is similarly larger in the northern OMZ over 200-400 m under a reduced O:C utilization ratio with and without the addition of background diffusion, and over 700-1000 m under enhanced vertical mixing (i.e., with additional background diffusion) with and without the change in the O:C utilization ratio. Our analyses suggest that the dominant process regulating the DO dynamics is biological consumption over 200-700 m, but physical supply over 400-1000 m.

We also assess the response of mid-depth DO to the combination of reduced remineralization rate and enhanced vertical mixing (Cd0.5Kb0.5 minus reference run). Overall, the increase of DO is greater over 200-400 m (~10-24 mmol m^{-3}) than over 400-700 m (~8-18 mmol m^{-3}) and 700-1000 m (~6-12 mmol m^{-3}) (Figure 7c, 7f & 7j). The spatial pattern and magnitude of increased DO resulted from the combined changes of remineralization rate and vertical mixing have a large similarity to those caused by reduced remineralization rate for the 200-400 m layer (Figure 7a), but are similar to those due to enhanced mixing below 400 m (Figure 7d & 7h). Our analyses indicate that DO dynamics is regulated by biological processes above 400 m, but by physical processes over 400-1000 m. The larger biological influence on the upper OMZ is attributable to the greater rate of DO consumption (Karstensen *et al.*, 2008) whereas the greater physical impact on the lower OMZ reflects the relatively larger role of supply than consumption.

~~4.2 Responses of~~ 4.2 Effects of reduced O:C utilization ratio and enhanced vertical mixing on consumption and supply ~~to reduced remineralization and enhanced mixing~~

~~We then~~ To better understand the effects of changes in the biological and/or physical parameters on the DO dynamics, we then evaluate the ~~changes~~responses of biological consumption and physical supply ~~of DO due to reduced remineralization and/or enhanced mixing. Reducing remineralization rate by 50% (Cd0.5 minus reference) leads to~~. As illustrated in Figure 8, changes in biological consumption are almost identical under a reduced O:C utilization ratio with or without background diffusion. In particular, biological consumption shows a large decrease (~~~1.5~~ 2.~~0~~-8 mmol m^{-3} yr^{-1}) over 200-400 m~~, modest~~ (Figure 8b), and a small decrease (~0.2-1.0~~.5~~ mmol m^{-3} yr^{-1}) over 400-700 m ~~and small decrease (~0.~~, with the largest decrease in the northern OMZ (Figure 8e); there is a very small change in biological consumption over 700-1000 m, i.e., a decrease of <0.1~~-0.2~~ mmol m^{-3} yr^{-1}~~)~~ over ~~700-1000~~majority of the basin but an increase of <0.1 mmol m^{-3} yr^{-1} in some parts of subtropical region (Figure ~~8a, 8d and 8h~~8i). On the other hand, enhanced vertical mixing ~~causes much greater increase of supply over 400-1000 m than over 200-400 m.~~ leads to a small increase (<0.2 mmol m^{-3} yr^{-1}) in biological consumption in all three layers, with a relatively larger increase in the northern OMZ (Figure 8c, 8f and 8j).

Figure 9 shows the effects of a reduced O:C utilization ratio and enhanced vertical mixing on physical supply. With the combination of a reduced O:C utilization ratio and enhanced vertical mixing, physical supply shows a small increase (by ~0.2-1.0 mmol m^{-3} yr^{-1}) in the whole basin over 700-1000 m (Figure 9h) and only outside the OMZs over 400-700 m (Figure 9d), but a relatively larger decrease in the OMZs over 200-700 m (by ~0.2-6 mmol m^{-3} yr^{-1}) (Figure 9a and 9d). Clearly, enhanced vertical mixing leads to an increase of physical supply over majority of the basin, with greater increase over 400-1000 m (~0.2-1.0 mmol m^{-3} yr^{-1}) than over 200-400 m (~0-0.4 mmol m^{-3} yr^{-1}) (Figure 9c, 9f and 9j). However, applying a reduced O:C utilization ratio causes a large decrease of physical supply above 700 m, with greater decrease over 400-700 m in the OMZs (~0.2-6 mmol m^{-3} yr^{-1}), and very small changes (<0.2 mmol m^{-3} yr^{-1}) over 700-1000 m (Figure 9b, 9e and 9i). Overall, rate of physical supply is largely determined by vertical mixing over 700-1000 m, by both vertical mixing and biological consumption over 400-700 m, but by consumption over 200-400 m, implying complex physical-biological interactions and feedbacks in the tropical Pacific OMZs.

4.3 Interactive effects of physical and biological processes on source and sink of mid-depth DO

There is evidence that enhanced mixing can have large influences not only on physical processes (e.g., the strength of water mixing) but also on biological processes (e.g., transport of organic materials), which have direct or indirect effects on the evolution of mid-depth DO (Andrews et al., 2017; Duteil and Oschlies, 2011; Stramma et al., 2012). Our analyses show an increase in physical supply under enhanced vertical mixing in most parts of the 200-1000 m layer in the eastern tropical Pacific (over 120°W-90°W) (Figure 10). Interestingly, the greater increase (>1 mmol m^{-3} yr^{-1}) is below the OMZs over 15°S-10°N using 1.3 as the O:C utilization ratio (Figure 10a), but occurs over a much larger area (i.e., over 15°S-20°N) and within the OMZs using a reduced (and also varying) O:C utilization ratio (Figure 10d). Enhanced vertical mixing also results in a generally small increase in biological consumption, with greater increases in OMZs using a reduced O:C utilization ratio (Figure 10e) than using a constant Redfield ratio of 1.3 (Figure 10b). The small increase in consumption outside of OMZs is largely attributable to increased DON concentration (data not shown) that results from the enhanced vertical mixing whereas the increase of consumption inside the OMZs would be a result of the interactions and feedbacks of various physical, biological and chemical processes. Clearly, there is an overall increase in net flux, with the largest increases occurring mainly outside the OMZs (Figure 10c and 10f).

To further investigate the interactive effects of a reduced O:C utilization ratio and enhanced mixing, we then compare the responses of biological consumption and physical supply to changes in the O:C utilization ratio with and without background diffusion (Figure 11). While a reduced O:C utilization ratio can result in a decrease in consumption above 600 m, the decrease is slightly less in the OMZs with background diffusion (Figure 11d) than without background diffusion (Figure 11a). Similarly, physical supply also shows a decrease in the OMZs under a reduced O:C utilization ratio (Figure 11b), with a lesser decrease under the addition of background diffusion (Figure 11e). The greatest difference is found in the core OMZs for both biological consumption (Figure 11h) and physical supply (Figure 11i), but larger differences are found in supply. A previous modeling study also demonstrates that physical contribution to the changes of DO is much greater than biogeochemical contribution (Montes et al., 2014). However, a reduced O:C utilization ratio results in a clear increase in net flux in the whole water column over 200-1000 m, with a great increase above the core OMZs within the 10°S-10°N band (Figure 11c and 11f).

Physical supply could be divided into horizontal advection, vertical advection, and vertical mixing. Our model performs well in simulating the meridional and zonal advections, and vertical mixing processes of DO transport (see Figure S2), which allows us to evaluate the responses of different supply components to the reduced O:C utilization ratio. As shown in Figure 12, there is no clear pattern in the responses of advective supply, with very small values (< ~1 mmol m^{-3} yr^{-1}) over the entire basin (Figure 12h and 12i). However, the DO supply by vertical mixing shows a strong response, with similar patterns to those of total supply and a large decrease in the suboxic waters (Figure 12c and 12f). While applying a reduced O:C utilization ratio causes a decrease in the DO supply (~1-6 mmol m^{-3} yr^{-1}) by vertical mixing, the decrease is larger in the OMZs without the addition of background diffusion. On the other hand, there is an increase in the supply by vertical mixing below the OMZs under a reduced O:C utilization ratio, in particular with the addition of background diffusion (Figure 12f). The largest difference (~1-2 mmol m^{-3} yr^{-1}) is found within the hypoxic waters (Figure 12j), which reflects the strong feedback between physical and biological processes in the OMZs.

There is evidence that the physical and biogeochemical processes have multiple interactions with impacts on various physical, chemical and biological fields and implications for DO dynamics (Breitburg et al., 2018; Duteil and Oschlies, 2011; Oschlies et al., 2018). For example, observational and modelling studies show that changes in vertical mixing intensity can affect the distributions of organic matter thus oxygen consumption at mid-depth (Duteil and Oschlies, 2011; Talley et al., 2016), and vertical distributions of DOM concentration and its remineralization around the OMZ in turn can alter the intensity of vertical mixing for DO (Loginova et al., 2019). Recent studies have demonstrated that a changing O:C utilization ratio (or respiration quotient) has various impacts on biological and chemical processes, with an impact on microbial respiration thus oxygen consumption (Moreno et al., 2020; Tanioka and Matsumoto, 2020). In particular, applying a smaller O:C utilization ratio leads to lower consumption rates, thus higher DO levels (Moreno et al., 2020), which would have large effects on DO gradients thus vertical mixing particularly in low-DO waters (e.g., in the OMZs).

4.4 Impacts of biological and physical processes on asymmetric OMZs

There is evidence of asymmetric features in many biogeochemical parameters in the tropical Pacific. For example, POC flux at 500 m is greater in the northern tropical Pacific (~4 mmol C m^{-2} d^{-1}) (Van Mooy et al., 2002) than in the southern tropical Pacific (<1 mmol C m^{-2} d^{-1}) (Pavia et al., 2019). Similarly, our regional model reproduces an asymmetric pattern for POC flux, with larger values to the north than to the south. Field studies have reported an asymmetry in DOM distribution over ~200-1000 m in the central-eastern tropical Pacific, i.e., higher levels of DON and DOC to the north than to the south (Hansell, 2013; Libby and Wheeler, 1997; Raimbault et al., 1999). Our model simulation also reveals an asymmetric DON at mid-depth, i.e., ~6-7 mmol m^{-3} in the ETNP and ~4-5 mmol m^{-3} in the ETSP (data not show). However, an earlier field study reported higher rates of organic carbon remineralization over 200-1000 m to the south (~2-10 mmol m^{-3} yr^{-1}) than to the north (~1-6 mmol m^{-3} yr^{-1}) in the eastern/central tropical Pacific (Feely et al., 2004). Similarly, our model simulation also shows such asymmetric feature of biological consumption below 200 m in the tropical Pacific, i.e., ~2-8 mmol m^{-3} yr^{-1} in the ETSP and ~1-6 mmol m^{-3} yr^{-1} in the ETNP.

It appears that the asymmetric distributions differ largely between biological parameters, and there are almost opposite patterns between oxygen consumption (or DOM remineralization) and DOM concentration. This discrepancy may be attributed to the rates of DOM remineralization in the water column, which is determined not only by DOM concentration, but also by the stoichiometry associated with microbial respiration (Wang et al., 2008; Zakem and Levine, 2019). Recent studies on respiration quotient demonstrate that the O:C utilization ratio is lower to the north than to the south in the tropical Pacific (Tanioka and Matsumoto, 2020; Wang et al., 2019), which primarily reflects the difference in oxygen limitation on microbial respiration (Kalvelage et al., 2015). Apparently, such asymmetry in biological consumption cannot explain the asymmetry in the tropical Pacific OMZs (i.e., lower DO levels to the north than to the south), indicating that other processes are responsible for the asymmetry.

Numerous studies have indicated that physical mixing is the only source of DO for the tropical OMZs ~~(Czeschel *et al.*, 2012; Brandt *et al.*, 2015; Talley *et al.*, 2016)~~(Brandt et al., 2015; Czeschel et al., 2012; Duteil et al., 2020). For example, turbulent ~~background~~ diffusion ~~accounts~~is argued to account for 89% of the net DO supply for the core OMZ ~~layer~~ of south tropical Pacific ~~(Llanillo *et al.*, 2018)~~(Llanillo et al., 2018)~~. Figure 8e and 8i illustrate that physical supply is increased by ~0.2-0.6~~

~~mmol m^{-3} yr^{-1} in most of the mid-waters, with the largest increase in the southern part of central equatorial Pacific over 400-700 m. However, there is somehow a small decrease of physical supply in the ETNP over 200-400 m (by ~0.03 mmol m^{-3} yr^{-1}, Figure 8b) and 400-700 m (<0.02 mmol m^{-3} yr^{-1}, Figure 8e), implying that increased DO under enhanced vertical mixing may be attributable to changes in biological consumption~~. There is evidence that larger-scale mass transport due to circulation and ventilation is more efficient in the south Pacific than in the north Pacific (Kuntz and Schrag, 2018), and the transit time from the surface to the OMZ is much longer in the ETNP than in the ETSP (Fu et al., 2018). Both our analyses and other modeling studies (Duteil, 2019; Shigemitsu et al., 2017) demonstrate that DO supply via vertical mixing is much weaker in the northern OMZ than in the southern OMZ in the tropical Pacific. All these analyses indicate that physical processes play a major role in shaping the asymmetry of the OMZs over the tropical Pacific.

~~We further compare biological consumption between Cd0.5Kb0.5 and the Cd0.5. Interestingly, enhanced vertical mixing results in a decrease in consumption, with the largest decreases (~0.03-0.07 mmol m^{-3} yr^{-1}) over 400-700 m (Figure 8f), the smallest decrease (~0.01-0.04 mmol m^{-3} yr^{-1}) over 200-400 m (Figure 8c) and modest decrease of ~0.02-0.04 mmol m^{-3} yr^{-1} over 700-1000 m (Figure 8j). For the northern OMZ, biological consumption decreases by ~0.03-0.07 mmol m^{-3} yr^{-1} over 200-700 m (Figure 8c and 8f), which is larger than the decreased rate (~0.01-0.03 mmol m^{-3} yr^{-1}) of physical supply (Figure 8b and 8e).~~

~~Remineralization rate of DOM in the ocean is determined by the size of DOM pool and temperature~~ 4.5 Implications and limitations of the current research

There are inter-dependencies between the physical and biogeochemical processes ~~(Wang *et al.*, 2008; Brewer and Peltzer, 2016)~~(Duteil and Oschlies, 2011; Gnanadesikan et al., 2012; Niemeyer et al., 2019)~~. Given that there is little difference (<10^{-5} °C) in seawater temperature between different model experiments, the reduced consumption rates due to DOM remineralization would be a result of a smaller amount of DOM. Here, we evaluate the zonal and meridional distributions of DON together with remineralization rate. As shown in Figure 9a-9d, modelled consumption decreases from ~8 mmol m^{-3} yr^{-1} in the euphotic zone to ~1-2 mmol m^{-3} yr^{-1} below 400 m, and modelled DON decreases from 5-8 mmol N m^{-3} near the surface to 1-4 mmol N m^{-3} over 400-1000 m. Limited field studies reported that surface DON concentration was ~5-7 mmol N m^{-3} in the ETSP (Loginova *et al.*, 2019), and consumption rate ranged from 8.3 mmol m^{-3} yr^{-1} at ~200 m to <3.1 mmol m^{-3} yr^{-1} below 500 m in the subtropical North Pacific~~, which may have influences on the asymmetry of OMZs in the tropical Pacific. Our study shows that rate of physical supply is sensitive to changes in both physical and biological parameterizations, particularly in low-DO waters. Since the physical contribution exceeds the biological contribution to mid-depth DO in the tropical Pacific (Llanillo et al., 2018; Montes et al., 2014), and the physical processes are more dominant in the ETSP, one may expect that physical-biological feedbacks are stronger to the south, which can lead to relatively larger net flux into the south OMZ.

Physical and biogeochemical interactions are complex over space, which have direct and indirect effects on the source and sink of DO ~~(Sonnerup *et al.*, 2013)~~(Levin, 2018; Oschlies et al., 2018)~~, which are comparable to our model results. Our model simulations indicate that enhanced vertical mixing leads to a redistribution of DON below 200 m, with a decrease in DON concentration (0.06-0.12 mmol N m^{-3}) over 600-900 m, but an increase (<0.04 mmol N m^{-3}) below 1000 m in the eastern tropical Pacific (Figure 9h, 9i and 9j).~~

~~4.3 Impacts of biological consumption and physical supply on asymmetry of OMZs~~

~~Previous studies have demonstrated meridional asymmetric features in many physical and biological fields in the tropical Pacific, e.g., temperature and salinity (Fiedler and Talley, 2006), circulation and ventilation~~ . On the one hand, supply of DO is greater under stronger physical transport in the south tropical Pacific. On the other hand, stronger physical processes can also lead to higher levels of nutrients and biological production and thus enhanced export production and oxygen consumption at mid-depth (Duteil and Oschlies, 2011), which can offset the rate of physical supply. In addition, stronger physical processes can also result in strengthened transport of DO and OM out to other regions ~~(Kessler, 2006; Kuntz and Schrag, 2018)~~(Gnanadesikan et al., 2012; Yu et al., 2021), which has complex impacts on DO balance in the southern OMZ.

There is evidence of strong interactions and feedbacks between carbon, nitrogen and ~~carbon~~oxygen cycles in marine ecosystem. Limited studies indicate that O:C:N utilization ratios during microbial respiration vary largely in the water column ~~(Libby and Wheeler, 1997; Wang *et al.*, 2009b)~~(Moreno et al., 2020; Zakem and Levine, 2019)~~, which may be largely associated with the asymmetries in water mass exchange between the equatorial and off-equator Pacific Ocean~~ , and nitrogen cycling (e.g., oxidation, nitrification and denitrification) not only has impacts on oxygen consumption/production but also is influenced by the oxygen level ~~(Kug *et al.*, 2003)~~(Beman et al., 2021; Kalvelage et al., 2013; Oschlies et al., 2019; Sun et al., 2021)~~. Accordingly, one may assume that the hemisphere asymmetry of OMZs could be related to the differences in physical supply and biological consumption between the ETNP and ETSP.~~

~~There is evidence that the size of tropical OMZ is largely influenced by biological processes, such as organic matter export and oxygen consumption (Keller *et al.*, 2016; Cavan *et al.*, 2017). Figure 10a illustrates that DO is increased in both ETNP and ETSP over 200-1000 m when remineralization rate decreases by 50%. The increase of DO is generally greater in the ETSP than in ETNP, except in the core OMZ (~300-500 m). Earlier field studies have revealed that DON concentration is much higher to the north than to the south in the central-eastern tropical Pacific (Libby and Wheeler, 1997; Raimbault *et al.*, 1999). Later studies showed that rates of DOM remineralization and/or oxygen consumption are also greater at mid-depth in the ETNP than in the ETSP (Feely *et al.*, 2004; Tiano *et al.*, 2014; Kalvelage *et al.*, 2015), indicating that biological processes play a big role in determining the asymmetry of upper OMZs.~~

~~Recent studies also emphasized the role of changes in physical processes for the observed asymmetric OMZs in the tropical oceans. For instance, there is evidence that larger-scale mass transport related to circulation and ventilation in the southern hemisphere is more efficient than in the northern hemisphere (Kuntz and Schrag, 2018), and the transit time from the surface to the OMZ is much longer in the ETNP than in the ETSP (Sonnerup *et al.*, 2013; Fu *et al.*, 2018). Clearly, our model experiment shows that enhanced vertical mixing leads to a significant increase in DO concentration below 200 m (Figure 10b). The increase of DO is similar below 1000 m in the ETNP and ETSP, but differs largely between the two regions, with much greater values over 200-1000 m in the ETSP. Our analysis indicates that enhanced vertical mixing increases the physical supply of DO over most of the water column, except over 300-500 m in the ETNP showing a small decrease (Figure 10c). The increase of supply is greater over 200-1000 m in the ETSP than in the ETNP, and significant increases (>0.2 mmol m^{-3} yr^{-1}) are below 600 m (500 m) in the ETNP (ETSP). These analyses indicate that physical transport may be largely responsible for the asymmetry of lower OMZs.~~

. However, little attention has been paid to understand the coupling of carbon and oxygen cycles. It should be noted that the available data are also not sufficient for the parameterizations of relevant processes, which has hampered our ability to assess the impacts of biogeochemical processes associated with the nitrogen cycle on oxygen fields. Future observational and modelling studies are needed not only to improve our knowledge on the coupling of carbon, nitrogen and oxygen cycles in the ocean, but also to advance our understanding on the physical and biogeochemical interactions and feedbacks associated with the marine stoichiometry.

5. Conclusion

~~This~~In this paper ~~describes an evaluation and validation of~~ , we use a ~~fully coupled~~ basin-~~ ~~scale model ~~(OGCM-DMEC V1.2), focusing on the sensitivity of the asymmetric OMZs in the tropical Pacific~~ to ~~different~~ investigate the impacts of parameterizations of vertical mixing and DOM remineralization on the dynamics of mid-depth DO, and ~~vertical mixing.~~analyse the underlying mechanisms for asymmetric OMZs in the tropical Pacific. Our ~~results show~~study shows that the ~~improved~~ model ~~with enhanced vertical mixing combined with reduced remineralization successfully reproduces~~is capable of reproducing the observed DO distributions and asymmetric OMZs ~~in the tropical Pacific.~~

~~Our results demonstrate that reduced remineralization rate leads to remarkable decrease of biological consumption over 200-400 m, which largely affects~~ with the ~~distribution of DO in the upper OMZ. On the other hand,~~ combination of enhanced vertical mixing and reduced O:C utilization ratio that causes an increase in DO concentration (or net flux) at mid-depth. Overall, enhanced vertical mixing ~~causes~~makes a ~~significant~~greater contribution to the increase over 400-1000 m, and the contribution from reduced O:C utilization ratio is greater over 200-700 m.

Our analyses demonstrate that there is a large increase in physical supply ~~of DO over 400-1000 m. Apart from the direct impact on physical supply,~~ and a small increase in biological consumption under enhanced vertical mixing ~~also results in the~~ , and the increase in consumption is a result of redistribution of DOM in the water column~~, i.e., an increase over 200-1000 m and a decrease below 1000 m, leading to lower consumption in the OMZs.~~

~~Further analyses indicate that the asymmetric OMZs in the tropical Pacific are attributable to the asymmetry in both physical supply and~~ . On the other hand, applying a reduced O:C utilization ratio leads to a large decrease in biological consumption~~. The larger volume of northern OMZ is a result of greater biological consumption~~, and ~~weaker~~ a small decrease in physical supply (due to the ~~north, in which~~ vertical changes in DO gradients). These findings point to strong physical ~~supply plays a dominant role in the lower OMZs but biological consumption also has impacts on the asymmetric DO for the upper OMZs. Future studies utilizing advanced models are needed to better understand the impacts of physical and~~ biological interactions ~~on the variability~~ and ~~drivers of~~ feedbacks in the tropical Pacific OMZs.

Code and data availability. The exact version of the software code used to produce the results presented in this paper is archived on Zenodo (http://doi.org/10.5281/zenodo.4384131, Wang et al., 2020). Other code and data are available upon request from the authors. Request for materials should be addressed to X.J.W. (xwang@bnu.edu.cn).

Author contributions. X.J.W. and K.W. designed the study, performed the simulations and prepared the manuscript. R.M., D.X.Z. and R.H.Z. contributed to analysis, interpretation of results and writing.

Competing interests. The authors declare that they have no conflict of interest.

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Tables

Table 1. Model experiments with different values for remineralization rate (C_{DON}) and vertical background diffusion (Kb).

Parameter	Unit	Reference	Cd0.5	Cd0.5 Kb0.1	Cd0.5 Kb0.3	Cd0.5 Kb0.5
C_{DON} (0-100 m)	d^{-1}	0.001	0.0005			
C_{DON} (100-600 m)		0.001-0.0005	0.0005-0.00025			
C_{DON} (600-1000 m)		0.0005	0.00025			
Kb	$cm^2 s^{-1}$	0	0	0.1	0.3	0.5

Table 2. Statistics for DO (mmol m^{-3}) comparisons between WOA2013 and model experiments over 1981-2000 in the Eastern Tropical North Pacific (ETNP) and Eastern Tropical South Pacific (ETSP).

Layers	Statistics	ETNP (165°W-90°W, 5°N-20°N)					ETSP (110°W-80°W, 10°S-3°S)				
		Reference	Cd0.5	Cd0.5 Kb0.1	Cd0.5 Kb0.3	Cd0.5 Kb0.5	Reference	Cd0.5	Cd0.5 Kb0.1	Cd0.5 Kb0.3	Cd0.5 Kb0.5
200-400 (m)	Bias	-9.45	-4.00	-3.96	-3.82	-3.60	-11.89	-3.59	-3.33	-2.67	-1.84
	MAE	15.17	15.70	15.56	15.27	14.98	11.89	3.72	3.55	3.15	3.12
	RMSE	19.01	17.34	17.18	16.82	16.44	12.18	4.44	4.28	3.92	3.57
400-700 (m)	Bias	-7.24	-4.99	-4.19	-2.49	-0.72	-10.36	-7.17	-5.79	-2.92	-0.04
	MAE	9.01	8.25	7.99	7.44	6.95	10.38	7.99	7.12	5.59	4.85
	RMSE	10.86	9.72	9.29	8.48	7.88	12.33	9.61	8.54	6.75	5.88
700-1000 (m)	Bias	-7.19	-4.49	-2.44	1.08	3.98	-12.90	-9.11	-6.48	-2.34	0.78
	MAE	7.18	4.67	4.12	4.17	5.28	13.33	10.42	8.81	6.98	6.47
	RMSE	9.22	6.85	5.49	4.67	5.92	16.14	12.81	10.79	8.33	7.59

Table 3. Comparisons of OMZ volume (10^{15} m^3) between WOA2013 and sensitivity experiments.

Regions	Waters	WOA2013	Reference	Cd0.5	Cd0.5 Kb0.1	Cd0.5 Kb0.3	Cd0.5 Kb0.5
North Pacific	Suboxic	5.97	10.47	8.87	8.29	7.36	6.61
	Hypoxic	19.98	21.21	20.48	20.35	20.01	19.62
South Pacific	Suboxic	1.43	3.49	2.42	2.20	1.85	1.56
	Hypoxic	7.12	9.90	8.73	8.35	7.70	7.13

Suboxic: DO <20 mmol m^{-3}; Hypoxic: DO <60 mmol m^{-3}.

Figures

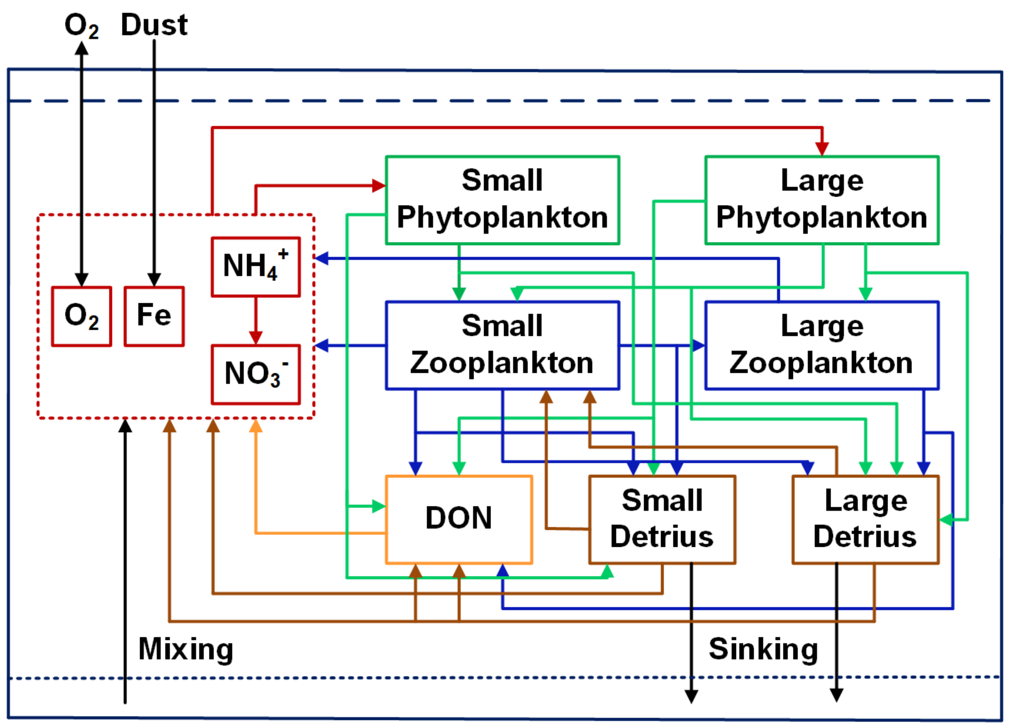


Figure 1. Flow diagram of ecosystem model. Red, green, blue, yellow and brown lines and arrows denote fluxes originating from inorganic forms, phytoplankton, zooplankton, DON and detritus, respectively.

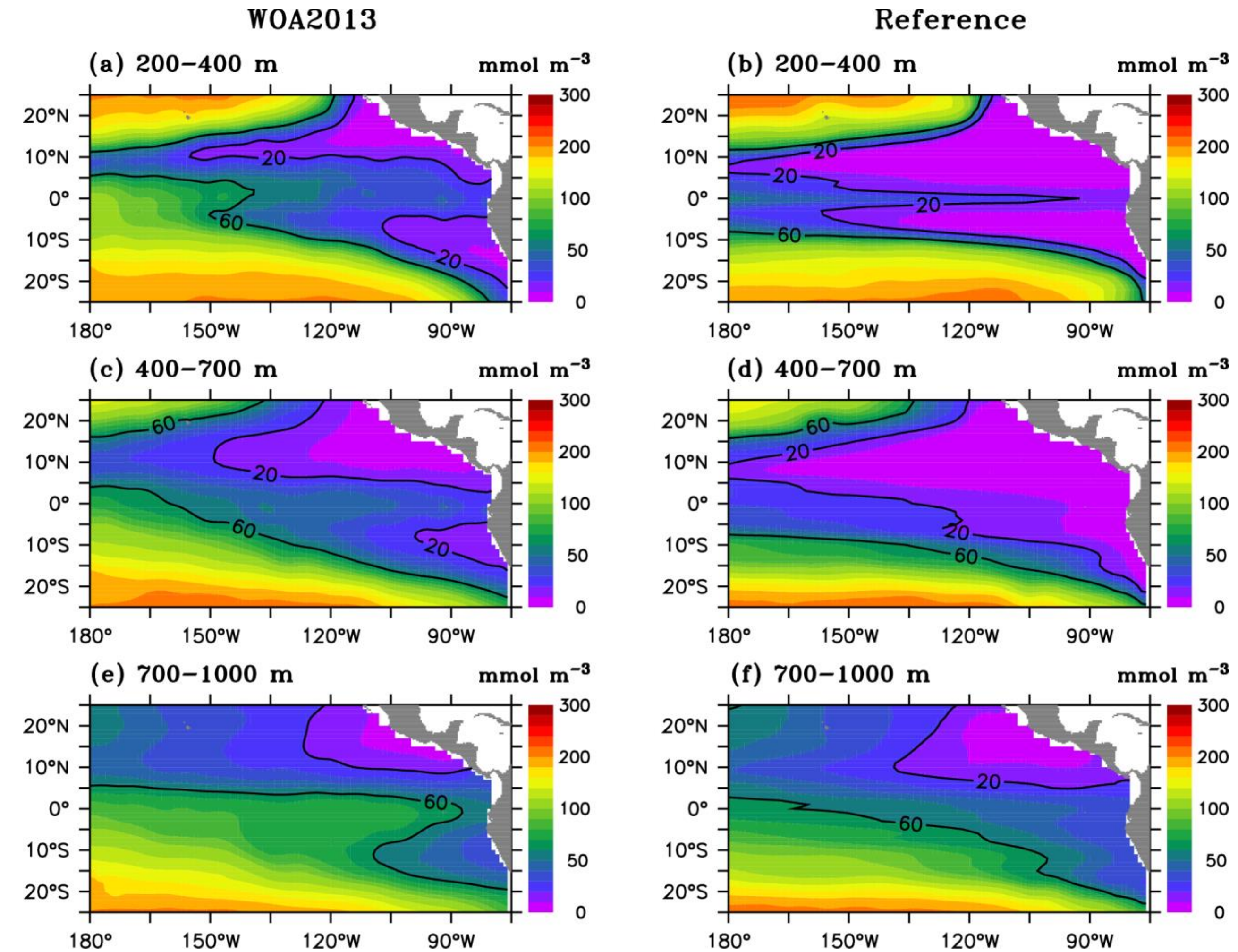
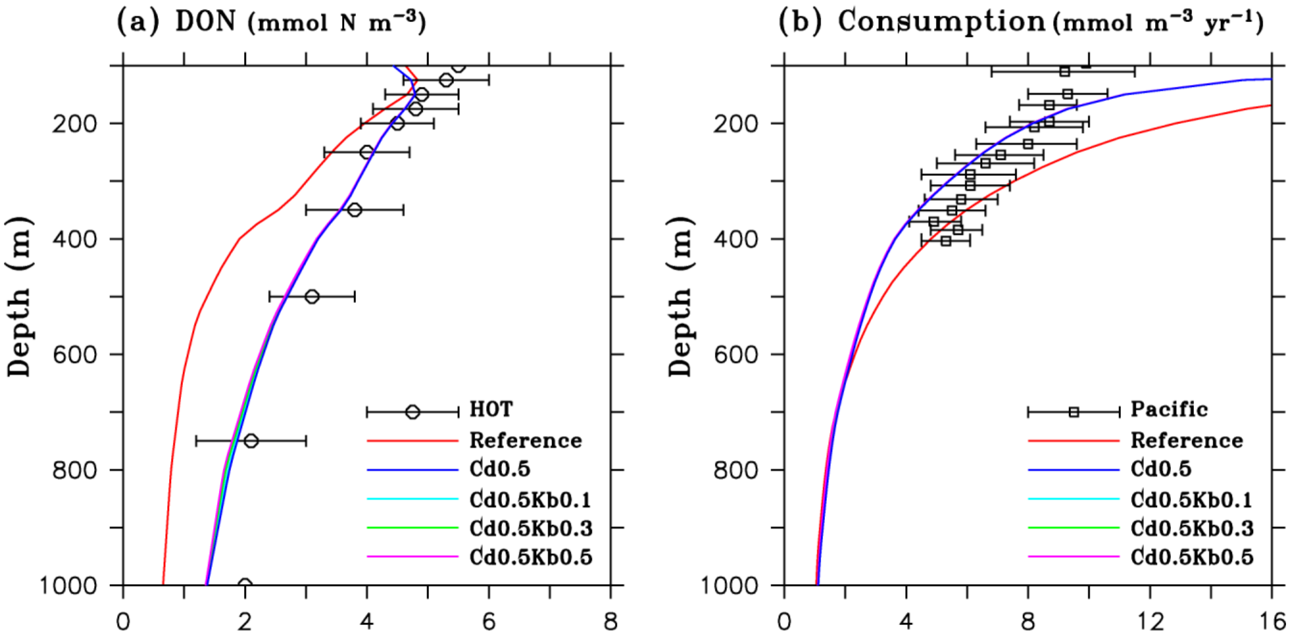


Figure 2. Comparisons of DO concentration between WOA2013 (left panel) and reference run during 1981-2000 (right panel).



~~**Figure 3.** Comparisons of DON concentration **(a)** and consumption rate **(b)** between observation and model experiments. 660 Observed DON data are from Hawaii Ocean Time-series program (HOT, 22°45'N, 158°00'W) (https://hahana.soest.hawaii.edu/hot/hot_jgofs.html). Observed consumption data are obtained from Karastensen et al., (2008) for the entire Pacific.~~

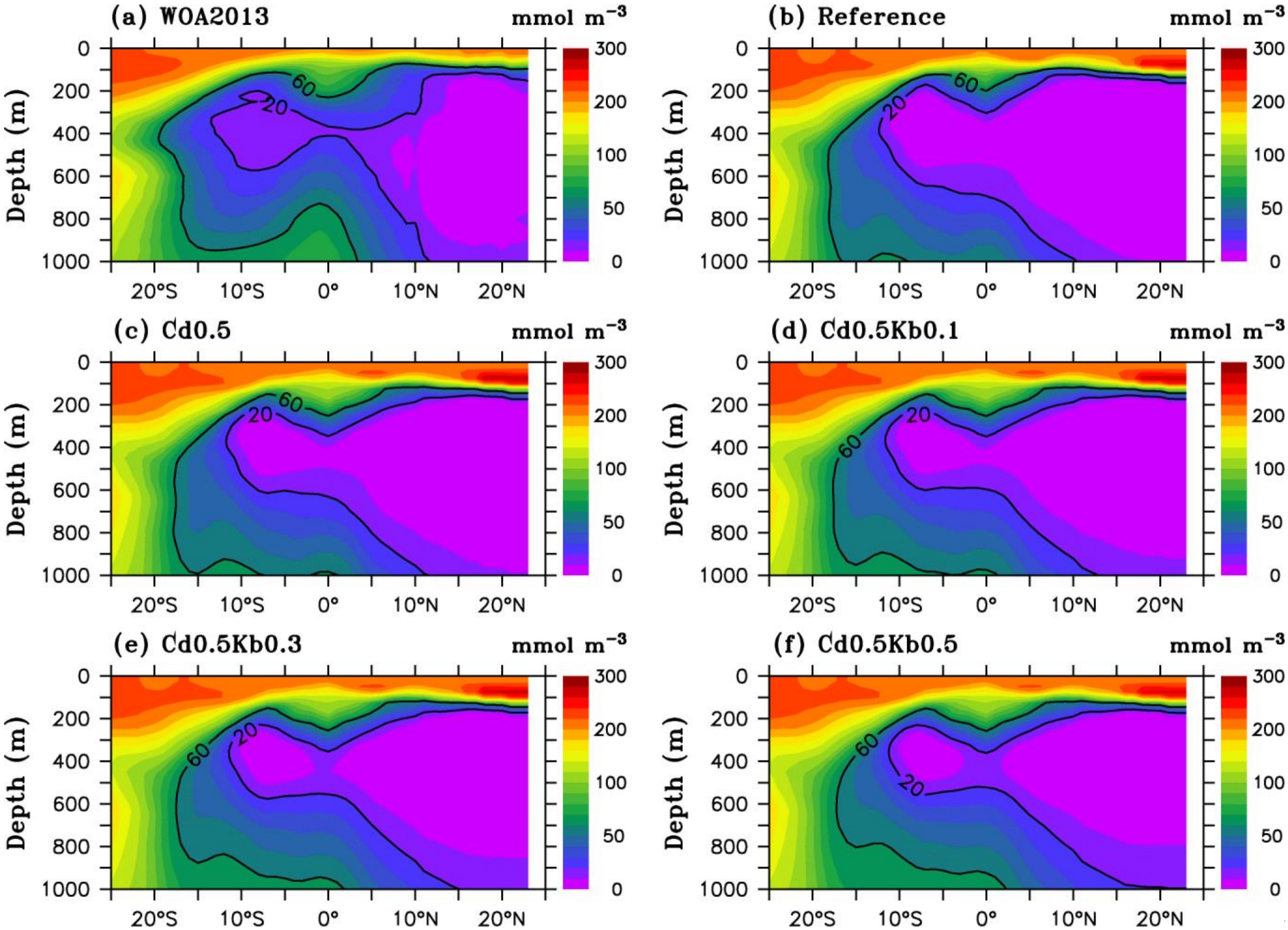
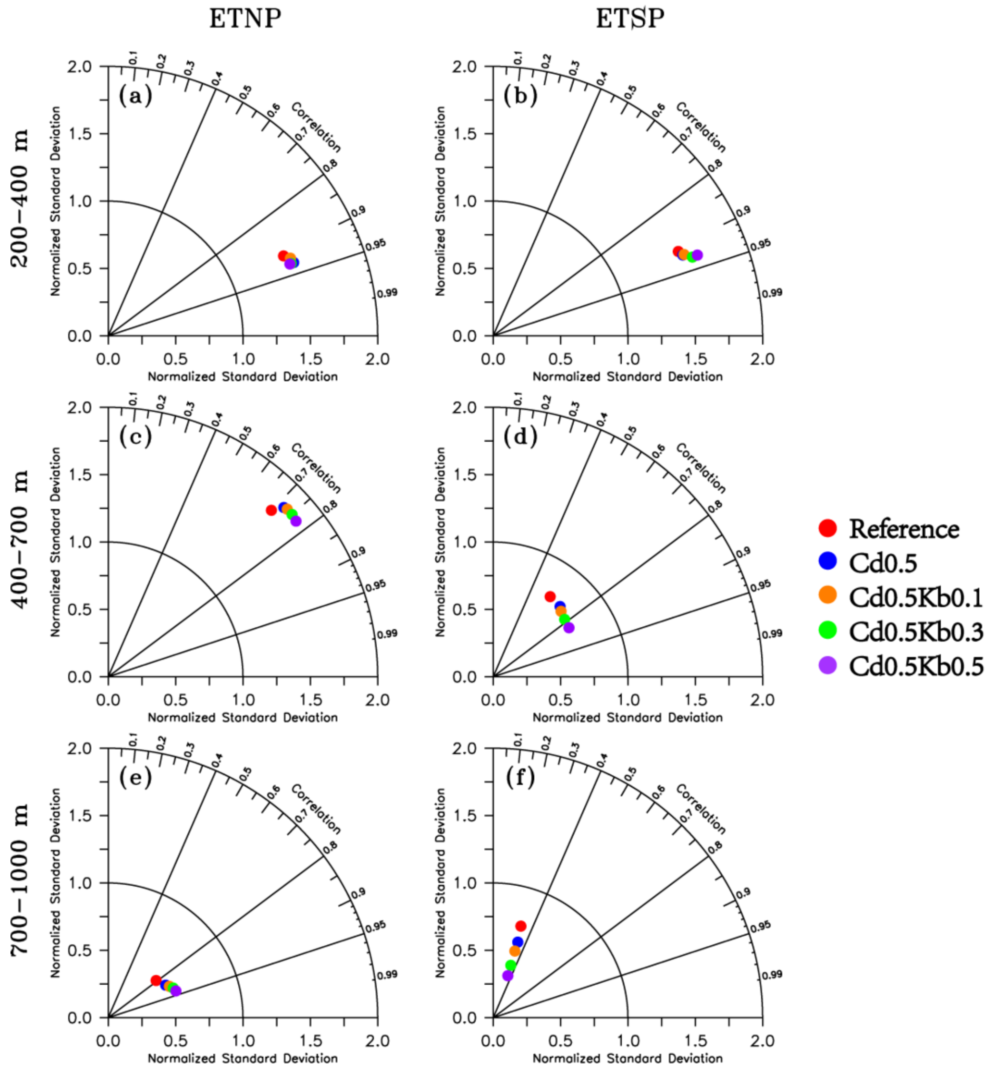
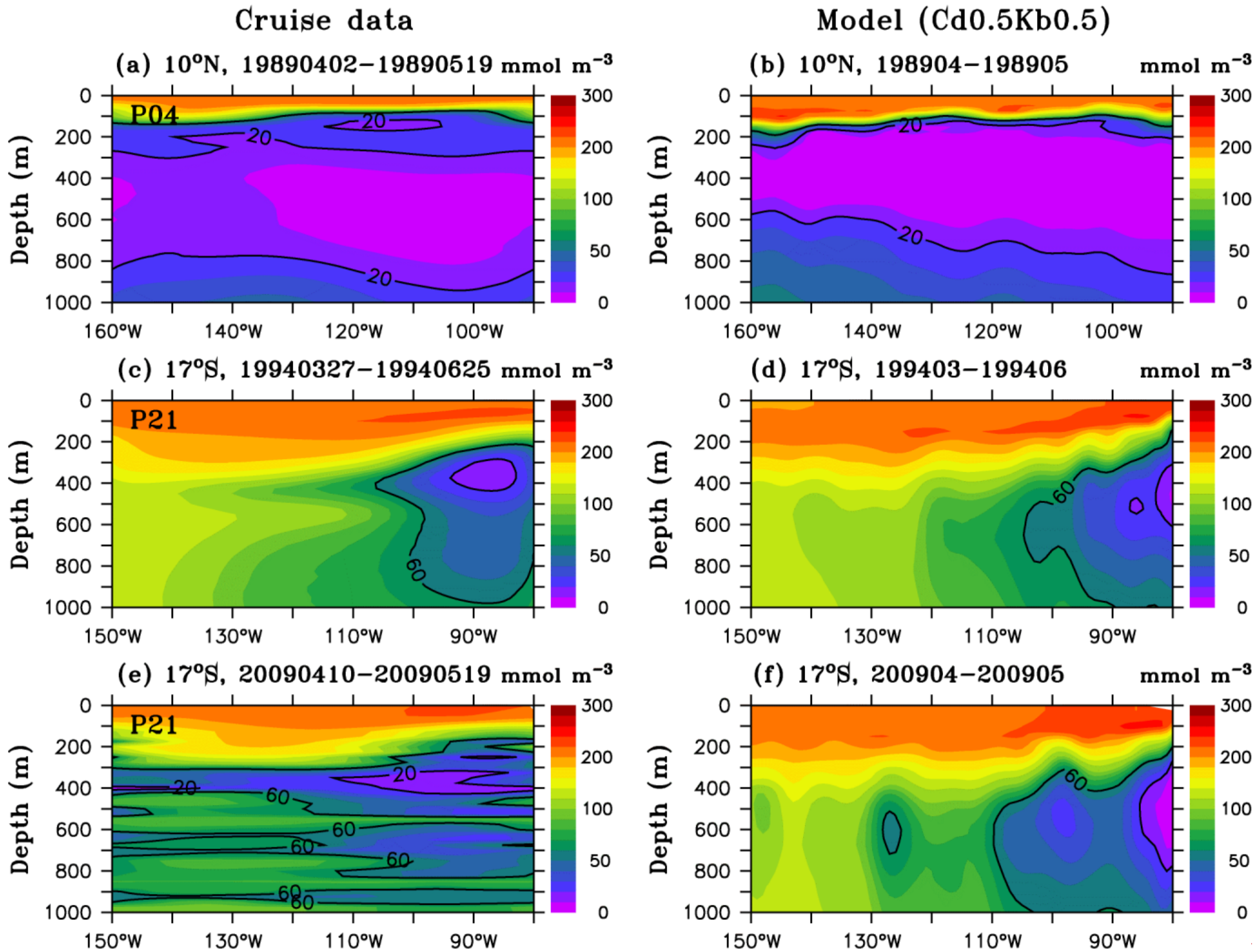


Figure 4. Observed and simulated DO from model experiments over 110°W-85°W. **(a)** WOA2013, **(b)** reference run, **(c)** Cd0.5, **(d)** Cd0.5Kb0.1, **(e)** Cd0.5Kb0.3, and **(f)** Cd0.5Kb0.5 over 1981-2000.



~~**Figure 5.** Taylor diagrams performed on the simulation of DO concentration between WOA2013 and model experiments for the left panel (ETNP: 165°W-90°W, 5°N-20°N) and right panel (ETSP: 110°W-80°W, 10°S-3°S) over 200-400 m, 400-700 m, and 700-1000 m.~~



~~**Figure 6.** Distribution of DO from cruise data (left panel) and model results (right panel). Observed DO along the P04 and P21 lines are from CCHDO (https://cchdo.ucsd.edu/), which provides access to high quality global CTD and hydrographic data from GO-SHIP, WOCE, CLIVAR and other repeat hydrography programs.~~

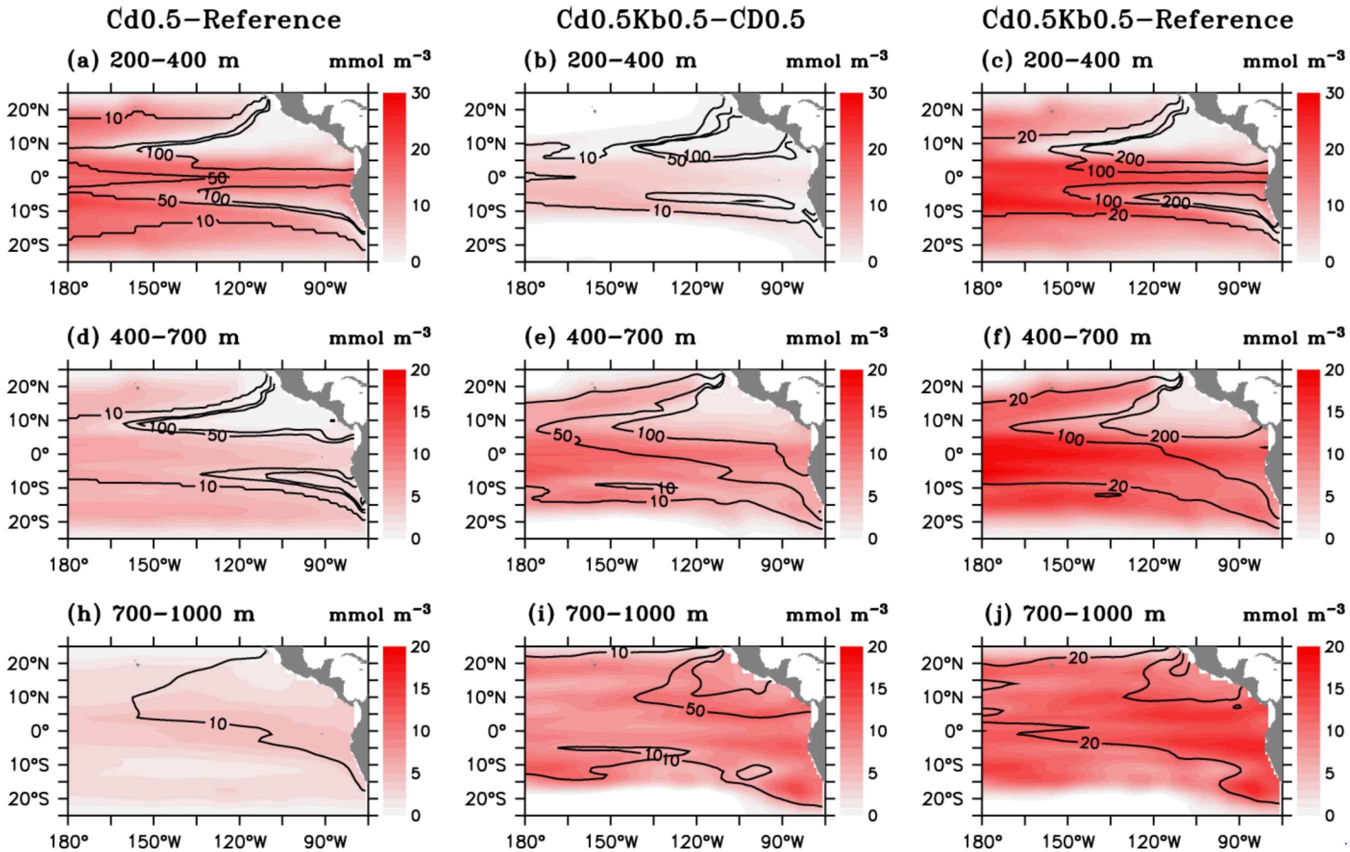
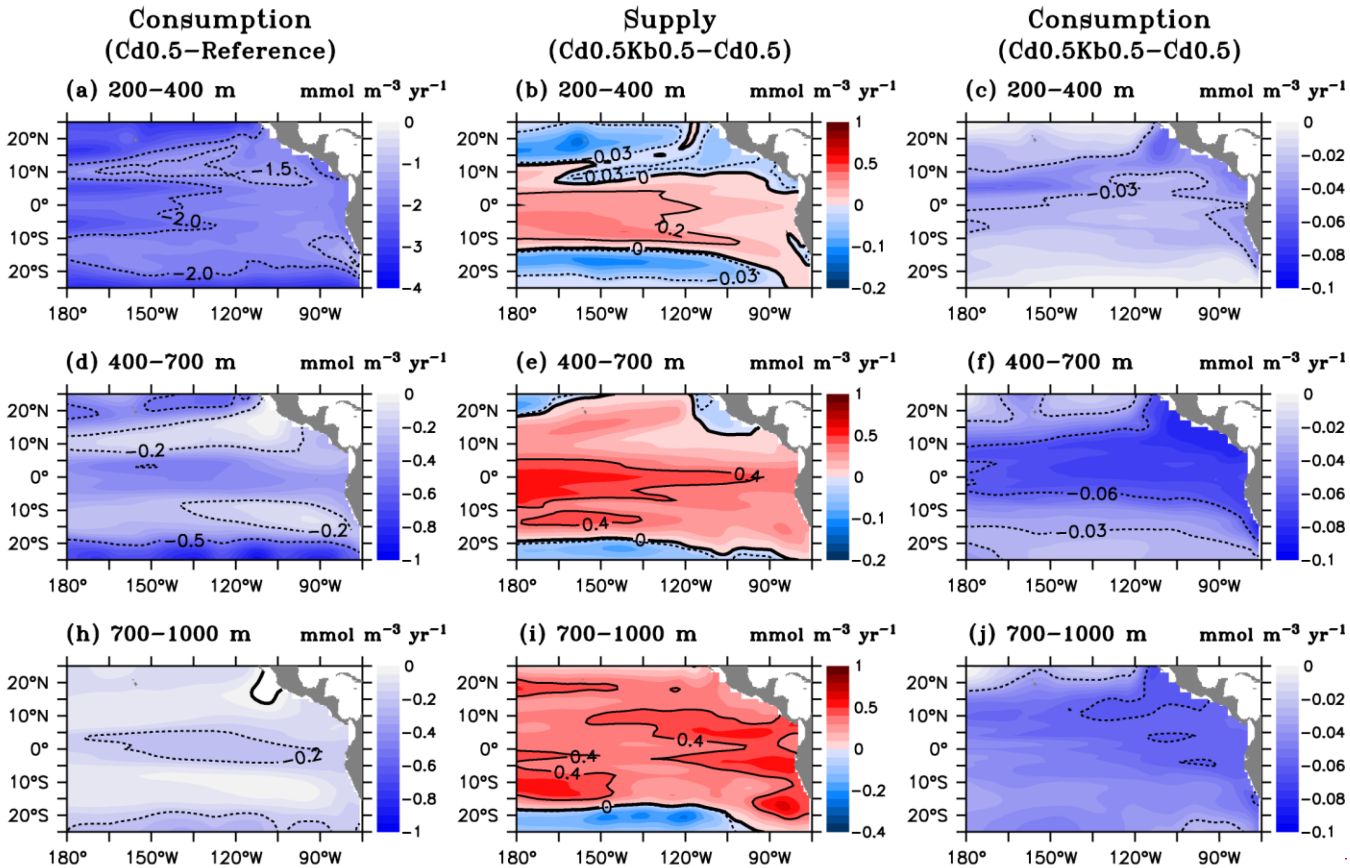


Figure 7. Changes of DO concentration due to reduced remineralization rate (left panel, Cd0.5 minus reference), enhanced mixing (middle panel, Cd0.5Kb0.5 minus Cd0.5), and their combination (right panel, Cd0.5Kb0.5 minus reference). Superimposed solid black lines denote the percentage of DO change relative to the reference run contoured by 10%, 50% and 100% in the left and middle panel, and 20%, 100% and 200% in the right panel.



~~**Figure 8.** Decrease of DO consumption due to reduced remineralization rate (left panel, Cd0.5 minus reference), and changes in DO supply (middle panel, Cd0.5Kb0.5 minus Cd0.5) and decrease of DO consumption due to enhanced mixing (right panel, Cd0.5Kb0.5 minus Cd0.5).~~

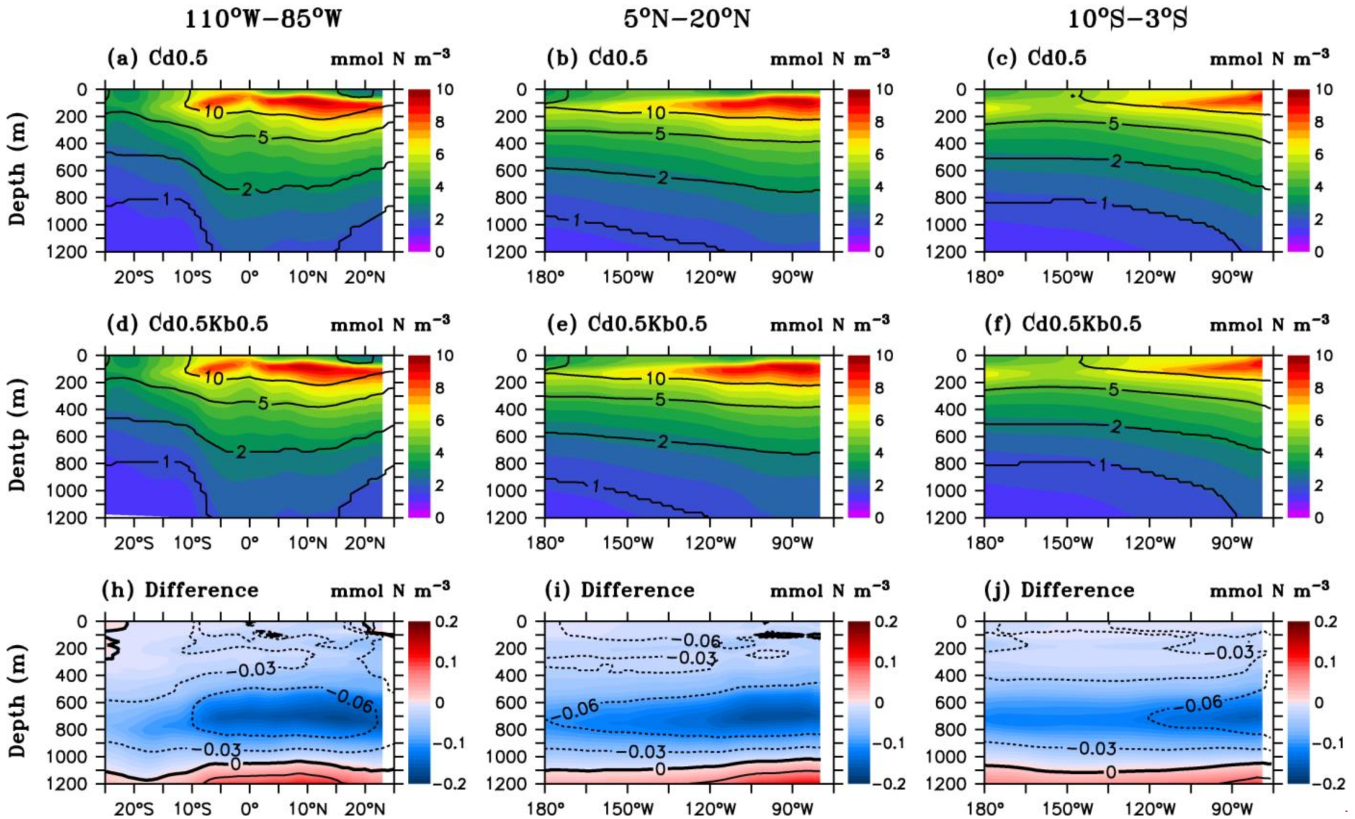


Figure 9. Distribution of DON and DON remineralization (mmol m^{-3} yr^{-1}) over 110°W-85°W (left panel), 5°N-20°N (middle panel), and 10°S-3°S (right panel) from **(a-c)** Cd0.5, **(d-f)** Cd0.5Kb0.5, and **(e-f)** their differences (Cd0.5Kb0.5 minus Cd0.5). Superimposed black lines denote consumption rate (mmol m^{-3} yr^{-1}) by remineralization of DON in **(a-f)** and the difference of consumption rate between Cd0.5Kb0.5 and Cd0.5 in **(h-j)**.

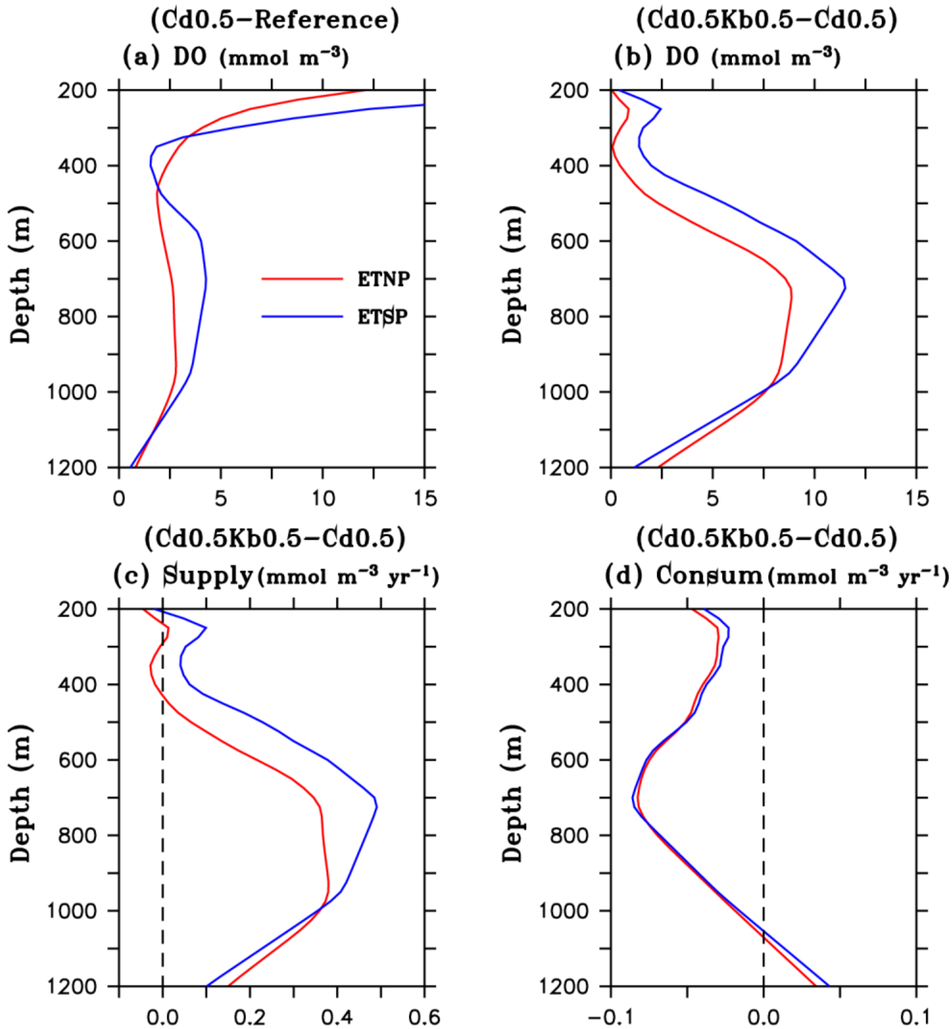


Figure 10. Changes due to reduced remineralization rate (Cd0.5 minus reference) for **(a)** DO, and enhanced mixing (Cd0.5Kb0.5 minus Cd0.5) for **(b)** DO, **(c)** physical supply, and **(d)** biological consumption. ETNP: 165°W-90°W, 5°N-20°N; ETSP: 110°W-80°W, 10°S-3°S.

This study suggest that biological consumption (i.e., greater rate to the south) cannot explain the asymmetric feature in the tropical Pacific OMZs (i.e., lower DO levels to the north), but physical processes (i.e., stronger supply to the south) play a major role in shaping the asymmetric OMZs of the tropical Pacific. In addition, the interactions between physical and biological processes are also stronger in the southern OMZ than in the northern OMZ, probably because physical supply is sensitive to changes in both parameterizations of vertical mixing and DOM remineralization. Further studies with improved approaches will enable to better understand the interactions and feedbacks between physical and biogeochemical processes.

Appendix A

: Model biogeochemical equations

Phytoplankton equations

$$\frac{\partial P_S}{\partial t} = \mu_S P_S - g_{P_S}(1 - e^{-\Lambda P_S}) Z_S - m_S P_S \qquad \text{(B1)}$$

$$\frac{\partial P_L}{\partial t} = \mu_L P_L - g_{P_L1}(1 - e^{-\Lambda P_L}) Z_L - g_{P_L2}(1 - e^{-\Lambda P_L}) Z_S - m_L P_L \qquad \text{(B2)}$$

Zooplankton equations

$$\frac{\partial Z_S}{\partial t} = [\lambda(g_{P_S}(1 - e^{-\Lambda P_S}) + g_{P_L2}(1 - e^{-\Lambda P_L})) + g_{D_S}(1 - e^{-\Lambda D_S}) + g_{D_L2}(1 - e^{-\Lambda D_L}) - (r_s + \delta_s)] Z_S - g_{Z_S}(1 - e^{-\Lambda Z_S}) Z_L \qquad \text{(B3)}$$

$$\frac{\partial Z_L}{\partial t} = [\lambda(g_{P_L1}(1 - e^{-\Lambda P_L}) + g_{Z_S}(1 - e^{-\Lambda Z_S})) + g_{D_L1}(1 - e^{-\Lambda D_L}) - (r_L + \delta_L)] Z_L \qquad \text{(B4)}$$

Detritus equations

$$\frac{\partial D_S}{\partial t} = (m_S P_S + m_L P_L + (r_s Z_S + r_L Z_L)\chi)(1 - \gamma) - g_{D_S}(1 - e^{-\Lambda D_S}) Z_S - (c_{D_S} + \omega_{D_S} h^{-1}) D_s \qquad \text{(B5)}$$

$$\frac{\partial D_L}{\partial t} = (1 - \lambda)[\left(g_{P_S}(1 - e^{-\Lambda P_S}) + g_{P_L2}(1 - e^{-\Lambda P_L})\right) Z_S + \left(g_{P_L1}(1 - e^{-\Lambda P_L}) + g_{Z_S}(1 - e^{-\Lambda Z_S})\right) Z_L] + \delta_S Z_S + \delta_L Z_L - (c_{D_L} + \omega_{DL} h^{-1}) D_L - g_{D_L2}(1 - e^{-\Lambda D_L}) Z_S - g_{D_L1}(1 - e^{-\Lambda D_L}) Z_L \qquad \text{(B6)}$$

DON equations

$$\frac{\partial DON}{\partial t} = (m_S P_S + m_L P_L + (r_s Z_S + r_L Z_L)\chi)\gamma + (c_{D_S} D_S + c_{D_L} D_L)\zeta - c_{DON} DON \qquad \text{(B7)}$$

Nutrients equations

$$\frac{\partial \mathrm{NO_3}}{\partial t} = -\mu_S P_S \frac{N_{S\_UP}}{N_{S\_UP} + A_{UP}} - \mu_L P_L \frac{N_{L\_UP}}{N_{L\_UP} + A_{UP}} + \varphi NH_4 \qquad \text{(B8)}$$

$$\frac{\partial \mathrm{NH_4}}{\partial t} = -\mu_S P_S \frac{A_{up}}{N_{S\_UP} + A_{UP}} - \mu_L P_L \frac{A_{up}}{N_{L\_UP} + A_{UP}} + (r_S Z_S + r_L Z_L)(1 - \chi) + c_{DON} DON + (c_{D_S} D_S + c_{D_L} D_L)(1 - \zeta) - \varphi NH_4 \qquad \text{(B9)}$$

$$\frac{\partial \mathrm{Fe}}{\partial t} = -(\mu_S P_S R_S + \mu_L P_L R_L - s_{Fe} D_L Fe) + R_S[(r_S Z_S + r_L Z_L)(1 - \chi) + c_{DON} DON + c_{D_S} D_S + c_{D_L} D_L (1 - \zeta)] \qquad \text{(B10)}$$

Nitrogen uptake

$$N_{S\_UP} = \frac{NO_3}{K_{S\_NO_3}+NO_3}(1-\frac{NH_4}{K_{NH_4}+NH_4}) \quad \text{(B11)}$$

$$N_{L\_UP} = \frac{NO_3}{K_{L\_NO_3}+NO_3}(1-\frac{NH_4}{K_{NH_4}+NH_4}) \quad \text{(B12)}$$

$$A_{UP} = \frac{NH_4}{K_{NH_4}+NH_4} \quad \text{(B13)}$$

Other equations

Phytoplankton growth rate

$$\mu_S = \mu_{S0} e^{k_T T} f(I) \psi_S(N, Fe) \quad \text{(B14)}$$

$$\mu_L = \mu_{L0} e^{k_T T} f(I) \psi_L(N, Fe) \quad \text{(B15)}$$

Nutrient limitation

$$\psi_S(N, Fe) = \min(\frac{NO_3+NH_4}{K_{S\_N}+NO_3+NH_4}, \frac{\text{Fe}}{K_{S\_\text{Fe}}+\text{Fe}}) \quad \text{(B16)}$$

$$\psi_L(N, Fe) = \min(\frac{NO_3+NH_4}{K_{L\_N}+NO_3+NH_4}, \frac{\text{Fe}}{K_{L\_\text{Fe}}+\text{Fe}}) \quad \text{(B17)}$$

Light limitation

$$f(I) = 1 - e^{-\frac{\alpha I}{\eta P_{MAX}}} \quad \text{(B18)}$$

Light attenuation

$$I(z) = I_0 exp^{-k_A z} \quad \text{(B19)}$$

$$k_A = k_W + k_C \text{Chl} + k_D(D_S + D_L) \quad \text{(B20)}$$

Detritus decomposition and DON remineralization

$$c_{DS} = c_{DS0} e^{k_B(T-10)} e^{k_B(T-T_0)} \quad \text{(B21)}$$

$$c_{DL} = c_{DL0} e^{k_B(T-10)} e^{k_B(T-T_0)} \quad \text{(B22)}$$

$$c_{DON} = c_{DON0} e^{k_B(T-10)} e^{k_B(T-T_0)} \quad \text{(B23)}$$

Phytoplankton carbon to chlorophyll ratio (η)

$$\mathrm{Chl} = \left(\frac{P_S}{\eta_S} + \frac{P_L}{\eta_L}\right) R_{C:N} \qquad \text{(B24)}$$

$$\eta_S = \eta_{S0} - (\eta_{S0} - \eta_{MIN}) \frac{lnI_0 - lnI}{4.605} \qquad \text{(B25)}$$

$$\eta_L = \eta_{L0} - (\eta_{L0} - \eta_{MIN}) \frac{lnI_0 - lnI}{4.605} \qquad \text{(B26)}$$

$$\eta_{S0} = \eta_{S\_MAX} - k_{PS}\mu_S^* \qquad \text{(B27)}$$

$$\eta_{L0} = \eta_{L\_MAX} - k_{PL}\mu_L^* \qquad \text{(B28)}$$

$$\mu_S^* = \mu_{S0} e^{k_T T} \min\left(\frac{NO_3}{K_{S\_N} + NO_3}, \frac{\mathrm{Fe}}{K_{S\_\mathrm{Fe}} + \mathrm{Fe}}\right) \qquad \text{(B29)}$$

$$\mu_L^* = \mu_{L0} e^{k_T T} \min\left(\frac{NO_3}{K_{L\_N} + NO_3}, \frac{\mathrm{Fe}}{K_{L\_\mathrm{Fe}} + \mathrm{Fe}}\right) \qquad \text{(B30)}$$

Appendix B

: Model biogeochemical parameters

Symbol	Parameter	Unit	Value
m_S	Small phytoplankton mortality rate	d^{-1}	0.15
m_L	Large phytoplankton mortality rate	d^{-1}	0.35
r_S	Small zooplankton excretion rate	d^{-1}	0.53
r_L	Large zooplankton excretion rate	d^{-1}	0.44
δ_S	Small zootoplankton mortality rate	d^{-1}	0.12
δ_L	Large zootoplankton mortality rate	d^{-1}	0.12
g_{PS}	Maximum grazing rate for small phytoplanktion	d^{-1}	2.6
g_{PL1}	Maximum grazing rate for large phytoplanktion	d^{-1}	1.2
g_{ZS}	Maximum grazing rate for small zootoplanktion	d^{-1}	1.7
g_{PL2}	Maximum grazing rate for large phytoplanktion	d^{-1}	0.9
g_{DS}	Maximum grazing rate for small detritus	d^{-1}	1.0
g_{DL1}	Maximum grazing rate for large detritus	d^{-1}	3.0
g_{DL2}	Maximum grazing rate for large detritus	d^{-1}	1.5
Λ	Ivlev coefficient	$(mmol\ m^{-3})^{-1}$	0.5
λ	Zootoplankton assimilation coefficient	%	75
χ	Excretion coefficient	%	55
γ	Dissolution coefficient	%	90
ξ	Dissolution coefficient	%	90
$R_{C:N}$	C:N ratio	mol:mol	6.625
R_S	Fe:N ratio for small phytoplankton	μmol:mol	15
R_L	Fe:N ratio for large phytoplankton	μmol:mol	40
η_{S_MIN}	Minimum PhyC:Chl ratio in small phytoplanktion	g:g	30
η_{L_MIN}	Minimum PhyC:Chl ratio in large phytoplanktion	g:g	15
η_{S_MAX}	Maximum PhyC:Chl ratio in small phytoplanktion	g:g	200
η_{L_MAX}	Maximum PhyC:Chl ratio in large phytoplanktion	g:g	120
k_{PS}	Photoacclimation coefficient for small phytoplanktion	(g:g)d	95
k_{PL}	Photoacclimation coefficient for large phytoplanktion	(g:g)d	70
w_{DS}	Sinking velocity for small detritus	$m\ d^{-1}$	1

w_{DL}	Sinking velocity for large detritus	m d^{-1}	3.5
φ	Nitrification rate (when I<5 μmolEm^{-2} s^{-1})	d^{-1}	0.04
s_{Fe}	Iron scavenge coefficient	d^{-1} (nmol Fe $m^{-3})^{-1}$	0.00001
μ_{S0}	Maximum growth rate at 0°C for small phytoplankton	d^{-1}	0.58
μ_{L0}	Maximum growth rate at 0°C for large phytoplankton	d^{-1}	1.16
k_T	Temp. Dependent coefficient for μ	°C^{-1}	0.06
K_{S_N}	Half saturation constant for N limitation	mmol m^{-3}	0.3
K_{L_N}	Half saturation constant for N limitation	mmol m^{-3}	0.9
K_{S_Fe}	Half saturation constant for iron limitation	mmol m^{-3}	14
K_{L_Fe}	Half saturation constant for iron limitation	mmol m^{-3}	150
K_{S_NO3}	Half saturation constant for nitrate uptake	mmol m^{-3}	0.3
K_{L_NO3}	Half saturation constant for nitrate uptake	mmol m^{-3}	0.9
K_{NH4}	Half saturation constant for ammonium uptake	mmol m^{-3}	0.05
α	Initial slope of the P – I curve	mg C mg chl^{-1}(μmol E m^{-2} s^{-1})$^{-1}$	0.02
P_{MAX}	Maximum carbon specific growth rate	h^{-1}	0.036
k_W	Light attenuation constant for water	m^{-1}	0.028
k_C	Light attenuation constant for chlorophyll	m^{-1} (mg chl $m^{-3})^{-1}$	0.058
k_D	Light attenuation constant for detritus	m^{-1} (mg chl $m^{-3})^{-1}$	0.008
c_{DS0}	Small detritus decomposition rate at ~~10~~0°C	d^{-1}	0.001
c_{DL0}	Large detritus decomposition rate at ~~10~~0°C	d^{-1}	0.008
~~c_{DON0}~~	~~DON remineraization rate (0-100 m) at 10°C~~	~~d^{-1}~~	~~0.001~~
	~~100-500 m at 10°C~~	~~d^{-1}~~	~~0.0002-0.001~~
	~~>500 m at 10°C~~	~~d^{-1}~~	~~0.0002~~
~~k_B~~	~~Temp. dependent coefficient for c~~	~~°C^{-1}~~	~~0.02~~

Appendix C: Comparisons in biogeochemical parameters

Symbol	Parameter	Unit	Yu et al. (2021)	This study
T_0	Limit temperature	°C	10	0
k_B	Temperature dependent coefficient	-	0.002	0.001
C_{DON0}	DON remineralization constant	d^{-1}		
	0-100 m		0.001	0.00075
	100-600 m		0.0002-0.001	0.00013-0.00075*
	600-1000 m		0.0002	0.00003-0.00013*

* C_{DON0} decreases with depth by an exponential function.

Code and data availability. The exact version of the software code used to produce the results presented in this paper is archived on Zenodo (https://doi.org/10.5281/zenodo.5148146, Wang et al., 2021). Other code and data are available upon request from the authors. Request for materials should be addressed to X.J.W. (xwang@bnu.edu.cn).

Author contributions. X.J.W. and K.W. designed the study, performed the simulations and prepared the manuscript. R.M., D.X.Z. and R.H.Z. contributed to analysis, interpretation of results and writing.

Competing interests. The authors declare that they have no conflict of interest.

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Tables

Table 1. Bias and root mean square error (RMSE) for DO (mmol m^{-3}) comparisons between WOA2013 and model simulations over 1991-2010 in the Eastern Tropical North Pacific (ETNP) and Eastern Tropical South Pacific (ETSP).

Layers	Statistics	Ref	Km6.9	Km18.7	Kb0.25	Kb0.5	Km6.9 Kb0.25	Km6.9 Kb0.5	Km18.7 Kb0.25	Km18.7 Kb0.5
ETNP (165°W-90°W, 5°N-20°N)										
200-400 m	Bias	-17.44	-14.84	-11.32	-16.34	-14.87	-13.51	-11.85	-9.71	-7.8
	RMSE	16.35	14.63	12.43	15.73	14.91	13.83	12.84	11.4	10.2
400-700 m	Bias	-16.35	-14.95	-12.51	-11.85	-7.5	-9.98	-5.39	-6.88	-2.04
	RMSE	10.6	9.83	8.45	8.26	6.73	7.49	6.38	6.5	6.78
700-1000 m	Bias	-9.22	-8.32	-5.99	-3.58	0.62	-2.71	1.38	-5.75	3.27
	RMSE	5.1	4.29	2.64	2.93	6.52	3.59	7.19	5.39	9.08
ETSP (110°W-80°W, 10°S-3°S)										
200-400 m	Bias	-7.09	-3.91	0.19	-6.43	-5.39	-2.84	-1.13	2.09	4.85
	RMSE	7.39	4.46	2.36	6.83	5.98	3.69	2.86	3.27	5.51
400-700 m	Bias	-11.3	-10.43	-7.94	-5.94	-0.88	-4.51	1.34	-1.21	5.23
	RMSE	12.98	12.15	10.06	8.52	6.03	7.41	5.65	5.81	7.38
700-1000 m	Bias	-7.3	-7.08	-5.13	-0.97	3.38	-0.62	3.94	1.05	5.46
	RMSE	12.82	12.49	11.22	8.98	8.63	8.76	8.68	8.59	9.34

Table 2. Volumes (10^{15} m^3) of suboxic and hypoxic water from WOA2013 and model simulations.

Regions	Waters	WOA2013	Reference	Km6.9	Km18.7	Kb0.25	Kb0.5	Km6.9 Kb0.25	Km6.9 Kb0.5	Km18.7 Kb0.25	Km18.7 Kb0.5
North Pacific	Suboxic	5.97	10.61	9.98	8.83	8.73	7.33	8.08	6.68	6.88	5.55
	Hypoxic	19.98	22.67	22.5	22.17	22.32	21.61	22.11	21.35	21.71	20.91
South Pacific	Suboxic	1.43	3.78	3.39	2.78	2.86	2.15	2.42	1.71	1.81	1.12
	Hypoxic	7.12	10.42	10.21	9.8	9.19	8.17	8.94	7.88	8.49	7.39

Suboxic: DO <20 mmol m^{-3}; Hypoxic: DO <60 mmol m^{-3}.

Figures

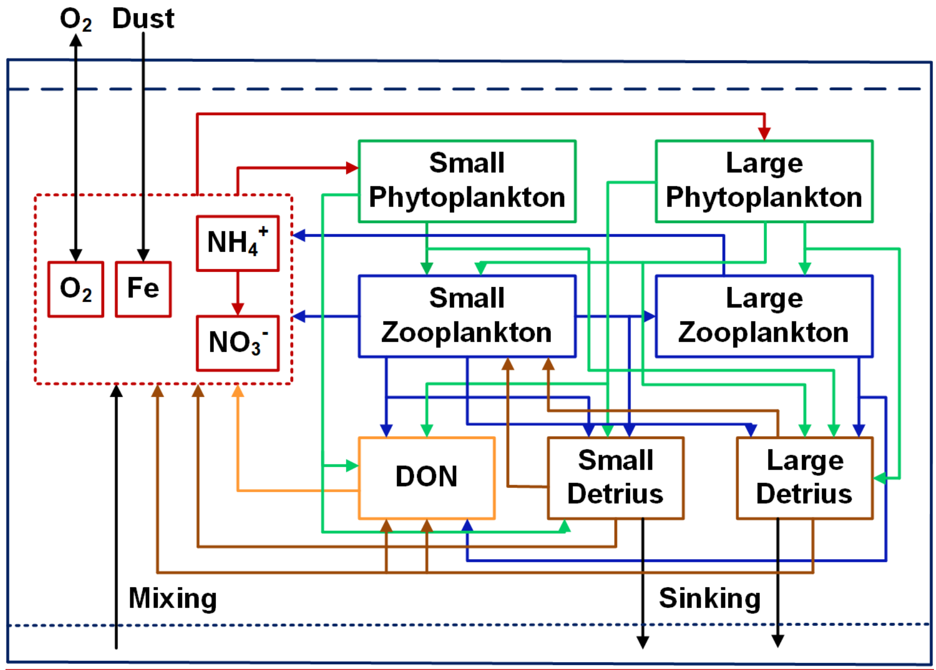


Figure 1. Flow diagram of ecosystem model. Red, green, blue, yellow and brown lines and arrows denote fluxes originating from inorganic forms, phytoplankton, zooplankton, DON and detritus, respectively.

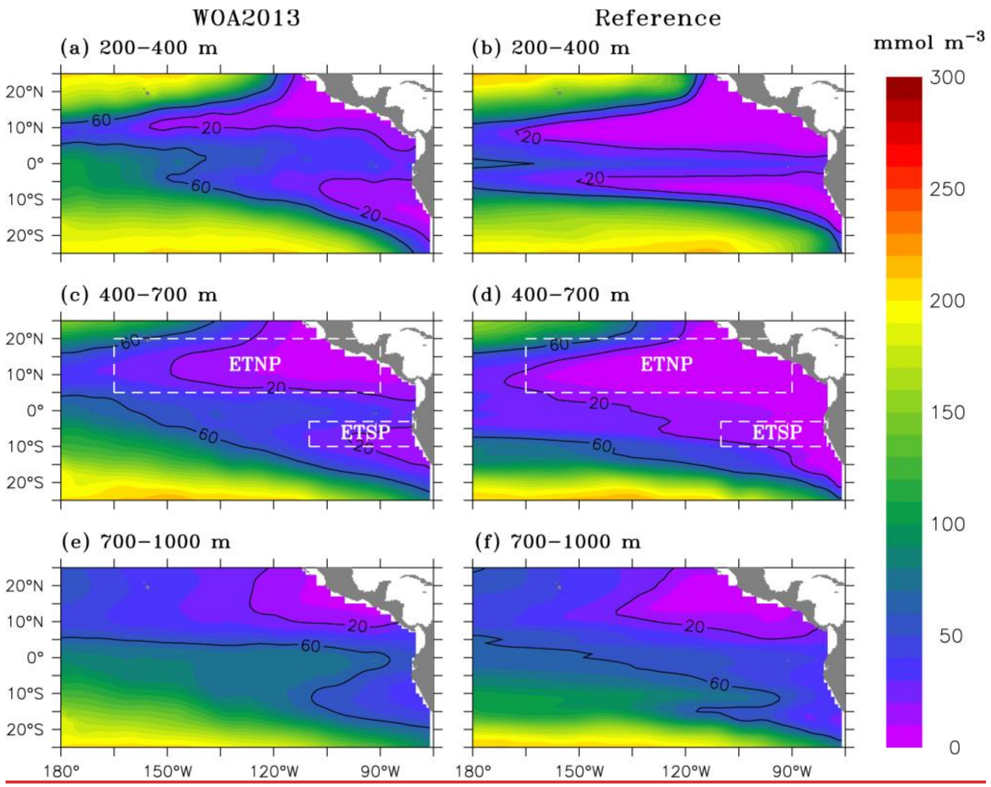


Figure 2. Comparisons of DO concentration between WOA2013 (left panel) and reference run (right panel) during 1991-2010. White dash lines in **(c)** and **(d)** denotes two boxes for ETNP (165°W-90°W, 5°N-20°N) and ETSP (110°W-80°W, 10°S-3°S).

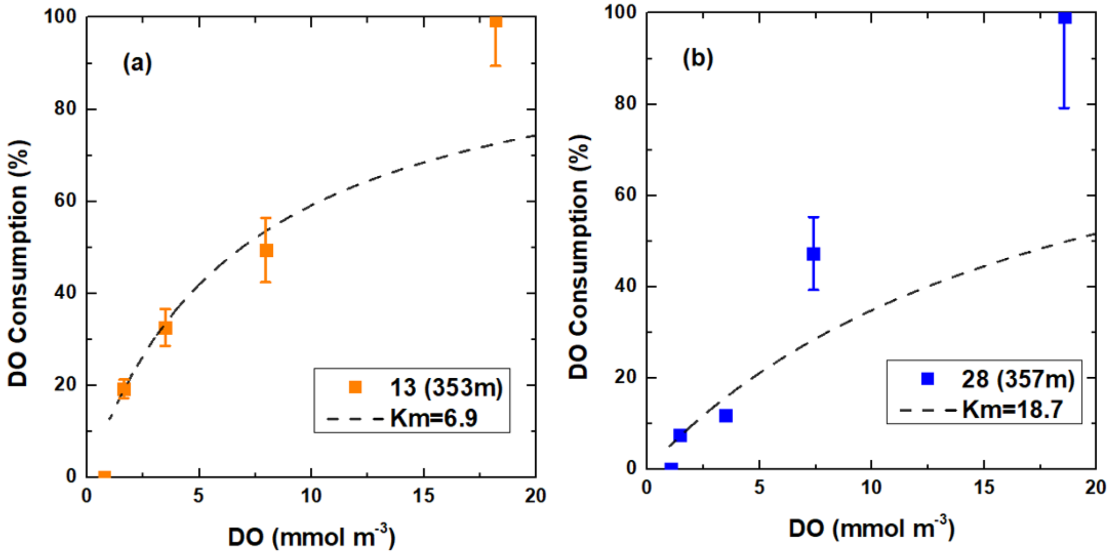


Figure 3. Biological consumption vs. DO concentration at (**a**) station 13 (353 m) and (**b**) station 28 (357 m) in the Peruvian OMZ. Data are from Kalvelage (2015).

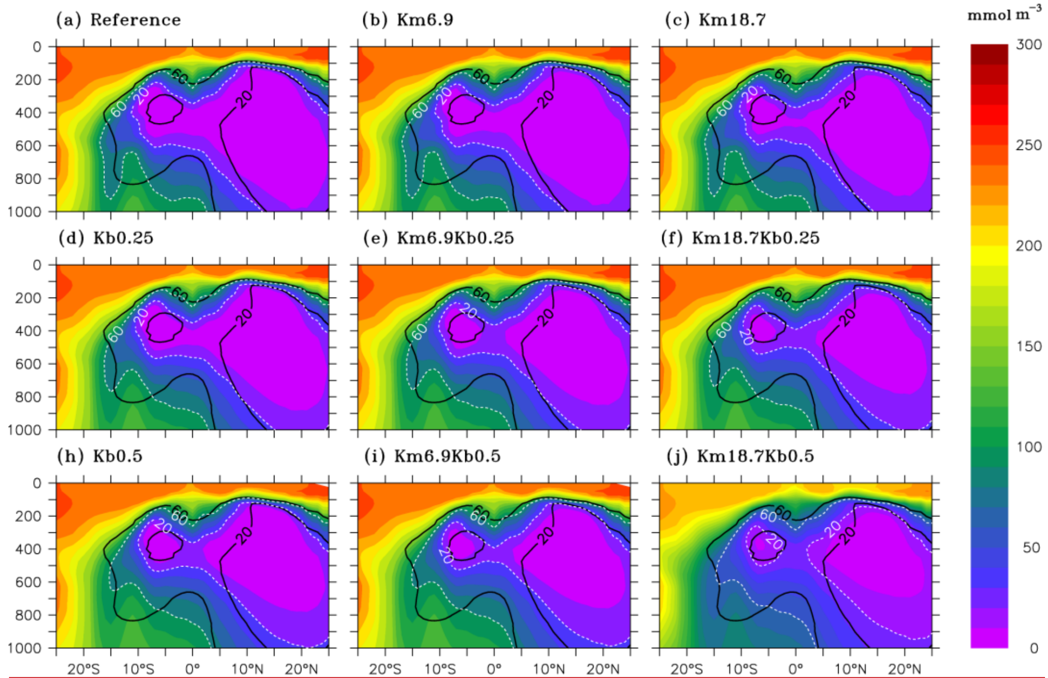


Figure 4. Vertical distribution of DO and asymmetric OMZs over 120°W-90°W from different model simulations for **(a)** reference run, **(b and c)** reduced O:C utilization ratio, **(d and h)** enhanced vertical mixing, and (**e, f, i, and j**) combination of reduced O:C utilization ratio and enhanced vertical mixing. Black lines denote contours of DO concentrations of 20 mmol m^{-3} and 60 mmol m^{-3} from WOA2013 data.

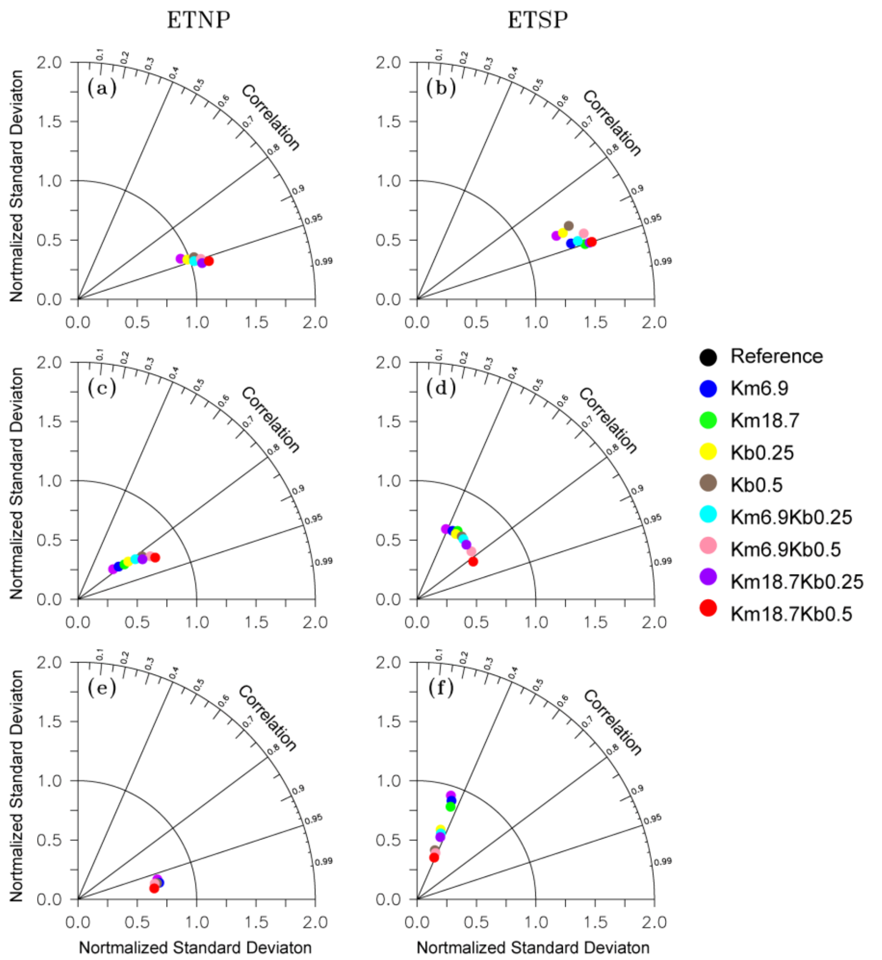


Figure 5. Taylor diagrams for the performance of simulated DO concentration (against WOA2013) from model simulations for ETNP (165°W-90°W, 5°N-20°N, left panel) and ETSP (110°W-80°W, 10°S-3°S, right panel) over **(a and b)** 200-400 m, **(c and d)** 400-700 m, and **(e and f)** 700-1000 m.

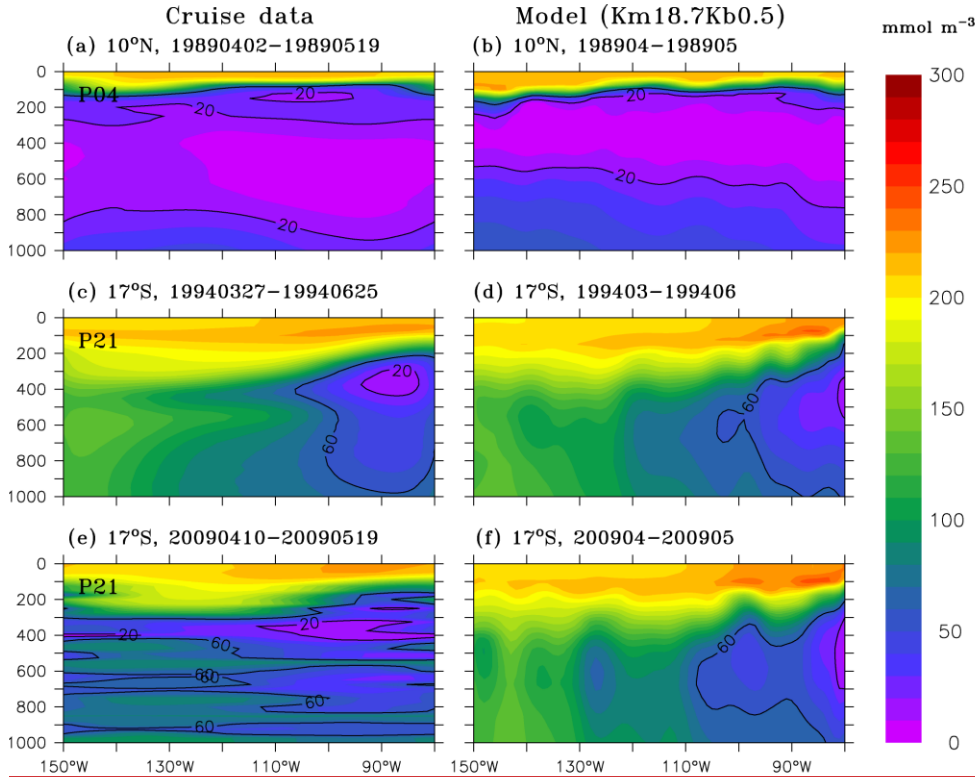


Figure 6. Distribution of DO from cruise data (left panel) and model simulation from the Km18.7Kb0.5 (see text for explanation; right panel). Observed DO along the P04 and P21 lines are from CCHDO (https://cchdo.ucsd.edu/).

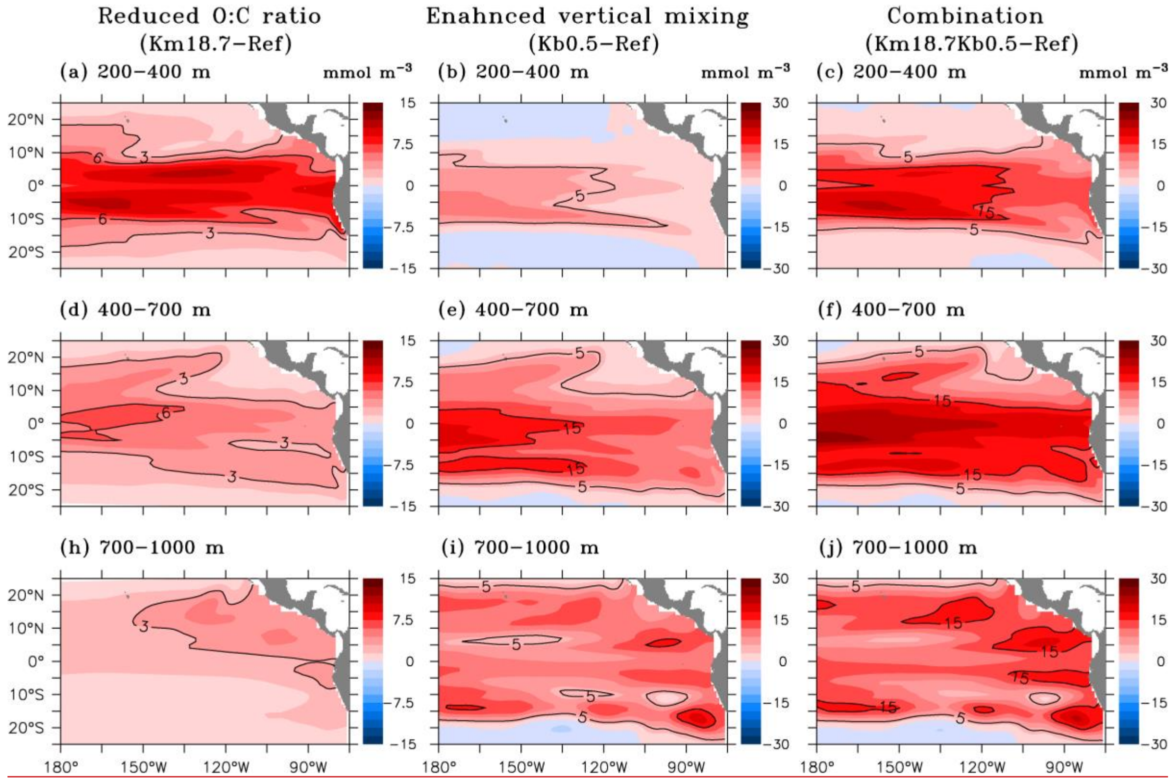
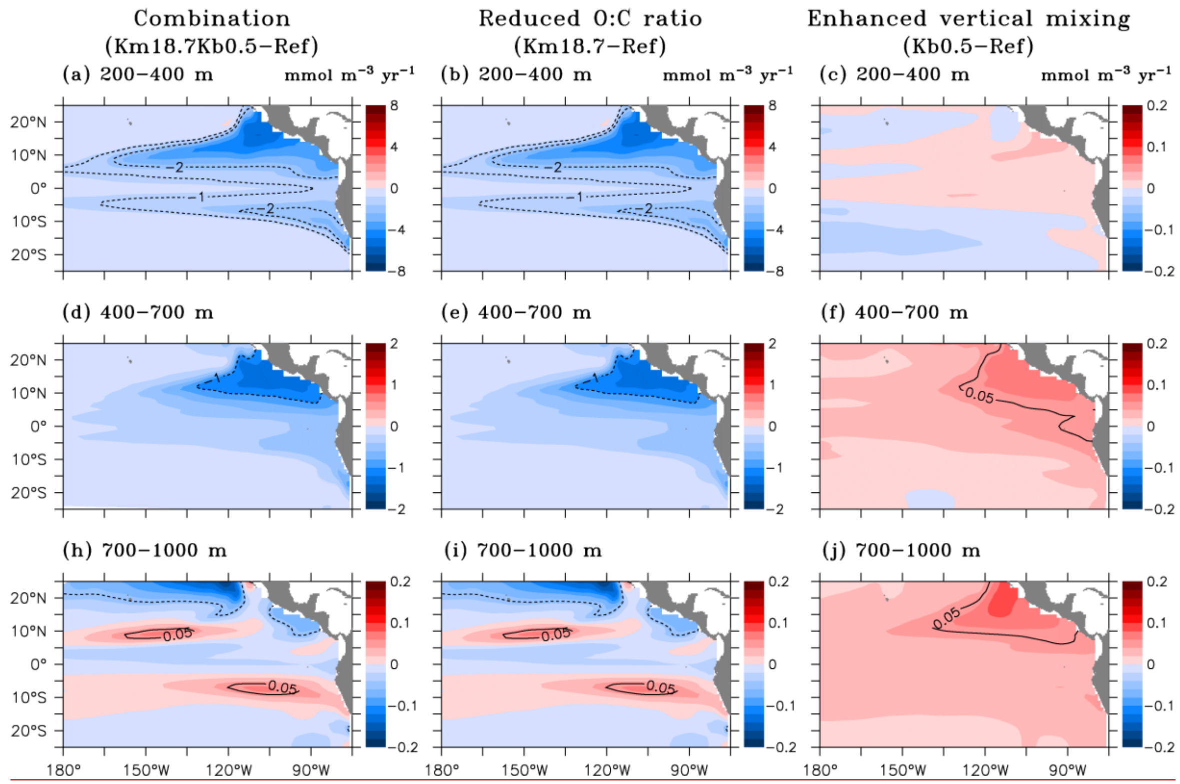


Figure 7. Changes of DO concentration averaged over **(a, b and c)** 200-400 m, **(d, e and f)** 400-700 m, and **(h, i and j)** 700-1000 m due to reduced O:C utilization ratio (left panel), enhanced vertical mixing (middle panel), and the combination of reduced O:C utilization ratio and enhanced vertical mixing (right panel).



1030 **Figure 8.** Changes in biological consumption over **(a, b and c)** 200-400 m, **(d, e and f)** 400-700 m, and **(h, i and j)** 700-1000 m due to the combination of reduced O:C utilization ratio and enhanced vertical mixing (left panel), reduced O:C utilization ratio (middle panel), and enhanced vertical mixing (right panel).

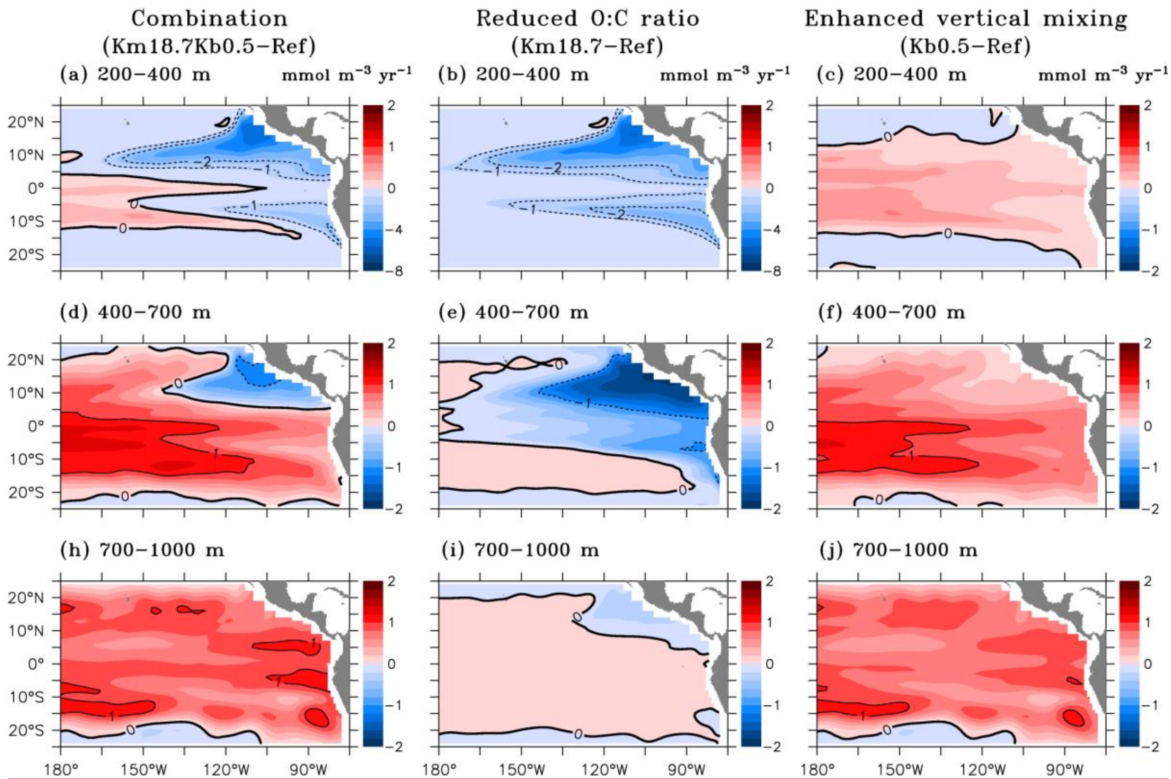


Figure 9. Changes in physical supply due to over **(a, b and c)** 200-400 m, **(d, e and f)** 400-700 m, and **(h, i and j)** 700-1000 m the combination of reduced O:C utilization ratio and enhanced vertical mixing (left panel), reduced O:C utilization ratio (middle panel), and enhanced vertical mixing (right panel).

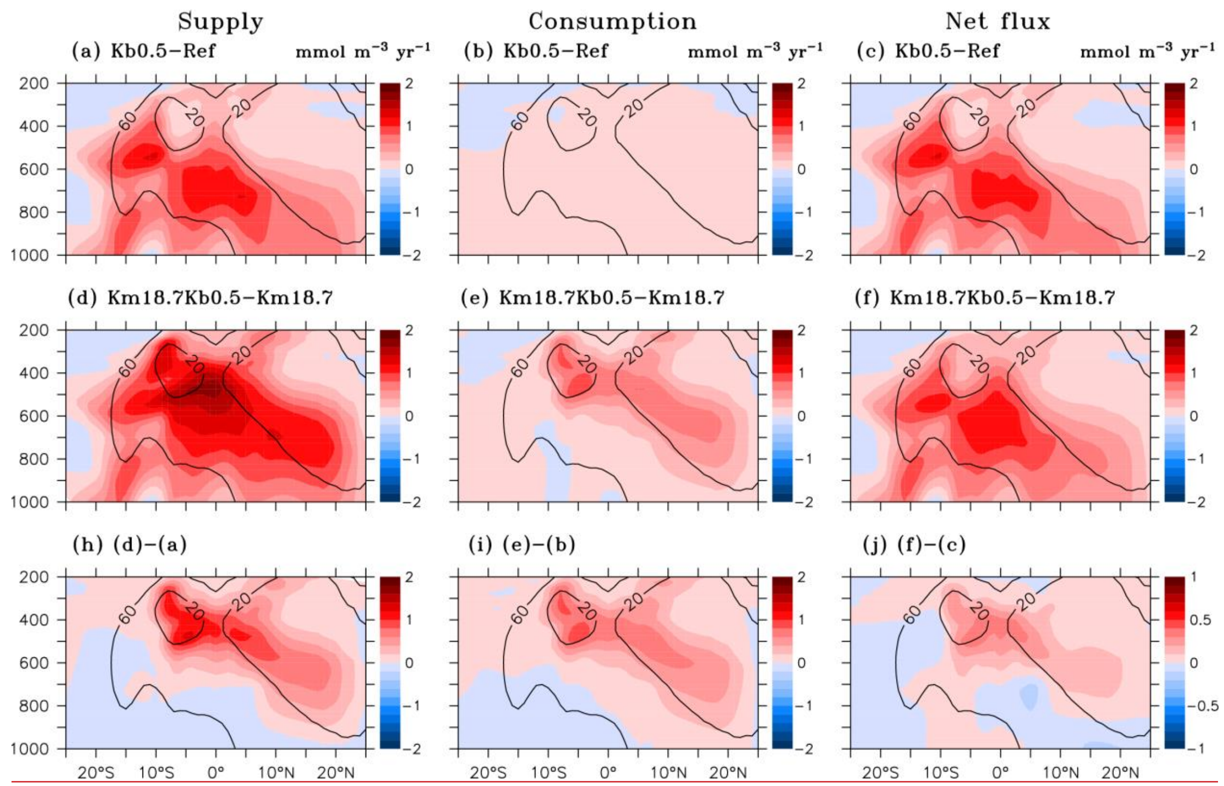


Figure 10. Changes in physical supply (left panel), biological consumption (middle panel), and net flux (right panel) under enhanced vertical mixing with **(d, e, and f, middle row)** and without **(a, b, and c, top row)** reduced O:C utilization ratio, and the differences between them (**h, i, and j, bottom row**).

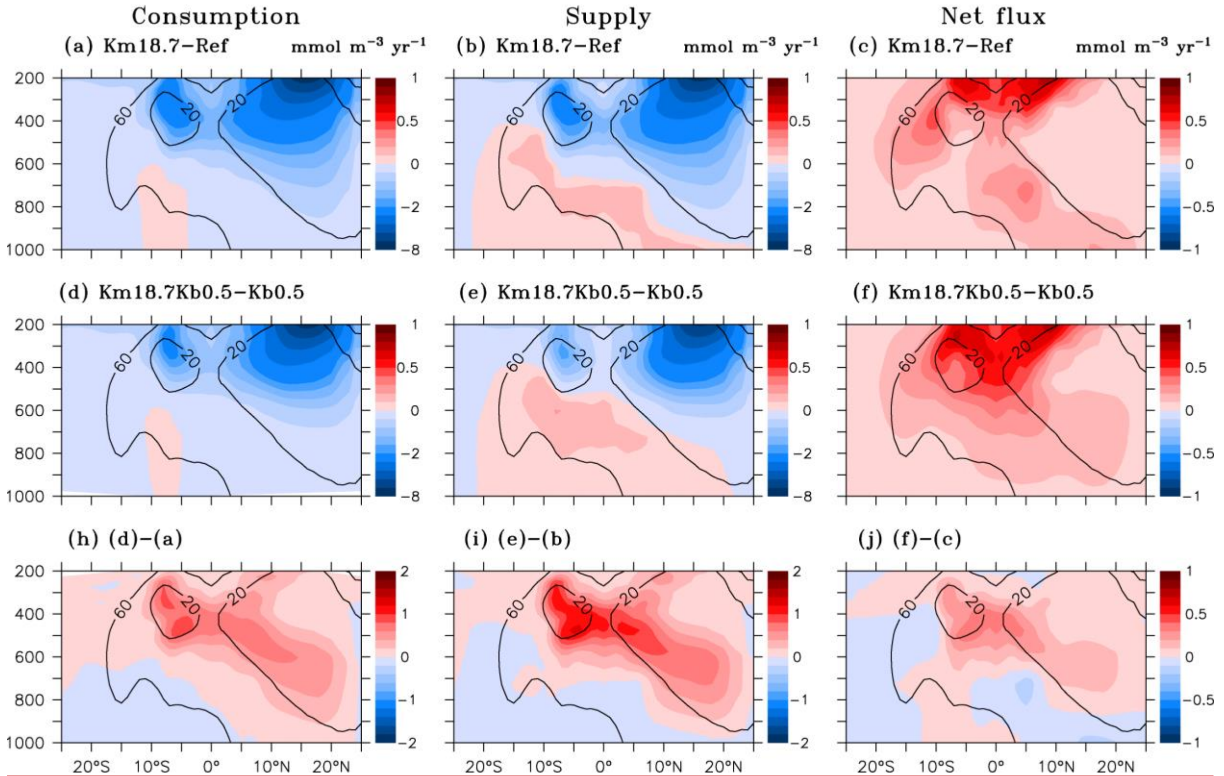


Figure 11. Changes in biological consumption (left panel), physical supply (middle panel), and net flux (right panel) under a reduced O:C utilization ratio with **(d, e, and f, middle row)** and without enhanced vertical mixing **(a, b, and c, top row)**, and the differences between them **(h, i, and j, bottom row)**.

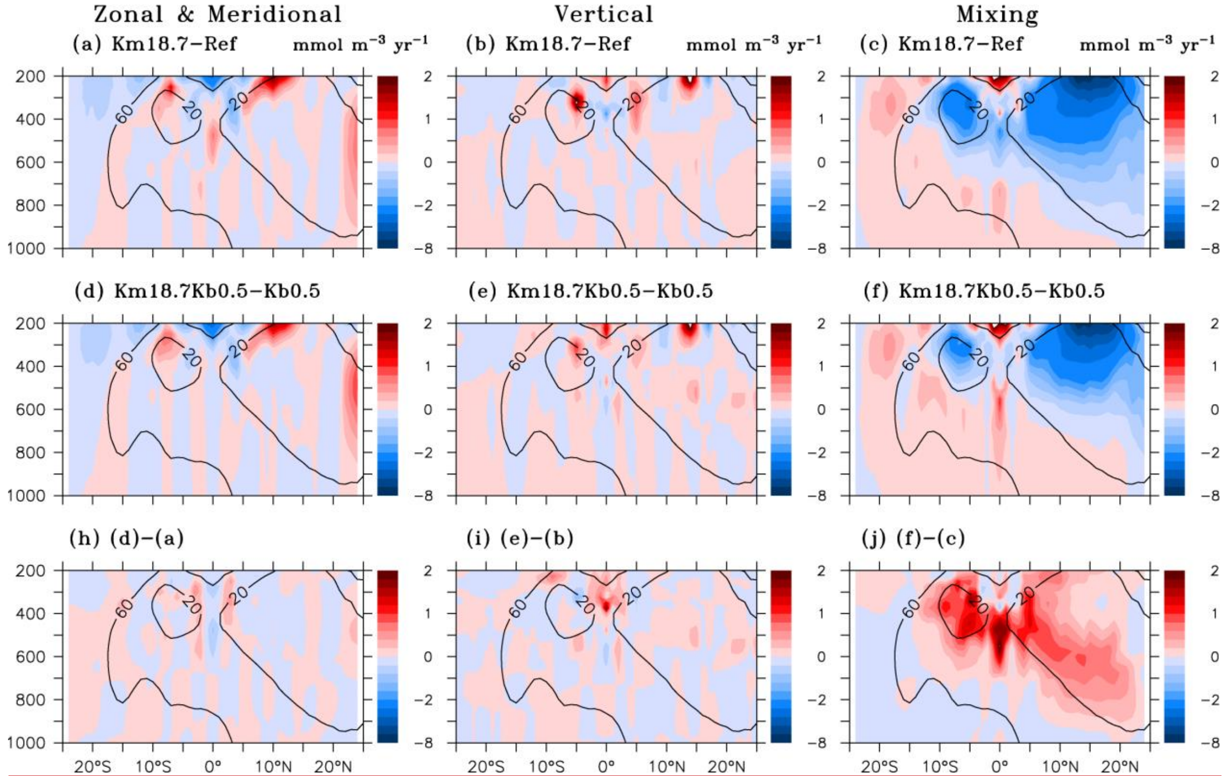


Figure 12. Changes and differences in zonal and meridional advections (left panel), vertical advection (middle pane), and vertical mixing (right panel) under a reduced O:C utilization ratio with **(d, e, and f, middle row)** and without enhanced vertical mixing **(a, b, and c, top row)**, and the differences between them **(h, i, and j, bottom row)**.