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The riddle of eastern tropical Pacific Ocean oxygen levels: the role of the supply by intermediate-depth waters

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Supplement

1. Forcings and integration duration

The differences in oxygen levels between the "models groups" (GFDL suite, UVIC, NEMO2) are partly related to differences in the atmospheric fields employed and the integration time (see 2).

1. Wind forcing

Zonal wind mean stress typically varies by 5 to 20 % between the different wind products (Chauduri et al., 2013). To test this impact, we performed an experiment using the UVIC model using 2 different wind products (NCEP and COREv2 – Large and Yeager, 2009) (Figure A1). While the shape of the OMZ shows slight differences, the volume of the OMZ and the mean oxygen levels in the tropical regions and in the mid latitudes are similar. Consistent with the Figure 2, higher oxygen levels at 30°S lead to higher oxygen levels in the tropical ocean and to a smaller OMZ volume (Figure A2)

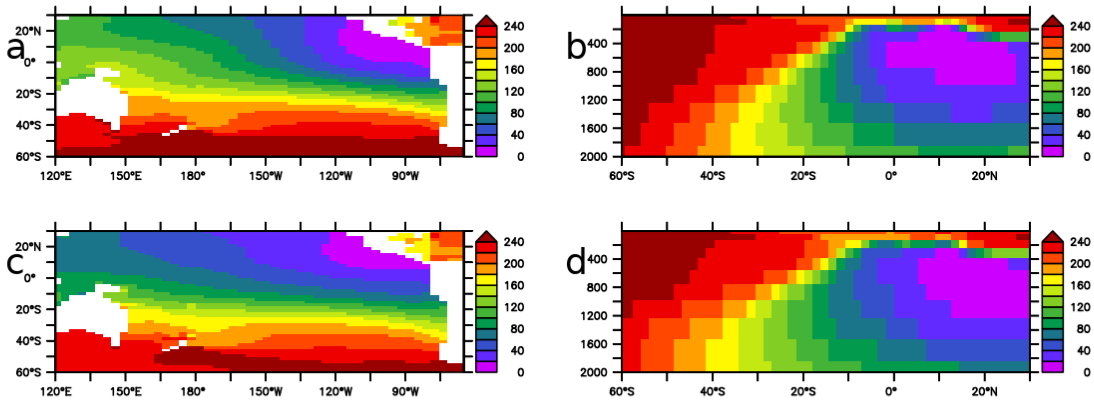

Figure S1 : Oxygen levels in UVIC (10000 years integration) a- mean 500-1500 m forcing NCEP. b- section 120°W forcing NCEP. c- mean 500-1500 m forcing COREv2, d- section 120°W forcing COREv2.

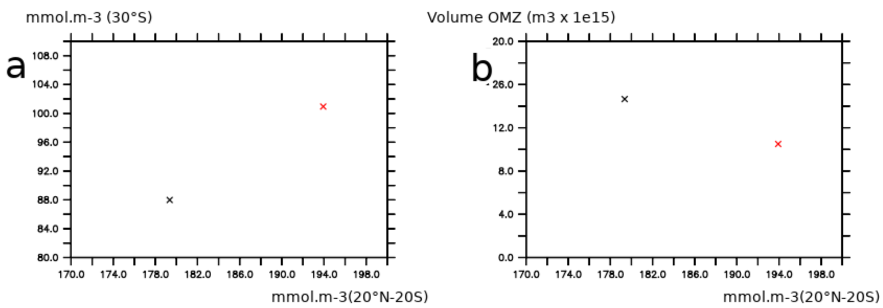

Figure S2 : a - Oxygen levels in UVIC (10000 years integration) at 30°S (zonal mean in the Pacific Ocean from surface to 2000 m depth) and in the tropical regions (20°S-20°N, averaged over the whole Pacific Ocean). b - Oxygen levels in UVIC (10000 years integration) at 30°S (zonal mean in the Pacific Ocean, from surface to 2000 m depth) and volume of the OMZ in the Pacific Ocean.

The configuration forced by COREv2 is shown in black, the configuration forced by NCEP is shown in red.

2. Spinup state

In complement, the spinup state of the model also impacts the oxygen levels as the deep ocean needs thousands of years to be in equilibrium. It may explain why UVIC (integrated for 10000 years) is characterized by much larger oxygen levels than the GFDL model suite (integrated for 190 years). As an example, the Figure A3 shows the evolution of oxygen levels during spinup in NEMO2. Larger oxygen levels at 30°S (e.g after 1000 years of integration) are characterized by a smaller OMZ volume (which is consistent with Fig 2) (Figure A4)

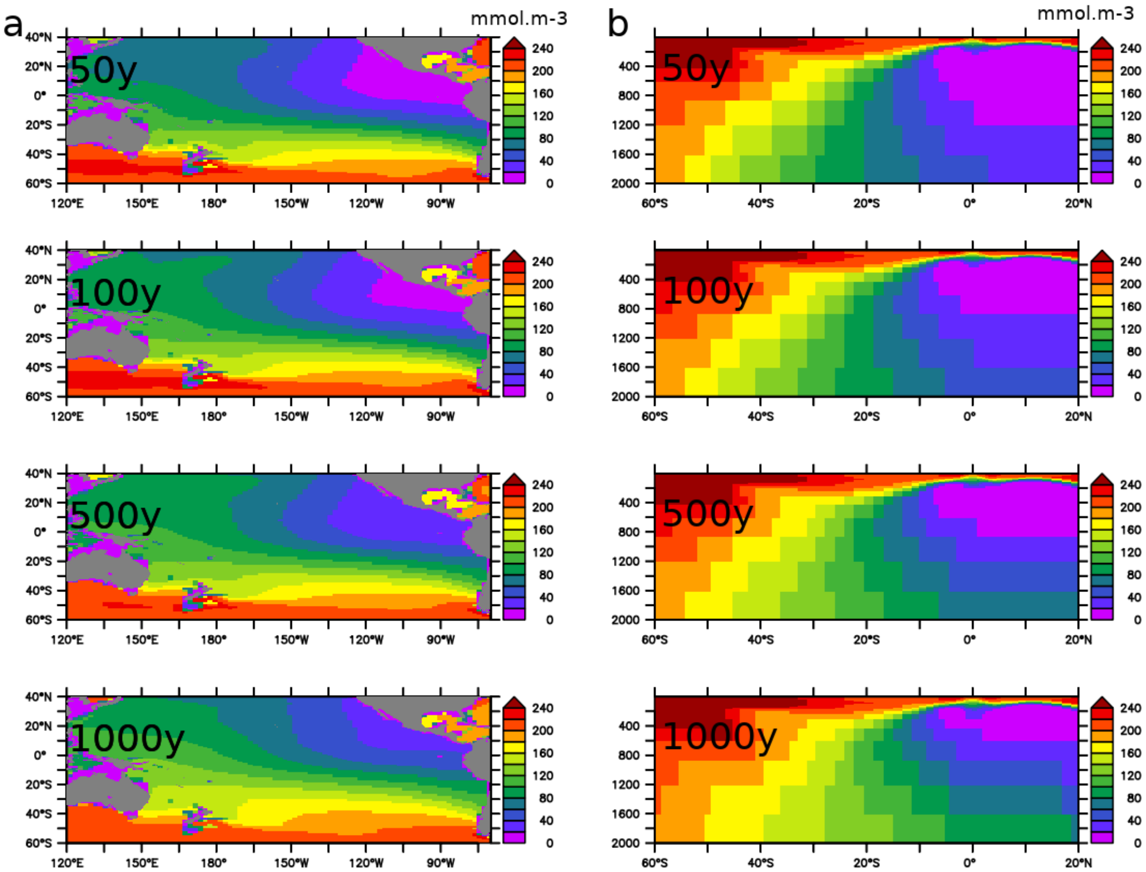

Figure S3 : oxygen levels at a - intermediate depth (average 500 – 2000 m) and b - 120°W in NEMO2 after 50, 100,500 and 1000 years integration

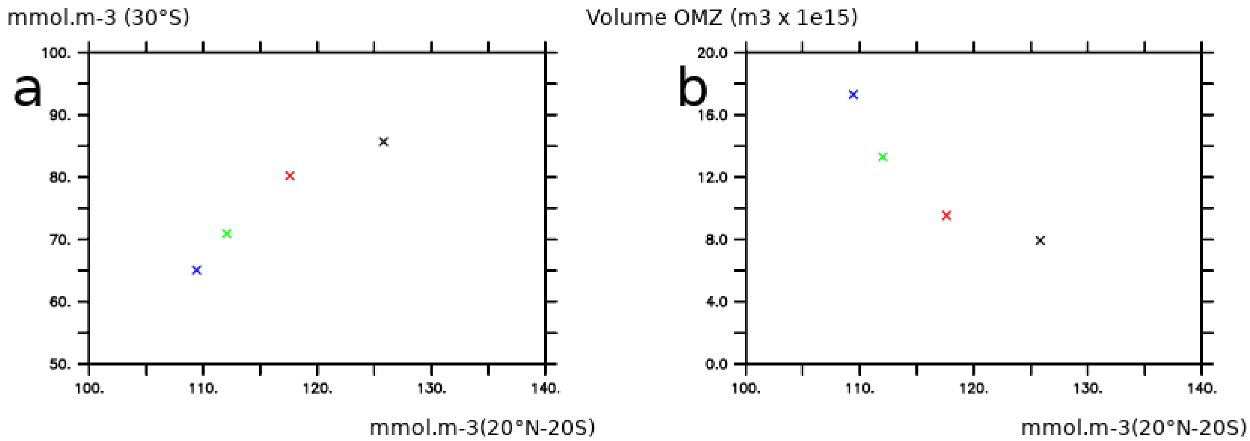

Figure S4 : a - Oxygen levels in NEMO2 at 30°S (zonal mean in the Pacific Ocean from surface to 2000 m depth) and in the tropical regions (20°S-20°N, averaged over the whole Pacific Ocean from surface to 2000 m depth). b - Oxygen levels in NEMO2 at 30°S (zonal mean in the Pacific Ocean from surface to 2000 m depth) and volume of the OMZ in the Pacific Ocean. The color of the cross depends of the integration duration (black : 50 years, red : 100 years, green : 500 years, blue 1000 years).

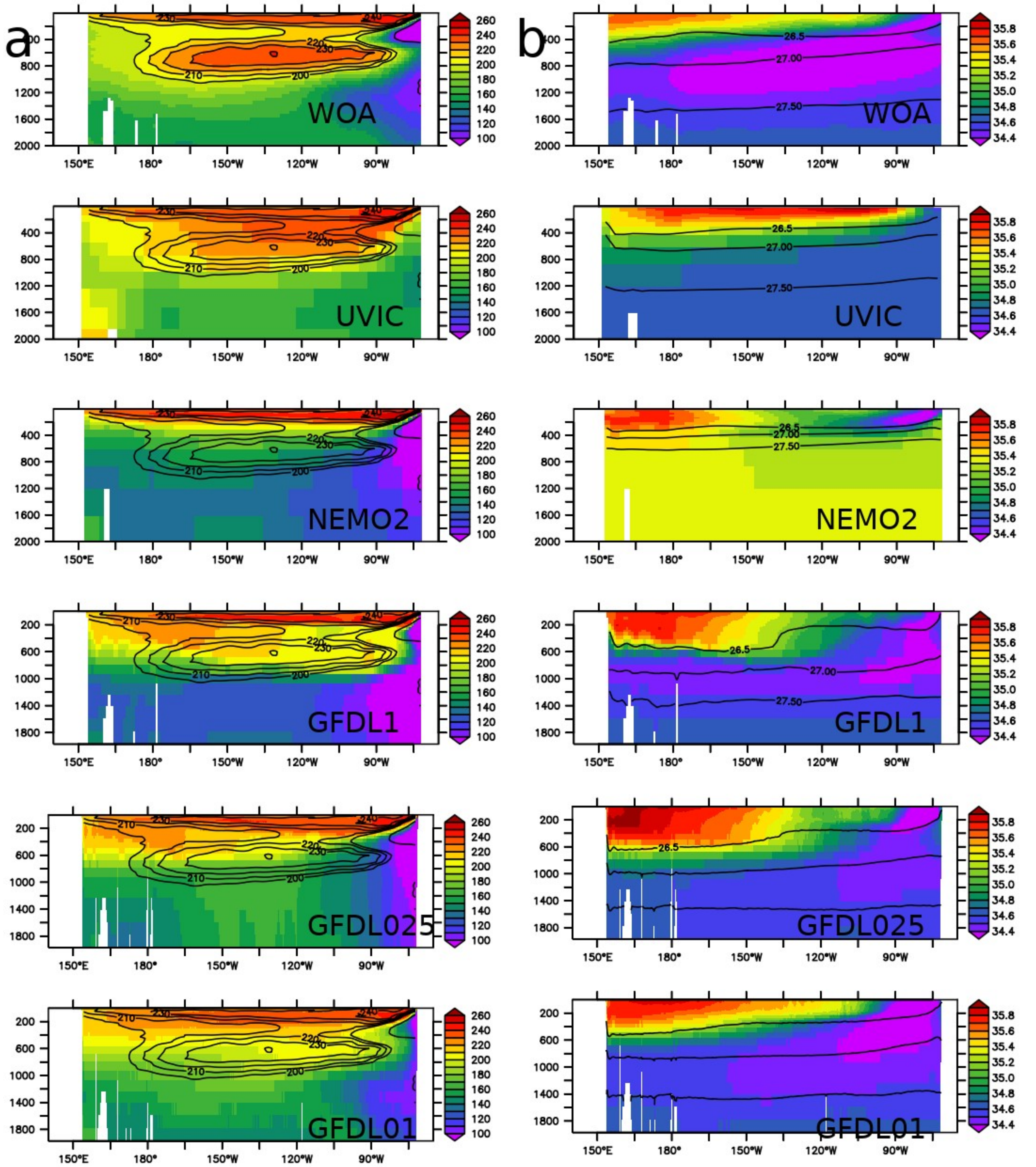

Figure S5 : a - oxygen levels (mmol.m-3) in observations and models at 30°S. The WOA oxygen levels are displayed in contour. b- salinity in observations and models at 30°S. The density anomaly (26.5, 27, 27.5) is displayed in contour.

References

Chaudhuri, Ayan & Ponte, Rui & Forget, Gael & Heimbach, Patrick. (2013). A Comparison of Atmospheric Reanalysis Surface Products over the Ocean and Implications for Uncertainties in Air-Sea Boundary Forcing. Journal of Climate. 26. 153-170. 10.1175/JCLI-D-12-00090.1.

Large, W.G., Yeager, S.G. (2009). The global climatology of an interannually varying air–sea flux data set. Clim Dyn 33, 341–364. 10.1007/s00382-008-0441-3

2. Comparison NEMO2-REF and World Ocean Atlas

The deficiency in oxygen in NEMO2-REF is clearly highlighted at 30°S, between 400 and 1500m. In comparison, the density field is well represented in NEMO2-REF. At 500m, density is about 26.6 in both WOA and NEMO2-REF. At 1500 m , the density is 27.6 in WOA and only 27.4 in NEMO2-REF, highlighting some potential water mass formation issue in NEMO2, as in most of models. A section at 100°W shows that isopycnal are almost horizontal at intermediate depth (500 – 1500 m) in WOA and NEMO2 in the subtropical and tropical ocean.

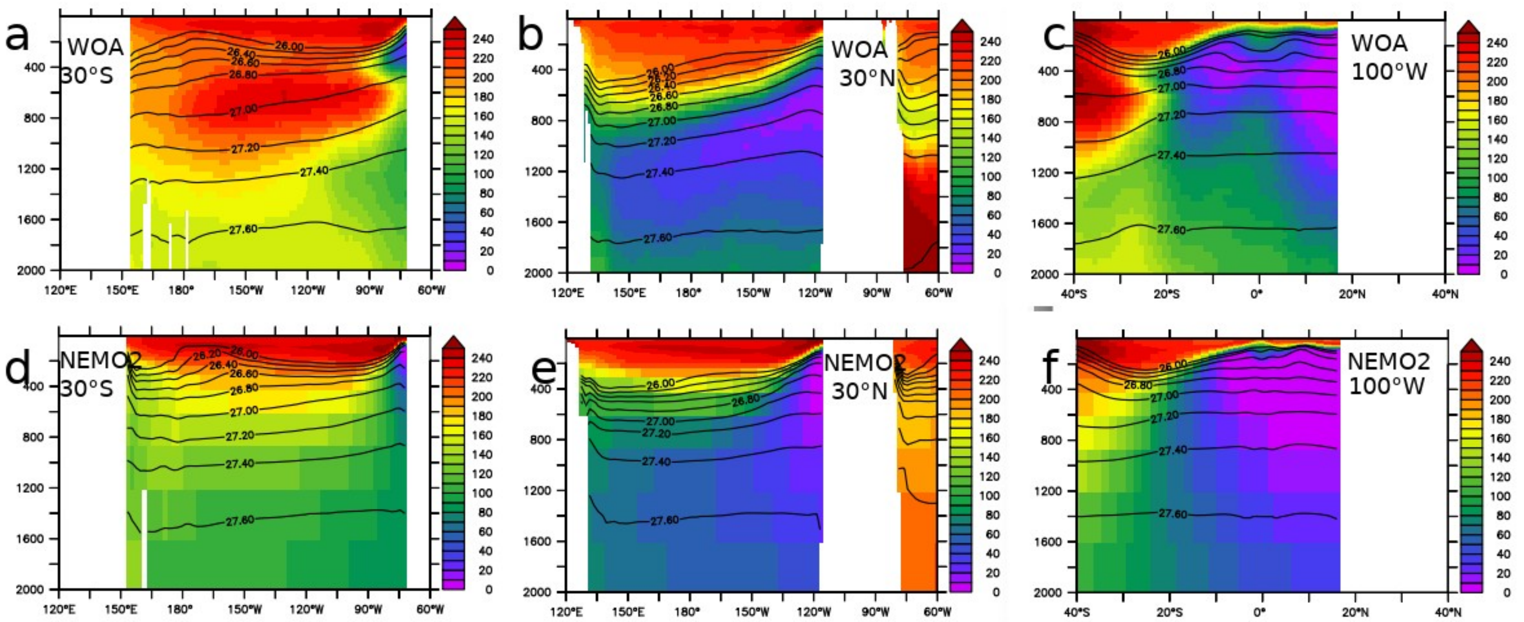

Fig S6 : oxygen levels (mmol.m^{-3}) (color) and density levels (contour) at 30°S, 30N and 100°W in the WOA dataset (a,b,c) and NEMO2-REF experiment (d,e,f)

3. Differences in oxygen supply NEMO2-30S30N1500M and NEMO2-REF

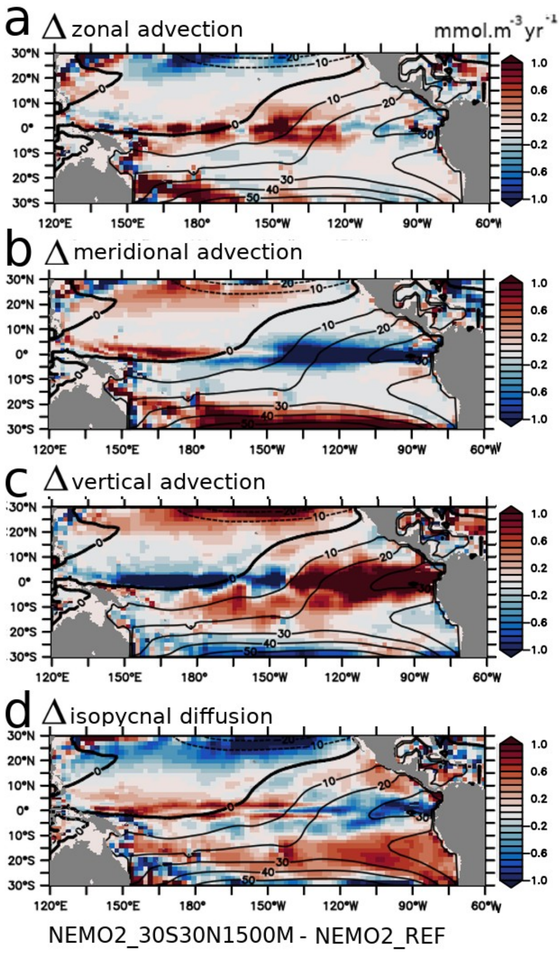

Figure S7 : Difference in oxygen supply processes (mmol.m^{-3}.year^{-1} – average 500-1500m) between NEMO2_30S30N1500M and NEMO2_REF : a- zonal advection, b- meridional advection, c- vertical advection, d- isopycnal diffusion. The NEMO2_30S30N1500M – NEMO2_REF oxygen anomaly (mmol.m^{-3}) is displayed in contour.

4. GFDL model suite and oxygen levels

The experiments discussed in 4.2 were not coupled with biogeochemical cycles for computational cost reasons. In order to assess the robustness of our findings (EICS plays a large role in setting tropical oxygen levels), we next analyze equatorial oxygen in a set of climate models similar to CMIP models. To this end we use the GFDL model suite, characterized by a resolution increase (GFDL1, GFDL025 and GFDL01 - see Table 1).

The striking difference between GFDL01 and GFDL025 / GFDL1 are the high oxygen levels in the eastern part of the ocean below 1000 m in GFDL01 compared to GFDL025/GFDL1 (Fig 2). The oxygen levels show weaker zonal gradient in GFDL01, consistent with the tracer experiment that we performed in 4.2. and a more ventilated intermediate equatorial ocean. High values of mean kinetic energy are associated with higher oxygen values (Fig C1). This is particularly clear in GFDL01 at around 1500 m depth, where strong values of MKE are present and form the “bottom” of the low oxygen volume (oxygen lower than 50 mmol.m-3). Conversely GFDL025 and GFDL1 do not present high MKE values below 1000 m in the eastern part of the basin; the low oxygen volume extends till depths greater than 2000 m. It suggests that intermediate currents participate in the ventilation of the eastern tropical ocean and thus in limiting the vertical extension of the OMZ.

Oxygen levels do not increase linearly with the currents strength, i.e while currents strength increase in GFDL1, GFDL025 and GFDL01, oxygen levels are relatively similar in GFDL1 and GFDL025 (see Fig 5 and Fig C1). The relatively small net balance between large fluxes of respiration and oxygen supply (Duteil et al., 2014) may be responsible for this behavior. If the supply is slightly higher compared to the consumption by respiration, it will lead to an increase of oxygen concentration. If it is slightly lower, the oxygen levels will decrease. A small difference in supply (e.g slightly weaker currents) may therefore lead to a large difference in oxygen levels when integrated over decades. For this reason, the impact of the EICS is more visible below 1000 m as the respiration decreases following a power-law with depth (Martin et al., 1987) and is therefore easier to offset even by a moderate oxygen supply.

Resolving explicitly the EICS results in a similar oxygen distribution to what Getzlaff and Dietze (2013) (GD13) achieved with a simple EICS parameterization (Fig C1a): to compensate for the “missing” EICS in UVIC, a coarse resolution model, they enhanced anisotropically the lateral diffusivity in the equatorial region. The oxygen levels from UVIC GD13 are shown in blue contours on top of the UVIC oxygen distribution (black) in Fig C1. Implementing this approach tends to homogenize oxygen levels zonally, with an increase of the mean levels by 30-50 mmol.m-3 in the eastern basin and a decrease of oxygen concentrations in the western basin. While this approach may be useful to better represent the oxygen mean state, it however does not take into account the potential variability and future evolution of the EICS.

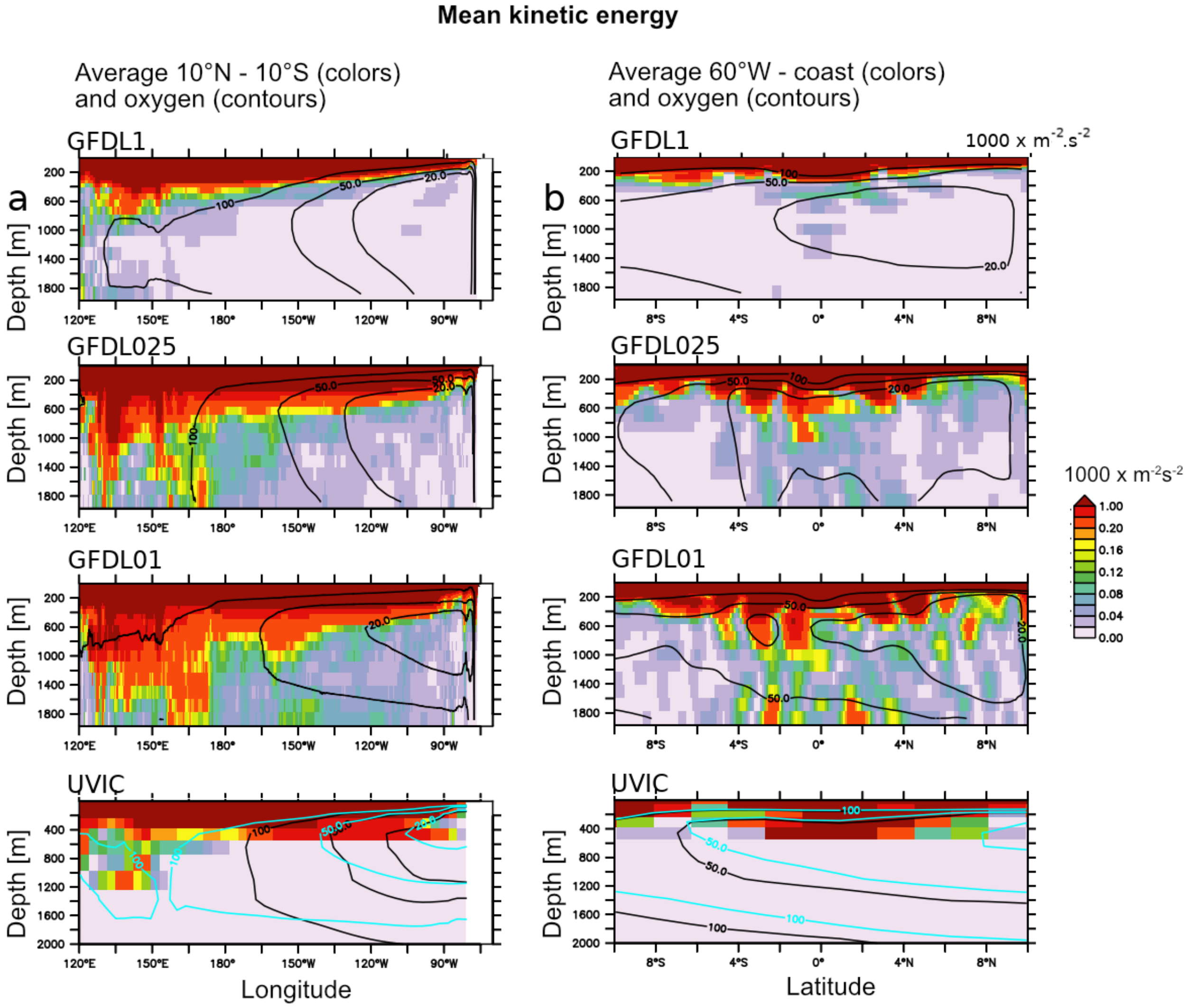

Figure S8 : a - Mean Kinetic Energy (m2.s-2 x 1000) (average 10°N-10°S) in GFDL01, GFDL025, GFDL01, UVIC, b - similar to a. but average 160°W- coast. Oxygen levels (mmol.m-3) are displayed in black contour. The blue contour corresponds to UVIC GD13 (Getzlaff and Dietze, 2013, including an anisotropical increase of lateral diffusion at the equator)