**Intermediate water masses, a major supplier of oxygen for the eastern tropical Pacific ocean" by Olaf Duteil et al.**

**A. Reply to Referee #1**

**Main Objective of this Study and General Comments**

This study investigates the impact of intermediate water masses (IMW) and it's pathway and supply along Equatorial Intermediate Current System (EISC) on dissolved oxygen content in the Pacific Oxygen Minimum Zone (OMZ) (in the eastern tropical Pacific ocean). The authors utilized a suite of simulations to address these questions.The manuscript consists of) mean state diagnostics and evaluations from suite of models (NEMO (ocean stand-alone simulation), UVIC (coupled, energy moisture balance model, forced wind stress), GFDL (coupled) and ii) sensitivity simulations (or transient simulations over 60 years) (oxygen restoring, conservative tracer release, and Lagrangian tracking of tracers) elucidating the role of subtropical IMW on dissolved oxygen supply (through EICS) in eastern tropical Pacific ocean. Despite the limitations (or discrepancies) in simulating properties of IWM in the current climate models, the authors did a nice set of simulations tackling how bias in IMW and EICS could impact on dissolved oxygen (and possibly impact on projections of OMZs due to climate change). This could provide insights on improving ocean bio-geochemistry in ESMs and I think the work contains interesting and important results.

We thank the reviewer for her/his positive evaluation.

However, I have several comments and some sections and figure presentations should be revisited before publication. Therefore, I suggest a major revision. I state specific comments below and hope this helps to improve the manuscript.

**Major Comments**

[1] The heterogeneous subset of models (simulations) will be an advantage exploring model and resolution dependencies (as author stated in L116−118) on IMW characteristics and tracers (here dissolved oxygen) but also makes the results difficult to interpret to some extent. I still think the results will have impacts from not only the differences in model structures and resolutions, but also the forcing (forcing dataset, prescribed vs. coupled) and model integration time (spinup states) (some specific comment on forcing dataset is stated below). I would like to ask authors to discuss further on these points since for example, the wind and buoyancy forcing bias could be one of the reasons introducing errors in climate (and ocean) models as stated in the introduction.

We agree with the reviewer that extracting information from a heterogeneous subset of simulations is not straightforward and needs a specific conceptual reasoning, that we clarify in a first step. In a second step, we reply specifically to the comments of the reviewer.

1. Conceptual reasoning

We compare the oxygen levels in a set of models characterized by different resolutions, integration time scale, forcings, etc.. Despite all these differences, we found common behaviours (part 3.1): the properties of the intermediate waters are poorly represented in all simulations that we analyzed and we found a correlation between oxygen levels in intermediate waters and oxygen levels in tropical regions (part 3.1 of the ms).

It suggests that intermediate waters affect oxygen levels and OMZ volume in tropical regions. We test this hypothesis using a "what if ?" experiment : "If the oxygen levels are realistic south of 30°S and/or below 1500m does it have an impact on OMZs ?". These sensitivity simulations are performed using a single model framework: same resolution, same forcings, same integration time. (part 3.2)

Another second hypothesis that we investigate is "do the intermediate circulation and associated jets play a large role in setting oxygen levels in the equator region ?". To reply to this question, we performed a set of sensitivity simulations using again a single model framework: same integration time, same forcings, but different spatial resolution. (part 4.2).

In addition (part 4.3) we compare the oxygen levels in a climate model suite: similar model framework, same integration time, different ocean resolution.

In summary, we investigate the mechanisms impacting tropical oxygen levels at intermediate depths in a very heterogeneous set of models, by performing dedicated sensitivity simulations that are easy to interpret.

2. Reviewer comment on the heterogeneity of the models and model set-ups that makes it difficult to pinpoint causes for differences of the simulations.
- Atmospheric forcing

We agree that the atmospheric forcing data play a large role in setting ocean properties. Differences in wind stress between reanalyses data are of the order of 5-20 % (zonal mean wind stress), as shown by the figure below (Chauduri et al., 2013)

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.
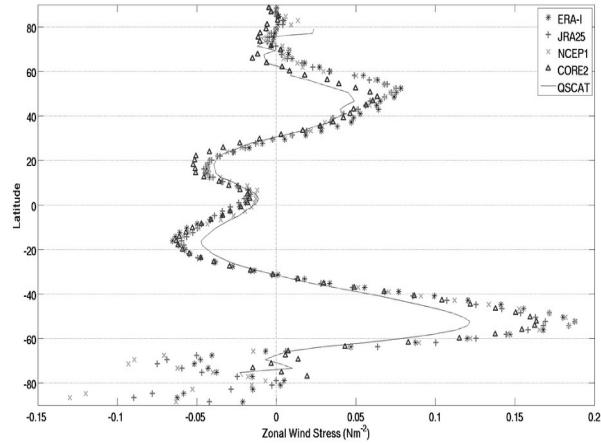
Figure 1: Zonally averaged profiles of zonal wind stress from 1999–2006 for ERA-Interim, JRA-25, NCEP1, CORE2, and QuikSCAT (Chauduri et al., 2013).

Large differences exist especially in the eastern tropical Pacific Ocean where the wind is weak. The Figure 2 below shows the relative difference in wind speed between NCEP and CORE (Large and Yeager, 2009), i.e., it shows that winds of the different products in the eastern tropical Pacific differ by up to 50%.
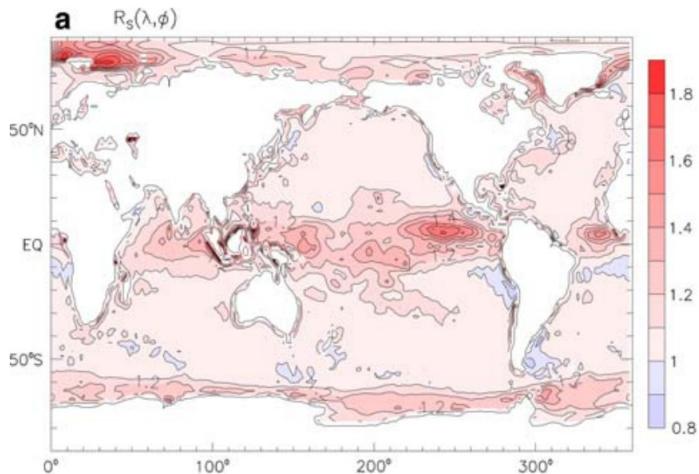


Figure 2: Global distributions of the multiplicative speed applied to NCEP wind vectors to obtain CORE wind vectors (Large and Yeager, 2009)

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

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 3)
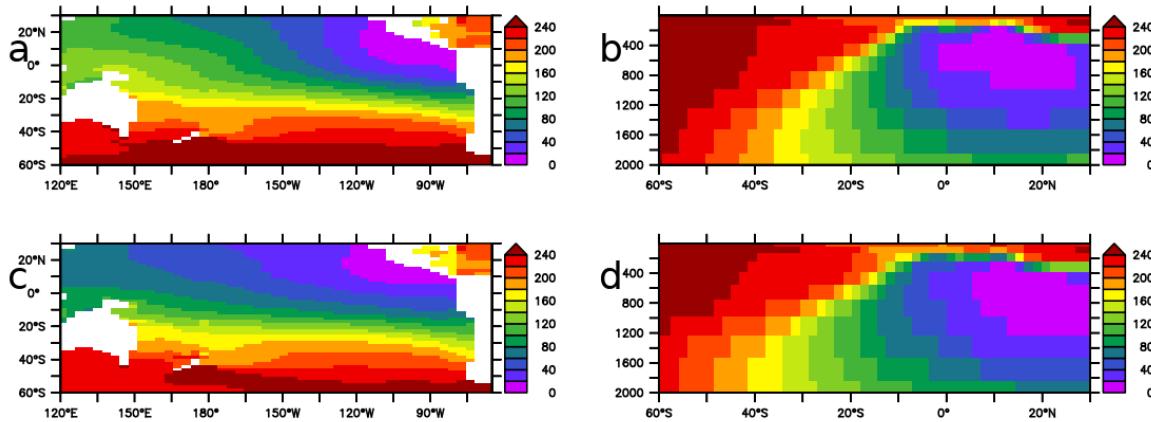


Figure 3 : Oxygen levels in UVIC (10000 years integration) a- mean 500-1500 m forcing NCEP. b- section 120°W forcing NCEP. c- mean 500-1500 m forcing COREv2, d- section 120°W forcing COREv2.
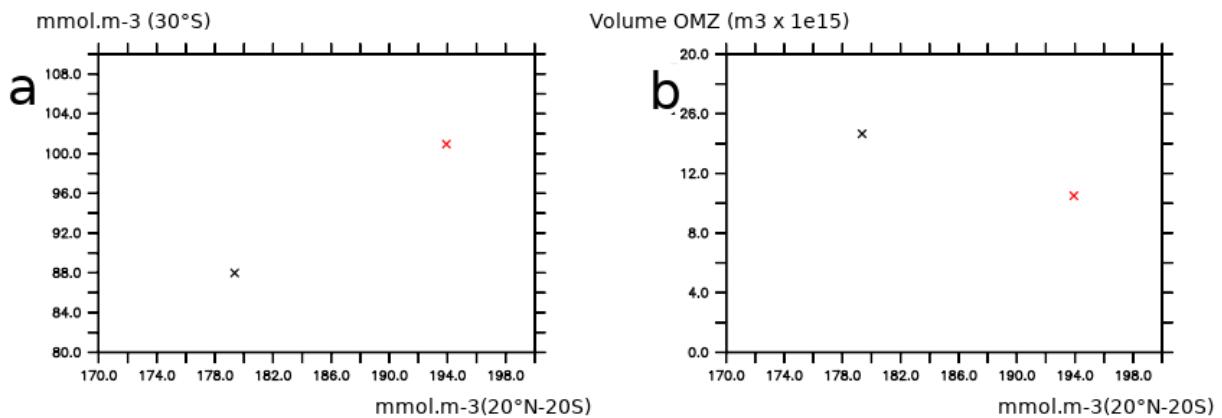


Figure 4 : a - Oxygen levels in UVIC (10000 years integration) at 30°S (zonal mean in the Pacific Ocean from surface to 2000 m depth) and in the tropical regions (20°S-20°N, averaged over the whole Pacific Ocean). b - Oxygen levels in UVIC (10000 years integration) at 30°S (zonal mean in the Pacific 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.

## Coupled ocean atmosphere experiments

Coupled ocean-atmosphere experiments introduce further discrepancies compared to the use of realistic atmospheric forcings. However, the mean surface velocity is similar in the suite of GFDL models (especially GFDL01 and GFDL025) that we analyzed, suggesting that the effect of atmospheric forcing is likely not dominant when comparing this subset of models (part 4.3).
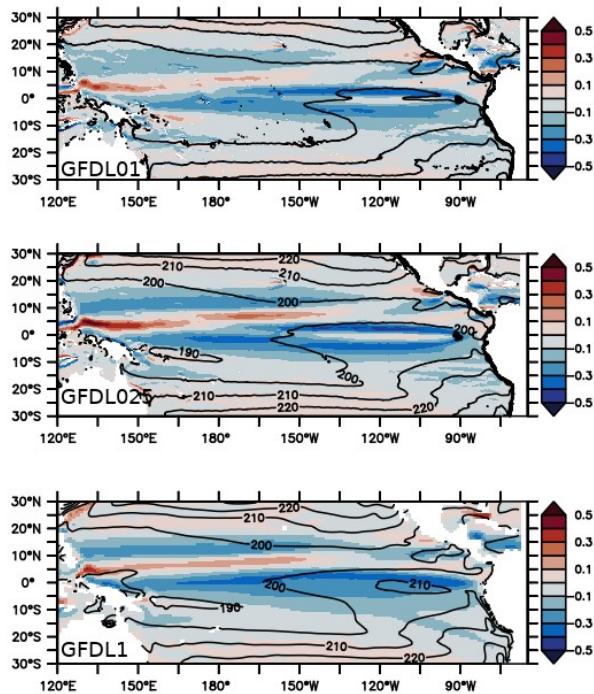


Figure 5: ocean zonal surface velocity (ms-1) in GFDL01, GFDL025 and GFDL1

## Model integration time

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 6 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 7)
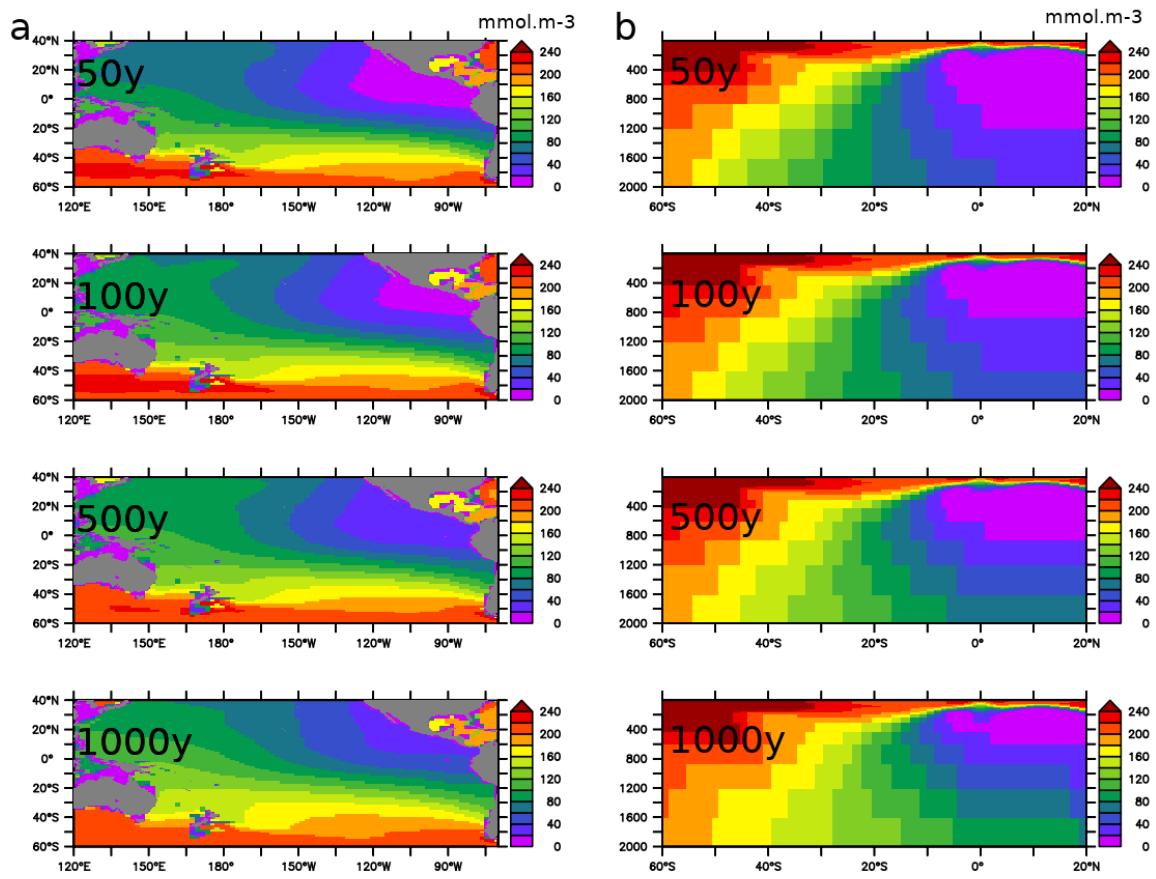
Figure 6 : oxygen levels at a - intermediate depth (average 500 – 2000 m) and b - 120°W in NEMO2 after 50, 100,500 and 1000 years integration
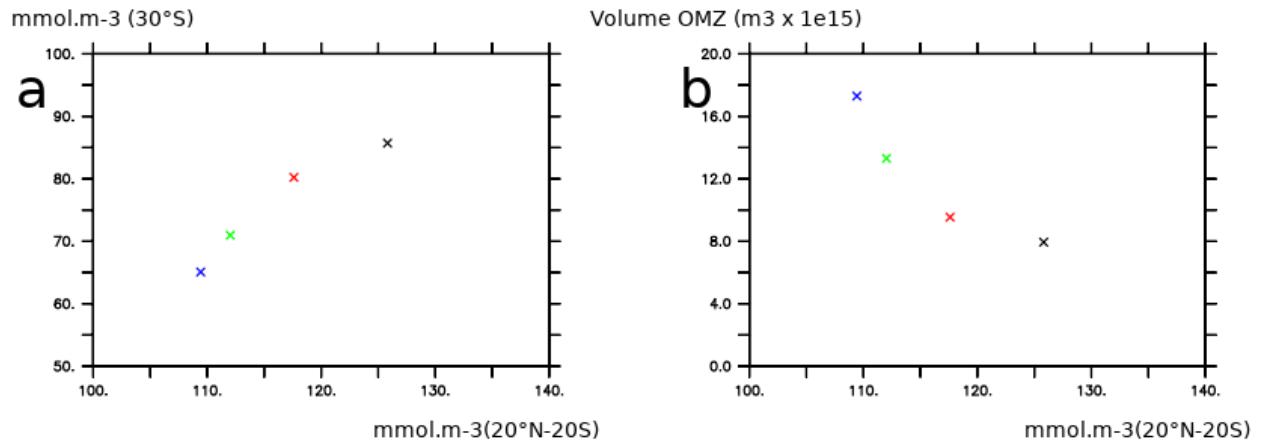


Figure 7 : a - Oxygen levels in NEMO2 at 30°S (zonal mean in the Pacific Ocean from surface to 2000 m depth) and in the tropical regions (20°S-20°N, averaged over the whole Pacific Ocean from surface to 2000 m depth). b - Oxygen levels in NEMO2 at 30°S (zonal mean in the Pacific Ocean from surface to 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).

3. Conclusion

The differences induced by the different forcings and integration time have (not surprisingly) an impact on water masses and oxygen levels. Despite the heterogeneity of our simulations, our results nevertheless suggest a strong coupling between subtropical and tropical oxygen content and justify our questioning and the experiments performed in the part 3 and 4 of this study (see 1. Conceptual reasoning)

[2] Regarding to sensitivity of tropical IWM oxygen to subtropical and deep dissolved oxygen levels, the authors refer AAIW, NPIW (and the upper part of the PDW) as IWM in this study. I was wondering what will be the relative contributions of each water masses to dissolved oxygen supply, ventilation in the eastern tropical Pacific ocean (particularly North (NPIW) vs South (AAIW)). My impression is that AAIW could be more dominant (e.g. Talley, 2013) but I would like to know what sensitivity simulations indicates. At least, I think it is possible to obtain insights from the Lagrangian tracking diagnostics (or if possible, conducting additional restoring simulations with 30◦S boundary only for example).[Reference] Talley, Lynne D., (2011), Descriptive Physical Oceanography: An Introduction, Academic Press.

We perform a complementary experiment using NEMO2 where the oxygen levels are forced (see Minor Comment 4) to WOA solely south of 30°S (experiment NEMO2_30S. The experiment where oxygen is restored both to the south and to the north. NEMO2_DEG30 has been renamed NEMO2_30S30N). It shows clearly that AAIW has a dominant impact in setting tropical Pacific Ocean intermediate oxygen levels and the OMZs volume. This is not surprising as AAIW recirculates till about 20°N and NPIW has a much smaller, regional extension (Talley, 2011)
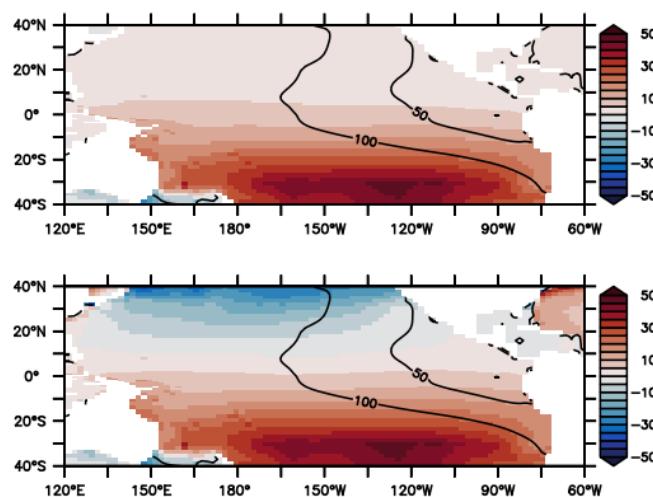


Figure 8: NEMO2-30S minus NEMO2-REF and NEMO2_30S30N minus NEMO2_REF (average 500-2000 m).

We decided to keep the original, classical, structure but agree that the methodology section need to be better connected with the results / discussions. We therefore added the following lines :

"L126: The mean state of the oxygen distributions is discussed below in section 3.1 "IWM Oxygen levels in models""

"L159 : The sensitivity of tropical IWM oxygen to subtropical and deep oxygen levels is discussed in section 3.2"

"L187 : The transport by the EICS is discussed in section 4.2 (tracers levels and Lagrangian pathways)."

The figures/labels/captions are revised in the final version of the ms. See the new set of figures at the end of the reply. When necessary, the figure / subpanel number has been modified in the text to match the new set of figures.

The transport terms (Fig 4) are labeled in the final version of the ms. See the new set of figures at the end of the reply.

The names are labeled in a more obvious way in the final version of the ms. See the new set of figures at the end of the reply.

Thanks to the reviewer for these suggestions. We have rechecked all captions to make sure that they are correctly describing the panels.

A new caption has been written.

The Figure 4 has been revisited (missing shading of the continent, captions, legend).  See the new set of figures at the end of the reply.

The experiment NEMO2-30DEG has been renamed NEMO2_30S30N for clarity reasons (see above comment). We show in Fig 4 both the transport terms of NEMO2_30S30N and of NEMO2_30S30N minus NEMO2_REF.  We do not show NEMO2_30S30N1500M as from Figure 3i it becomes clear that the processes transferring oxygen from the deeper layer toward the intermediate ocean are vertical advective processes. This is now stated explicitly in the new version of the ms.

Information labels have been added and the figure revisited. See the new set of figures at the end of the reply.

respectively.

Information labels have been added and the figure revisited. See the new set of figures at the end of the reply.

[1] I am curious whether CORE v2 climatological forcing (used for NEMO) and NCEP/NCAR climatological forcing (wind stress, used for UVIC) makes a difference in paper spinup states. As far as I know, CORE v2 forcing is based on NCEP/NCAR reanalysis but it has several corrections and adjustments in the forcing and difference between the two could lead to different results, particularly after long-term spinup. Do authors think this is a minor thing ?

The different climatological  forcings have indeed a significant impact (see Figure 3 of our response). However we think that differences in resolution play a larger role by resolving additional processes (in particular deep equatorial jets)


[2] Are all the GFDL model simulations integrated for the same period following high-resolution (GFDL01) for comparison (I assumed 200 years from Busecke et. al.,2018) or the low-resolution configurations are integrated for longer durations ?

All configurations have been integrated for 190 years (more precisely 48 years physics only + 142 years biogeochemical cycles), including the lower resolution version. This is now clearly stated in the new Table 1.


[3] Because of the high resolutions configurations for GFDL01, the integration time is limited but does this impact on IWM (and upper part of PDW) characteristics and tracers (i.e. insufficient spinup, drift in certain properties etc.)? Upper ocean could be quasi-equilibrated (say few hundred meters) but I am wondering about mid~deep ocean you are more focusing on in this study.

We agree with the reviewer, the model spin-up has a large impact on ocean properties. The mid-depth (500 – 1500 m) ocean is not fully equilibrated after 100/200 years. However, the experiments part 3.2 : "If the oxygen levels are realistic south of 30°S and/or below 1500m does it have an impact on OMZs ?" and 4.2/4.3 "do the intermediate circulation and associated jets play a large role in setting oxygen levels in the equator region ?" (see 1 - Conceptual reasoning) clearly show that a timescale of 100 - 200 years is sufficient to investigate the connectivity between mid-latitude / tropical regions, as well as the role of the intermediate current system in controlling oxygen (and more generally tracers) concentration. Even if a short integration timescale does not allow to characterize the steady state and the relative importance of all the processes at play, it permits nevertheless to assess the importance of specific processes (especially that the experiments, e.g the GFDL suite of models, have been integrated for the same duration (190 years).

[4] Regarding to dissolved oxygen restoring, are the boundaries (and depth inter-face at 1500m) all in the Pacific ocean only (e.g. thinking of for example, 30∘N and 30∘S zonal walls and 1500m layer in the entire Pacific ocean) or globally ? Also, how strong (i.e. timescale) is the restoring in these simulations ?

The term "restoring" is maybe inadequate and has been replaced by "forcing" L132, 139 and 142. of the manuscript including corrections as the oxygen levels are forced to the WOA monthly climatology. The latitude where the forcing is applied has been set globally (however as it is a "forcing", it does not make any difference if it were applied solely in the Pacific Ocean).

[5] Regarding to the respiration rate (in L144), did you set all the simulations respiration rate (similar to fixing oxygen utilization rate I would assume) to NEMO2-REF?

Respiration rates (as all other biogeochemical fluxes) are the same in all the experiments, as stated L147 : " The respiration rate (oxygen consumption) is identical in NEMO2-REF, NEMO2-30S30N and NEMO2-30S30N1500M". Solely the oxygen concentrations are forced by WOA values at 30N/30S/1500m depth. Forcing phosphate levels would complicate the picture (as stated L150-151), as the resulting differences of productivity and respiration would counteract the difference of advection of modified oxygen concentrations. Quantifying the sensitivity of respiration to a change in nutrients is an important aspect, but is outside the scope of this study which focuses on the transport of oxygen by intermediate water masses. Furthermore our Figure 2 (correlation oxygen content at 30°S and in tropical regions) suggests that differences in ocean circulation are dominant compared to differences in biology in the simulations that we consider.

[6] I am a bit confused by the locations of particle release and IETP/IWTP regions you were referring to (L363−383, Fig.7 and 8). While the the locations of particle release is in sections (shown as black bold lines (or dot) in Fig.7), I thought the IETP/IWTP are basins in specific rectangles and this is different from the locations of particle release (it contains of course) if I understand correctly. If that is the case, I suggest to revise the main text and Figure to include these information more explicitly (I think adding boxes in Fig.7 could help and you can refer to that interpreting Fig.8).

A new Figure 8a has been added, which shows the IETP/IWTP regions and the release locations R1 and R2. We state more explicitly in the text:

L389 : "The release location R1 is the eastern tropical Pacific (100°W, 5°N-5°S, 1000 m depth ) . R1 is included in the larger Intermediate Eastern Tropical Pacific (IETP) ocean region (160°W – coast / 10°N-10°S / 200 – 2000 m )"

L405 : "The location of the second release R2 (160°E, 5°N-5°S, 1000 m depth) is  included  in the Intermediate Western Tropical Pacific (IWTP) ocean region (160°W – coast / 10°N-10°S / 200 – 2000 m) (Fig 7b)"

Preindustrial pCO2 is used. This is now stated in the text L117.

Three versions at 2°,0.5° and 0.1° horizontal resolution of the general NEMO model engine (Madec et al., 2017) are used : NEMO2 (with biogeochemical cycles), NEMO05, NEMO01 (physics only). We refer specifically to these versions in the text.
L132 : we refer to generally to the NEMO model engine and state that explicitly to avoid confusion : "we perform two different sets of sensitivity simulations using the general NEMO model engine"

[9] For Table 1, I would suggest to include model integration time information.
The model integration time has been added in the Table 1 (see last section of this document)

3.1 Line Specific Comments
[L70]Cabre et l., : should be Cabre "et al.,"
This is corrected in the final version of the ms

[L85]eastern tropical (20∘S-20∘N): I think you should add longitude information since you mentioned "eastern" tropical Pacific.
We added "east of 160°W" in the final version of the ms

[L104](see Keller Keller 2012 for ... : delete "Keller" (duplicates).
This is corrected in the final version of the ms

[L124]more than 50 years: suggest to change to "60 years" (the same as the statement in latter section, L160).
This is corrected in the final version of the ms

[L167]5 daily means: I think "5-day mean" is more common.
This is corrected in the final version of the ms

[L262−263]Where is the information (figure) of total advective term? Fig. 4g is the vertical advection term difference and I could not find specific information on total term in the figure (although it is possible to infer from all the terms).

The objective of the Figure 4 is to better explain the differences between the model experiments (Fig 3g). As the patterns are mostly zonal, we did not show in Fig 4 the total term (the zonal mean of the total term is already displayed in Fig. 3g).

[L301]Tsuchuya jets: should be "Tsuchiya jets".
This is corrected in the final version of the ms

**B. Reply to Referee #2**

This paper highlights the role of intermediate waters as the O2 supply pathway for the waters of oxygen minimum zones primarily focusing on the Pacific basin. This study consists of three model simulation with different source code, resolution and biogeochemical parameterizations. In general current generation of earth system models tend to have difficulties representing this mode of oxygen supply, thus overestimating the size of low-oxygen waters.
Here are main conclusions;
(1) the O2 concentration of these water masses in the subtropics is biased in models. If restoring is used to correct the model bias in O2 entering into the subtropics, the tropical O2 representation improves significantly.
(2) the ocean jets and eddies play major role for the O2 transport of intermediate water, as supported by the runs with different model resolutions.Coarse resolution models must rely on parameterization for this process.
(3) Due to tropical upwelling, the biases in the deep and intermediate water can impact on the entire upper ocean water column.
I think these points are not really surprising, but the authors have done a detailed, systematic analysis of oxygen responses to model resolution and source water properties to support these conclusions. In my view, this paper is publishable perhaps with a few minor revisions.
We thank the author for her/his positive feedback.

Below are my technical comments. Main text has several typos. It will benefit from a careful proofreading.
The final version of the ms has been carefully proofread.

Fig 2b. If I'm reading this figure correctly, it is remarkable that not a single model can capture the peak of O2 at about 800m. I think this feature should be pointed out more clearly in the main text at about page 6. The caption does not indicate which line is WOA. I think it is obvious that the observation is the thick black line, but it needs to be spelled out in the caption.
The "missing" O2 peak is indeed a remarkable feature in the models. We point that out more clearly in the new version of the ms.

We added to the paragraph L209-213 : "The IWM oxygen maximum is apparent at 30°S throughout the lower thermocline (600 – 1000 m) in observations (Fig 2b), consistent with the circulation of IWM with the gyre from the mid/high latitude formation regions towards the northwest in subtropical latitudes, and followed by a deflection of the waters in the tropics towards the eastern basin", the sentence L213 : " This oxygen peak is missing in all the models analyzed here".

The figure 2 has been updated and is reproduced at the end of the reply.

Fig 3 and main text in page 7. I really like this figure and the discussion in the main text, up to panel f. Then I'm confused. The figure caption says the panels g, h, i are zonal mean tendencies of O2. The main text talks about something different about deep O2. It doesn't even mention how these tendencies are calculated. This probably means there is some version inconsistency between Figure 3 and the main text. This obviously needs a revision.

The text L229 (page 7)  to which the reviewer refers reads : "The difference NEMO2-30DEG1500M – NEMO2-30DEG (Fig 3f-h) shows a deep positive anomaly in oxygen, as oxygen levels are lower than in observations by 30-40 mmol.m-3 in the eastern tropical regions". The reference to Fig 3 f-h is wrong. It has been corrected in the new version of the ms.

We added a brief description of the budget terms L265 :

"The oxygen budget is :

$$\frac{dO_2}{dt} = Adv_x + Adv_y + Adv_z + Diff_{Dia} + Diff_{Iso} + SMS$$

where $Adv_x, Adv_y, Adv_z$, are respectively the zonal, meridional and vertical advection terms, $Diff_{dia}$ and $Diff_{iso}$ are the diapycnal and isopycnal diffusion. SMS (Source Minus Sink) is the biogeochemical component (respiration at depth, below the euphotic zone)

L284 and in some other places; What is meant by the "upper layer"? I interpreted as the surface, but please be more specific (such as the surface or sigma-theta level or z-level).

The upper layer corresponds to the mixed layer. This is clearly specified in the new version of the ms.

The text related to Fig 4 is confusing, if I read it correctly, the net advective transport divergence is not affected but is not shown (L262-263). Is the change in O2 concentration entirely caused by the eddy parameterization part of the transport? In my opinion this type of budget analysis may be more interesting if it is applied to contrast the low-and high-resolution runs and separate the mean flow and (resolved or parameterized) eddy contribution.

We show below the total advective transport in NEMO2_REF and its anomaly (NEMO2_30S30N minus NEMO2_REF) (Figure 7)
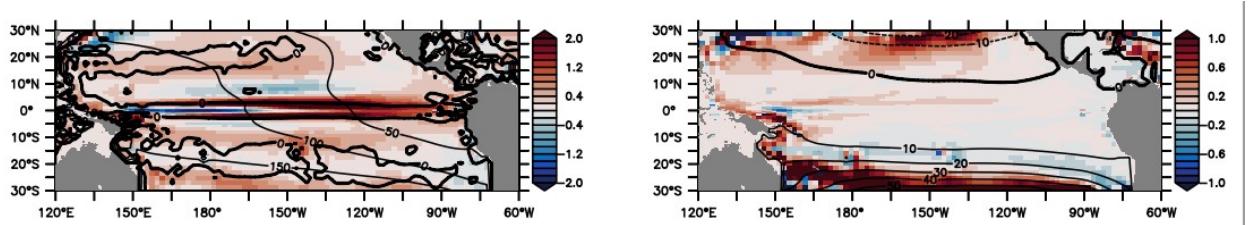
Figure 7: left : total advection term in NEMO2_REF. Right : difference in the total advection term between NEMO2_30S30N – NEMO2_REF

The Fig 7 right panel in our response letter shows clearly that the total advection terms are similar in NEMO2_30S30N and NEMO2_REF at the equator. In contrast, the differences are large in the gyres as the anomaly is advected by the strong westward currents. In the tropics, most of the anomaly is due to isopycnal mixing (or "eddy parameterization" transport as stated by the reviewer), see Fig 4b in the new version of the ms. This is maybe not surprising as the intermediate currents are weak in NEMO2 (coarse resolution). Higher resolutions models will likely be characterized by the imprint the of zonal jets. We agree with the reviewer, a similar experiment but performed at high resolution would be very useful to quantify precisely the impact of these jets. Unfortunately a high resolution eddy resolving simulation coupled with biogeochemical cycle was not available due to computational expenses (which is the reason why we compare coarse and high resolution simulations coupled to a single passive tracer in part 4 of this ms).

## C. Updated Figures and Table
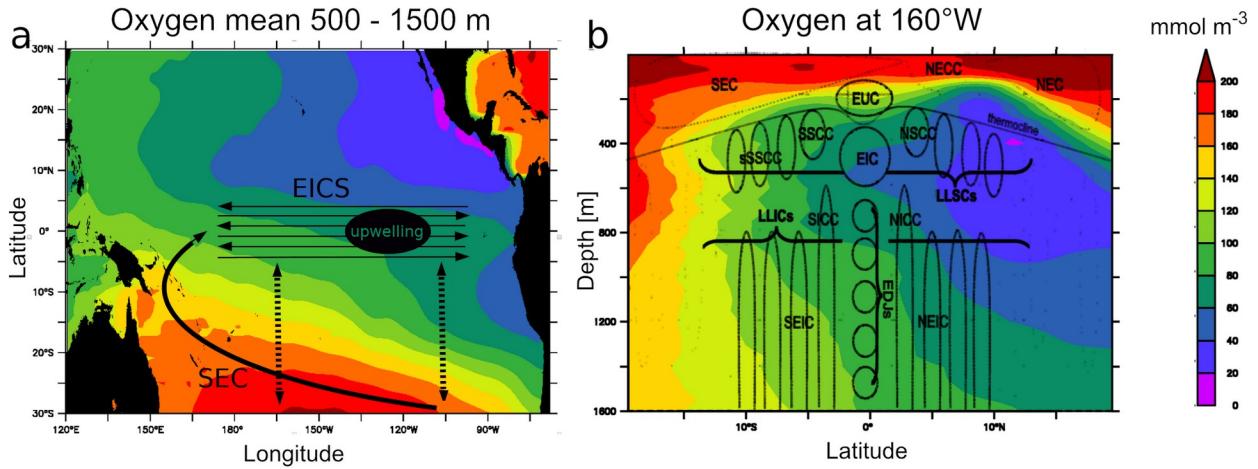


Figure 1 : a- schema summarizing the intermediate water masses (IWM) pathway from the subtropics into the equatorial regions. EICS : Equatorial Intermediate Current System. SEC : South Equatorial Current. Dashed line : isopycnal diffusive processes. Observed (World Ocean Atlas) oxygen levels (mmol.m$^{-3}$) in the lower thermocline (mean 500-1500m) are represented in color. b - schema (adapted from Menesguen et al., 2019) illustrating the complexity of the EICS, extending below the thermocline till more than 2000 m depth (see section 4.1 for a detailed description). Observed (World Ocean Atlas) oxygen levels at 160°W are represented in color.

Figure 2 : a- oxygen levels (mmol.m$^{-3}$)  in observations (World Ocean Atlas - WOA) (mean 500 – 1500 m) and models (UVIC, NEMO2, GFDL1, GFDL025, GFDL01). Contours correspond to WOA values. b: average "30°S" (120°E-65°W, 30°S) c : average "tropics" (160°W-coast, 20°N-20°S). d: average "30°S" vs "tropics". e: average "30°S" vs volume of tropical suboxic ocean (oxygen lower than 20 mmol.m$^{-3}$) regions (1e15m3). b-e : UVIC : black, NEMO2 : cyan, GFDL1 : red, GFDL025, green; GFDL01 : blue, WOA: bold line (b,c) and star (d,e).

Figure 3 : a,b: Oxygen (mmol.m$^{-3}$) in the experiments NEMO2_REF (color) and World Ocean Atlas (contour) (a- average 500-1500 m, b- 100°W). c,d: Oxygen (mmol.m$^{-3}$) difference (c- average 500 – 1500m, d- 100°W) between the experiments NEMO2_30S30N minus NEMO2_REF. e,f : Oxygen (mmol.m$^{-3}$) difference (e- average 500-1500m, f- 100°W) between the experiments NEMO2_30S30N1500M minus NEMO2_REF. g- basin zonal average (average 500 - 1500 m) of the oxygen total supply (bold) (mmol.m$^{-3}$.year$^{-1}$), advective processes (blue) and isopycnal diffusion (red) in NEMO2_REF, NEMO2_30S30N, NEMO2_30S30N1500M. The dashed line is the oxygen total supply in NEMO2_REF.

Figure 4 : a- Oxygen supply processes (mmol.m$^{-3}$.year$^{-1}$ – average 500 - 1500m) in NEMO2_REF : zonal advection, meridional advection, vertical advection, isopycnal diffusion. The mean meridional and zonal currents are displayed as vectors (meridional, zonal advection). The mean vertical current (0 isoline) is represented as bold contour (vertical advection). Oxygen levels (mmol-m.$^{-3}$) are displayed in black contour. b- Difference in oxygen supply processes (mmol.m$^{-3}$.year$^{-1}$ – average 500-1500m) between NEMO2_30S30N and NEMO2_REF : zonal advection, meridional advection, vertical advection, isopycnal diffusion. The NEMO2_30S30N – NEMO2_REF oxygen anomaly (mmol.m$^{-3}$) is displayed in contour.

Zonal velocity component at 1000 m (colors) and oxygen (contours)
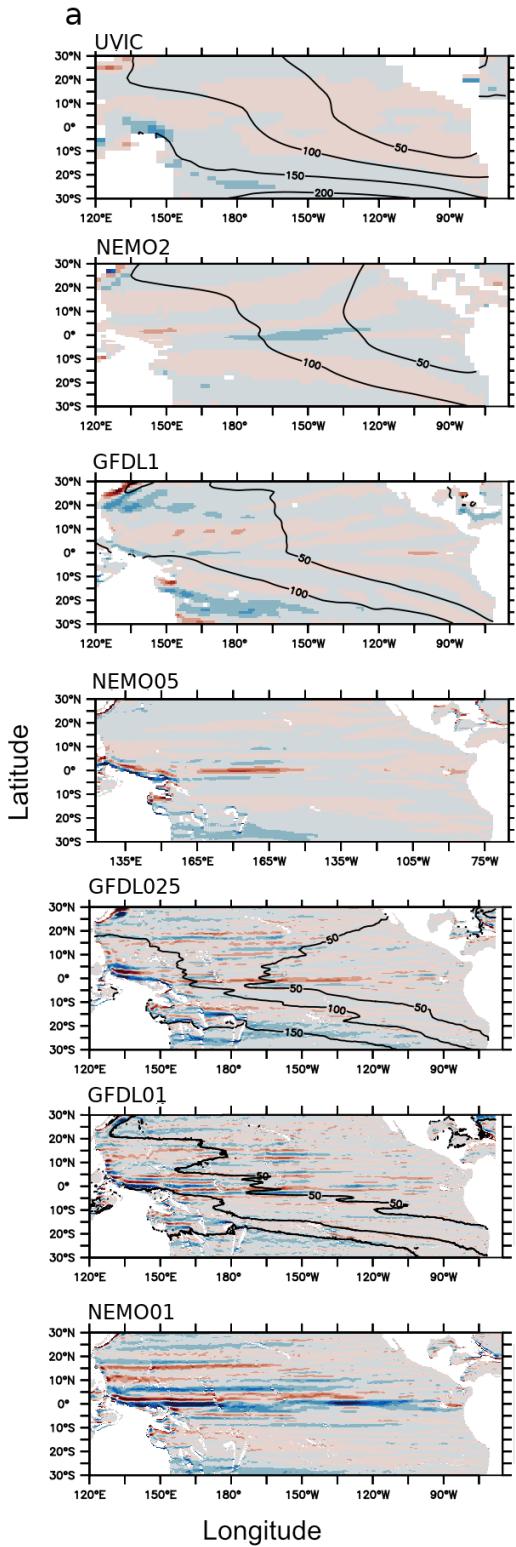
Zonal velocity component at 100°W (colors) and oxygen (contours)



Figure 5 : mean currents velocity (ms$^{-1}$) at a- 1000 m depth  b- 100°W in UVIC, NEMO2,  NEMO05, GFDL025, GFDL01, NEMO01. The mean oxygen levels (mmol.m$^{-3}$) (when coupled circulation-biogeochemical experiments have been performed – see Table 1) are displayed in contour

NEMO05                                      NEMO001

Tracer concentration (colors) and WOA oxygen (contours)



Time of t10% (colors) and WOA oxygen (contours)



Fig

Figure 6: a : tracer concentration (arbitrary unit) after 60 years integration in NEMO05 and NEMO01: average 500-1500m, section 100°W, equatorial section. b: Time (years) at which the released tracer reaches the concentration 0.1 (t10%) in NEMO05 and NEMO01: average 500-1500m, section 100°W, equatorial section. In all the subpanels, the WOA oxygen levels are displayed in contour. The red contour is the WOA 150 mmol.m$^{-3}$ oxygen isoline, used to initialize the tracer level.

Figure 7 : Density (number of particles in a 1°x1°x100m depth box) distribution of the location of released Lagrangian particles (15 years backward integration starting from the final experiment state) in NEMO05 and NEMO01. The release location is identified in bold and is located a- at 100°W/5°N-5S/1000 m depth (R1). b- at 160°E/5°N-5°S/1000 m depth (R2). The particles have been integrated vertically, zonally and meridionally. The observed mean oxygen levels (WOA) are displayed in contour.

Figure 8 :  a- schema summarizing the releases (R1: 100°W / 5°N-5°S / 1000 m , R2: 160°E / 5N°5S / 1000 m) location, the IETP (Intermediate Eastern Tropical Pacific), IWTP (Intermediate Western Tropical Pacific) regional extension. b. percentage of particles (release R1) originating from outside the IETP ocean region. b- percentage of particles (release R2) originating from outside the IWTP ocean region. d- percentage of particles (release R1) originating from the upper ocean (shallower than 200 m), the deeper ocean (deeper than 2000 m), subtropical regions (poleward 10°), the IWTP. e- percentage of particles (release R2) originating from the upper ocean (shallower than 200 m), the deeper ocean (deeper than 2000 m), subtropical regions (poleward 10°), the IETP.

**Mean kinetic energy**
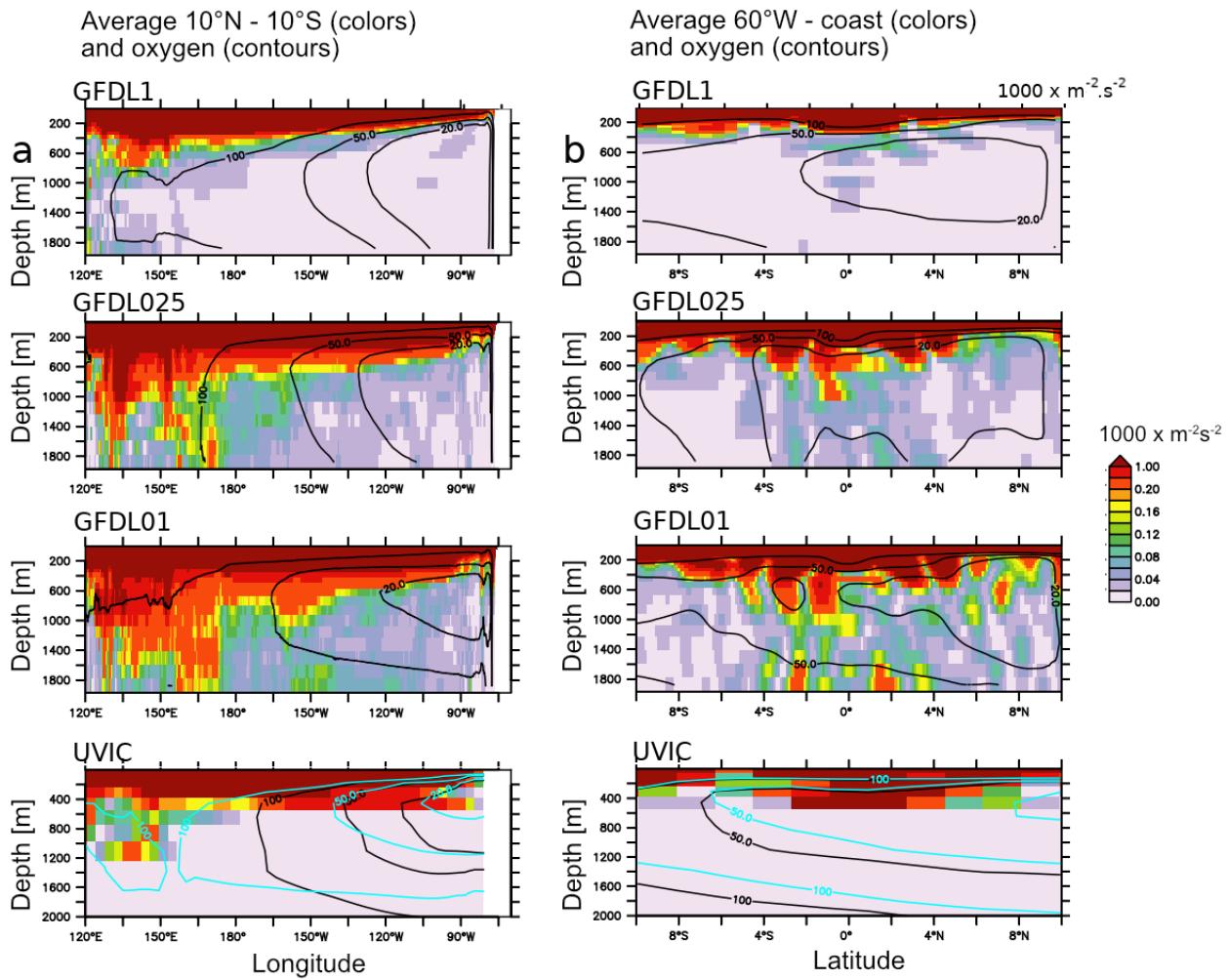


Figure 9 : a -  Mean Kinetic Energy (m2.s$^{-2}$ x 1000) (average 10°N-10°S) in GFDL01, GFDL025, GFDL01, UVIC, b - similar to a. but average 160°W- coast. Oxygen levels (mmol.m$^{-3}$) are displayed in black contour. The blue contour corresponds to UVIC GD13 (Getzlaff and Dietze, 2013, including an anisotropical increase of lateral diffusion at the equator)

Table 1 :

| Model | Resolution | Atmosphere | Integration (years) | BGC | Model Reference (circulation) | Model Reference (BGC) |
|---|---|---|---|---|---|---|
| **Mean state comparison** | | | | | | |
| UVIC | 2.8° | Coupled (temperature, humidity) Forced (NCEP/ NCAR wind stress) | 10000 | UVIC-BGC | Weaver et al., 2001 | Keller et al., 2012 |
| NEMO2 | 2° (0.5 eq) | Forced COREv2 "normal year" | 1000 | NPZD-O2 | Madec et al., 2015 | Kriest et al, 2010 Duteil et al., 2014 |
| GFDL1 | 1° | Coupled | 190 | BLING | Delworth et al, 2012, Griffies et al, 2015 | Galbraith et al., 2015 |
| GFDL025 | 0.25 ° | Coupled | 190 | BLING | | |
| GFDL01 | 0.1° | Coupled | 190 | BLING | | |
| | | | | | | |
| **Process oriented experiments** | | | | | | |
| Model | Resolution | Atmosphere | Integration (years) | BGC | Characteristics | |
| NEMO2 -REF -30N30S -30N30S1500M (section 2.2.1) | 2° (0.5 eq) | Forced COREv2 1948-2007 | 60 | NPZD-O2 | - control experiment - O2 restoring to WOA at 30°N/30°S - O2 restoring to WOA at 30°N/30°S/1500m | |
| NEMO05 (section 2.2.2) | 0.5° | Forced COREv2 1948 - 2007 | 60 | Tracer release | - Tracer initialized to 1 (O2 WOA > 150 mmol.m-3) or 0 (O2 WOA < 150 mmol-m-3) | |
| NEMO01 (section 2.2.2) | 0.1° | Forced COREv2 1948 – 2007 | 60 | Tracer release | | |

1   **Intermediate water masses, a major supplier of oxygen for the eastern tropical Pacific ocean**

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4

5   **Abstract**

6   It is well known that Intermediate Water Masses (IWM) are sinking in high latitudes and ventilate

7   the lower thermocline (500 – 1500 m depth). We here highlight how the IWM oxygen content and

8   the IWM pathway along the Equatorial Intermediate Current System (EICS) towards the eastern

9   tropical Pacific ocean are essential for the supply of oxygen to the lower thermocline and the

10  Oxygen Minimum Zones (OMZs). To this end, we assess here a heterogeneous subset of ocean

11  models characterized by a horizontal resolution ranging from 0.1° to 2.8°. Subtropical oxygen

12  levels in the lower thermocline, i.e., IWM are statistically correlated with tropical oxygen levels and

13  OMZs. Sensitivity simulations suggest that the oxygen biases of the subtropical IWM oxygen levels

14  contribute to oxygen biases of the tropical thermocline : an increase of the IWM oxygen by 60

15  mmol.m$^{-3}$ results in a 10 mmol.m$^{-3}$ increase in the tropical ocean in a timescale of 50 years. In the

16  equatorial regions, the IWM recirculates into the Equatorial Intermediate Current System (EICS).

17  By comparing tracer and particle release simulations, we show that a developed EICS increases

18  eastern tropical ventilation by 30 %. Typical climate models lack in representing crucial aspects of

19  this supply: biases in IWM properties are prominent across climate models and the EICS is

20  basically absent in models with typical resolutions of ~1°. We emphasize that these biases need to

21  be reduced in global climate models to allow reliable projections of OMZs in a changing climate.

22

23  **1. Introduction**

24  Oxygen levels in the ocean are characterized by high values in the high latitudes and the subtropical

25  gyres, while concentrations decrease to close to zero in the tropical oceans in the Oxygen Minimum

26  Zones (OMZs). While OMZs are natural features, climate change is potentially responsible for their

27  expansion (Breitburg et al., 2018), leading to a reshaping of the ecosystems and a potential loss of

28  biodiversity. In order to perform robust projections there is a need to better understand the processes

29  at play that are responsible for the supply of oxygen to the OMZ. We focus here on the Pacific

30  ocean, where the largest OMZs are located (Karstensen et al., 2008; Paulmier and Ruiz-Pino. 2009)

31

32  Oxygen rich waters are supplied into the ocean by subduction processes (Karstensen et al., 2008).

33  Oxygen solubility increases with lower temperatures, thus waters formed in– the Southern Ocean

34  and in the North Pacific are characterized by particularly high oxygen values. In particular, the

Antarctic Intermediate Water (AAIW) (Molinelli, 1981) ventilates large areas of the lower thermocline of the Pacific Ocean (Sloyan and Rintoul., 2001) and is characterized by oxygen values larger than 300 mmol.m$^{-3}$ at subduction time (Russel and Dickson, 2003). The oxygenated core of the AAIW in the tropical Pacific is located at about 500-1200 m depth at 40°S (Russell and Dickson, 2003) and with this at a depth directly below the depth of the OMZs in the eastern Pacific; the Pacific AAIW mixes down to 2000 m depth with the Pacific Deep Water (PDW) as determined by the OMP (Optimum Multiparameter) analysis (Pardo et al., 2012; Carrasco et al., 2017). The oxygen rich (> 200 mmol.m$^{-3}$ at 40°S) AAIW spreads from its formation side in the Southern Ocean to the subtropical regions ; conversely the oxygen poor PDW (below 150 mmol.m$^{-3}$), extends till 3000m depth and recirculates poleward (Koshlyakov and Tarakanov, 2003). The northern part of the Pacific basin is characterized by the North Pacific Intermediate Water (NPIW) (Talley, 1993) confined to the northern Pacific conversely to the AAIW, which spreads far northward as it signature reaches 15°N (Qu and Lindstrom., 2004). AAIW, NPIW and the upper part of the PDW are oxygenated water masses occupying the lower thermocline between 500 and 1500 m depth. We will refer to these waters as Intermediate Water Masses (IWM) in the following.

In the subtropics, the IWM (more particularly the AAIW) circulates into the intermediate flow of the South Equatorial Current and the New Guinea Coastal Undercurrent (Qu and Lindstrom, 2004) where it retroflects in the zonal equatorial flows of the Southern Intermediate Countercurrent (SICC) and Northern Equatorial Intermediate Current (NEIC) within about ±2° off the equator (Zenk et al., 2005; Kawabe et al., 2010) (Fig 1). These currents are part of the Equatorial Intermediate Current System (EICS) constituted by a complex system of narrow jets extending below 500 m in the lower thermocline (Firing, 1987; Ascani et al., 2010; Marin et al. 2010; Cravatte et al., 2012, 2017; Menesguen et al., 2019). While the existence of this complex jet system has been shown to exist in particular using argo floats displacements (Cravatte et al., 2017) the spatial structure and variability of the jets are still largely unknown. In addition, there is little knowledge about their role in transporting properties such as oxygen.

The simulation of the supply of oxygen to the eastern tropical Pacific is a difficult task as it depends on the realistic simulation of the IWM properties (in particular the oxygen content) and the IWM pathway (through the EICS). –It is known that current climate models, in particular CMIP5 (Coupled Model Intercomparison Project phase 5) models, have deficiencies in correctly representing the IWM, and in particular the AAIW. They generally display too shallow and thin IWM, with a limited equatorward extension compared to observations (Sloyan and Kamenkovich,

2007; Sallee et al., 2013; Meijers, 2014; Cabre et al., 2015; Zhu et al., 2018 for the south Atlantic ocean). Discrepancies in the simulated properties of IWM compared to observations are due to a combination of many errors in the climate models, including simulation of wind and buoyancy forcing, inadequate representation of subgrid-scale mixing processes in the Southern Ocean, and midlatitude diapycnal mixing parameterizations (Sloyan and Kamakovich, 2007; Zhu et al., 2018). In addition, the representation of the EICS is lacking in coarse resolution models (Dietze and Loeptien, 2013; Getzlaff and Dietze, 2013). Higher resolution (0.25°, 1/12°) configurations partly resolve the EICS but with a smaller amplitude than observed (Eden and Dengler, 2008; Ascani et al., 2015). The mechanisms forcing the EICS are complex and still under debate (see the review by Menesguen et al., 2019).

-

In this study we focus on the impact of IWM (and of the deficiencies in the representation of their properties and transport) on the oxygen content in the eastern tropical Pacific in a set of model simulations. Section 2 gives an overview of all models that we used as well as of the sensitivity simulations. Next, we assess to which extent the IWM modulate (or drive) the oxygen levels in the eastern tropical (20°S – 20°N; 160°W-coast) Pacific ocean in this set of models. The role of the IWM depends i) on the oxygen content of the IWM in the lower thermocline of the subtropical regions (section 3) and ii) on the zonal recirculation of the oxygen by the EICS toward the eeastern part of the basin (section 4). We conclude in section 5.


**2. Analyzed models and experiments**

2.1 Mean state

We analyze the mean state of the oxygen fields, OMZ, EICS of the following model experiments (see Table 1), which previously have been used in recent studies focusing on the understanding of the tropical oxygen levels mean state or variability :

- thea NEMO (Nucleus for European Modelling of the Ocean) model configuration (Madec et al., 2017) with a resolution of 2°, refined meridionally to 0.5° in the equatorial region n (NEMO2) (NEMO2 configuration). The circulation model is coupled to a simple NPZD (Nutrient Phytoplankton Zooplankton Detritus) biogeochemical model that comprises 6 compartments (e.g used in Duteil et al., 2018; Duteil, 2019). The simulation has been forced by climatological forcings based on the Coordinated Reference Experiments (CORE) v2 reanalysis (1948-2007) (Large and Yeager, 2009) and integrated for 1000 years.

- the UVIC (University of Victoria) model (e.g used in Getzlaff et al., 2016; Oschlies et al., 2017), an earth System Model (ESM) that has a horizontal resolution of 1.8° latitude x 3.6° longitude. The

3

experiment has been integrated for 10000 years. The biogeochemical model is a NPZD-type model of intermediate complexity that describes the full carbon cycle (see Keller et al., Keller 2012 for a detailed description). This model is forced by monthly climatological NCAR/NCEP wind stress fields.

- the GFDL (Geophysical Fluid Dynamics Laboratory) CM2-0 suite (Delworth et al., 2012; Griffies et al., 2015, Dufour et al, 2015): the suite is based on the GFDL global climate model and includes a fully coupled atmosphere with a resolution of approximately 50 km. It consists of three configurations that differ in their ocean horizontal resolutions: GFDL1 with a nominal 1° resolution, GFDL025 with a nominal 0.25° and GFDL01 with a nominal 0.1° resolution (e.g used in Frenger et al., 2018 and Busecke et al., 2019 for studies on ocean oxygen). The climate models are forced with preindustrial atmospheric pCO2 concentrations. At simulation year 48, the simplified ocean biogeochemistry model miniBLING is coupled to the models, with three prognostic tracers, phosphate, dissolved inorganic carbon and oxygen (Galbraith et al., 2015). Due to the high resolution of GFDL01, the integration time is limited. We here analyze simulation years 186 to 190. All the models (NEMO2, UVIC, GFDL suite) are forced using preindustrial atmospheric pCO2 concentrations.

The heterogeneity of the configurations that we analyze permits to determine whether the simulated oxygen distributions of the models display systematic biases or are strongly configuration dependent (e.g dependent on resolution). Differences in model resolution but also in atmosphere forcings or spinup duration strongly impact oxygen distribution (see Annex A). However, the heterogeneity of the configurations that we analyze permits to determine whether the simulated oxygen distributions display systematic biases / similar patterns.

The mean states of the oxygen distributions are discussed below in section 3.1 "TWM Oxygen levels in models".

-

## 2.2 Sensitivity simulations

In order to disentangle the different processes at play we perform two different sets of sensitivity simulations using the ewith one of the models, NEMO model engine. NEMO allows to test effects of increasing the ocean resolution and to integrate the model over a relatively long time span. All sensitivity experiments are integrated for 60 more than 50 years (1948 to 2007) using the CORE

4

135  (Coordinated Ocean-Ice Reference Experiments) v2 interannual (Large and Yeager, 2009) forcings.

136  This time scale permits the recirculation from the interior subtropical regions to the tropical area (as

137  suggested in the model study by SenGupta and England, 2007).

138

139  2.2.1 Oxygen forcing ~~restoring~~ to observations in the subtropical regions

140  In the first set of experiments the focus is on the role of the lower thermocline oxygen content for

141  the ventilation of the eastern equatorial Pacific. We use NEMO2, the oceanic component of the

142  IPSL-CM5A (Mignot et al., 2013), that is part of CMIP5. NEMO2 shows mid-latitudes oxygen

143  biases consistent with CMIP5 models. We compare three experiments :

144  - NEMO2-REF: the experiment is integrated from 1948 to 2007 starting from the spinup state

145  described in 2.1.

146  - NEMO2-30S30N~~DEG~~: the oxygen boundaries are forced ~~restored~~ to observed oxygen

147  concentrations (WOA) at the boundaries 30°N and 30°S : the mid-latitude supply of oxygen by the

148  IWM is therefore correctly represented.

149  - NEMO2-30S30N~~DEG~~1500M: same as NEMOO2-30S30N~~DG~~ ; in addition oxygen is ~~also~~ forced

150  ~~restored~~ at the depth interface of 1500m, mimicking a correct oxygen state of the deeper water

151  masses (lower part of the AAIW, upper part of the PDW)

152

153  We focus with the above three experiments on the transport of IWM oxygen levels to the tropical

154  ocean and the OMZs. The respiration rate (oxygen consumption) is identical in NEMO2-REF,

155  NEMO2-30S30N~~DEG~~ and NEMO2-30S30N~~DEG~~1500M in order to avoid compensating effects

156  between supply and respiration that depend~~s~~ on biogeochemical parameterizations (e.g Duteil et al.,

157  2012). We aim to avoid such compensating effects to ease interpretation and be able to focus on the

158  role of physical transport. The sensitivity of tropical IWM oxygen to subtropical and deep oxygen

159  levels is discussed in section 3.2

160

161  2.2.2 Conservative Tracer Release in oxygenated waters

162  In a second set of experiments, we performed tracer release experiments in a coarse 0.5°

163  (NEMO05) and high resolution 0.1° (NEMO01) configuration~~s~~ of the NEMO model engine (Table

164  1) to examine the transport of oxygenated IWM from the subtropical regions into the oxygen

165  deficient tropics. NEMO01 is a configuration based on NEMO05 and where a 0.1° two-ways nest

166  has been embedded in the whole Pacific Ocean, from 49°S to 31°N (Czeschel et al, 2011). In these

167  experiments, we initialized the regions with climatological (WOA) oxygen levels greater than 150

168  mmol.m$^{-3}$ with a value of 1 (and 0 when oxygen is lower than 150 mmol.m$^{-3}$). In the model

simulations, the tracer is subject to the same physical processes as other physical and biogeochemical tracers, i.e. advection and diffusion but it does not have any sources and sinks. The experiments have been integrated for 60 years (1948 – 2007) using realistic atmosphere forcing (COREv2). NEMO05 and NEMO01 display a similar upper ocean circulation (Fig 5) but NEMO05 does not simulate a developed EICS contrary to NEMO01.

In order to complement the tracer experiment we performed Lagrangian particle releases. Lagrangian particles allow to trace the pathways of water parcels due to the resolved currents, and to track the origin and fate of water parcels. They are not affected by subgrid scale mixing processes. The particles are advected offline with 5 days daily means of the NEMO05 and NEMO01 currents. The NEMO01 circulation fields have been interpolated on the NEMO05 grid in order to allow a comparison of the large scale advective patterns between NEMO01 and NEMO05. We used the ARIANE tool (Blanke and Raynaud, 1997). A first particle release has been performed in the eastern tropical OMZ at 100°W in the tropical region between 5°S - 5°N, a second release has been performed in the western part of the basin at 160°E. The particles have been released in the lower thermocline at 1000 m and integrated backward in time from 2007 to 1948 in order to determine their pathways and their location of origin. We released 120 particles every 5 days during the last year of the experiment, for a total of 8760 particles. The transport by the EICS is discussed in section 4.2 (tracers levels and Lagrangian pathways).

**3. Intermediate water properties and oxygen content**

3.1. IWM Oxygen levels in models

The IWM subducted in mid/high latitudes are highly oxygenated waters. As part of the deficient representation of IWM, the subducted "oxygen tongue" (oxygen values up to 240 mmol.m$^{-3}$) is not reproduced in most of the models part of CMIP5 (Fig 8 from Cabre et al., 2015, Fig 4 from Takano et al., 2018) and in the models analyzed here (Fig 2a), with biases of about 20-60 mmol.m$^{-3}$ (NEMO2, GFDL1, GFDL025, GFDL01). UVIC, a coarse resolution model, shows oxygenated waters in the lower thermocline at mid latitudes (30°S-50°S); the oxygenation however arises due to a too large vertical diffusion from the mixed layer rather than by an accurate representation of the water masses.

GFDL01, even though still biased low, presents larger oxygen values than the coarser resolution models GFDL1, GFDL025 and NEMO2. A possible explanation is a better representation of the water masses and in particular the AAIW in eddy-resolving models (Lackhar et al., 2009).

The IWM oxygen maximum is apparent at 30°S throughout the lower thermocline (600 – 1000 m) in observations (Fig 2b), consistent with the circulation of IWM with the gyre from the mid/high latitude formation regions towards the northwest in subtropical latitudes, and followed by a deflection of the waters in the tropics towards the eastern basin. This oxygen peak is missing in all the models analyzed here.

Consistent with the low oxygen bias of models at subtropical latitudes (Fig 2b), models also feature a bias in the tropical ocean (20°S-20°N) by 20 – 50 mmol.m$^{-3}$ (Fig 2a, Fig 2c) at intermediate depths in the eastern part of the basin (similarly to CMIP5 models, as shown by Cabre et al., 2015). The basin zonal average of the mean oxygen level in the lower thermocline (layer 500 - 1500) m at 30°S and in the eastern part of the basin (average 20°S – 20°N, 160°W-coast; 500-1500 m) are positively correlated (Pearson correlation coefficient R=0.73) (Fig 2d, Annex A), suggesting a large role of the IWM in controlling the oxygen levels in the tropical oceans.

The models presenting the poorest oxygenated water at 30°S display the largest volume of OMZs (GFDL025 and GFDL1), though the negative correlation (Pearson correlation coefficient R=-0.52) is less pronounced between the volume of the OMZs and the mean oxygen levels in the layer 500 - 1500 m at 30°S (Fig 2e). Reasons of this weaker correlation are due to the OMZs being a result of several processes next to oxygen supply by IWM, e.g, vertical mixing with other water masses (Duteil et al., 2011), isopycnal mixing in the upper thermocline (Gnanadesikan et al., 2013; Bahl et al., 2019), supply by the upper thermocline circulation (Shigemitsu et al., 2017; Busecke et al., 2019). A correlation, even weak, suggests a major role of the IWM in regulating the OMZ volume.

In order to better understand the role of IWM entering the subtropical domain from higher latitudes for the oxygen levels in the eastern tropical Pacific Ocean, we perform sensitivity experiments (see 2.2.1) in the following.

3.2 Sensitivity of tropical IWM oxygen to subtropical and deep oxygen levels

3.2.1 Oxygen levels in the lower thermocline

The difference of the experiments NEMO2-30S30NDEG – NEMO2-REF (average 1997-2007) (Fig 3c,d) allows to quantify the effect of model biases of IWM at mid latitudes (30°N/30°S). As we restore oxygen to observed levels at 30°S/°N (see 2.2.1), the difference shows a large anomaly in oxygen levels at 30°S (more than 50 mmol.m$^{-3}$) at lower thermocline level (500 – 1500 m) corresponding to the missing deep oxygen maximum (Fig 3). The northern negative anomaly results from a deficient representation of the north Pacific OMZ, i.e., modeled oxygen is too high for NPIW. The northern low and southern high anomalies spread towards the tropics at intermediate depth. A fraction of the positive oxygen anomaly recirculates at upper thermocline level due to a combination of upwelling and zonal advection by the tropical current system (for instance the EUC at thermocline level is a major supplier of oxygen as shown in observations by Stramma et al., 2010 and in ocean models by Duteil et al., 2014, Busecke et al., 2019).

The difference NEMO2-30S30NDEG1500M – NEMO2-30S30NDEG (Fig 3e,f hf) shows a deep positive anomaly in oxygen, as oxygen levels are lower than in observations by 30-40 mmol.m$^{-3}$ in the eastern tropical regions. This anomaly is partially transported into the lower thermocline (500 - 1500 m). It shows that a proper representation of the deep oxygen level (> 1500 m) is important for a realistic representation of the lower thermocline and OMZs. Causes of the oxygen bias of the deeper water masses are beyond the scope of this study but may be associated with regional (tropical) issues, such as an improper parameterization of respiration (e.g a too deep remineralisation) (Kriest et al., 2010), or a misrepresentation of deeper water masses.

3.2.2 Oxygen budget and processes

To assess the processes that drive the oxygen content of the (sub)tropical lower thermocline, we analyzed the oxygen budget in NEMO2-REF and NEMO2-30S30NDEG. The budget is computed calculated as an average between 500 and 1500m and shown in Fig 3g and Fig.4.

The oxygen budget is :

$$\frac{\delta O_2}{\delta dt} = Adv_x + Adv_y + Adv_z + Diff_{Dia} + Diff_{Iso} + SMS$$

where $Adv_x$, $Adv_y$, $Adv_z$, are respectively the zonal, meridional and vertical advection terms, $Diff_{dia}$ and $Diff_{iso}$ are the diapycnal and isopycnal diffusion terms. SMS (Source Minus Sink) is the biogeochemical component (i.e respiration below the euphotic zone)

In NEMO2-REF, the physical oxygen supply is balanced by the respiration. The oxygen supply in the model is divided into advection, i.e., oxygen transport associated with volume transport, and isopycnal diffusion, i.e., subgrid scale mixing processes that homogenize oxygen gradients (Fig 4a). Diapycnal diffusion is comparatively small and can be neglected. The lower branches of the subtropical gyres transport the oxygen from the eastern to the western part of the basin (Fig 4a,b). Downwellings from the oxygen-rich mixed upper layer supply the interior of the subtropical gyres (Fig 4c). At the equator, the EICS transport westward oxygen-poor water originating in the eastern side of the basin (Fig 4a). Concomitantly, the meridional advection term transports oxygen originating from the subtropics in the tropical regions (Fig 4b), which is upwelled (Fig 4c). Isopycnal diffusion transfers oxygen from the oxygen-rich gyres to the poor oxygenated regions (Fig 4d).

The anomalies generated at 30°S and 30°N by the restoring experiment generate a disbalance between respiration (which remains identical in NEMO2-REF and NEMO2-30S30NDEG) and supply. This disbalance is most apparent in the tropics by an increase (south) or decrease (north) of isopycnal diffusion (Fig , g4Fig 3gh, Fig 4b). Changes in the advective terms can be found along the equator: as the vertical gradient of oxygen decrease (the intermediate ocean being more oxygenated), the vertical supply from the upper ocean decreases in the south (increases in the north) subtropical gyre and decreases at the equator (Fig 4bg). The meridional oxygen gradient between the southern subtropical gyre and the equator strengthens, and so the meridional transport from the subtropics to  the equator, partly by the western boundary currents (Fig 4f). The changes in zonal transport are comparatively small (Fig 4e). The total advective term does not present show significant change however (Fig 4g).

In the experiment NEMO2-30S30NDEG1500, in complement to the isopycnal propagation of the subtropical anomaly, the deep (> 1500 m) oxygen anomaly is upwelled in the eastern equatorial (500 – 1500 m) part of the basin (see Fig 3g4i) showing a large increase in advective terms, mostly due to an increase in vertical advection), consistent with the analysis by Duteil (2019) who showed that vertical advection is the dominant process to supply oxygen from the lower to the upper thermocline in the equatorial eastern Pacific Ocean in a similar NEMO2 configuration.

This simple set of experiment shows that in climate models oxygen in the lower thermocline (500 – 1500 m) ocean are partially controlled by properties of IWM that enter the tropics from higher latitudes. This presumably applies to other (biogeochemical) tracers. IWM oxygen propagates

equatorward mostly by small scale isopycnal processes and the western boundary currents. Further, upwelling in the tropics from deeper ocean layers (Pacific Deep Water, partially mixed with the lower IWM) play an important role-. Our budget analysis highlighted the importance of advective processes in the equatorial region in the lower thermocline which we will examine more closely in the following.

**4. Equatorial intermediate current system and oxygen transport**

4.1 Structure of the currents in the upper 2000 m in observations and models-

The current structure of the models analyzed in this study (see section 2.1, Table 1) is shown in Fig. 5. In the ~~upper~~ mixed layer, the broad westward drifting South and North Equatorial Currents (SEC, NEC) characterize the equatorial side of subtropical gyres. In the thermocline, the eastward flowing equatorial undercurrent (EUC), flanked by the westward flowing south and north counter currents are present in all models. This upper current structure is well reproduced (i.e the spatial structure and intensity are consistent with observations) across the different models (see 2.1 "Model analyzed") compared to observations. Previous studies already discussed -the upper thermocline current structure in the GFDL models suite (Busecke et al., 2019), NEMO2 and NEMO05 (e.g Izumo, 2005, Lübbecke et al., 2008), UVIC (Loeptien and Dietze, 2013); the upper thermocline will not be further discussed in this study.

At intermediate depth, in the observations, a relatively strong (about 0.1 ms$^{-1}$) westward flowing Equatorial Intermediate Current (EIC) is present below the EUC at about 400-600 m depth (Marin et al., 2010). A complex structure of narrow and vertically alternating jets every 200 m, so-called Equatorial Deep Jets (EDJ), extends below the EIC till 2000 m (Firing, 1987; Cravatte et al., 2012). Laterally to the EIC, in the upper thermocline, the Low Latitude Subsurface Countercurrents (LLSC) are observed. They include the North and South Subsurface Counter Currents (NSCC and SSCC), located around 5°N/5°S, and a series of jets between 5°N/S and 15°N/S (in particular the Tschuchiya jets in the southern hemisphere, described by Rowe et al., 2000). Below the LLSCs, the Low Latitude Intermediate Currents (LLICs) include the a series of westward and eastward zonal jets (500–1500-m depth range) alternating meridionally from 3°S to 3°N; the North and South Intermediate Countercurrents (NICC and SICC) flow eastward at 1.5°–2° on both flanks of the lower EIC. The North and South Equatorial Intermediate Currents (NEIC and SEIC) flow westward at about 3° (Firing, 1987). A detailed schematic view of the tropical intermediate circulation is shown in a recent review by Menesguen et al. (2019) and in Fig 1.

In coarse resolution models, the intermediate current system is not developed and sluggish (even missing in UVIC and GFDL1). NEMO2 and NEMO05 display a "primitive" EICS as the LLSCs are not represented. High resolution models (GFDL025, GFDL01, NEMO01) display a more realistic picture, even if the mean velocity is still weaker than in observations (smaller than 5 cm.s$^{-1}$), where it reaches more than 10 cm$^{-1}$ at 1000 m (Ascani et al., 2010; Cravatte et al., 2017). An interesting feature is that the jets are broader and faster in NEMO01 than in GFDL01. Possible causes include –a different wind forcing, mixing strength or topographic features as all these processes play a role in forcing the intermediate jets (see the review by Menesguen et al., 2019). The intermediate currents are less consistent vertically in NEMO01 than in GFDL01, due to their large temporal variability in NEMO01. A strong seasonal and interannual variability of the EICS has been observed that displays varying amplitudes and somewhat positions of the main currents/jets (Firing, 1998; Gouriou et al., 2006: Cravatte et al., 2017). A clear observational picture of the EICS variability is however not yet available. Outside the tropics (in particular south of 15°S), the interior velocity pattern is similar in coarse and high resolution models, suggesting a similar equatorward current transport at intermediate depth in the subtropics, in for instance NEMO05 and NEMO01.

## 4.2 Transport by the EICS

### 4.2.1 Tracer spreading towards the eastern tropical Pacific

We released a conservative tracer in the subtropical domain in well oxygenated waters (see 2.2.2) in a coarse (NEMO05) and a high resolution configuration (NEMO01). The tracer does not have sources or sinks and is advected and mixed as any other model tracer and allows to assess the spreading of tracer (such as oxygen) from oxygenated waters into the oxygen deficient eastern tropical Pacific.

The  ventilation by the oxygen rich waters, and in particular the IWM, is illustrated by the tropical tracer concentration after 50 years (Fig 6a-c) of integration (mean 2002-2007). Concentrations decrease from the release location to the northern part of the basin, where the lowest values (below 0.1) are located in NEMO05 and NEMO01. The 0.1 isoline is however located close to the equator in NEMO05 while it is found around 7°N in NEMO01. This feature is associated with a pronounced tongue of high tracer concentration (> 0.2) between 5°N and 5°S in NEMO1. Such a tongue is absent in NEMO05. The enhanced tracer concentration in the equatorial region suggests a stronger equatorial ventilation in NEMO01.

The preferential pathways of transport are highlighted by the determination of the transit time it takes for the tracer to spread from the oxygen rich regions to the tropical regions. We define a threshold called t10% when the tracer reaches a concentration of 0.1 (Fig 6~~bd~~ f) (similar to the approach of SenGupta and England, 2007). t10% highlights a faster ventilation of the equatorial regions in NEMO01 compared to NEMO05, as t10% displays maximum value of 10 (western part) to 30 years (eastern part) between 5°N/5°S in NEMO01 compared to 30 years to more than 50 years in NEMO05. The southern "shadow zone" is well individualized in NEMO01 compared to NEMO05 as the oxygen levels are high in the equator in NEMO01, suggesting a strong transport by the EICS. While t10% increases linearly at intermediate depth at 100°W in NEMO05 from 20°S to the equator, suggesting a slow isopycnal propagation (consistent with the experiments performed using NEMO2 in part 3.2), the tracer accumulation is faster in the equatorial regions than in the mid-latitudes in NEMO01, suggesting a large role of advective transport, faster than a transport by diffusive processes.

4.2.2 Equatorial lower thermocline water mass origin

Lagrangian Particles (see 2.2.3) allow us to understand the origin of the waters in the lower thermocline. They also allow to disentangle the transport of the resolved currents of the EICS (advection) from subgrid scale mixing processes, i.e. to assess the processes responsible for the equatorial ventilation. Two releases R1 and R2 have been performed in the eastern and western part of the basin in order to assess the equatorial circulation in NEMO05 and NEMO01.

The ~~particles of the first r~~release R1 ~~i~~in the eastern tropical Pacific (100°W, 5°N-5°S, ~~at~~ 1000 m depth ~~where the EICS are located~~) ~~origin from~~ is included in the larger intermediate eastern tropical pacific (IETP) ocean region (160°W – coast / 10°N-10°S / 200 – 2000 m ) ~~.~~ The particles originate close to the region of release (IETP)~~,~~ in 60 % of the cases in NEMO05 and 50 % of the cases in NEMO01, at a time scale of 50 years (Fig 7a ~~c~~ and 8~~b~~a). In NEMO05, after 50 years, the particles originating outside the IETP come either from the upper (0 – 200 m) ocean (5 %), deep ( > 2000 m) ocean (1%), higher ( > 10°) latitudes (23 %), western (west of 160°W) part of the basin (21 %) (Fig 8~~d~~e). The largest difference between NEMO05 and NEMO01 is the much larger amount of particles originating from the deep ocean in NEMO01 (8 % in NEMO01), suggesting the presence of vertical recirculation cells at intermediate depths. The advection processes are also considerably faster in NEMO01, in particular the zonal advective ones. The relative difference between NEMO05 and NEMO1 is particularly strong 15 years after the release (approximately corresponding to the t10% at 1000 m at the equator in NEMO01), as already 10 % of the particles originate outside the IETP,

in regions where the oxygen levels are high, in NEMO01 while this fraction is close to 0 in NEMO05.

The ~~particles~~ location of the second release R2 (160°E, 5°N-5°S, 1000 m depth)~~are originally~~ is included ~~located~~ in the intermediate western tropical pacific ~~Ocean~~ (IWTP) ocean region (160°W – coast / 10°N-10°S / 200 – 2000 m) (Fig 7b~~e-f~~). After 50 years, all the particles originate outside of the IWTP ~~is box~~ in NEMO01 (Fig 8c~~b~~) (50 % originate in the eastern basin, 23 % in the deep ocean, 24 % outside the equatorial band, 3 % in the upper 200 m) (Fig 8e~~d~~) while only 70 % of the particles originate outside the IWTP in NEMO05 (39 % in the eastern basin, 27 % outside the equatorial band, 2 % in the deep ocean and 2 % in the upper ocean).

The Lagrangian ~~particle~~ experiments ~~results~~ point to a generally stronger ventilation at intermediate depth in NEMO01 due to the EICS, which reinforces the connections between western / eastern part of the basin and thermocline / deep ocean.

4.3 Equatorial oxygen levels in models

Our analyses above permit to better understand the distribution of the oxygen levels at the equator in a suite of models characterized by an increasing resolution, such as the GFDL model suite. 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 are also more homogeneous zonally in GFDL01, with a weaker east/west gradient, consistent with the tracer experiment that we performed in 4.2. The oxygen distribution fits with the mean kinetic energy of the intermediate currents below 1000 m (Fig 9a), especially in the eastern part of the basin (Fig 9b). Resolving the EICS results in a similar distribution ~~results~~ as what Getzlaff and Dietze (2013) achieved with a simple parameterization of the EICS (Fig 9a). To compensate for the "missing" EICS in coarse resolution models, they enhanced anisotropically the lateral diffusivity in the equatorial region. Implementing this approach tends to homogeneize 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.

A possibly not intuitive feature is that the oxygen levels are relatively similar in GFDL025 and GFDL1, while the current system is relatively similar in GFDL025 and GFDL01 (see Fig 5 and Fig 9). An explanation lies in the relatively small net balance between large fluxes of respiration and oxygen supply (Duteil et al., 2014). If the supply is slightly higher compared to the consumption by

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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.

## 5. Summary and conclusions-

Intermediate water masses (IWM) are subducted in the Southern Ocean and  transported equatorward to the tropics by isopycnal processes (Sloyan and Kamenkovich, 2007; Sallee et al., 2013; Meijers, 2014). At lower latitudes they recirculate into the lower thermocline of the tropical regions at 500 - 1500 m and into  the EICS (Zenk et al., 2005; Marin et al., 2010; Cravatte et al., 2012; 2017; Ascani et al., 2015;  Menesguen et al., 2019) (see schema Fig 1). We show here that the representation of this ventilation pathway is important to take into account when assessing tropical oxygen levels and the extent of the OMZ in coupled biogeochemical circulation or climate models. Particularly, we highlight two critical, yet typical, biases that hamper the correct representation of the tropical oxygen levels.

5.1 Subducted I~M~WM properties and tropical oxygen

First, the current generation of climate models, such as the CMIP5 models, show large deficiencies in simulating I~M~WM. Along with an unrealistic representation of I~M~WM volume and properties when the waters enter the subtropics, the models also lack the observed prominent oxygen maximum associated with I~M~WM. Restoring oxygen levels to observed concentrations at 30°S/30°N and at 1500 m depth in a coarse resolution model, comparable to CMIP5 climate models in terms of resolution and oxygen bias, shows a significant impact on the lower thermocline (500 – 1500 m) oxygen levels : a positive anomaly of 60 mmol.m$^{-3}$ translates into an oxygen increase by 10 mmol-m$^{-3}$ in tropical regions after 50 years of integration.

The equatorward transport of the anomaly in the subtropics is mostly due to isopycnal subgrid scale mixing processes as shown by the NEMO2 budget analysis. While the models with differing ocean resolutions may differ in their transport of IWM between the subtropical regions and the tropics, it nevertheless suggests that mesoscale activity in higher resolution models is important to spread IWM (e.g Xu et al., 2016). This possibly includes subsurface eddies that show a signature well into the IWM depth range (Frenger et al., 2018, see their Fig 2).

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5.2 IMW transport and Equatorial Intermediate Current System

Second, the  Equatorial Intermediate Current System (EICS)  is not represented in coarse resolution models and only poorly represented in high resolution  ocean circulation models (0.25° and 0.1°), as its strength remains too weak by a factor of two (consistent with previous studies, e.g Ascani et al., 2015). The EICS transports the IWM that occupies the lower thermocline (500 – 1500 m depth) and the recirculation of the IWM in the tropical ocean, as suggested by the observational study of Zenk et al. (2005), and shown in our study.

We investigated the impact of the EICS on the oxygen supply with tracer release experiments: the concentration of a conservative tracer that originates from the subtropical ocean, is, after 50 years, 30 % higher in the eastern equatorial (5°N-5S) Pacific in an ocean model with 0.1° resolution, compared to an ocean model with 0.5 ° resolution. As the oxygen gradient along the equator is similar to the gradient of the conservative tracer, we assume a similar enhancement of oxygen supply by 30 % in the eastern equatorial Pacific at the same time scale. This means, if we account for oxygen consumption due to respiration (about 1 $mmol.m^{-3}.yr^{-1}$ between 5°N-5°S, see section 3.2), that the better resolved EICS in the higher resolution ocean leads roughly to higher intermediate oxygen levels of 15 - 30 $mmol-m^{-3}$ compared to the lower resolution ocean experiment in a timescale of 50 years. Consistently, 0.1°-ocean GFDL01 model displays oxygen concentrations larger by about 30 $mmol.m^{-3}$ in the eastern equatorial lower thermocline (500-1500 m) compared to the 1°-ocean GFDL1 configuration (with higher subtropical oxygen concentrations of IWM of 15 $mmol.m^{-3}$ in GFDL01 at 30°S)

We would like to highlight two potential implications of our finding of the important role of the EICS for the Pacific eastern tropical oxygen supply: i) First, we have shown that the intermediate current system EICS is important for the connection between the western and eastern Pacific Ocean at a decadal / multidecadal time scale. This suggests that the EICS modulates the mean state and the variability of the tropical oxygen in the lower thermocline, and subsequently the whole water column by upwelling of deep waters. ii) Second, we have found an enhancement of the connections between equatorial deep ocean (> 2000 m) and lower thermocline in the high resolution model compared to the lower resolution model. This result is consistent with the studies of Brandt et al. (2011, 2012), who suggested, based on observational data and on an idealized model, that Equatorial Deep Jets, part of the EICS (see Fig 1b), propagate their energy upward and impact the upper ocean properties of the ocean, including their oxygen content. Taken this into account, we

503  hypothesize that the Pacific Deep Water has a larger role than previously thought in modulating the

504  intermediate and upper ocean properties.

505

506  A pragmatic approach to account for the missing EICS is to increase diffusion anisotropically, with

507  increased zonal mixing in the tropics (Getzlaff and Dietze, 2013). This parameterization mimics a

508  more vigorous EICS and improves the simulated shape of the OMZ in climate models. However,

509  the prominent bias of IMWM in climate models, and therefore of the water masses entering the

510  EICS is not accounted for with this parameterization. Furthermore such a parameterization

511  improves the mean state but does not reproduce the variability of the EICS.

512

513  5.3 Implication for biogeochemical cycles

514  The IWM are important supplier of oxygen to the tropical oceans, but also of nutrients (Palter et al.,

515  2010) as well as anthropogenic carbon (e.g Kathiwala et al., 2012), which accumulates in mode and

516  intermediate waters of the Southern Ocean (Sabine et al., 2004; Resplandy et al., 2013). The

517  mechanisms that we discussed here may therefore play a role in ocean carbon climate feedbacks on

518  time scales of decades to a century.

519

520  Finally, this study suggests that changes of the properties of the IWM may contribute to the still

521  partly unexplained deoxygenation of 5 mmol.m$^{-3}$ / decade occurring in the lower thermocline of the

522  equatorial eastern Pacific Ocean (Schmidtko et al., 2017; Oschlies et al., 2018). In addition to an

523  oxygen decrease in tropical regions, Schmidtko et al. (2017) showed a decrease of oxygen levels by

524  2-5 mmol.m$^{-3}$ in the regions of formations of AAIW. Based on repeated cruise observations,

525  Panassa et al. (2018) highlighted an increase of the apparent oxygen utilization in the core of the

526  AAIW, related to a 5 % increase in nutrient concentrations from 1990 to 2014. The transport of this

527  modified AAIW, poorer in oxygen and richer in nutrients, toward the low latitudes both by small

528  scale processes (section 3) and at the equator by the EICS (section 4), may explain a significant part

529  of the occurring deoxygenation in the equatorial ocean. In complement to changes in the AAIW

530  properties, little is known about the variability and long term trend of the strength of the EICS, an

531  oceanic "bridge" between the western and the eastern part of the basin. A possible way forward

532  could be to perform idealized model experiments in high resolution configurations, aiming to assess

533  both the effect of the observed change in the AAIW properties and of a potential change of EICS

534  strength on oxygen levels.

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**Data and code availability**

The code for the Nucleus for European Modeling of the Ocean (NEMO) is available at: https://www.nemo-ocean.eu/. The code for the University of Victoria (UVIC) model is available at :http://terra.seos.uvic.ca/model/. The Lagrangian particles ARIANE code is available at http://stockage.univ-brest.fr/~grima/Ariane/. The Coordinated Ocean-ice Reference Experiments (COREv2) dataset is available at: https://data1.gfdl.noaa.gov/nomads/forms/core/COREv2.html. The experiments data is available on request.

**Authors contributions**

OD conceived the study, performed the NEMO model and ARIANE experiments and analyzed the data. IF preprocessed and helped to analyze the GFDL data. JG preprocessed and helped to analyze the UVIC data. All authors discussed the results and wrote the manuscript.

**Competing interest**

The authors declare that they have no conflict of interest.

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**References**

Ascani, F., Firing, E., Dutrieux, P., McCreary, J. P., & Ishida, A. (2010). Deep Equatorial Ocean

Circulation Induced by a Forced–Dissipated Yanai Beam. Journal of Physical Oceanography, 40(5),

1118–1142. doi:10.1175/2010jpo4356.1

Ascani, F., Firing, E., McCreary, J. P., Brandt, P., & Greatbatch, R. J. (2015). The Deep Equatorial

Ocean Circulation in Wind-Forced Numerical Solutions. Journal of Physical Oceanography, 45(6),

1709–1734. doi:10.1175/jpo-d-14-0171.1

Bahl, A., Gnanadesikan, A., & Pradal, M. A. (2019). Variations in Ocean Deoxygenation Across

Earth System Models: Isolating the Role of Parameterized Lateral Mixing. Global Biogeochemical

Cycles, 33(6), 703–724. doi:10.1029/2018gb006121

Blanke, B., & Raynaud, S. (1997). Kinematics of the Pacific Equatorial Undercurrent: An Eulerian

and Lagrangian Approach from GCM Results. Journal of Physical Oceanography, 27(6), 1038–

1053. doi:10.1175/1520-0485(1997)027<1038:kotpeu>2.0.co;2

Brandt, P., Funk, A., Hormann, V., Dengler, M., Greatbatch, R. J., & Toole, J. M. (2011).

Interannual atmospheric variability forced by the deep equatorial Atlantic Ocean. Nature,

473(7348), 497–500. doi:10.1038/nature10013

Brandt, P., Greatbatch, R. J., Claus, M., Didwischus, S.-H., Hormann, V., Funk, A., … Körtzinger,

A. (2012). Ventilation of the equatorial Atlantic by the equatorial deep jets. Journal of Geophysical

Research: Oceans, 117(C12), n/a–n/a. doi:10.1029/2012jc008118

Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., … Zhang, J.

(2018). Declining oxygen in the global ocean and coastal waters. Science, 359(6371), eaam7240.

doi:10.1126/science.aam7240

Busecke, J. J. M., Resplandy, L., & Dunne, J. P. (2019). The Equatorial Undercurrent and the

Oxygen Minimum Zone in the Pacific. Geophysical Research Letters, 46(12), 6716–6725.

doi:10.1029/2019gl082692

Cabré, A., Marinov, I., Bernardello, R., & Bianchi, D. (2015). Oxygen minimum zones in the

tropical Pacific across CMIP5 models: mean state differences and climate change trends.

Biogeosciences, 12(18), 5429–5454. doi:10.5194/bg-12-5429-2015

Carrasco, C., Karstensen, J., & Farias, L. (2017). On the Nitrous Oxide Accumulation in

Intermediate Waters of the Eastern South Pacific Ocean. Frontiers in Marine Science, 4.

doi:10.3389/fmars.2017.00024

603    Cravatte, S., Kessler, W. S., & Marin, F. (2012). Intermediate Zonal Jets in the Tropical Pacific

604    Ocean Observed by Argo Floats. Journal of Physical Oceanography, 42(9), 1475–1485.

605    doi:10.1175/jpo-d-11-0206.1

606    Cravatte, S., Kestenare, E., Marin, F., Dutrieux, P., & Firing, E. (2017). Subthermocline and

607    Intermediate Zonal Currents in the Tropical Pacific Ocean: Paths and Vertical Structure. Journal of

608    Physical Oceanography, 47(9), 2305–2324. doi:10.1175/jpo-d-17-0043.1

609    Czeschel, R., Stramma, L., Schwarzkopf, F. U., Giese, B. S., Funk, A., and Karstensen, J. ( 2011),

610    Middepth circulation of the eastern tropical South Pacific and its link to the oxygen minimum zone,

611    J. Geophys. Res., 116, C01015, doi:10.1029/2010JC006565

612    Delworth, T. L., Rosati, A., Anderson, W., Adcroft, A. J., Balaji, V., Benson, R., … Zhang, R.

613    (2012). Simulated Climate and Climate Change in the GFDL CM2.5 High-Resolution Coupled

614    Climate Model. Journal of Climate, 25(8), 2755–2781. doi:10.1175/jcli-d-11-00316.1

615    Dietze, H., & Loeptien, U. (2013). Revisiting "nutrient trapping" in global coupled biogeochemical

616    ocean circulation models. Global Biogeochemical Cycles, 27(2), 265–284. doi:10.1002/gbc.20029

617    Dufour, C. O., Griffies, S. M., de Souza, G. F., Frenger, I., Morrison, A. K., Palter, J. B., … Slater,

618    R. D. (2015). Role of Mesoscale Eddies in Cross-Frontal Transport of Heat and Biogeochemical

619    Tracers in the Southern Ocean. Journal of Physical Oceanography, 45(12), 3057–3081. doi:10.1175/

620    jpo-d-14-0240.1

621    Duteil, O., & Oschlies, A. (2011). Sensitivity of simulated extent and future evolution of marine

622    suboxia to mixing intensity. Geophysical Research Letters, 38(6), n/a–n/a.

623    doi:10.1029/2011gl046877

624    Duteil, O., Koeve, W., Oschlies, A., Aumont, O., Bianchi, D., Bopp, L., … Segschneider, J. (2012).

625    Preformed and regenerated phosphate in ocean general circulation models: can right total

626    concentrations be wrong? Biogeosciences, 9(5), 1797–1807. doi:10.5194/bg-9-1797-2012

627    Duteil, O., Böning, C. W., & Oschlies, A. (2014). Variability in subtropical-tropical cells drives

628    oxygen levels in the tropical Pacific Ocean. Geophysical Research Letters, 41(24), 8926–8934.

629    doi:10.1002/2014gl061774

630    Duteil, O., Oschlies, A., & Böning, C. W. (2018). Pacific Decadal Oscillation and recent oxygen

631    decline in the eastern tropical Pacific Ocean. Biogeosciences, 15(23), 7111–7126. doi:10.5194/bg-

632    15-7111-2018

633    Duteil, O. (2019). Wind Synoptic Activity Increases Oxygen Levels in the Tropical Pacific Ocean.

634    Geophysical Research Letters, 46(5), 2715–2725. doi:10.1029/2018gl081041

635    Eden, C., & Dengler, M. (2008). Stacked jets in the deep equatorial Atlantic Ocean. Journal of

636    Geophysical Research, 113(C4). doi:10.1029/2007jc004298

19

637  Firing, E., Wijffels, S. E., & Hacker, P. (1998). Equatorial subthermocline currents across the

638  Pacific. Journal of Geophysical Research: Oceans, 103(C10), 21413–21423. doi:10.1029/98jc01944

639  Firing, E. (1987). Deep zonal currents in the central equatorial Pacific. Journal of Marine Research,

640  45(4), 791–812. doi:10.1357/002224087788327163

641  Frenger, I., Bianchi, D., Stührenberg, C., Oschlies, A., Dunne, J., Deutsch, C., … Schütte, F.

642  (2018). Biogeochemical Role of Subsurface Coherent Eddies in the Ocean: Tracer Cannonballs,

643  Hypoxic Storms, and Microbial Stewpots? Global Biogeochemical Cycles, 32(2), 226–249.

644  doi:10.1002/2017gb005743

645  Galbraith, E. D., Dunne, J. P., Gnanadesikan, A., Slater, R. D., Sarmiento, J. L., Dufour, C. O., …

646  Marvasti, S. S. (2015). Complex functionality with minimal computation: Promise and pitfalls of

647  reduced-tracer ocean biogeochemistry models. Journal of Advances in Modeling Earth Systems,

648  7(4), 2012–2028. doi:10.1002/2015ms000463

649  Getzlaff, J., & Dietze, H. (2013). Effects of increased isopycnal diffusivity mimicking the

650  unresolved equatorial intermediate current system in an earth system climate model. Geophysical

651  Research Letters, 40(10), 2166–2170. doi:10.1002/grl.50419

652  Gnanadesikan, A., Bianchi, D., & Pradal, M. (2013). Critical role for mesoscale eddy diffusion in

653  supplying oxygen to hypoxic ocean waters. Geophysical Research Letters, 40(19), 5194–5198.

654  doi:10.1002/grl.50998

655  Gouriou, Y., Delcroix, T., & Eldin, G. (2006). Upper and intermediate circulation in the western

656  equatorial Pacific Ocean in October 1999 and April 2000. Geophysical Research Letters, 33(10), n/

657  a–n/a. doi:10.1029/2006gl025941

658  Griffies, S. M., Winton, M., Anderson, W. G., Benson, R., Delworth, T. L., Dufour, C. O., …

659  Zhang, R. (2015). Impacts on Ocean Heat from Transient Mesoscale Eddies in a Hierarchy of

660  Climate Models. Journal of Climate, 28(3), 952–977. doi:10.1175/jcli-d-14-00353.1

661  Iudicone, D., Rodgers, K. B., Schopp, R., & Madec, G. (2007). An Exchange Window for the

662  Injection of Antarctic Intermediate Water into the South Pacific. Journal of Physical Oceanography,

663  37(1), 31–49. doi:10.1175/jpo2985.1

664  Izumo, T. (2005). The equatorial undercurrent, meridional overturning circulation, and their roles in

665  mass and heat exchanges during El Niño events in the tropical Pacific ocean. Ocean Dynamics,

666  55(2), 110–123. doi:10.1007/s10236-005-0115-1

667  Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S. C., Graven, H. D., …

668  Sabine, C. L. (2013). Global ocean storage of anthropogenic carbon. Biogeosciences, 10(4), 2169–

669  2191. doi:10.5194/bg-10-2169-2013

Kawabe, M., & Fujio, S. (2010). Pacific ocean circulation based on observation. Journal of Oceanography, 66(3), 389–403. doi:10.1007/s10872-010-0034-8

Keller, D. P., Oschlies, A., & Eby, M. (2012). A new marine ecosystem model for the University of Victoria Earth System Climate Model. Geoscientific Model Development, 5(5), 1195–1220. doi:10.5194/gmd-5-1195-2012

Koshlyakov, M.N. and Tarakanov, R.Y. (2003). Antarctic Bottom Water in the Pacific sector of the Southern Ocean, Oceanology 43(1):1-15

Kriest, I., Khatiwala, S., & Oschlies, A. (2010). Towards an assessment of simple global marine biogeochemical models of different complexity. Progress in Oceanography, 86(3-4), 337–360. doi:10.1016/j.pocean.2010.05.002

Lachkar, Z., Orr, J. C., & Dutay, J.-C. (2009). Seasonal and mesoscale variability of oceanic transport of anthropogenic CO2. Biogeosciences, 6(11), 2509–2523. doi:10.5194/bg-6-2509-2009

Large, W. G., & Yeager, S. G. (2008). The global climatology of an interannually varying air–sea flux data set. Climate Dynamics, 33(2-3), 341–364. doi:10.1007/s00382-008-0441-3

Lübbecke, J. F., Böning, C. W., & Biastoch, A. (2008). Variability in the subtropical-tropical cells and its effect on near-surface temperature of the equatorial Pacific: a model study. Ocean Science, 4(1), 73–88. doi:10.5194/os-4-73-2008

Madec, G.Gurvan, M., Bourdallé-Badie, R., Pierre-Antoine Bouttier, Bricaud, C., Bruciaferri, D., Calvert, D., Chanut, J., Clementi, E., Coward, A., Delrosso, D., Ethé, C., Flavoni, S., Graham, T., Harle, J., Iovino, D., Lea, D., Lévy, C., Lovato, T., Martin, N., … Vancoppenolle, M. (2017). <i>NEMO ocean engine</i>. https://doi.org/10.5281/ZENODO.3248739Marin, F., Kestenare, E., Delcroix, T., Durand, F., Cravatte, S., Eldin, G., & Bourdallé-Badie, R. (2010). Annual Reversal of the Equatorial Intermediate Current in the Pacific: Observations and Model Diagnostics. Journal of Physical Oceanography, 40(5), 915–933. doi:10.1175/2009jpo4318.1

Martin, J. H., Knauer, G. A., Karl, D. M., & Broenkow, W. W. (1987). VERTEX: carbon cycling in the northeast Pacific. Deep Sea Research Part A. Oceanographic Research Papers, 34(2), 267–285. doi:10.1016/0198-0149(87)90086-0

Meijers, A. J. S. (2014). The Southern Ocean in the Coupled Model Intercomparison Project phase 5. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2019), 20130296. doi:10.1098/rsta.2013.0296

Ménesguen, C., Delpech, A., Marin, F., Cravatte, S., Schopp, R., & Morel, Y. (2019). Observations and Mechanisms for the Formation of Deep Equatorial and Tropical Circulation. Earth and Space Science, 6(3), 370–386. doi:10.1029/2018ea000438

703  Molinelli EJ (1981) The Antarctic influence on Antarctic Intermediate Water. J Mar Res 39:267–

704  293

705  Oschlies, A., Brandt, P., Stramma, L., & Schmidtko, S. (2018). Drivers and mechanisms of ocean

706  deoxygenation. Nature Geoscience, 11(7), 467–473. doi:10.1038/s41561-018-0152-2

707  Palter, J. B., Sarmiento, J. L., Gnanadesikan, A., Simeon, J., and Slater, R. D. (2010). Fueling

708  export production: nutrient return pathways from the deep ocean and their dependence on the

709  Meridional Overturning Circulation, Biogeosciences, 7, 3549–3568, doi:10.5194/bg-7-3549-2010

710  Panassa, E., Santana-Casiano, J. M., González-Dávila, M., Hoppema, M., van Heuven, S. M. A. .,

711  Völker, C., … Hauck, J. (2018). Variability of nutrients and carbon dioxide in the Antarctic

712  Intermediate Water between 1990 and 2014. Ocean Dynamics, 68(3), 295–308.

713  doi:10.1007/s10236-018-1131-2

714  Pardo, P. C., Pérez, F. F., Velo, A., & Gilcoto, M. (2012). Water masses distribution in the Southern

715  Ocean: Improvement of an extended OMP (eOMP) analysis. Progress in Oceanography, 103, 92–

716  105. doi:10.1016/j.pocean.2012.06.002

717  Paulmier, A., Ruiz-Pino (2009), D. Oxygen minimum zones (OMZs) in the modern ocean,Progress

718  in Oceanography, 80(3), 113-128, doi:10.1016/j.pocean.2008.08.001.

719  Qu, T., & Lindstrom, E. J. (2004). Northward Intrusion of Antarctic Intermediate Water in the

720  Western Pacific*. Journal of Physical Oceanography, 34(9), 2104–2118. doi:10.1175/1520-

721  0485(2004)034<2104:nioaiw>2.0.co;2

722  Resplandy, L., Bopp, L., Orr, J. C., & Dunne, J. P. (2013). Role of mode and intermediate waters in

723  future ocean acidification: Analysis of CMIP5 models. Geophysical Research Letters, 40(12),

724  3091–3095. doi:10.1002/grl.50414

725  Rowe, G. D., Firing, E., & Johnson, G. C. (2000). Pacific Equatorial Subsurface Countercurrent

726  Velocity, Transport, and Potential Vorticity*. Journal of Physical Oceanography, 30(6), 1172–1187.

727  doi:10.1175/1520-0485(2000)030<1172:pescvt>2.0.co;2

728  Russell, J. L., & Dickson, A. G. (2003). Variability in oxygen and nutrients in South Pacific

729  Antarctic Intermediate Water. Global Biogeochemical Cycles, 17(2), n/a–n/a.

730  doi:10.1029/2000gb001317

731  Sabine, C. L. (2004). The Oceanic Sink for Anthropogenic CO2. Science, 305(5682), 367–371.

732  doi:10.1126/science.1097403

733  Sallée, J.-B., Shuckburgh, E., Bruneau, N., Meijers, A. J. S., Bracegirdle, T. J., Wang, Z., & Roy, T.

734  (2013). Assessment of Southern Ocean water mass circulation and characteristics in CMIP5

735  models: Historical bias and forcing response. Journal of Geophysical Research: Oceans, 118(4),

736  1830–1844. doi:10.1002/jgrc.20135

737 Schmidtko, S., Stramma, L., & Visbeck, M. (2017). Decline in global oceanic oxygen content

738 during the past five decades. Nature, 542(7641), 335–339. doi:10.1038/nature21399

739 Sen Gupta, A., & England, M. H. (2007). Evaluation of Interior Circulation in a High-Resolution

740 Global Ocean Model. Part II: Southern Hemisphere Intermediate, Mode, and Thermocline Waters.

741 Journal of Physical Oceanography, 37(11), 2612–2636. doi:10.1175/2007jpo3644.1

742 Shigemitsu, M., Yamamoto, A., Oka, A., & Yamanaka, Y. (2017). One possible uncertainty in

743 CMIP5 projections of low-oxygen water volume in the Eastern Tropical Pacific. Global

744 Biogeochemical Cycles, 31(5), 804–820. doi:10.1002/2016gb005447

745 Sloyan, B. M., & Kamenkovich, I. V. (2007). Simulation of Subantarctic Mode and Antarctic

746 Intermediate Waters in Climate Models. Journal of Climate, 20(20), 5061–5080.

747 doi:10.1175/jcli4295.1

748 Sloyan, B. M., & Rintoul, S. R. (2001). Circulation, Renewal, and Modification of Antarctic Mode

749 and Intermediate Water*. Journal of Physical Oceanography, 31(4), 1005–1030. doi:10.1175/1520-

750 0485(2001)031<1005:cramoa>2.0.co;2

751 Takano, Y., Ito, T., & Deutsch, C. (2018). Projected Centennial Oxygen Trends and Their

752 Attribution to Distinct Ocean Climate Forcings. Global Biogeochemical Cycles, 32(9), 1329–1349.

753 doi:10.1029/2018gb005939

754 Talley, L. D. (1993). Distribution and Formation of North Pacific Intermediate Water. Journal of

755 Physical Oceanography, 23(3), 517–537. doi:10.1175/1520-0485(1993)023<0517:dafonp>2.0.co;2

756 Weaver, A. J., Eby, M., Wiebe, E. C., Bitz, C. M., Duffy, P. B., Ewen, T. L., … Yoshimori, M.

757 (2001). The UVic earth system climate model: Model description, climatology, and applications to

758 past, present and future climates. Atmosphere-Ocean, 39(4), 361–428.

759 doi:10.1080/07055900.2001.9649686

760 Xu, L., Li, P., Xie, S. et al. (2016). Observing mesoscale eddy effects on mode-water subduction

761 and transport in the North Pacific. Nature Communications, 10505 (2016),

762 doi.org/10.1038/ncomms10505

763 Zenk, W., Siedler, G., Ishida, A., Holfort, J., Kashino, Y., Kuroda, Y., … Müller, T. J. (2005).

764 Pathways and variability of the Antarctic Intermediate Water in the western equatorial Pacific

765 Ocean. Progress in Oceanography, 67(1-2), 245–281. doi:10.1016/j.pocean.2005.05.003

766 Zhu, C., Liu, Z., & Gu, S. (2017). Model bias for South Atlantic Antarctic intermediate water in

767 CMIP5. Climate Dynamics, 50(9-10), 3613–3624. doi:10.1007/s00382-017-3828-1

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**Table and Figures**

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Table 1 :

| Model | Resolution | Atmosphere | BGC | Model Reference (circulation) | Model Reference (BGC) |
|---|---|---|---|---|---|
| **Mean state comparison** | | | | | |
| UVIC | 2.8° | Coupled (temperature, humidity) Forced (NCEP/NCAR wind stress) | UVIC-BGC | Weaver et al., 2001 | Keller et al., 2012 |
| NEMO2 | 2° (0.5 eq) | Forced COREv2 "normal year" | NPZD-O2 | Madec et al., 2017 | Kriest et al, 2010 Duteil et al., 2014 |
| GFDL1 | 1° | Coupled (~50 km) | miniBLING | Delworth et al, 2012, Griffies et al, 2015 | Galbraith et al., 2015, Dufour et al, 2015 |
| GFDL025 | 0.25 ° | Coupled (~50 km) | miniBLING | | |
| GFDL01 | 0.1° | Coupled (~50 km) | miniBLING | | |
| **Sensitivity experiments** | | | | | |
| Model | Resolution | Atmosphere | BGC | Experiments | |
| NEMO2 (section 2.2.1) | 2° (0.5 eq) | Forced COREv2 1948-2007 | NPZD-O2 | REF: control experiment 30N30S: O2 restoring to WOA at 30°N/30°S 30N30S1500M: O2 restoring to WOA at 30°N/30°S/1500m | |
| NEMO05 (section 2.2.2) | 0.5° | Forced COREv2 1948 - 2007 | Tracer release | Tracer initialized to 1 (O2 WOA > 150 mmol.m$^{-3}$) or 0 (O2 WOA < 150 mmol-m-3) | |
| NEMO01 (section 2.2.2) | 0.1° | Forced COREv2 1948 – 2007 | Tracer release | | |

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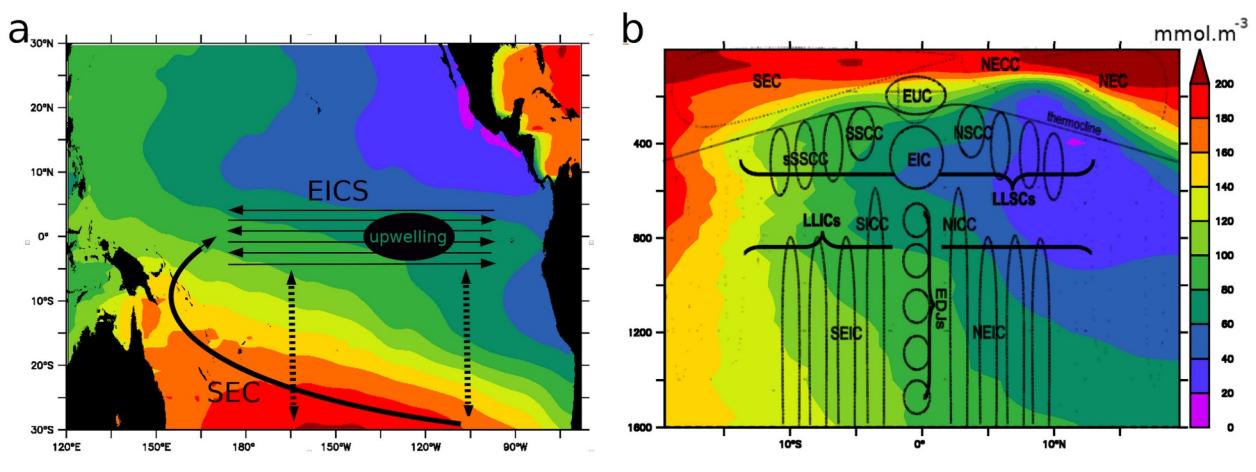
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Figure 1 : a- schema summarizing the intermediate water masses (IWM)  pathway from the subtropics into the equatorial regions. EICS : Equatorial Intermediate Current System. SEC : South Equatorial Current. Dashed line : isopycnal diffusive processes. Oxygen levels (mmol.m$^{-3}$) in the lower thermocline (mean 500-1500m) are represented in color. b - schema (adapted from Menesguen et al., 2019) illustrating the complexity of the EICS, extending below the thermocline till more than 2000 m depth (see section 4.1 for a detailed description). Oxygen levels (mean 500 – 1500m) at 160°W are represented in color (mmol.m$^{-3}$).
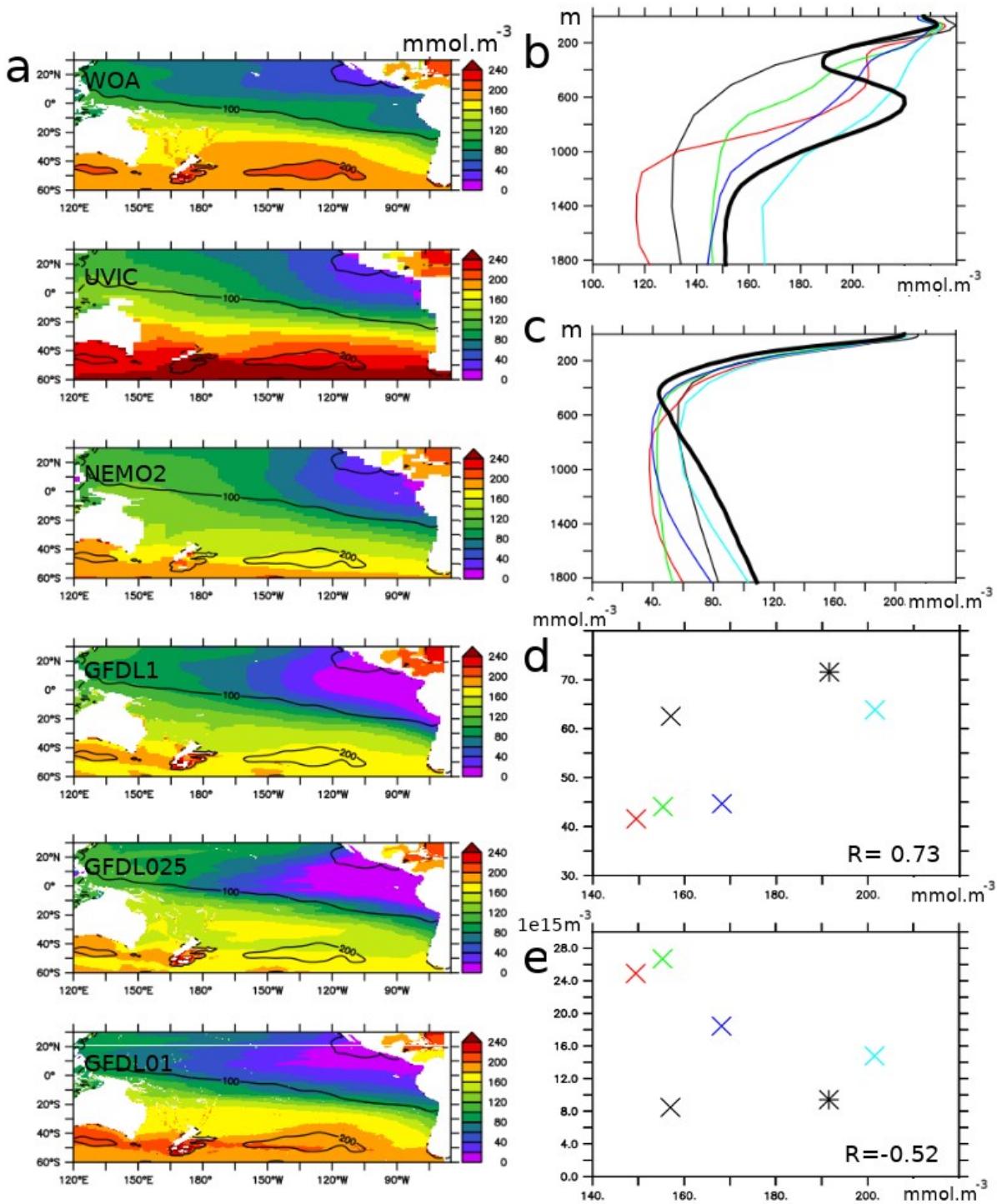
Figure 2 : a- oxygen levels (mmol.m$^{-3}$) in observations (World Ocean Atlas - WOA) (mean 500 – 1500 m) and models (UVIC, NEMO2, GFDL1, GFDL025, GFDL01). Contours correspond to WOA values. b: average "30°S" (120°E-65°W, 30°S) c : average "tropics" (160°W-coast, 20°N-20°S). d: average "30°S" vs "tropics". e: average "30°S" vs volume of tropical suboxic ocean (oxygen lower than 20 mmol.m$^{-3}$) regions (1e15m3). UVIC : black, NEMO2 : cyan, GFDL1 : red, GFDL025, green; GFDL01 : blue, WOA: star.

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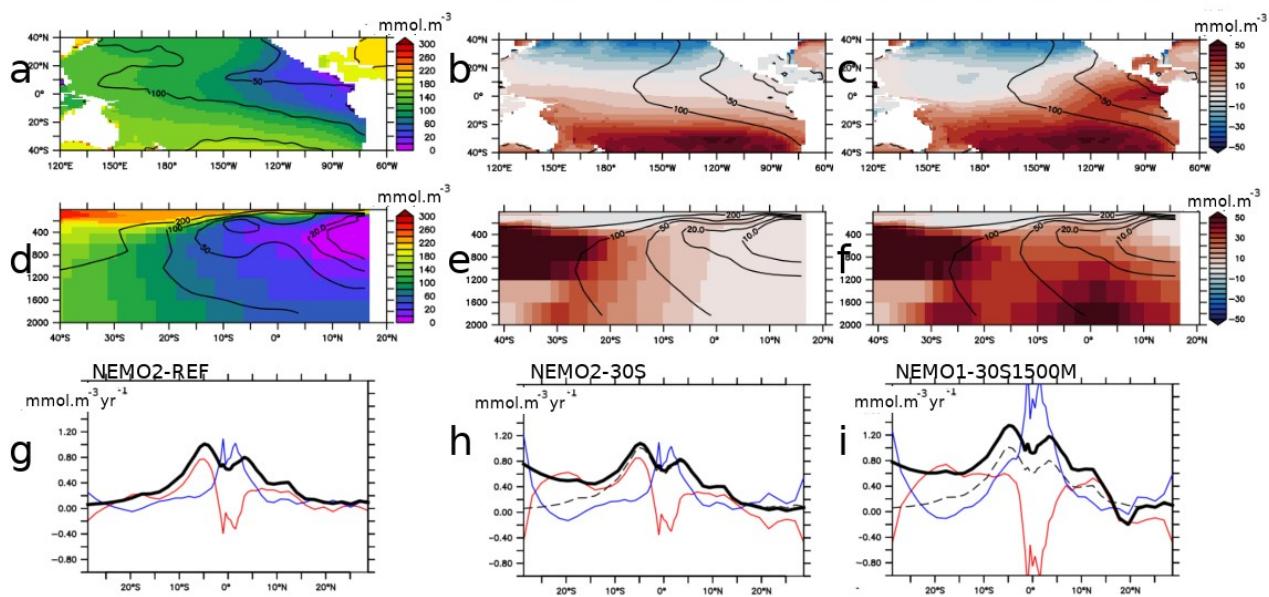
Figure 3 : a- Oxygen (mmol.m$^{-3}$) in the experiments NEMO2-REF (color) and World Ocean Atlas (contour) (average 500-1500 m). b- Oxygen (mmol.m$^{-3}$) difference (average 500 - 1500 m) between the experiments NEMO2-30S minus NEMO2-REF and c- NEMO2-30S1500M minus NEMO2-REF (contour NEMO2-REF). d- Oxygen (mmol.m$^{-3}$) in the experiments NEMO2-REF (color) and World Ocean Atlas (contour) (100°W). e- Oxygen (mmol.m$^{-3}$) difference (100°W) between the experiments NEMO2-30S minus NEMO2-REF and f- NEMO2-30S1500M minus NEMO2-REF (contour NEMO2-REF). g-i : basin zonal average (average 500 - 1500 m) of the oxygen total supply (bold) (mmol.m$^{-3}$.year$^{-1}$), advective processes (blue) and isopycnal diffusion (red) in g - NEMO2-REF, h- NEMO2-30DEG, i-NEMO2-30DEG1500M. The dashed line in is the oxygen total supply in NEMO2-REF.
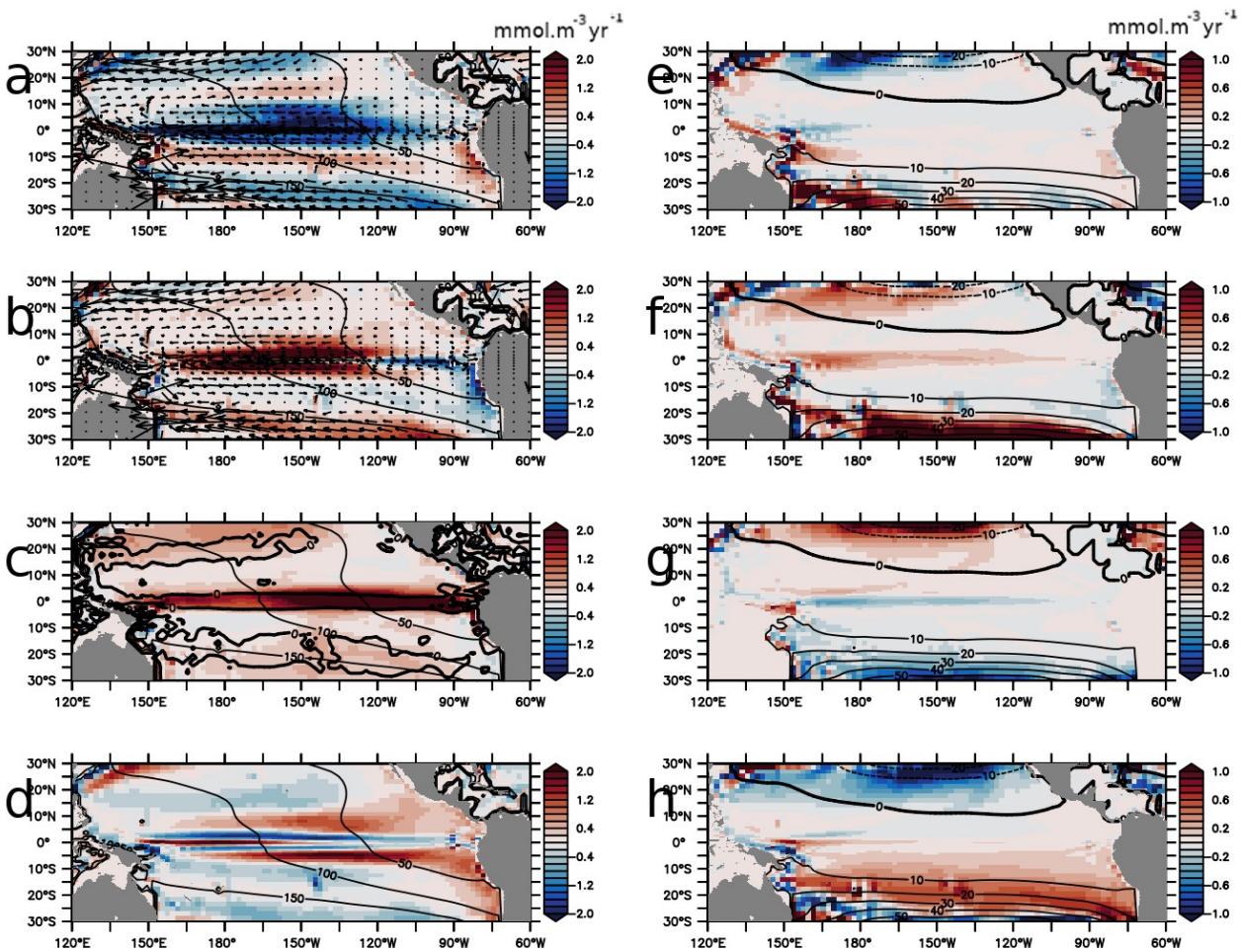
Figure 4 : Oxygen supply processes (mmol.m$^{-3}$.year$^{-1}$ – average 500 - 1500m) in NEMO2-REF : a- zonal advection, b– meridional advection, c- vertical advection, d- isopycnal diffusion. The meridional and zonal currents are displayed as vectors in a,b and the vertical current as contour in c. Oxygen levels (mmol-m.$^{-3}$) are displayed in contour. Difference in oxygen supply processes (mmol.m$^{-3}$.year$^{-1}$ – average 500-1500m) between NEMO2-30DEG and NEMO2-REF : e- zonal advection, f – meridional advection, g- vertical advection, h- isopycnal diffusion. The NEMO2-30DEG – NEMO2-REF oxygen anomaly (mmol.m$^{-3}$) is displayed in contour.
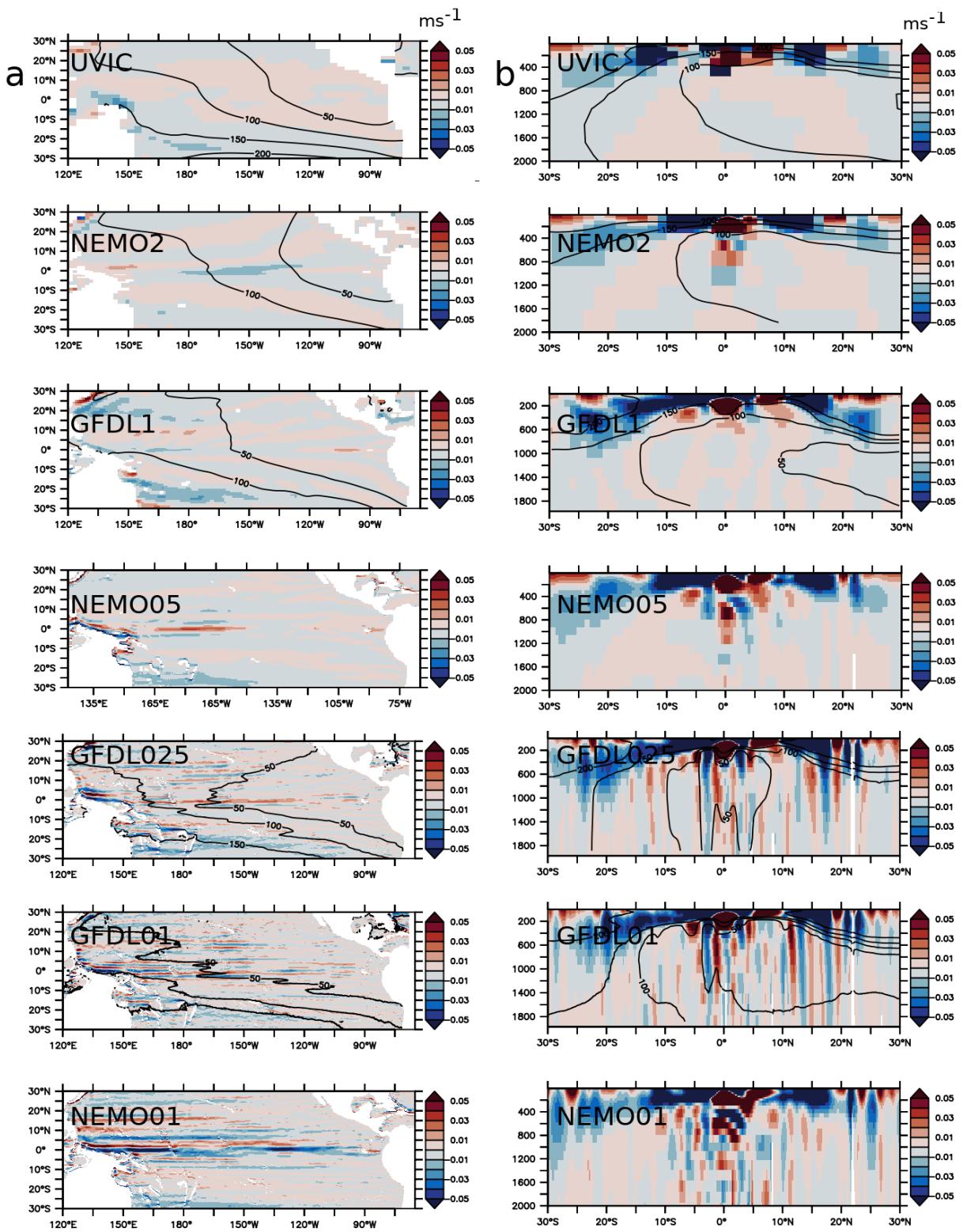
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Figure 5 : mean currents velocity (ms⁻¹) at a- 1000 m depth  b- 100°W in UVIC, NEMO2, NEMO05, GFDL025, GFDL01, NEMO01. The mean oxygen levels (mmol.m⁻³) (when coupled circulation-biogeochemical experiments have been performed – see Table 1) are displayed in contour
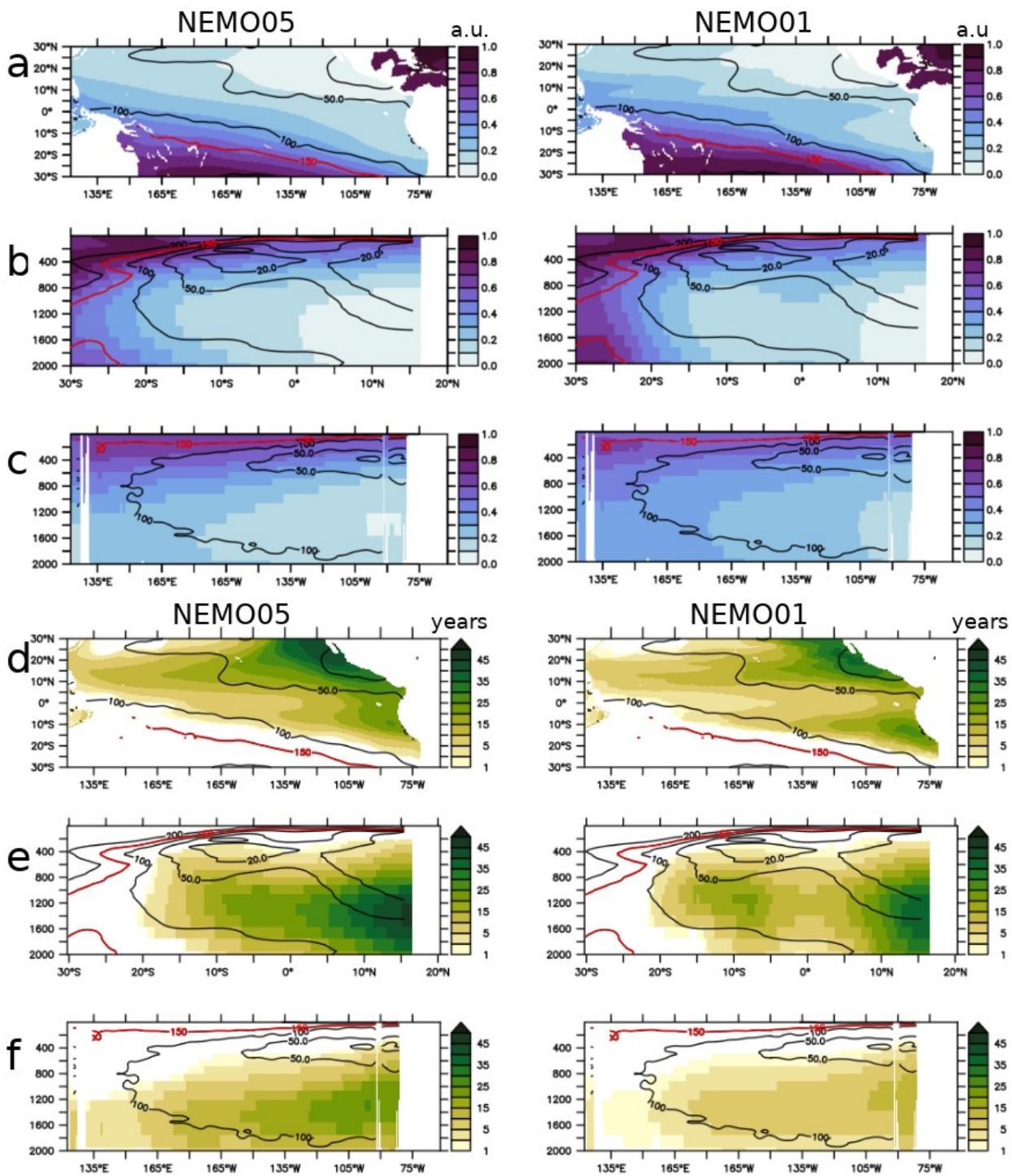
Figure 6: a-c : tracer concentration (arbitrary unit) after 60 years integration in NEMO05 (left) and NEMO01 (right). a- average 500-1500m, b- section 100°W, c- equatorial section. d-f: Time (years) at which the released tracer reaches the concentration 0.1 (t10%) in NEMO05 and NEMO01. d- average 500-1500m, e- section 100°W, f- equatorial section. In all the subpanels, the WOA oxygen levels are displayed in contour. The red contour is the WOA 150 mmol.m$^{-3}$ oxygen isoline, used to initialize the tracer level.
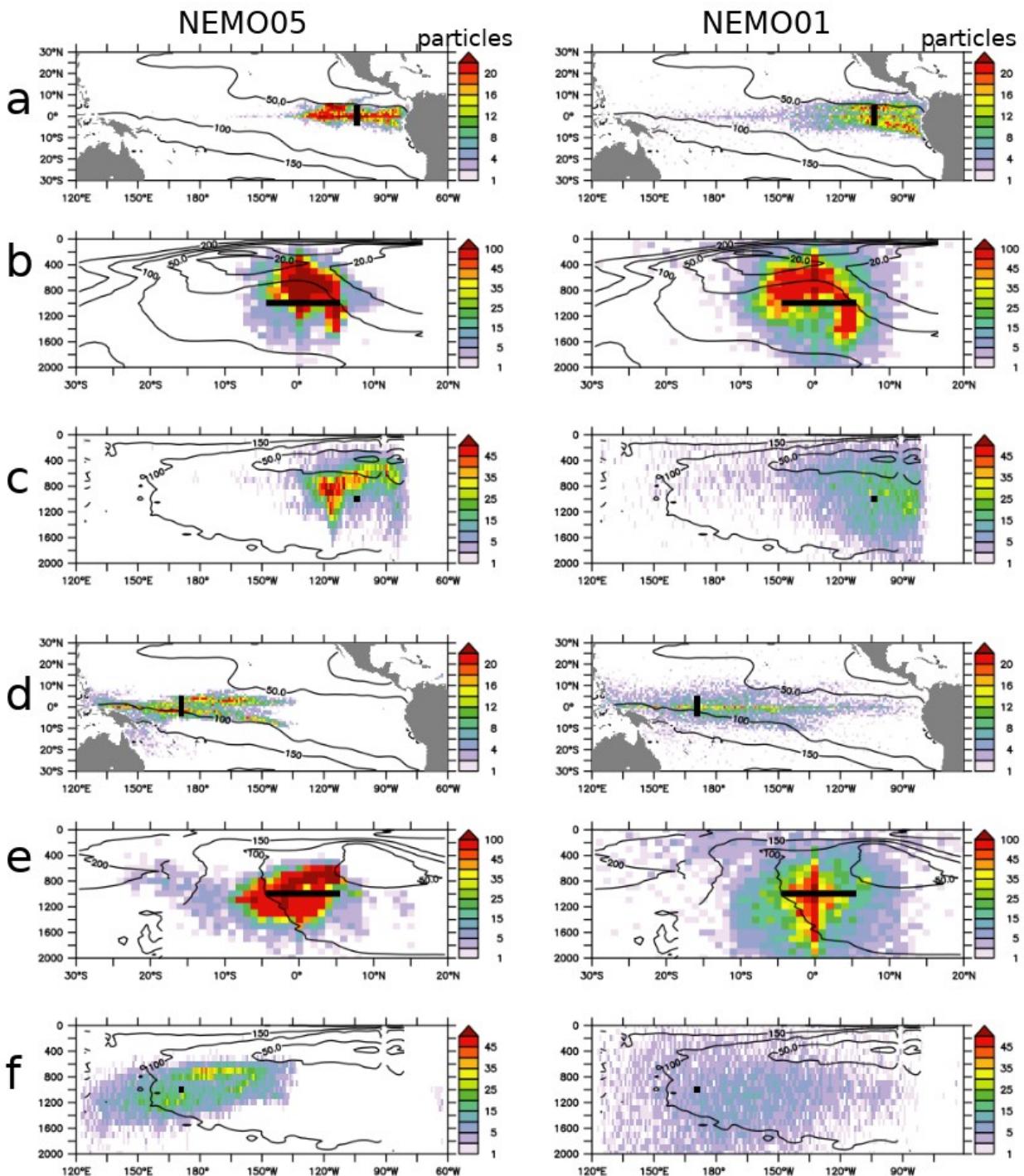
Figure 7 : Density (number of particles in a 1°x1°x100m depth box) distribution of the location of released Lagrangian particles (15 years backward integration starting from the final experiment state) in NEMO05 (left) and NEMO01 (right). The release location is identified in bold and is located at 100°W/5°N-5S/1000 m depth. a- vertical integrated density; b- zonal integrated density; c- meridional integrated density. d-f : Similar to a-c but with a release location located at 160°E/5°N-5°S/1000 m depth. The mean oxygen levels are displayed in contour.
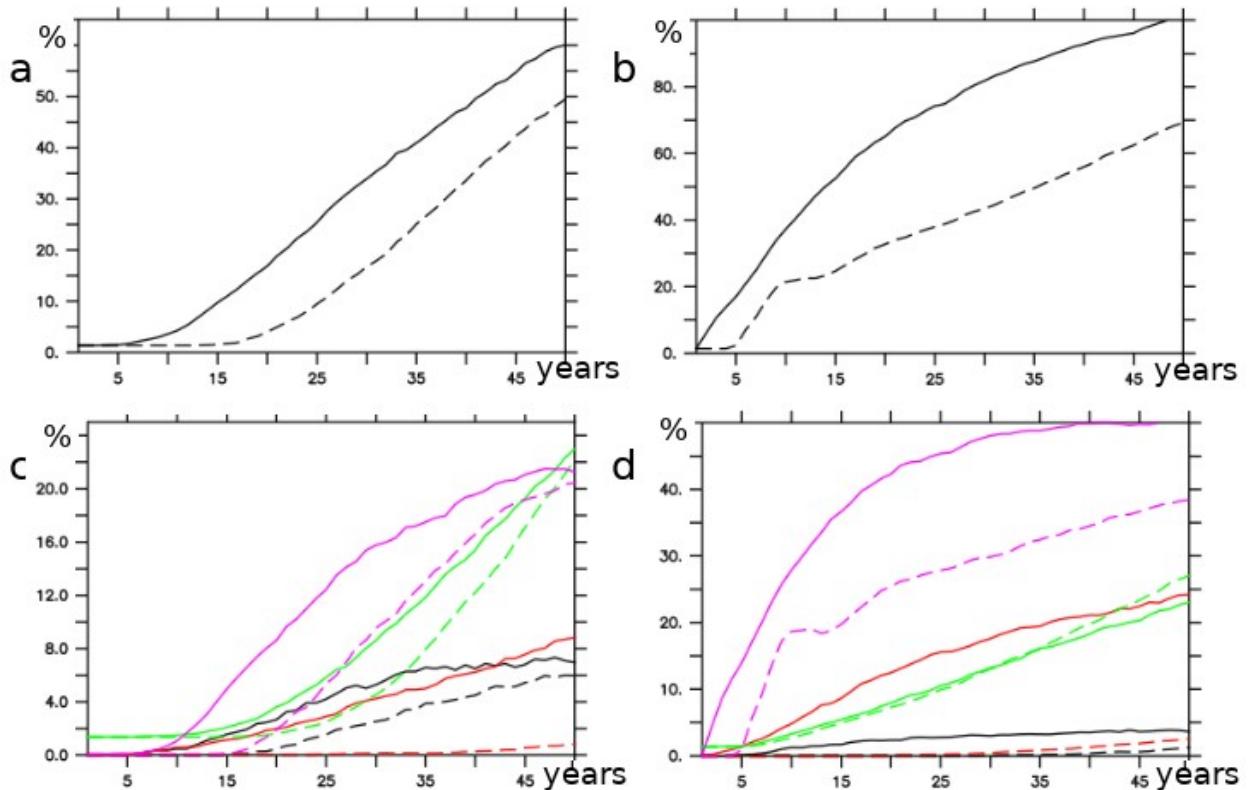
Figure 8 : a : percentage of particles originating from outside the Intermediate Eastern Tropical Pacific (IETP) ocean region (release 100°W / 5°N-5°S / 1000 m) or b- originating from outside the Intermediate Western Tropical Pacific (IWTP) ocean region (release 160°E / 5N°5S / 1000 m) in NEMO01 (black) and NEMO05 (dash). c,d ; percentage of particles originating from outside the IETP (c) and the IWTP (d): upper ocean ( < 200 m) (black), deep ocean (> 2000 m) (red), subtropical region (> 10°N/S) (green), panel c: western (west of 160°W) - or panel d: eastern (east of 160°W) part of the basin (magenta).
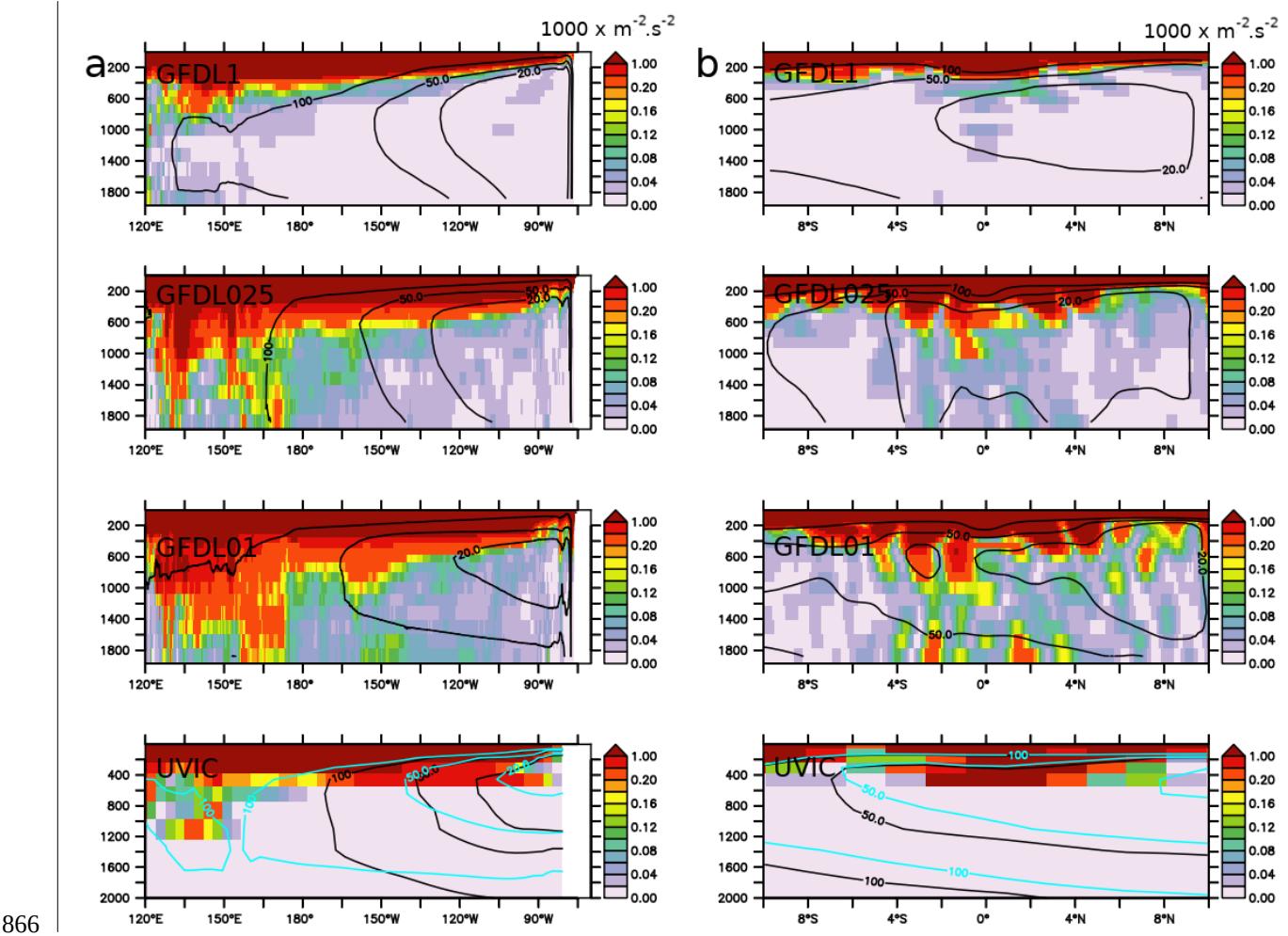
866
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870 Figure 9 : a -  Mean Kinetic Energy (m2.s$^{-2}$ x 1000) (average 10°N-10°S) in GFDL01, GFDL025,
871 GFDL01, UVIC, b - similar to a. but average 160°W-coast. Oxygen levels (mmol.m$^{-3}$) are displayed
872 in contour. The blue contour corresponds to UVIC GD13 (Getzlaff and Dietze, 2013, including an
873 anisotropical increase of lateral diffusion at the equator)
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900 **Figures and Table**
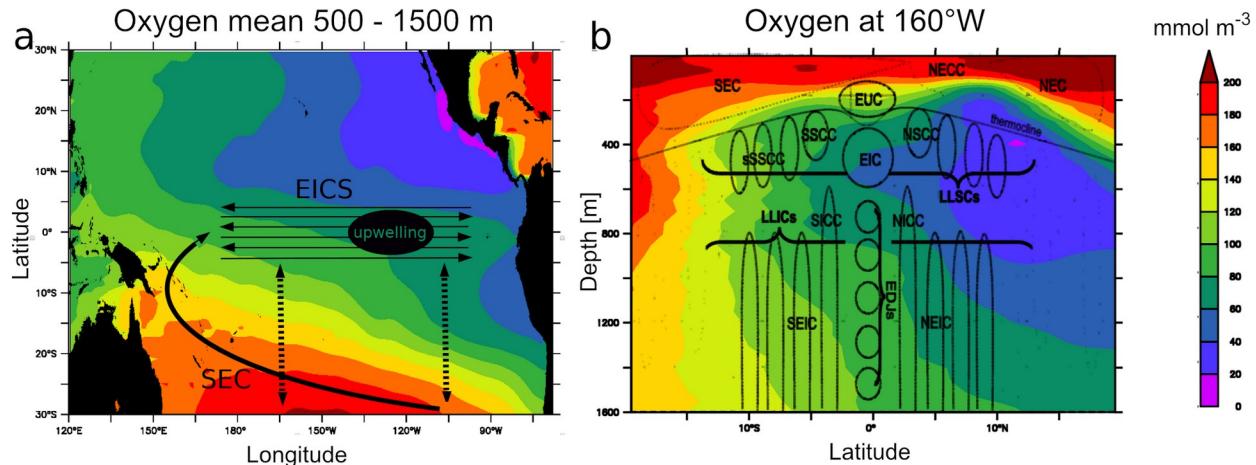


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903 Figure 1 : a- schema summarizing the intermediate water masses (IWM)  pathway from the
904 subtropics into the equatorial regions. EICS : Equatorial Intermediate Current System. SEC : South
905 Equatorial Current. Dashed line : isopycnal diffusive processes. Observed (World Ocean Atlas)
906 oxygen levels (mmol.m$^{-3}$) in the lower thermocline (mean 500-1500m) are represented in color. b -
907 schema (adapted from Menesguen et al., 2019) illustrating the complexity of the EICS, extending

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908    below the thermocline till more than 2000 m depth (see section 4.1 for a detailed description).

909    Observed (World Ocean Atlas) oxygen levels at 160°W are represented in color.

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Figure 2 : a- oxygen levels (mmol.m$^{-3}$)  in observations (World Ocean Atlas - WOA) (mean 500 – 1500 m) and models (UVIC, NEMO2, GFDL1, GFDL025, GFDL01). Contours correspond to WOA values. b: average "30°S" (120°E-65°W, 30°S) c : average "tropics" (160°W-coast, 20°N-20°S). d: average "30°S" vs "tropics". e: average "30°S" vs volume of tropical suboxic ocean (oxygen lower than 20 mmol.m$^{-3}$) regions (1e15m3). b-e : UVIC : black, NEMO2 : cyan, GFDL1 : red, GFDL025, green; GFDL01 : blue, WOA: bold line (b,c) and star (d,e).

**Figure 3 :** a,b: Oxygen (mmol.m$^{-3}$) in the experiments NEMO2_REF (color) and World Ocean Atlas (contour) (a- average 500-1500 m, b- 100°W). c,d: Oxygen (mmol.m$^{-3}$) difference (c- average 500 – 1500m, d- 100°W) between the experiments NEMO2_30S30N minus NEMO2_REF. e,f : Oxygen (mmol.m$^{-3}$) difference (e- average 500-1500m, f- 100°W) between the experiments NEMO2_30S30N1500M minus NEMO2_REF. g- basin zonal average (average 500 - 1500 m) of the oxygen total supply (bold) (mmol.m$^{-3}$.year$^{-1}$), advective processes (blue) and isopycnal diffusion (red) in NEMO2_REF, NEMO2_30S30N, NEMO2_30S30N1500M. The dashed line is the oxygen total supply in NEMO2_REF.

Figure 4 : a- Oxygen supply processes (mmol.m^{-3}.year[-1] – average 500 - 1500m) in NEMO2_REF : zonal advection, meridional advection, vertical advection, isopycnal diffusion. The mean meridional and zonal currents are displayed as vectors (meridional, zonal advection). The mean vertical current (0 isoline) is represented as bold contour (vertical advection). Oxygen levels (mmol-m.[-3]) are displayed in black contour. b- Difference in oxygen supply processes (mmol.m^{-3}.year[-1] – average 500-1500m) between NEMO2_30S30N and NEMO2_REF : zonal advection, meridional advection, vertical advection, isopycnal diffusion. The NEMO2_30S30N – NEMO2_REF oxygen anomaly (mmol.m^{-3}) is displayed in contour.

Figure 5 : mean currents velocity (ms$^{-1}$) at a- 1000 m depth  b- 100°W in UVIC, NEMO2,  NEMO05, GFDL025,  GFDL01,  NEMO01. The  mean  oxygen  levels  (mmol.m$^{-3}$)  (when  coupled  circulation-biogeochemical experiments have been performed – see Table 1) are displayed in contour

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Figure 6:  a : tracer concentration (arbitrary unit) after 60 years integration in NEMO05 and NEMO01: average 500-1500m, section 100°W, equatorial section. b: Time (years) at which the released tracer reaches the concentration 0.1 (t10%) in NEMO05 and NEMO01: average 500-1500m, section 100°W, equatorial section. In all the subpanels, the WOA oxygen levels are

displayed in contour. The red contour is the WOA 150 mmol.m$^{-3}$ oxygen isoline, used to initialize

979 the tracer level.



Figure 7 : Density (number of particles in a 1°x1°x100m depth box) distribution of the location of released Lagrangian particles (15 years backward integration starting from the final experiment state) in NEMO05 and NEMO01. The release location is identified in bold and is located a- at 100°W/5°N-5S/1000 m depth (R1). b- at 160°E/5°N-5°S/1000 m depth (R2). The particles have

been integrated vertically, zonally and meridionally. The observed mean oxygen levels (WOA) are displayed in contour.

Figure 8 :  a- schema summarizing the releases (R1: 100°W / 5°N-5°S / 1000 m , R2: 160°E / 5N°5S / 1000 m) location, the IETP (Intermediate Eastern Tropical Pacific), IWTP (Intermediate Western Tropical Pacific) regional extension. b. percentage of particles (release R1) originating from outside the IETP ocean region. b- percentage of particles (release R2) originating from outside the IWTP ocean region. d- percentage of particles (release R1) originating from the upper ocean (shallower than 200 m), the deeper ocean (deeper than 2000 m), subtropical regions (poleward 10°), the IWTP. e- percentage of particles (release R2) originating from the upper ocean

**Mean kinetic energy**

1003    Figure 9 : a - Mean Kinetic Energy (m2.s$^{-2}$ x 1000) (average 10°N-10°S) in GFDL01, GFDL025,

1004    GFDL01, UVIC, b - similar to a. but average 160°W- coast. Oxygen levels (mmol.m$^{-3}$) are displayed

1005    in black contour. The blue contour corresponds to UVIC GD13 (Getzlaff and Dietze, 2013,

1006    including an anisotropical increase of lateral diffusion at the equator)

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1015 Table 1 :

| Model | Resolution | Atmosphere | Integration (years) | BGC | Model Reference (circulation) | Model Reference (BGC) |
|---|---|---|---|---|---|---|
| **Mean state comparison** | | | | | | |
| UVIC | 2.8° | Coupled (temperature, humidity) Forced (NCEP/NCAR wind stress) | 10000 | UVIC-BGC | Weaver et al., 2001 | Keller et al., 2012 |
| NEMO2 | 2° (0.5 eq) | Forced COREv2 "normal year" | 1000 | NPZD-O2 | Madec et al., 2015 | Kriest et al, 2010 Duteil et al., 2014 |
| GFDL1 | 1° | Coupled | 190 | BLING | Delworth et al, 2012, Griffies et al, 2015 | Galbraith et al., 2015 |
| GFDL025 | 0.25 ° | Coupled | 190 | BLING | | |
| GFDL01 | 0.1° | Coupled | 190 | BLING | | |
| | | | | | | |
| **Process oriented experiments** | | | | | | |
| Model | Resolution | Atmosphere | Integration (years) | BGC | Characteristics | |
| NEMO2 -REF -30N30S -30N30S1500M (section 2.2.1) | 2° (0.5 eq) | Forced COREv2 1948-2007 | 60 | NPZD-O2 | - control experiment - O2 restoring to WOA at 30°N/30°S - O2 restoring to WOA at 30°N/30°S/1500m | |
| NEMO05 (section 2.2.2) | 0.5° | Forced COREv2 1948 - 2007 | 60 | Tracer release | - Tracer initialized to 1 (O2 WOA > 150 mmol.m-3) or 0 (O2 WOA < 150 mmol-m-3) | |
| NEMO01 (section 2.2.2) | 0.1° | Forced COREv2 1948 – 2007 | 60 | Tracer release | | |

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1. Wind forcing

Zonal wind mean stress typically vary 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)
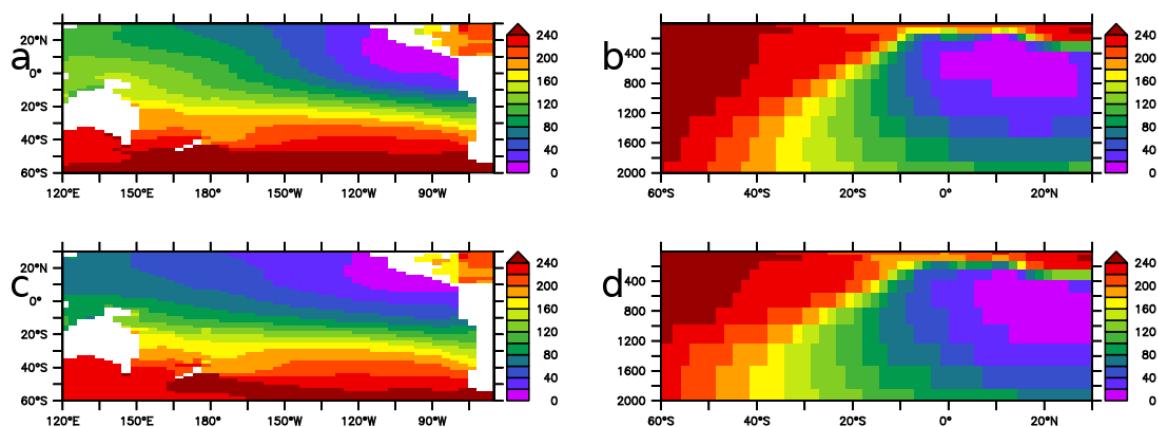


Figure A1 : Oxygen levels in UVIC (10000 years integration) a- mean 500-1500 m forcing NCEP. b- section 120°W forcing NCEP. c- mean 500-1500 m forcing COREv2, d- section 120°W forcing COREv2.

**mmol.m-3 (30°S)** / **mmol.m-3(20°N-20S)**

**Volume OMZ (m3 x 1e15)** / **mmol.m-3(20°N-20S)**
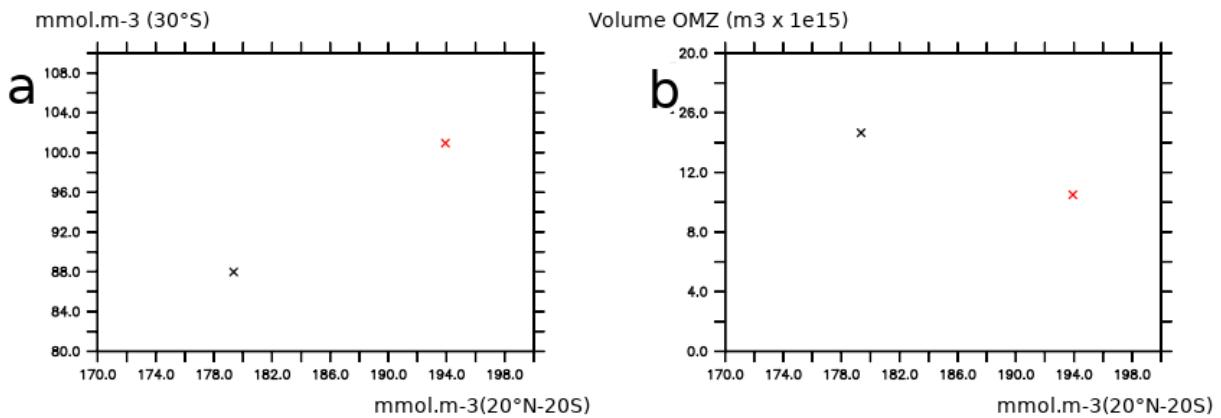
Figure A2 : a - Oxygen levels in UVIC (10000 years integration) at 30°S (zonal mean in the Pacific Ocean from surface to 2000 m depth) and in the tropical regions (20°S-20°N, averaged over the whole Pacific Ocean). b - Oxygen levels in UVIC (10000 years integration) at 30°S (zonal mean in the Pacific 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)
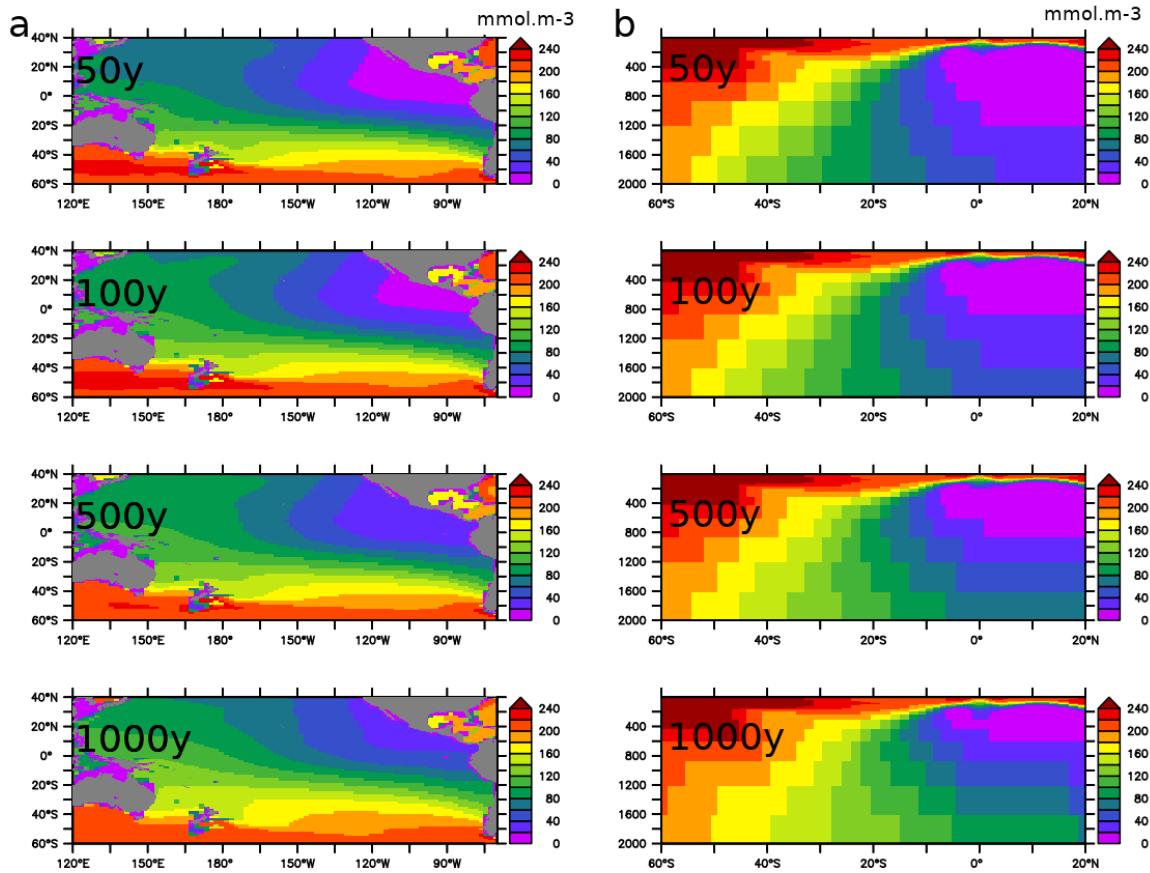
Figure A3 : oxygen levels at a - intermediate depth (average 500 – 2000 m) and b - 120°W in NEMO2 after 50, 100,500 and 1000 years integration
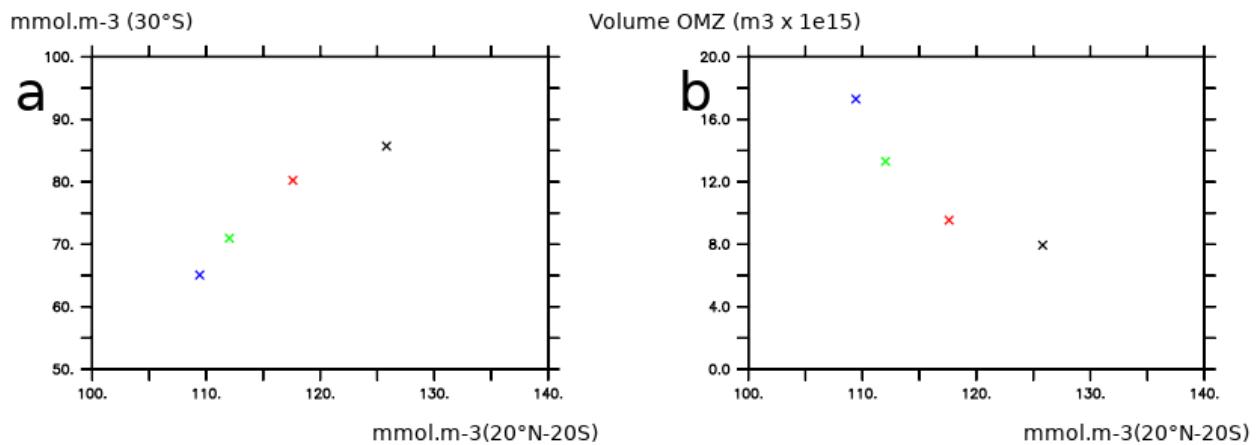


Figure A4 : a - Oxygen levels in NEMO2 at 30°S (zonal mean in the Pacific Ocean from surface to 2000 m depth) and in the tropical regions (20°S-20°N, averaged over the whole Pacific Ocean from surface to 2000 m depth). b - Oxygen levels in NEMO2 at 30°S (zonal mean in the Pacific Ocean from surface to 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).

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