Physical and biological processes driving seasonal variability of Nitrate budget and biological productivity in the Gabon-Congo upwelling system

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REVIWER1

Dear Reviewers,

We would like to express our sincere gratitude for your constructive comments and insightful suggestions, which have greatly helped us improve the quality of our manuscript.

Please note the following points regarding the presentation of this document:

- **Color Coding:** For ease of reading, the reviewers' original comments are presented in **black**, while our detailed responses and the specific changes made to the text are highlighted in **blue**.
- **Figure Renumbering:** Following a specific recommendation from one of the reviewers, the **original Figure 3 has been removed**. As a result, the numbering of all subsequent figures has been updated throughout the revised manuscript. We apologize for any inconvenience this may cause when cross-referencing with the previous version.

Please find below our detailed responses to the comments.

This study investigated physical and biogeochemical processes responsible for seasonal variability in nitrate and biological productivity in the Congolese upwelling system using a high-resolution ocean-BGC coupled model. The authors performed the detailed budget analysis for seasonal change in nitrate and ecosystem and suggested that vertical motion is responsible for the nitrate tendency in the upwelling season. This vertical motion also includes some clue of coastal Kelvin waves. On the other hand, around the Congo River mouth, horizontal advection is an important player in supplying nitrate provided by the riverine flux of the Congo. I found this work quite interesting and revealed details of physical and biogeochemical processes in the high-productivity region. However, one concern is that the mixed-layer depth defined in this study is a bit skeptical: in the entire year, the depth is 10m and almost constant (Figs.12-14). According to the definition in this study, I would think that the authors capture a “barrier layer” created by fresh water, not mixed-layer. Therefore, some budget analysis might not capture the processes in mixed-layer properly. I would recommend testing other criteria of mixed-layer depth and see the differences. Further comments are given as below..

List of comments

Line 109-111: better to be careful describing. According to those references, only N_2O is addressed in the EBUS. Not sure CH_4 flux is also active in the region. For CO_2, I could imagine some CO_2 flux due to rich DIC. But, cold SST can suppress the CO_2 outgassing, so curious which factor is more responsible for CO_2 flux there. Any observed data/indication available?

Thank you for this insightful comment regarding the specific drivers of Greenhouse Gases fluxes in EBUS. We agree that the description needs to be more nuanced, particularly regarding CH_4 and the specific mechanisms driving CO_2 outgassing in the EBUS.

Regarding CH_4, we acknowledge that evidence for significant fluxes in EBUS is less systematic than for N_2O. As highlighted in the recent global synthesis by **Resplandy et al. (2024)**, marine CH_4 emissions are primarily driven by shallow sediment interactions (<50m) rather than the upwelling process itself or the water-column OMZ. We have therefore removed the emphasis on CH_4 in this general description.

Regarding CO_2, the reviewer correctly identifies the competition between the thermal effect (cold SST enhancing solubility) and the chemical inventory (DIC supply). According to **Resplandy et al. (2024)** (and references therein like *Dai et al., 2013* or *Capelle et al., 2020*), EBUS are indeed characterized as **sources** of CO_2 near the coast. Observations confirm that the **vertical transport of DIC-rich deep waters overwhelms the thermal effect** of cooling, leading to strong outgassing at the upwelling center where the coastal Ekman upwelling dominates. This physical supply of carbon is the dominant factor, although rapid biological uptake with enriched nutrient upwelled waters can switch the system to a sink further offshore along the Ekman offshore horizontal transport.

We have rewritten **Lines 108-114** to reflect these distinct mechanisms in the revised manuscript

See **Lines 110-114** of the current muscript

Line 111-112: do you mean such greenhouse gases are drivers of climate variability? If so, what type of variability is driven?

Response:
Thank you for pointing this out. Indeed, the term "climate variability" was ill-chosen in this context. We did not intend to suggest that these local gas fluxes drive internal climate modes (like ENSO or NAO). Rather, we meant that these gases contribute to the global atmospheric greenhouse gas budget and, consequently, to **global warming** (radiative forcing).

As highlighted in the synthesis by **Resplandy et al. (2024)**, the emission of non-CO_2 gases (N_2O and CH_4) in coastal regions can offset a significant portion (30–60%) of the CO_2 uptake in terms of radiative balance. Therefore, EBUS are relevant for understanding **climate change** rather than climate variability. In the revised manuscript, we removed this part of the sentence “Greenhouse gases are drivers of climate varibility” to avoid any confusion.

Line 113: Apart from?

Response: Corrected **Line 115**

Line 114: should be switched. Sea surface temperature (SST, ...).

Response: Thank you,we have switched the terms to follow the standard convention: defining the full term first, followed by the abbreviation in parentheses. This has now been corrected in the revised version of the manuscript (**Line 116**)

Line 134: twitch =>which

Response: Thanks, we replaced "twitch" with **"**which**"** C**orrected in the revised version of the manuscript (line 137)**

Line 149-150: This sentence is partially finished? Or want to say "Whereas the total advection contribution is less important, it plays a secondary role in the mixed layer heat budget". ?

Response: We want to say that “Where as the total adection contribution is less important, it plays a secondary role in the mixed lalyer heat budget” However, below the mixed layer, vertical advection by upwelling CTWs was crucial to raise the thermocline high enough so that cool waters can penetrate in the mixed layer by vertical mixing.. Thank you to point out this problem. In the revised manuscript, we rephrased this sentence: “The total advection contribution as less important and payed a secondary role in the mixed layer heat budget’’. **Lines 152-154**

Line 170: reveal or other verbs sound better.

Réponse: we have replace ‘**highlight’** by ‘**investigate**’. This has now been corrected in the revised manuscript (**line 177**)

Line 209: year of 2011, I am wondering how the year of 2011 was in terms of trpical Atlnaitc ocean climate. Any strong Atlantic NIño/Niña and/or Benguela Niño/Niña? Maybe some brief information could added.

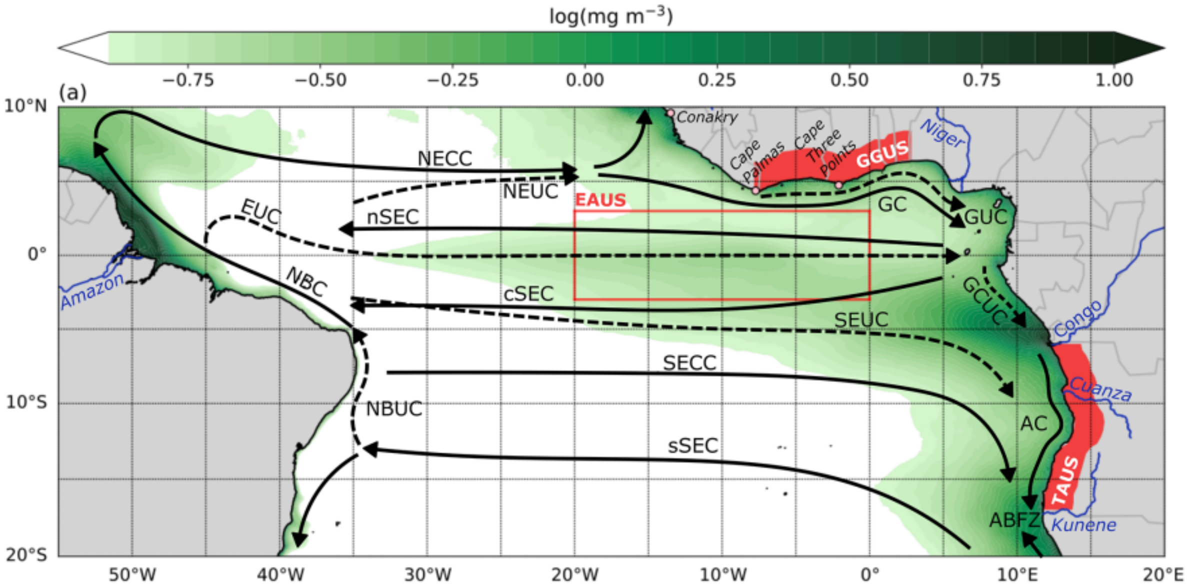


Fig. R1: (a) Mean chlorophyll concentration in the tropical Atlantic with circulation schematic superimposed. Surface (solid arrows) and thermocline (dashed arrows) current branches shown are the North Equatorial Countercurrent (NECC); the North Equatorial Undercurrent (NEUC); the Guinea Undercurrent (GUC); the Guinea Current (GC); the North Brazil Undercurrent (NBUC); the North Brazil Current (NBC); the Equatorial Undercurrent (EUC); the northern, central and southern branches of the South Equatorial Current (nSEC, cSEC and sSEC); the South Equatorial Undercurrent (SEUC); the South Equatorial Countercurrent (SECC); the Gabon–Congo Undercurrent (GCUC) and the Angola Current (AC). Also marked are the Angola–Benguela Frontal Zone (ABFZ) at about 17◦ S and the rivers Amazon, Niger, Congo, Cuanza and Kunene. The red box marks the equatorial Atlantic upwelling system (EAUS; 3◦ N–3◦ S, 20–0◦ W). Red patches mark the coastal extent of the Gulf of Guinea upwelling system (GGUS; 8◦ W–3◦ E, 1◦ width coastal band) and the tropical Angolan upwelling system (TAUS; 6–17◦ S, 1◦ width coastal band). **Brandt et al. (2023)**

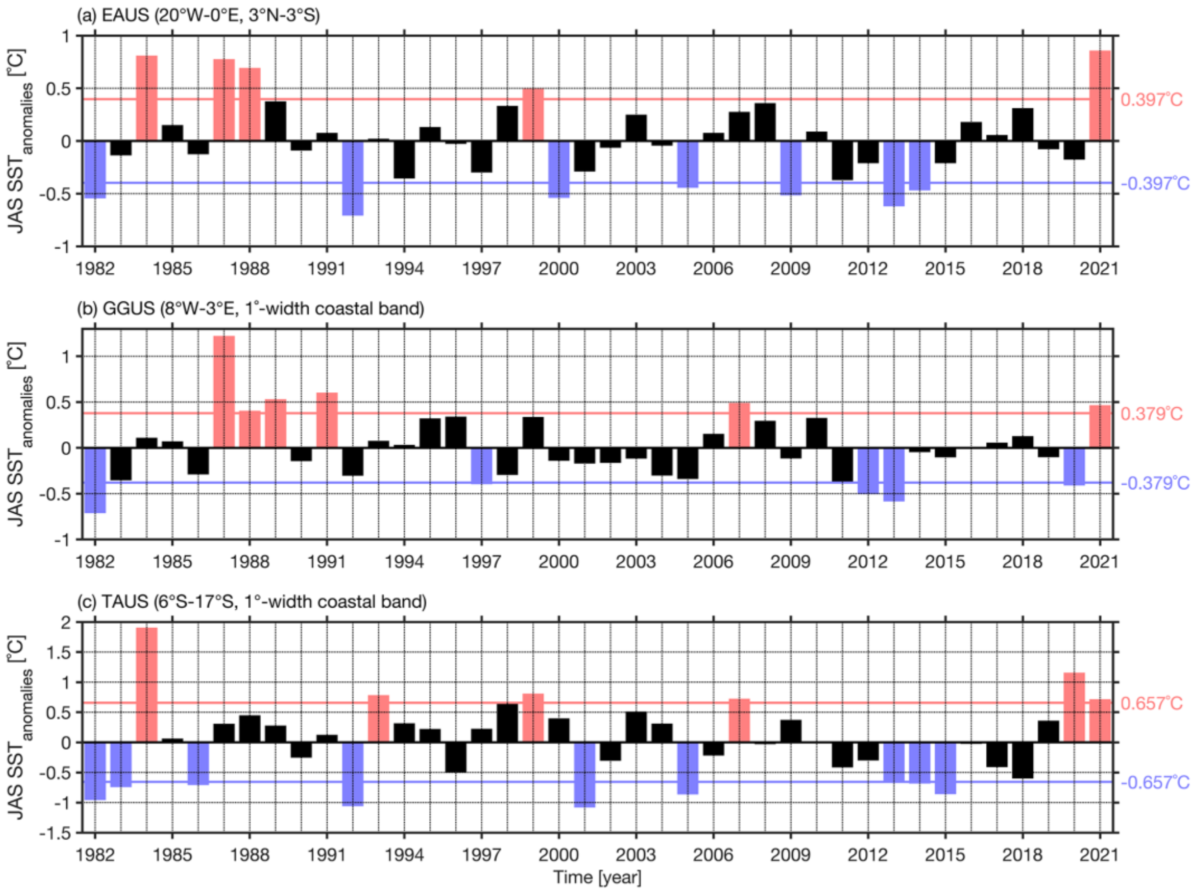


Fig. R2: SST anomalies from 1982–2021 during the main upwelling season (July–September) averaged in the EAUS (a), GGUS (b) and TAUS (c). The red and blue rectangles highlight the extreme warm and cold events in the different regions, respectively. The horizontal red and blue lines show the standard deviation of the interannual SST anomalies during the main upwelling season (July–September). Anomalies are derived with respect to the seasonal cycle between 1982 and 2021 after subtracting the trend. SST data are from OI-SST (https://www.esrl.noaa.gov/psd/data/gridded/, last access: 11 April 2023). **Brandt et al. (2023).**

Réponse : To address the reviewer's comment regarding the climatic context of 2011 (Line 209), we have analyzed the JAS (July-August-September) SST anomaly indices from Brandt et al. (2023). According to their classification, Atlantic Niño/Niña events are monitored in the EAUS region (Equatorial Atlantic Upwelling System), while Benguela Niño/Niña events are monitored in the TAUS region (Tropical Angolan Upwelling System)(see Figure R1).

As shown in the indices for 2011 (see Figure R2), the SST anomaly in the EAUS remained relatively weak and within the ±0.397°C threshold, indicating the absence of an Atlantic Niño or Niña. Similarly, the anomaly in the TAUS region (see Figure R2) was neutral, staying within the ±0.657°C threshold, confirming that no Benguela Niño or Niña occurred that year. Therefore, 2011 represents a climatically 'normal' or neutral year, providing an ideal baseline to study the seasonal physical and biogeochemical processes without the influence of extreme interannual variability**.** We added this information in the revised manuscript: "which is characterised by neutral conditions regarding the Atlantic Nino and Benguela Nino interannual variability (Brandt et al., 2023)". Lines (224-225)

The end of Section 1: please give a summary of strcture of this paper in the last part of the Section 1.

Réponse : Thanks, the paper is organized as follows: Section 2 describes the numerical model and the datasets used for validation. Section 3 presents the results, including a model-data comparison and an analysis of the nitrate budget in the mixed layer and euphotic zone. Section 4 discusses the findings in the context of other tropical upwelling systems, and Section 5 provides the conclusions. We have now added this in the revised manuscript (**Lines 180-183**)

Line 229: some typo?

Yes, it is corrected in the revised manuscript (**Line 246**)

Line 231: no comma?

Thanks, it is corrected in the revised manuscript (**Line 246**).

Line 232: 5^{th} daily?

we replaced the 'temporal resolution of 5 days' by 'with a **5-day** temporal resolution'.(**Line 248**)

Line 247-248, Eq.1: Perhaps, this term is missing in the equation (1). In the equaiton, 4th terms looks like "vertical" diffusion.

we thank you for this observation. It is corrected in the revised manuscript (**Lines 260-271**)

Line 262: italic?

Réponse : In the revised manuscript, we made this correction in the sentence : The second and third terms on the right of equation (2) are the growth of nanophytoplankton and diatoms, where μ_{NO3}^{P} and μ_{NO3}^{D} are their growth rates, *P* and *D* are their concentrations respectively. R_{NH4} and R_{NO3} are the stoichiometric *N/C* ratios of ammonification and nitrification respectively. (**Lines 279-282**)

Line 295-303: perhaps, better to refer each panel of Fig.2.

Réponse : We refered each panel of fig.2 : 'winter (June-August) which is the main Congolese upwelling period. As can be seen, the upwelling feature is well captured by the model with cooling of surface water at the coast below 23°C in the model and 22°C in the MUR product **(Fig. 2a,b)**. This cooling feature is consistent with high nitrate **(Fig. 2c,d)** and CHLa **(Fig. 2e,f)** concentrations in both models and observation, particularly north of the Congo estuary (6°S) and nearby Kouilou River mouth **(Fig. 2e)** at 4.47°S. These cool and enriched nutrient coastal waters are spread offshore displaying a cross-shore gradient, with a greater extension in the observation than the model. The highest nitrate concentration in the coastal waters is greater than 10 mmolN.m-3 in the model (8 mmolN.m-3 in the observation) located mainly in the Congo River plume area, inducing enhancement of PP resulting in a strong CHLa signature'. In the revised manuscript (**Lines 336-347**)

Line 306: (e,f) is missing

Thanks, it is now corrected in the revised manuscript (**Lines 350-351**) we added (e,f) panel in the legend ' Figure 2: Comparison between model (left hand side) and observations (right hand side) with regional distribution of sea surface temperature (a, b), nitrate concentration (c, d) and CHLa concentration averaged (e,f) for austral winter (June, July, August)'.

Line 313: In the model, it looks like that the coastal upwelling is not very realistic as seen by warm SST. The cold SST is mainly coming from the Congo river plume. I am wondering how JRA-55's performance in reproducing coastal level jet. Could you find any clues on this from this paper?, https://journals.ametsoc.org/view/journals/clim/31/4/jcli-d-17-0395.1.xml

We thank the Reviewer for pointing out the study by Lima et al. (2018). We have carefully reviewed their findings regarding the JRA-55 performance in reproducing Coastal Low-Level Jets (CLLJs). However, we believe that this does not explain the SST patterns in our specific study area for several reasons:

1. **Geographic location:** Lima et al. (2018) show that the South Atlantic CLLJs are primarily located south of 10°S (off the coasts of Namibia and Southern Angola). Our study area, focused on the Congo River plume (~6°S), lies north of this jet's influence zone.
2. **Wind Forcing:** In our model configuration, we use **ASCAT satellite products** to force the ocean stress, while JRA-55 is only used for atmospheric heat fluxes. Therefore, potential biases in JRA-55 surface winds do not affect the wind-driven upwelling in our simulation.
3. **Nature of the bias:** The warm SST bias observed along the African coast is a well-known systematic issue in most ocean and climate models in the Tropical Atlantic (e.g., Voldoire et al., 2019).
4. **Congo Plume vs. Upwelling:** As noted by the reviewer, the cold signature in our model is dominated by the Congo River plume rather than classical wind-driven upwelling. This is consistent with recent studies (e.g., Aroucha et al., 2025) showing that the river discharge significantly impacts the local thermal structure and stratification, creating a cooling effect that can be more prominent in the model than the coastal upwelling itself.

Lines 699-708

Line 313-314: Also I am curious how the NEMO's performance in ocean current system in this region. From nitrate and SST distribution, south of Congo river mouth, nitrate is quite poor compared to observation (perhaps, less upwelling). On the other hand, north of the River Mouth, coastal nitrate is enriched even though SST is warmer indicating the weak upwelling. Maybe this high concentration in the north of River Mouth is influenced by the current?

Response: We thank the reviewer for these relevant observations. Several factors, both data-related and physical, explain these patterns:

1. **Data Source Discrepancy:** The CARS 2009 nitrate product is a climatology with relatively low data density in this region, mostly relying on interpolation of historical data (pre-2011). Its horizontal resolution is 1/2° (~50 km), whereas our NEMO-PISCES simulation is at 1/36° (~3 km). The higher resolution of the model allows for a more detailed representation of localized structures that are naturally smoothed out in the CARS climatology.
2. **Congo River Plume Dynamics:** The high nitrate concentration north of the Congo mouth, despite warmer SSTs, is primarily driven by the **Congo River plume**. During this season, the plume is oriented North-West due to surface current forced by the winds (northward direction).
3. This freshwater mass is highly enriched in nutrients (nitrates), which explains the high concentrations observed in the model north of the estuary even if the coastal upwelling is weak.
4. **Angola Current (AC) influence:** Regarding ocean currents, the region is dominated by the southward-flowing **Angola Current (AC)**. As highlighted by Radenac et al. (2020), the AC is fed by the **Equatorial Undercurrent (EUC)**, which transports relatively low-nitrate waters into

the system. This contributes to the lower nitrate levels south of the mouth or further offshore, where the riverine influence is weaker.

5. **Current Validation:** To address the reviewer's curiosity, we have included/referenced a comparison between NEMO and OSCAR surface currents (Fig. R3,R4,R5). The model successfully reproduces the main circulation features, including the AC and the plume's trajectory.

Note however there are important differences near the coast for satellite-derived OSCAR and GlobCurrent products (Figs R3 & R4). Also near theCongo mouth, the northwesward current in the model is consistent with the recently developed eOdyn ship-drift product, for which observation density is higher near the coast (fig R5).

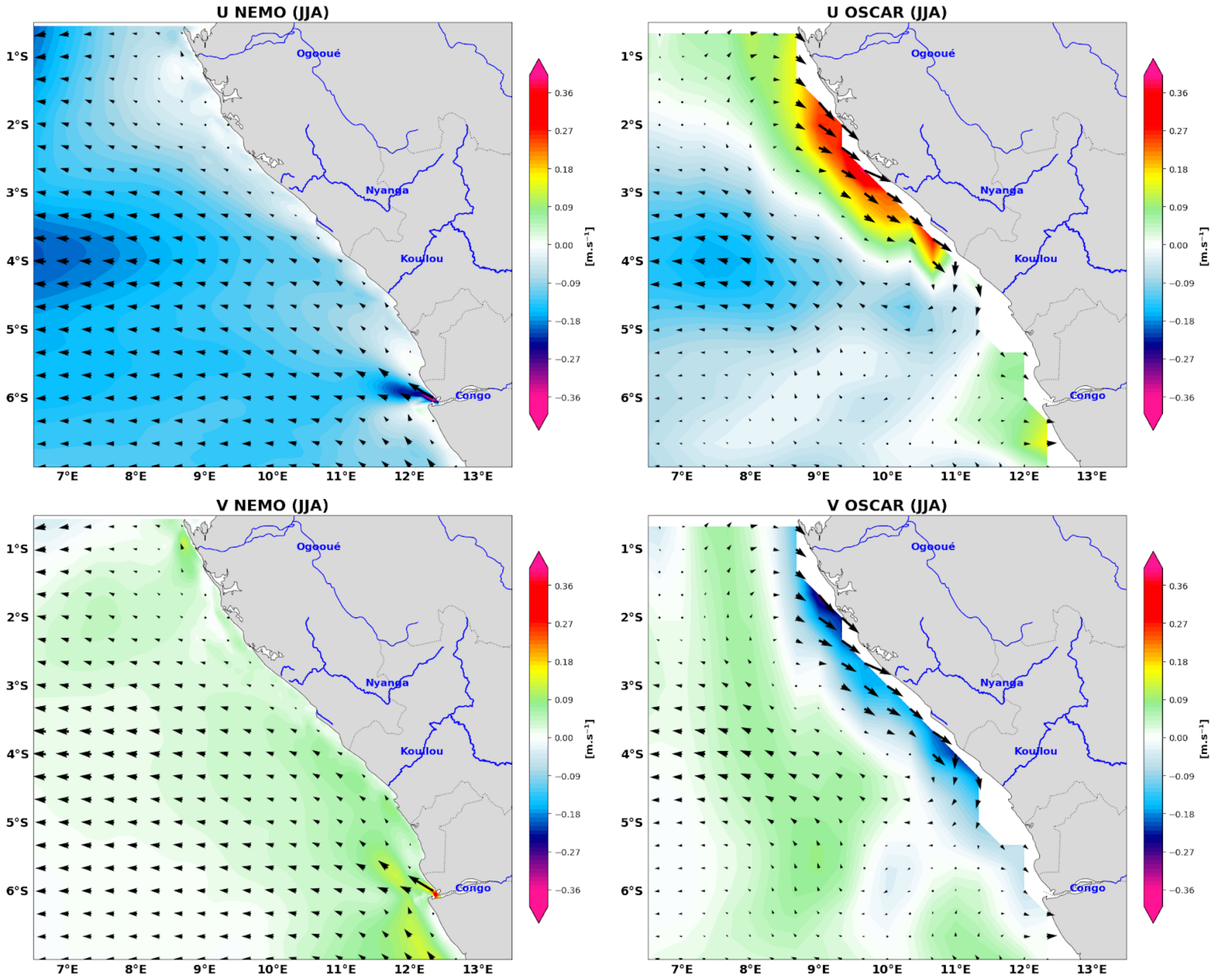


Fig.R3: Spatial distribution of the mean zonal (U) and meridional (V) current components averaged over the upper 30 m during the main upwelling season (JJA). Left panels show NEMO model outputs and right panels show OSCAR observations. Black arrows represent the total current vectors.

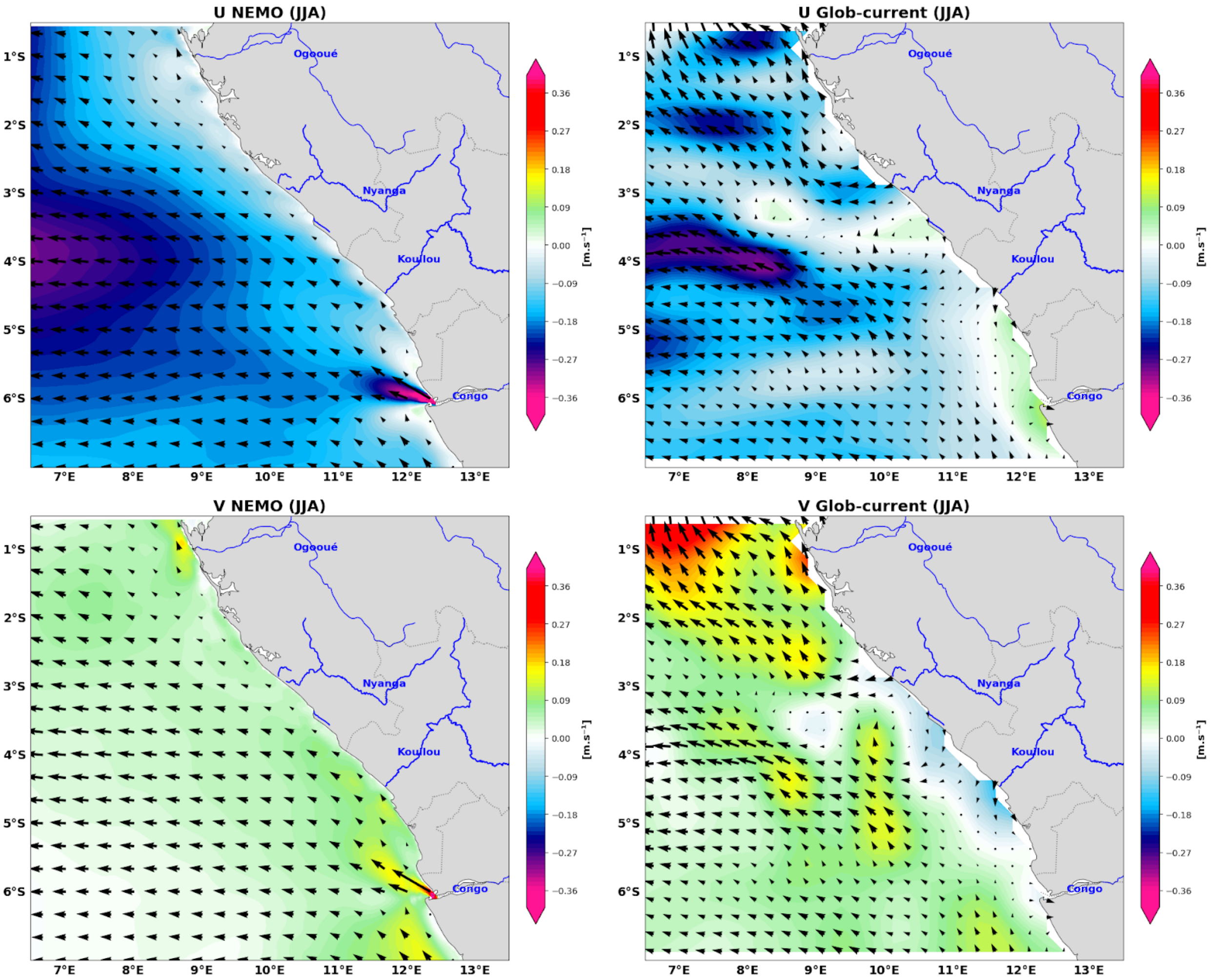


Fig.R4: Spatial distribution of the mean zonal (U) and meridional (V) current components averaged over the upper 15 m during the main upwelling season (JJA). Left panels show NEMO model outputs and right panels show GLOBCURRENT observations. Black arrows represent the total current vectors.

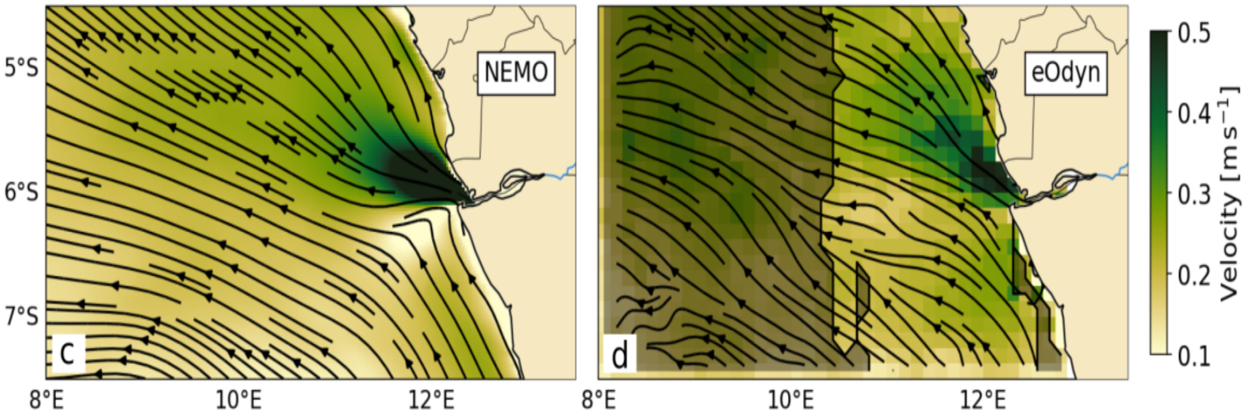


Fig.R5: Annual mean distribution over the year 2016 of surface currents with intensity in the background colors and streamlines in black lines of the NEMO model (c) and of eOdyn (d). Shaded aeras denote low density of observations. From Cardot et al., JGR, in revision).

Line 317: how about in the observation?

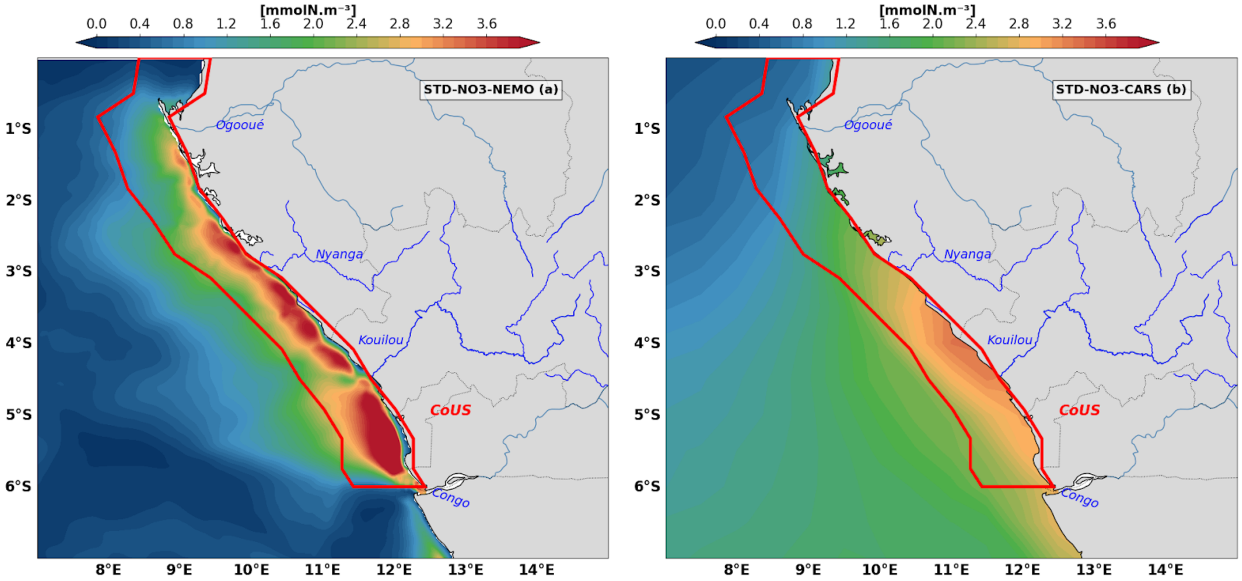


Fig.R6: Comparison of surface Nitrate variability between model outputs and observations.,(a) Standard deviation of surface Nitrate concentration (STD−NO3) simulated by the NEMO model [mmolN m^{-3}]. (b) Standard deviation of surface Nitrate concentration from the CARS 2009 climatology [mmolN m^{-3}]. The red polygon delimits the Congolese Upwelling System (CoUS), the primary study area extending from the Congo River mouth to Cape Lopez. Blue labels indicate major river discharge points (Ogooué, Nyanga, Kouilou, and Congo). Both panels highlight the coastal corridor as the region of maximum nutrient variability, although the climatology (CARS) exhibits smoother patterns and lower amplitudes due to data interpolation.

Response:
"Following the reviewer's suggestion, we have included a comparison of the Nitrate standard deviation (STD-NO3) between the NEMO model and the CARS 2009 climatology (Fig. R6b). The observations (CARS) show a spatial distribution of nutrient variability that is highly consistent with the model results, with a clear maximum located along the coast within the Congolese Upwelling System (CoUS), particularly between 3°S and 6°S.

We note that the amplitude of the variability in the model (~3.6 mmolN.m^{-3}) is higher than in the observations (~2.6 mmolN.m^{-3}). This difference is expected, as CARS is a climatological product based on objective interpolation of historical data, which inherently smooths out spatial gradients and extreme seasonal values. In contrast, the NEMO model captures more high-frequency and mesoscale processes. Despite this difference in magnitude, The clear spatial consistency between the two products validates the model's ability to accurately represent the core areas of nutrient enrichment and seasonal dynamics in the region."

Line 318: dot is missing.

Response: we have replace the comma after ‘$NO3$’ by a point. In the revised manuscript **(line 362)**

Figure4: Why the observation CARS does not have a peak around 6S close to the Congo River Mouth? Due to the relatively coarse resolution or NEMO-PISCES has a large bias of nitrate input of riverine flux?

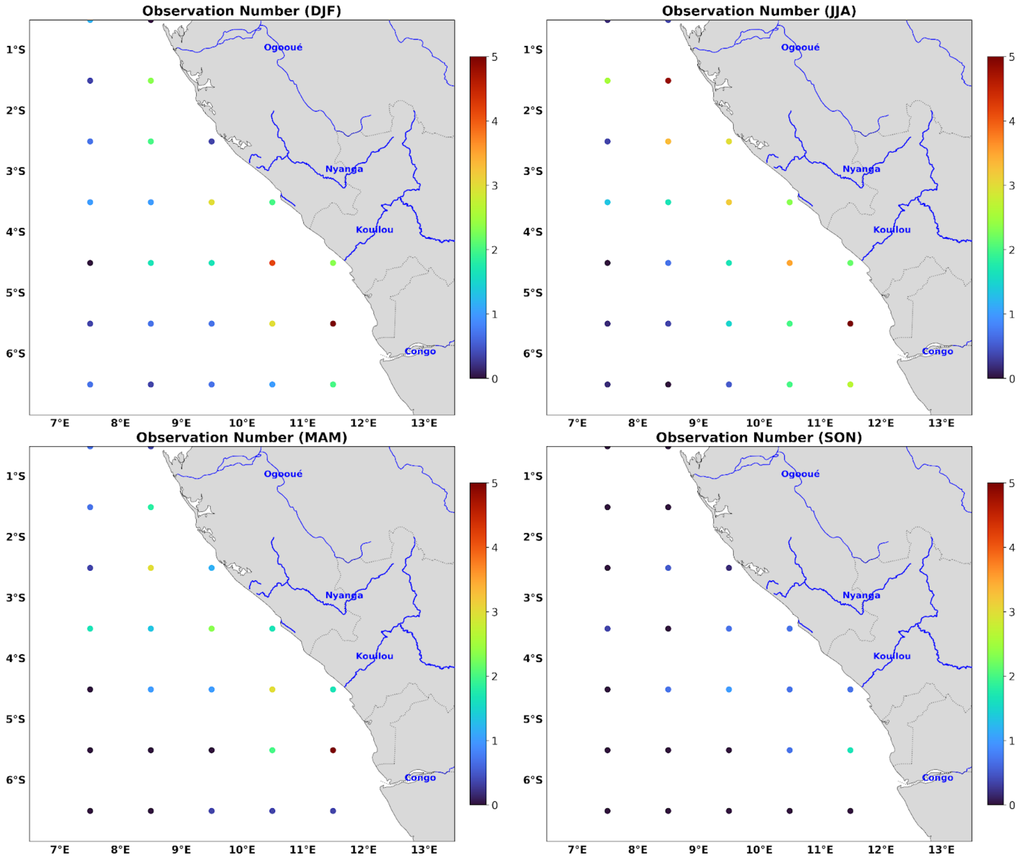


Fig.R7: Regional data density of the CARS2009 dataset across the four seasons: (a) DJF, (b) JJA, (c) MAM, and (d) SON. Shaded dots represent the number of raw observations used to generate the climatology at each specific grid point along the Gabon-Congo margin.

We thank the reviewer for this relevant question. The discrepancy between the model and the CARS climatology at 6°S is explained mainly by: the severe lack of oceanic in-situ data in this region and the difference in the representation of riverine inputs.

1. **Data Scarcity and CARS Limitations:** Historical oceanic in-situ observations near the Congo River mouth are extremely sparse (Fig. R7). CARS 2009 is a global climatology (0.5° resolution) that relies on the interpolation of available profiles. In data-poor regions like the Congolese coast, the interpolation process significantly smooths out localized signals. Consequently, the narrow, nutrient-rich plume of the Congo River is "diluted" in CARS, explaining the absence of a sharp peak.
2. **Reliability of Riverine Forcing (HYBAM):** To ensure a realistic representation of the Congo River input, we used data from the **HYBAM observation network**, which provides the only reliable nutrient time series for this system. The measurements are taken at the Brazzaville station, located approximately 480 km from the mouth. This station is of primary importance as it captures the flux from **98% of the entire Congo basin watershed**. These HYBAM data is not used in the CARS climatology dedicated to the ocean.
3. **Validation of the Reference Source:** Although the river traverses the Livingstone Falls and receives minor local tributaries between Brazzaville and the ocean, the Brazzaville data are internationally recognized as the most accurate reference for calculating nutrient fluxes for the oceanic plume. As shown in **Fig. R8**, the HYBAM data (red curve) confirm very high nitrate concentrations peaking in August (>1.4 mg/l), which NEMO-PISCES (blue curve) replicates consistently.

In conclusion, the nitrate peak in the model is not a bias but a **realistic feature** driven by high-quality riverine observations, whereas CARS fails to capture this signal due to its coarse resolution and the lack of coastal oceanic data.

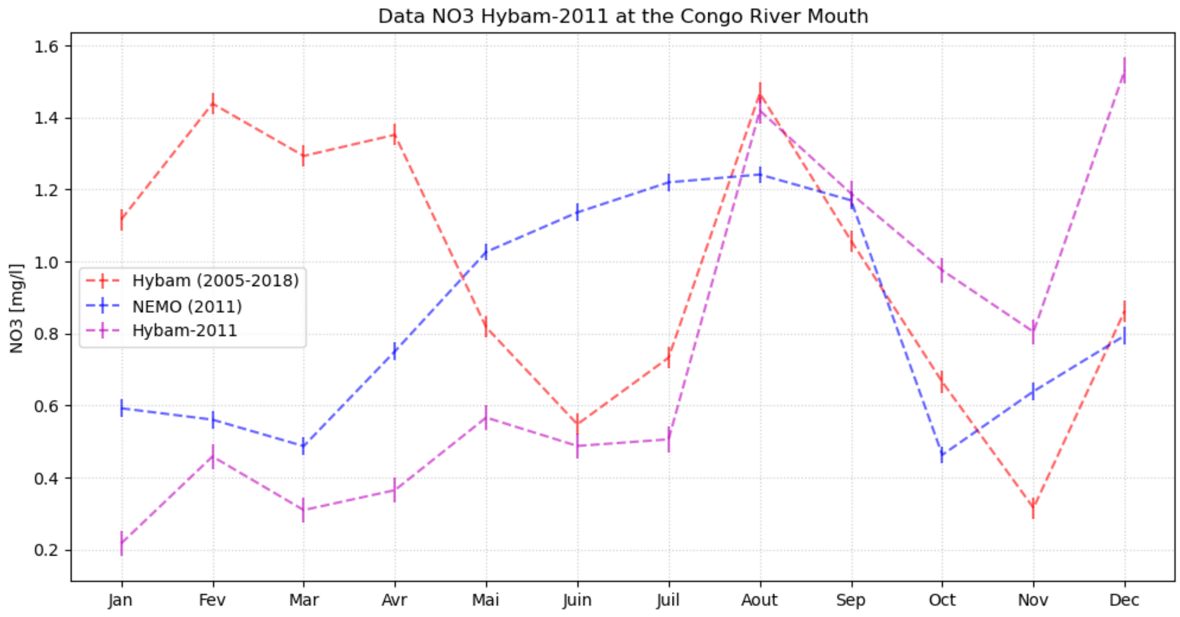


Fig. R8: Validation of simulated Nitrate concentrations (NO_3) at the Congo River mouth for the year 2011. The plot displays monthly mean NO_3 concentrations [mg/l] from HYBAM in-situ data and NEMO model outputs. The red line represents the climatological mean (2005–2018) as a regional benchmark. The magenta line shows the specific observed values for 2011, while the blue line illustrates the corresponding model performance for the same period.

Line 341: seasonal variability

Thanks, we added seasonal variability in the revised manuscript (**Line 383**).

Line 344: December-to-January(or February)?

Response: We thank the reviewer for the question. Based on the analysis of the seasonal cycles in Figure 4, the secondary cooling event (SST minimum) and the associated nitrate enrichment (NO_3 maximum) are primarily centered in **December**.
As shown in Figure 4c-d, the SST reaches its secondary minimum in December before rising significantly in January and February, which corresponds to the start of the main warming period. Similarly, the nitrate concentration (Fig. 4e-f) shows a brief but distinct peak in December. This timing is consistent with the propagation of the secondary upwelling Coastal Trapped Wave (CTW). In January and February, the arrival of downwelling waves and increased solar radiation lead to a rapid depletion of surface nitrates and a sharp increase in SST.

Line 352-356: This argument makes sense. Here, linking to Fig.4, I am wondering if upwelling due to CTWs is too strong in the model as I can see the 15mm/m3 line is too shallow compared to the observation. Any argument is possible?

Response: We acknowledge the reviewer's observation regarding the depth difference of the 15 mmol/m³ isoline between the model and CARS. However, we argue that this discrepancy is primarily driven by the difference in resolution rather than an overestimation of the CTW forcing. CARS 2009 is a coarse-resolution climatology (0.5°) based on sparse historical data. The interpolation process used in such products inherently smooths vertical gradients and tends to deepen isolines in regions with low data density, such as the Congolese margin.

In contrast, the high-resolution NEMO-PISCES (1/36°) allows for a much sharper and shallower representation of the coastal nitracline, which is a common feature in high-resolution models compared to global climatologies. Furthermore, the strong vertical stratification induced by the Congo River plume in the model effectively traps nutrients in a thinner upper layer, a small-scale process that is likely smoothed out in the CARS product. Therefore, the shallower isoline in the model may actually reflect a more realistic coastal response than the smoothed climatological mean.

Line 367-369: Sound a bit repetitive with lines 352-356?

Response: We agree with the reviewer that these lines were redundant. We have merged the description of the physical mechanisms to avoid repetition. The revised text now integrates the role of remotely forced Equatorial Kelvin Waves (EKW) and the use of the thermocline as a nitracline proxy directly into the discussion of the seasonal cycle, providing a more concise and fluid explanation. In the new version of manuscript (**Lines 403-413**)

Line 372: "deepen" sounds better than lower.

Response: We have replaced "lower" with "deepen" as suggested. We have also removed the word repetition in the previous sentence and corrected the citation format. (**Line 412**)

Fig.6: no any description on wind stress. In October, the alongshore wind stress is stronger than other months. But, SST is warm and CHL-a is less (NO_3 as well). Does this indicate that offshore Ekman transport is not responsible for BGC process here? Or, should we consider some time lag between wind-stress and BGC response?

Response: We thank the reviewer for this observation. The lack of biological response (low NO_3 and CHLa) in October, despite the local wind stress maximum, is not due to a time lag but to a **triple physical and biogeochemical inhibition** that overrides the wind's influence:

1. **Remote Oceanic Forcing:** October is characterized by the passage of a **downwelling Coastal Trapped Wave (CTW)**, which deepens the thermocline and nitracline, preventing the wind from reaching nutrient-rich deep waters.
2. **Increased Stratification:** According to Hybam discharge data, the **Congo River volume** increases significantly in October. This strengthens the vertical haline stratification, creating a stable surface freshwater lens that acts as a physical barrier against wind-driven vertical mixing.
3. **Low Riverine Nutrient Supply (New Evidence):** By analyzing the riverine nitrate concentrations (**Fig. R8, red curve**), we observe that in October, the nitrate content of the Congo water is at a **seasonal relative minimum** (~0.65 mg/l) compared to the main upwelling season (peaking at >1.4 mg/l in August). Therefore, during this period, the river plume itself is nutrient-poor and cannot sustain high primary production.

In conclusion, the strong wind stress in October is "Simultaneously suppressed" (by remote forced coastal trapped waves and haline stratification) and is not supported by riverine nutrient input, explaining the absence of a BGC response. We have added this detailed explanation to the revised Section 3.1.2.

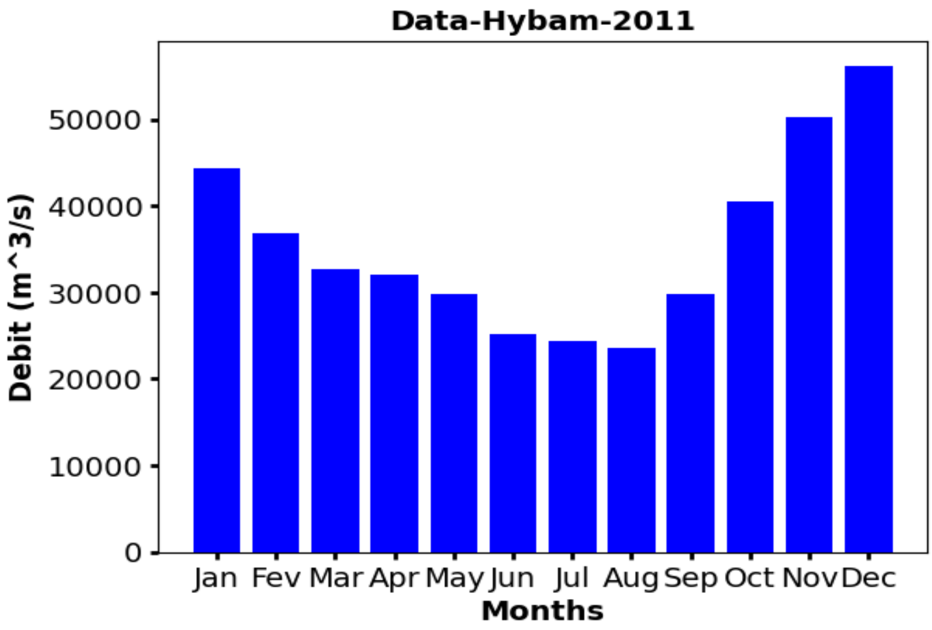


Fig. R9: Seasonal variability of Congo River freshwater and nutrient inputs from the HYBAM observatory data: (a) Monthly river discharge ($m^3 . s^{-1}$) at the Brazzaville/Kinshasa station for the study year 2011.

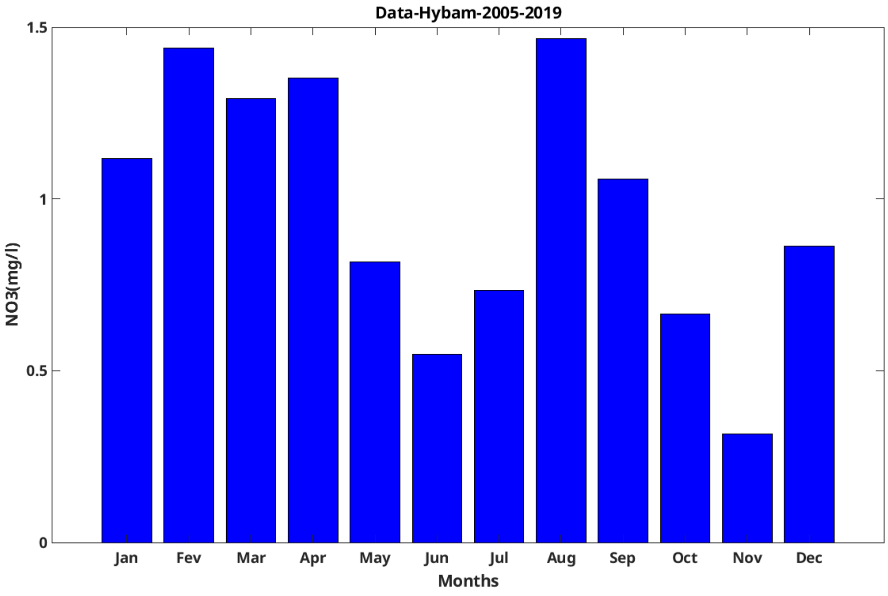


Fig. R10: Seasonal variability of Congo River freshwater and nutrient inputs from the HYBAM observatory data: Climatological monthly mean nitrate concentration (NO3, mg$\cdot L^{-1}$) averaged over the 2005–2019 period.

"The seasonal cycle of surface Chlorophyll-a (CHLa) is compared with coastal wind stress (**black arrows, Fig. 6**). Notably, wind stress reaches its annual maximum in **October**. Under typical conditions, this would suggest strong offshore Ekman transport; however, SST remains warm and CHLa concentrations stay low.

This paradox is explained by a competition of processes that suppress the upwelling potential. During October, a **downwelling Coastal Trapped Wave (CTW)** deepens the nitracline, while the increasing **Congo River discharge** strengthens vertical haline stratification, inhibiting the wind's ability to mix the water column. Furthermore, as shown by the riverine nitrate monitoring (**Fig. R8,R10**), the nitrate concentration in the Congo plume during October is relatively low (~0.6 mg/l) compared to its August peak (>1.4 mg/l). Consequently, the biological response is limited by both a physical block (waves and stratification) and a reduced nutrient supply from the riverine source. This confirms that the seasonal BGC signal in the Congolese system is primarily controlled by the interplay between remote forcing and the dual (hydrological and chemical) influence of the Congo River, rather than by local wind stress."

Fig.7: not sure what is the main philosophy to show this plot here. For example, latitude-time section of zonal current. Are the authors interested in vorticity associated with the current? How about if the authors show the latitude-time section of u-v vectors like Fig.6.

We thank the reviewer for this suggestion. The primary objective of Figure 7 is to validate the model's ability to reproduce the **seasonal phase and meridional structure** of the regional circulation (e.g., the peaks of the Angola Current and the SEUC).

Regarding the suggestion to show these sections within the narrow coastal box: we found that the **OSCAR satellite product exhibits significant data gaps in the immediate vicinity of the coast** (within ~50-100 km), as shown in the spatial maps (Fig. 7, right panels). Satellite-derived currents often suffer from land contamination and algorithm limitations near the shore. Therefore, we chose to show the sections slightly further offshore (at 10°E or integrating from 7°E to the coast) to **ensure a meaningful and robust comparison** between the model and observations. A coastal box average for OSCAR would result in an incomplete signal, biasing the validation.

Finally, regarding **vorticity**, it was not the focus of this study. Our aim was to analyze the horizontal advection terms of the nitrate budget, which depend on the seasonal timing of these main current branches.

Fig7a and b: might be better to rotate the plots by 90 degrees to see the longitude as x-axis.

We carefully considered the suggestion to rotate the Hovmöller diagrams. However, we have chosen to maintain the current orientation (Time on the x-axis and Space on the y-axis) for the following reasons:

1. **Temporal Alignment:** Keeping Time on the x-axis across all four panels allows for a direct vertical comparison of the seasonal phases between the meridional currents (a, b) and the zonal currents (c, d). This is crucial for analyzing the synchronous arrival of current branches like the AC and the SEUC.
2. **Consistency:** Time-on-X Hovmöller diagrams have been used everywhere else in the paper so we believe it more consistent to keep it the same for this plot.

To address the reviewer’s concern about readability, we have improved the axis labels and added explicit annotations (e.g., "Coast" or "Offshore") to help the reader orient themselves spatially.

Line 399: The plot is near surface, right? So, a bit hard to see undercurrent signature in the plot, I’d suppose.

Response: We acknowledge the reviewer's concern, which would be valid in the western or central Atlantic. However, a key feature of the circulation in the Gulf of Guinea is the **longitudinal shoaling of the undercurrent system**.

As illustrated in **Assene et al. (2020, Fig. 1)**—reproduced below for convenience—the vertical structure of the zonal velocity (U) changes significantly from west to east. While the South Equatorial

Undercurrent (SEUC) and the Equatorial Undercurrent (EUC) are deep at 30°W (Fig. 1a), their cores progressively rise as they move eastward. At 5°E (Fig. 1e), which is representative of our study area, the eastward velocity signatures (red areas) are clearly present in the upper 30–50 m of the water column. Consequently, the OSCAR product, which integrates the top 30 m, is perfectly capable of capturing these signatures in the eastern basin. The high degree of consistency between the seasonal phases of our model's subsurface layers and the OSCAR surface data (Fig. 7) further confirms that the undercurrent's dynamics are well-reflected in the near-surface observations in this region. (**Lines 441-446)**

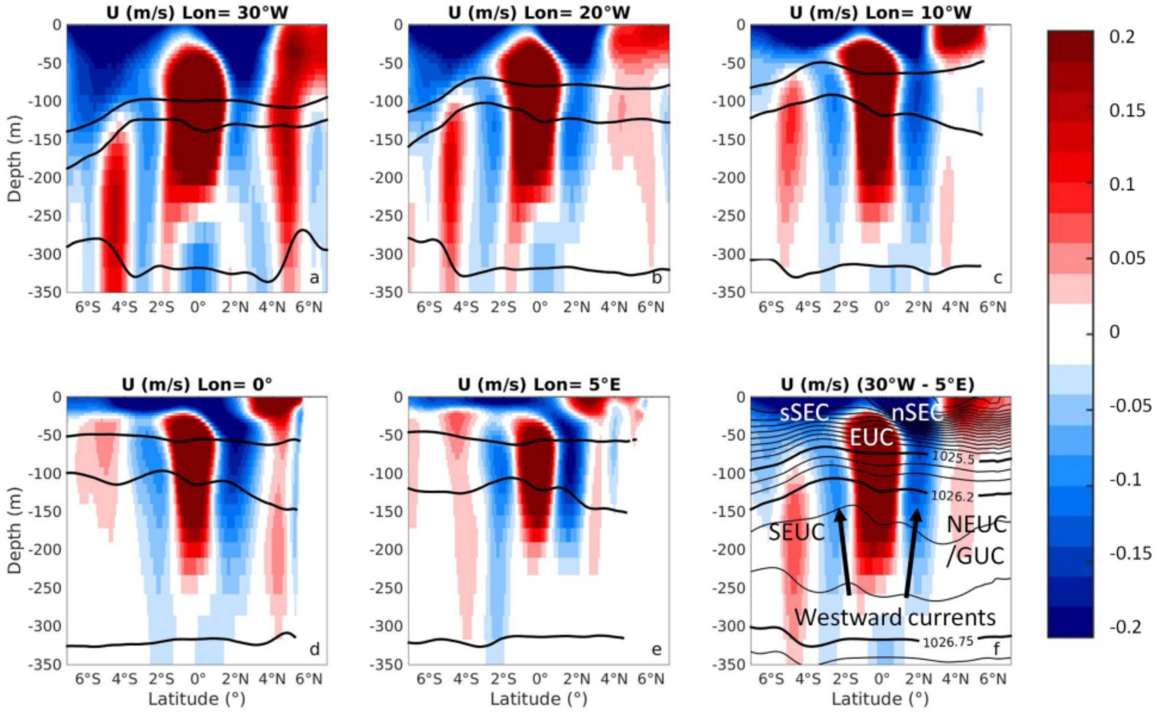


Fig. R11. Meridional sections of the zonal velocity U averaged over 2015 at longitudes 30◦ W, 20◦ W, 10◦ W, 0◦ , and 5◦ E (a–e) and zonal mean (30◦ W to 5◦ E) of the temporal averaged (f). Thick black lines are associated with the position of isopycnic surfaces with potential density ρ = 1025.5, 1026.2 and 1026.75 kg · m−3 defining layers 1 and 2. Thin black lines on the zonal mean are additional density contours (step Δρ = 0.2 kg · m−3). **ASSENE et al. (2020)**

Line 407: "Like" indicates the two seasonal cycle is similar/identical for me. But, Fig.8a and b have 45degree shift. So, "Corresponding to" or other expression could be better here.

Response: We thank the reviewer for this insightful remark. Indeed, as the nitrate change rate represents the time derivative of the nitrate concentration, a phase shift is mathematically expected. The word "Like" was imprecise as it implied the two cycles were in phase. We have revised the sentence to use **"Corresponding to"** to indicate that they share the same semi-annual periodicity without implying identical phasing. In the revised manuscript lines (**Line 452**)

Line 407: a bit unclear expression. “the seasonal cycle of nitrate tendency”.

We acknowledge that the term "nitrate tendency" might be ambiguous. We intended to refer to the local rate of change of nitrate concentration over time (the first term of equation (1) $\partial[NO_3]/\partial t$). To improve clarity, we have replaced this expression with **"the seasonal rate of change of nitrate concentration"** throughout the manuscript. We have replaced this expression in the key sections and figure captions

Line 408: August => July?

Line 409: July => June?

Line 409: September => August?

Response: We thank the reviewer these suggestions but do not agree with them. The ambiguity may come from the fact that monthly values are displayed in front of the tick, each thick should be interpreted as a mid-month value rather that the value at the 1st day of the month. We believe it is now clearer on the revised figure. Also the reviewer's suggestions made us realise that our description of the 4 phases, based on the sign of the NO_3 change, was incomplete and we tried to improve it. In the revised manuscript (**Line 452-455)**

Figure7: Before plotting this Hovmöller, better to show horizontal current plot how the surface current is going on. Otherwise, a bit hard to focus on which characteristics.

Response: done **Fig.R3**

Figure8: Fig.8c and d saturate its color, perhaps better to have a bit larger color scale in positive and negative.

Response: We thank the reviewer for this suggestion. Indeed, the intense nitrate supply near the Congo River mouth and the corresponding biological uptake led to saturation in the original color scale. In the revised Figure 7, we have expanded the colorbar limits (from ±0.6 to ±2 mmolN.m−3.d−1) and increased the number of color levels. This allows for a better visualization of the high-intensity signals and provides a clearer distinction between the riverine input and the upwelling-driven supply (**lines 469**)

Figure8: As commented above, Fig.7 could show the lat-time hovmöller of u-v vector so that readers can compare Fig.7 and Fig.8 and have some indication (and a good flow to the next subsection).

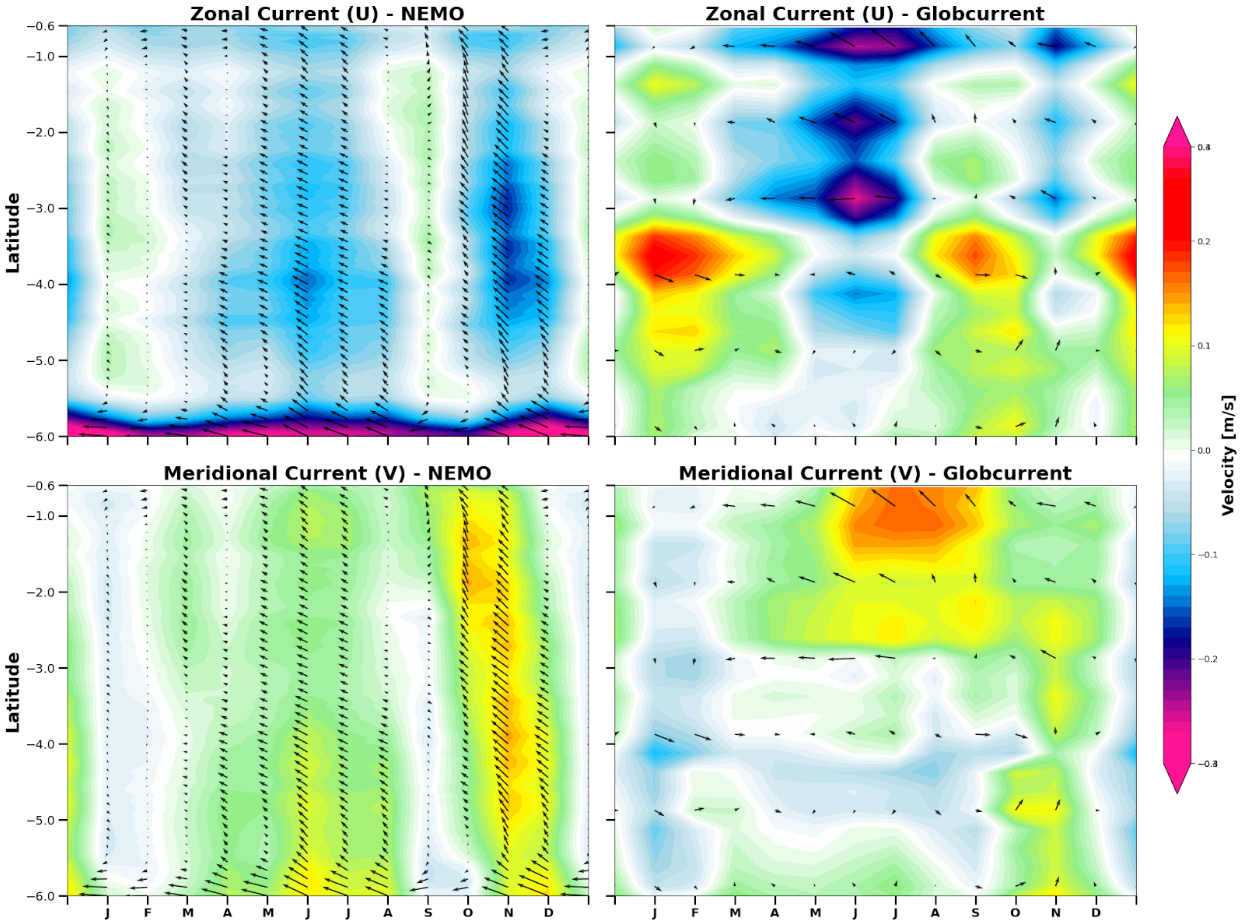


Fig. R12: Latitude-time Hovmöller diagram of the seasonal cycle of current components averaged over the upper 15 m along the coastal band (0.6°S–6°S). The top row shows the zonal current (U) and the bottom row shows the meridional current (V). Comparisons are made between the NEMO model (left) and Globcurrent observations (right). Color shading indicates velocity in $m \cdot s^{-1}$, and black arrows represent the total current vectors averaged over the same depth.

Response: We thank the reviewer for this excellent suggestion. But Owing to the limited availability of OSCAR data at the vicinity of the coast, we have updated Figure 6 to include **velocity vectors (u,v)** overlaid on the color-coded current components using Globcurrent data. This addition significantly improves the manuscript's flow by allowing the reader to directly visualize the seasonal arrival of the SEUC and Angola Current branches. It provides a clear dynamical context that bridges the general circulation (Fig. R12) .

Fig9c and Line 432: as the color is saturated, not veyr clear what the authors argue here.

Response: We acknowledge that the original color scale for Figure 8c (Zonal Advection) was saturated, particularly near the Congo River mouth where the advection of riverine nutrients is most intense. This saturation masked the spatial and temporal gradients we aimed to discuss. In the revised version of the manuscript, we have **broadened the colorbar limits** (now ranging from ±1.2 $mmolN.m^{-3}.d^{-1}$ instead of ±0.6) and used a **finer color scale**. This adjustment reveals the high-intensity core of the zonal advection signal and clarifies our argument: the westward currents act on the sharp riverine-induced nitrate gradient to create a massive and localized nutrient gain within the coastal box. In the new version of manuscript (**line 490**)

Line 434-435: A bit confused. In the nitrate budget, the zonal advection is internal component in the ocean. My understanding is that the riverine flux is external inputs in the budget.

Response: we agree with the reviewer that, in a strictly mathematical sense, river runoff is an external source term. However, our study domain (the coastal box) is defined such that it **includes the Congo River mouth**.

Once the nitrate is discharged into the coastal ocean, it creates a very strong longitudinal gradient (with higher concentrations at the coast than offshore). The dominant westward currents then **advect** this riverine nitrate toward the open ocean. In our budget calculation (Equation 1), this results in a **positive zonal advection term** (a gain), as the westward velocity (u<0) acts on the negative concentration gradient ($\partial(NO_3)/\partial x<0$). while the river is the *ultimate source*, **zonal advection is the internal mechanism that redistributes and spreads this riverine nitrate westward**, making it a dominant gain term for the nitrate budget within the study box.

Figure 9e: As commented above, Fig.7 could be a hovmöller plot of u-v vectors. Then, readers can understand this U-adv and V-adv contribution well.

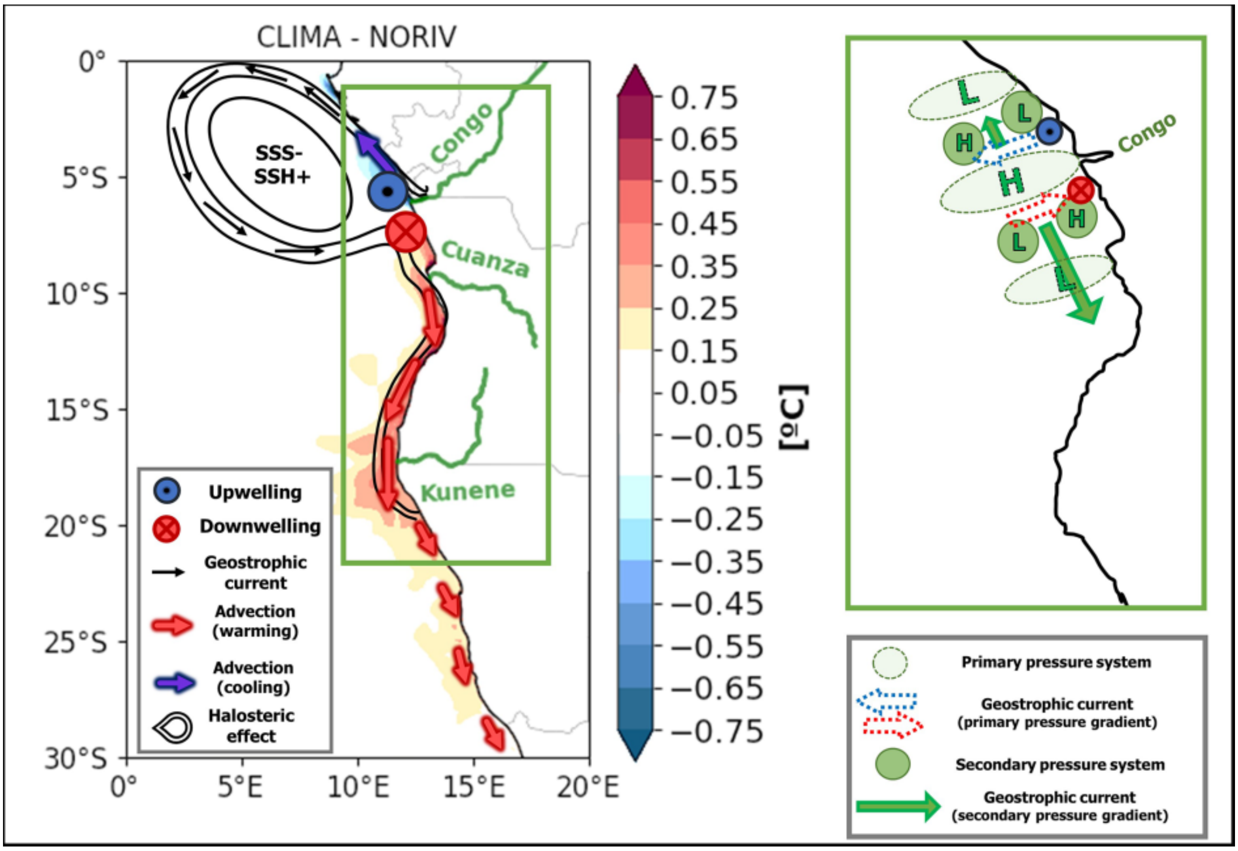
Response: Done see **Fig. R12**

Line 440-441: I am wondering the intense negative tendecy by vertical component. If this latitude is under the effect of Congo River discharge, the vertical motion could be suppressed due to fresh water input, thus, more stratification. Why in such situation, the vertical downward advection is strong?

Response: We thank the reviewer for this very relevant physical question. While it is true that freshwater plume increases stratification and can weaken **wind-driven upwelling (Topé et al., 2023)**, the situation at the Congo River mouth is dominated by the **momentum of the river discharge**:

- Regarding the plume dynamics, the Congo River enters the ocean with a high discharge velocity (≈2 m/s), generating a localized positive sea level anomaly (SLA). This elevation induces an alongshore pressure gradient which, through geostrophic adjustment, enhances upwelling (upward velocities,w>0) north of the river mouth (≈6°S) and promotes downwelling (downward velocities, w<0) to the south (Aroucha et al., 2025). (Fig. R13)
- **Nitrate Inversion (Gradient < 0):** As shown in the new vertical sections (**Fig. R14**, see Jan to Sep), the riverine plume is significantly more concentrated in nitrate than the underlying subsurface waters. Within the upper 10–20 meters (the plume layer), the vertical gradient of nitrate is therefore negative ($\partial[NO_3]/\partial z<0$)
- **Budget Impact (Loss):** In the budget equation, the vertical advection term is w∂[NO3]/∂z (we have remove minus sign (-) of formular because of negative sign of depth) With w>0 and a negative gradient, the term (positif)×(negative) results in a **negative value**, representing a **loss** of nitrate for the surface mixed layer.

In summary, the downward motion effectively "pumps" the high-concentration riverine nitrate out of the surface layer toward the subsurface, acting as a sink for the mixed-layer budget.



Schematic summarizing the processes related to the freshwater input effect on mean state SST at the southwestern African coast. The halosteric effect generates the primary alongshore pressure gradient, producing cross-shore geostrophic currents associated with upwelling (downwelling) north (south) of the Congo's mouth, which creates a secondary cross-shore pressure gradient. The secondary gradient drives the alongshore flow responsible for the advection. This signal propagates southward due to coastally trapped wave adjustment, while in the north it is restricted to a region close to river's mouth since there is no equatorward wave propagation. H (L) indicates a high-pressure (low-pressure) area. **Aroucha et al. (2025)**

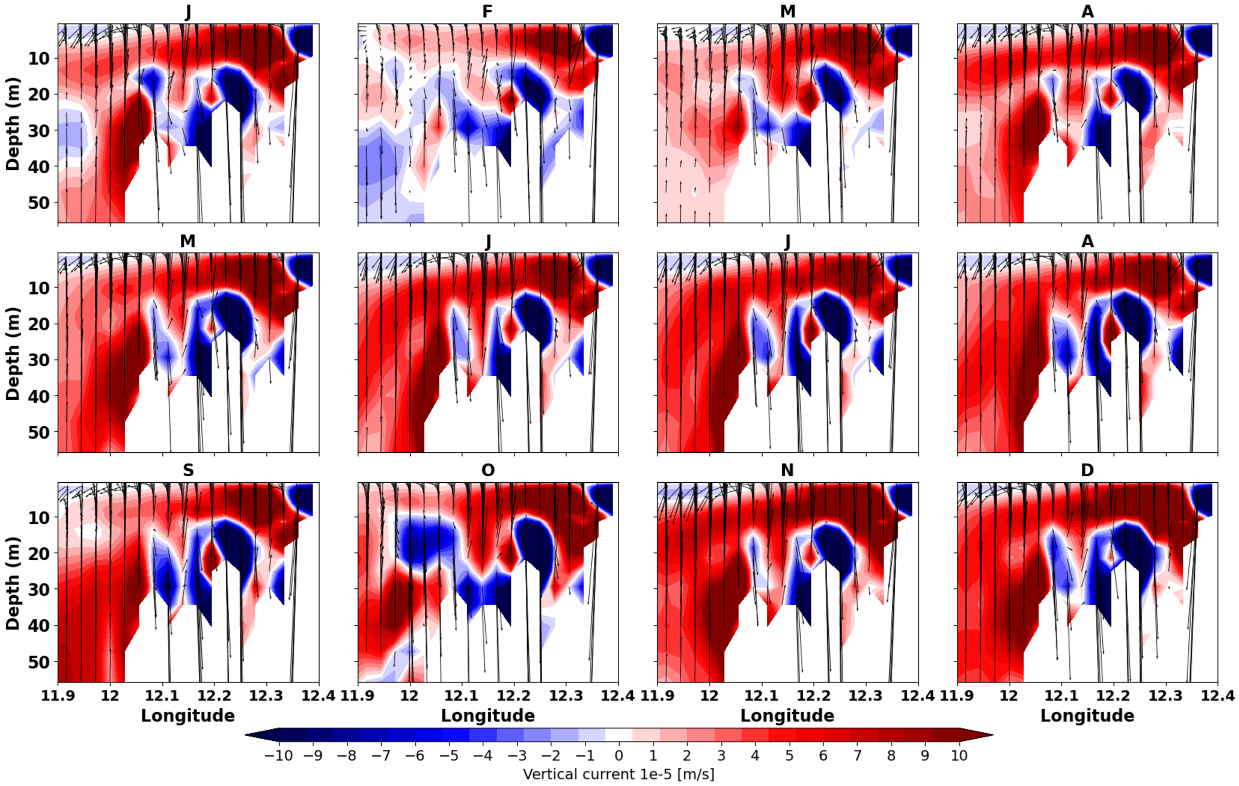


Fig. R13: Monthly mean vertical sections of vertical velocity (shading) and circulation vectors along a zonal transect (11.9°E–12.4°E) at the Congo River mouth (6°S). Positive values (red) indicate upward vertical motion associated with upwelling, while negative values (blue) indicate downward motion. The superimposed vectors represent the circulation in the vertical plane (zonal and vertical velocity components).

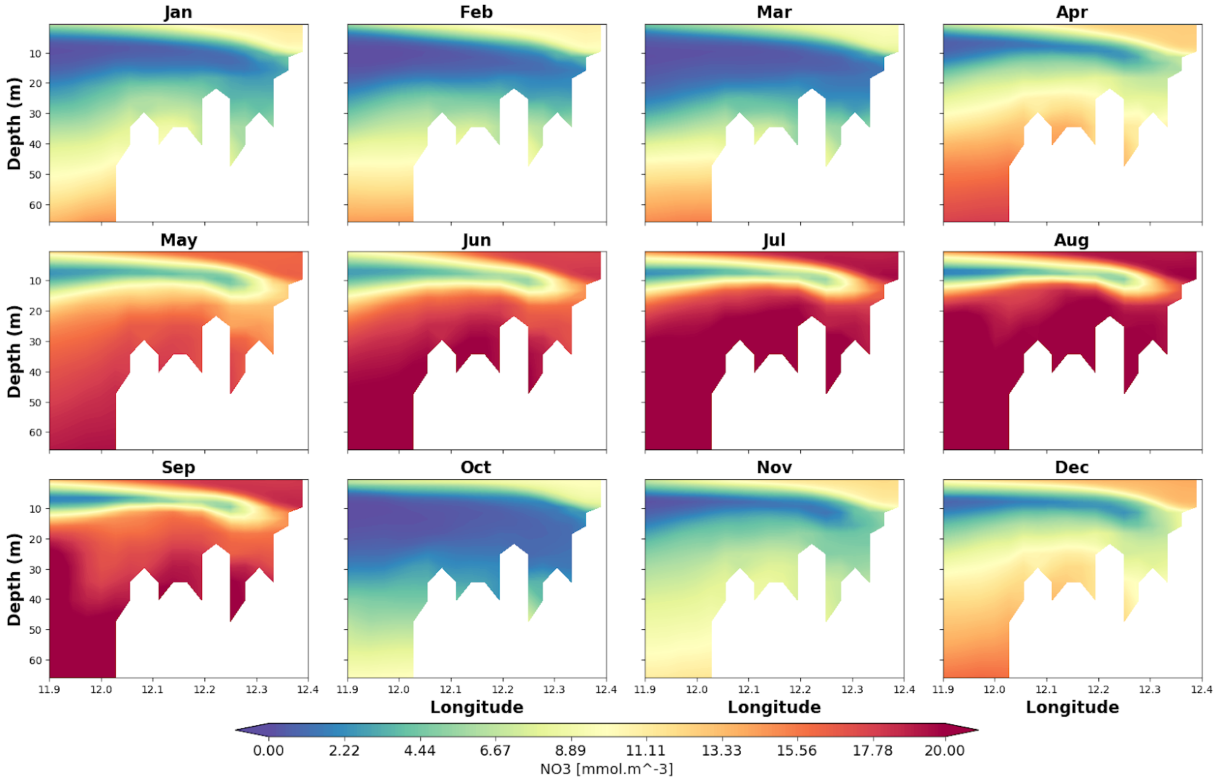


Fig. R14. Monthly mean vertical-zonal sections of nitrate concentration (NO_3) across the Congolese continental shelf. The panels show the seasonal evolution of the depth-longitude distribution of NO_3 (in mmol·m^{-3}) throughout the year. The longitude range (11.9°E–12.4°E) captures the near-shore vertical structure and the enrichment of the upper layers during the main upwelling season.

Line 443: Maybe this argument is an answer to my previous question. However, mixed-layer mean value of nitrate looks identical or slightly smaller than that of subsurface in Fig.4b. So, I wouldn't imagine such large negative value of vertical advection.

Response: We appreciate the reviewer's careful check of the vertical profiles. The discrepancy arises because the reviewer is comparing the model's budget with the **CARS climatology (Fig. 3b)**.

1. **Limitations of CARS:** As discussed previously, CARS 2009 is a coarse product (0.5°) that smooths vertical and horizontal gradients. In the vicinity of the Congo mouth, CARS fails to resolve the very thin (~10 m) and highly concentrated nitrate plume. In the climatology, the riverine signal is diluted, which makes the surface nitrate appear equal to or lower than the subsurface.
2. **Model Vertical Structure:** In our high-resolution model (1/36°), the vertical structure is much more detailed. As shown in the **new monthly vertical sections (Fig. R14)**, during the peak discharge and upwelling months (e.g., June to September), there is a clear **vertical inversion**: the nitrate concentration in the top 10m (river plume) is significantly higher (dark red, >15 mmol.m^{-3}) than in the layer immediately below (15–30 m, yellow/green, ~10 mmol.m^{-3}).

   Flux Intensity: The vertical advection term is the product of velocity (w) and the gradient. Near the mouth, the downward velocity induced by the river jet is exceptionally high (~2 m/s horizontal translating into significant w<0). Even a moderate vertical gradient, when multiplied by this strong downward flow, results in a substantial negative flux (nitrate export to the subsurface).

Line 451-452: which figures mentioned?

Response: We apologize for the missing explicit references. The comparison described in these lines refers to the seasonal cycles of Sea Level Anomaly (SLA), shown in **Figure 4a**, and the vertical processes (advection and diffusion), shown in **Figures 8d and 8f**, respectively. We have added these citations to the revised manuscript to help the reader follow the phase relationship described. In the new version of manuscript lines (**Lines 497**)

Figure 10: Fig.10 c and d. The color scale is saturated. Better to have a wider scale.

Response: We thank the reviewer for this suggestion. The color scale in the spatial maps of the nitrate budget (Figure 9c and 9d) has been updated to avoid saturation. We have expanded the limits from ±0.6 to ±1.2 mmolN.m−3.d−1 and increased the number of color levels. This change allows for a clearer distinction between the intense nitrate supply at the Congo River mouth and the supply driven by coastal upwelling along the Gabonese and Angolan shelves. It also reveals the specific spatial patterns of biological uptake that were previously masked by a uniform saturated color. **lines (504)**

Line 472: better to say with "km" not with degree.

Response: We thank the reviewer for this suggestion. We have converted the spatial scales from degrees to kilometers to provide a clearer physical representation of the width of the nitrate-enriched band. At a latitude of approximately 5°S, 1.5° of longitude corresponds to ~165 km. The text has been updated accordingly. (**Line 520)**

Line 476: while the....

Response: We have corrected the phrasing in Line 476. The redundant "the" has been removed, and we have used **"whereas"** to better contrast the dominance of vertical advection in the north with that of vertical diffusion in the south, as suggested. **Line (523-544)**

Line 480: look at

Response: We thank the reviewer for the stylistic suggestion. We have replaced "look for" with **"investigate"** to use more formal scientific language when describing the analysis of processes below the mixed layer. **Line (546)**

Figure 12: The black dashed line is referred as mixed-layer depth in the caption, but it looks fixed value in the entire year. Is this reasonable?

Response: we have update the mixed layer computation by using 3 m depth of reference (Aroucha et al., 2025) to compute the mixed layer. The new plot can be seen in **Lines 260-261** and **Line 587**

Figure12: Which region is taken for this analysis? Better to show a box in other figure and clarify it in the caption.

Response: the analysis in Figure 11 is based on a spatial average within the Gabon-**Congo coastal box (0°S–6°S, 1° wide coastal band)**. To improve clarity, we have now explicitly highlighted this box in . We have also updated the caption of Figure 11 to clearly state that the results are averaged over this specific coastal domain. **Lines (592-596)**

Line 490-497: I would guess the mixed-layer depth is mis-plotted in Fig.12 and the I cannot follow the argument here. According to the definition of MLD in this study, density at 10m is taken as reference and estimate 0.03kg/m3 exceeding level. However, as stated, if the estimated MLD in this study is 10m and almost constant (as commented in Figs.12,13, and, 14), I have an impression that 10m depth of the MLD here is not MLD, but barrier layer. I'd suggest that a different criteria might be implemented to estimate the MLD to avoid the strong influence of the fresh water and associated barrier layer.

Response:

Sensitivities test on Nitrate Budget in the MLD

MLD Nitrate Budget with MLD reference of 3 m (Aroucha et al. (2025)):

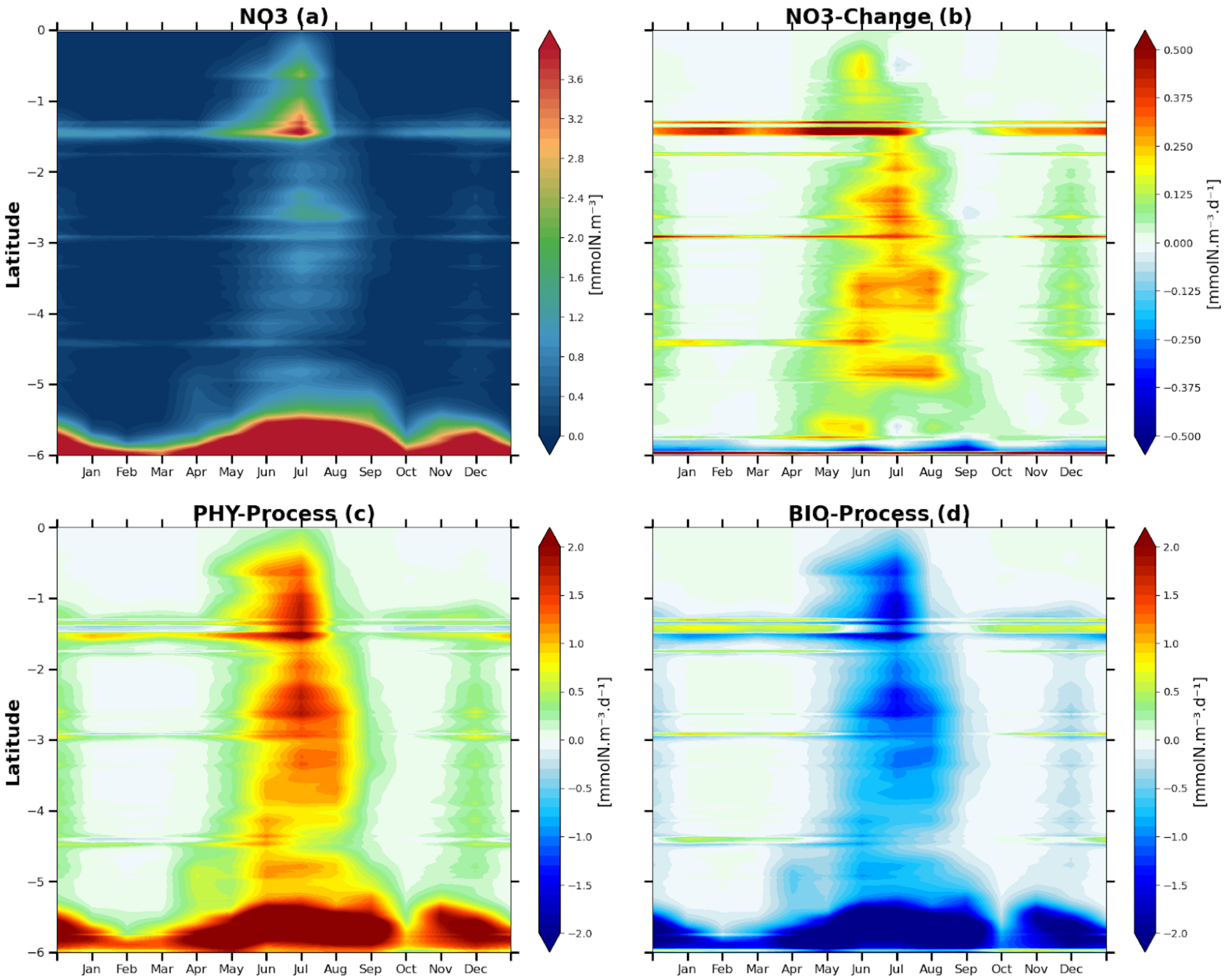


Fig. R15: Latitude-time Hovmöller diagram of the model seasonal cycle of Mixed Layer Nitrate (MLN) budget, a), the rate of the MLN change (b), the physical process contribution (c) and the biological process contribution (d) along the Congolese coast. Units are mmolN.m^{-3} and and mmolN.m^{-3}.d^{-1} for **Fig. R15**a and **Fig. R15**b,c,d, respectively.

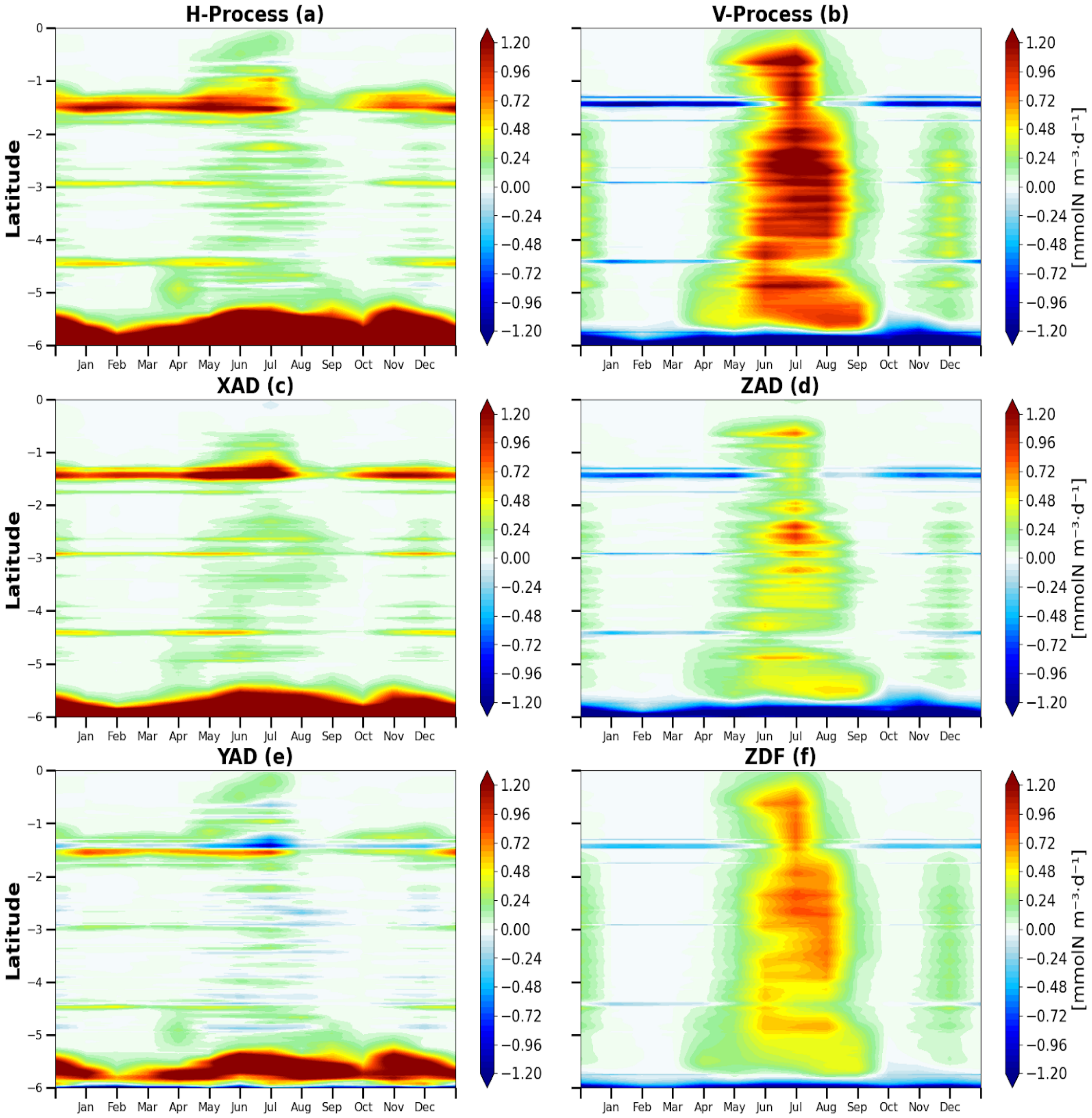


Fig. R16: Latitude-time Hovmöller diagram of the model seasonal cycle of horizontal (a) and vertical (b) process contributions , zonal (c), meridional (e), vertical (d) advections , vertical diffusion (f) averaged in the mixed layer along the Congolese coast. Units are mmolN.m^{-3}.d^{-1}.

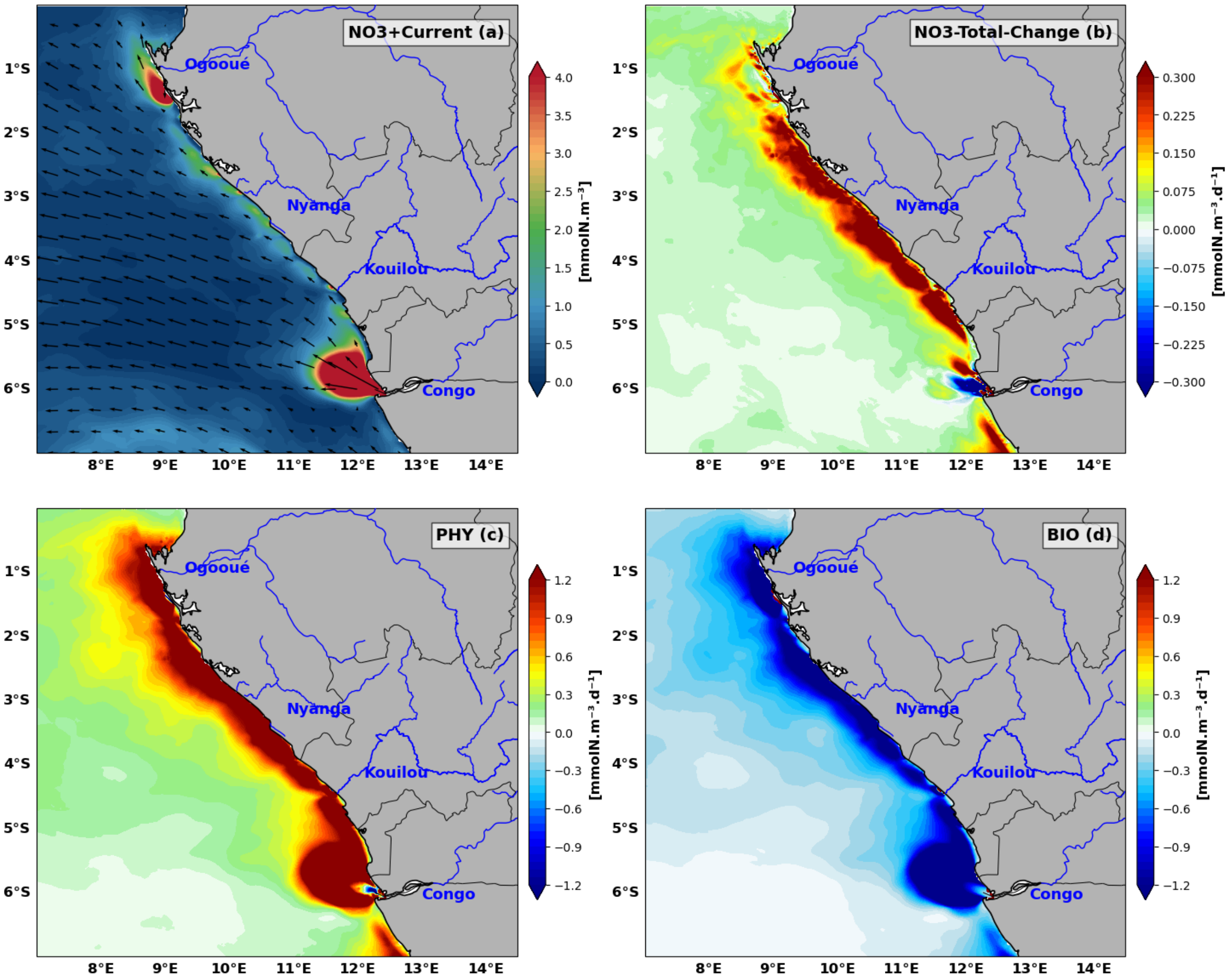


Fig. R17: Spatial distribution averaged over the main upwelling period of (a) nitrate, (b) nitrate tendency contributed by (c) physical processes and (d) biological processes, all averaged in the mixed layer in Austral winter. The mean current in the mixed layer is superimposed in (a). Nitrate concentration units are mmolN.m^{-3} and the tendency terms units are mmolN.m^{-3}.d^{-1}.

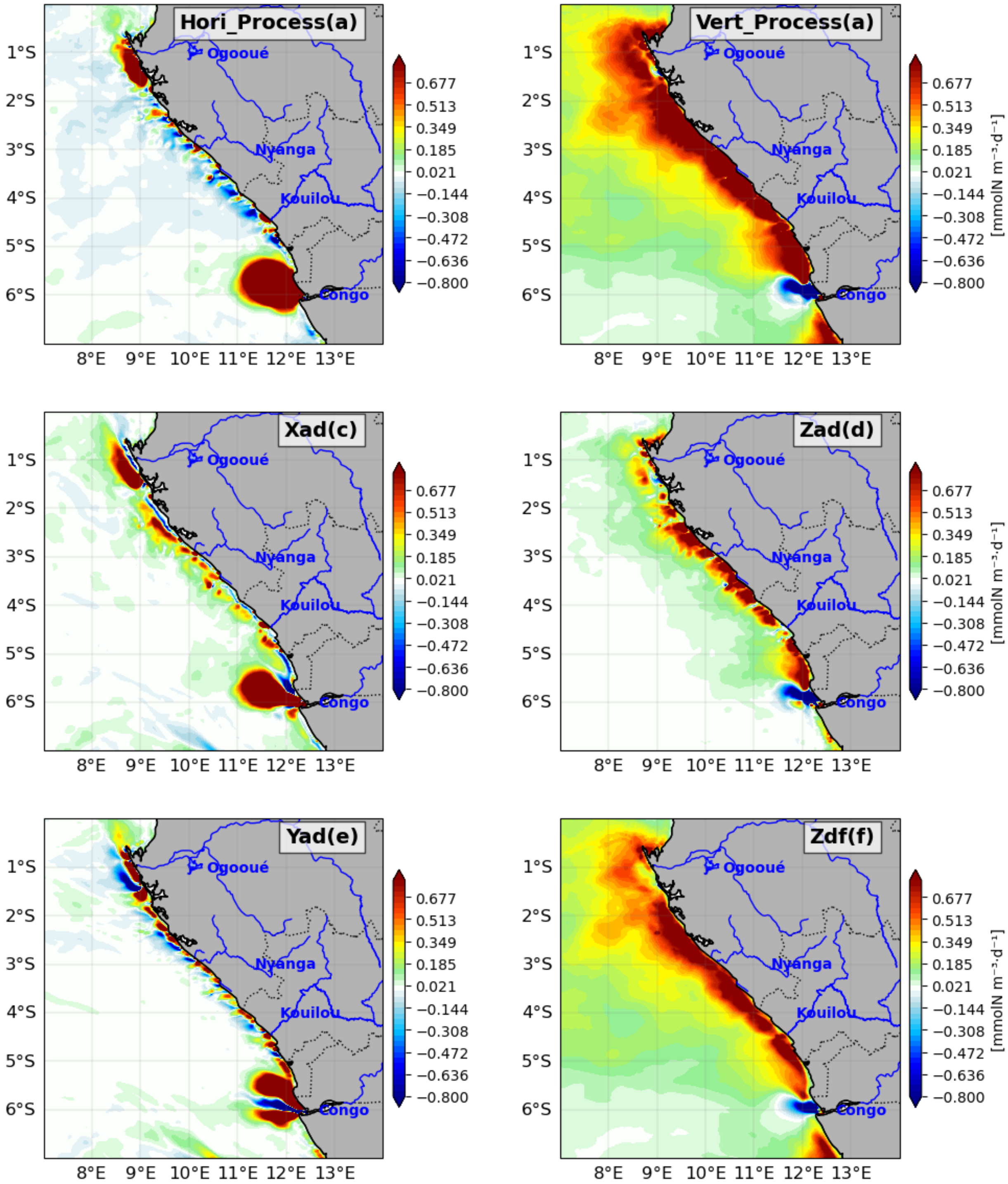


Fig. R18: Contribution of (a) the horizontal processes, including (c) zonal advection and (e) meridional advection, and (b) vertical processes, including (d) vertical advection and (f) vertical diffusion, to the nitrate budget averaged in the mixed layer during the austral winter. Units are mmolN.m^{-3}.d^{-1}.

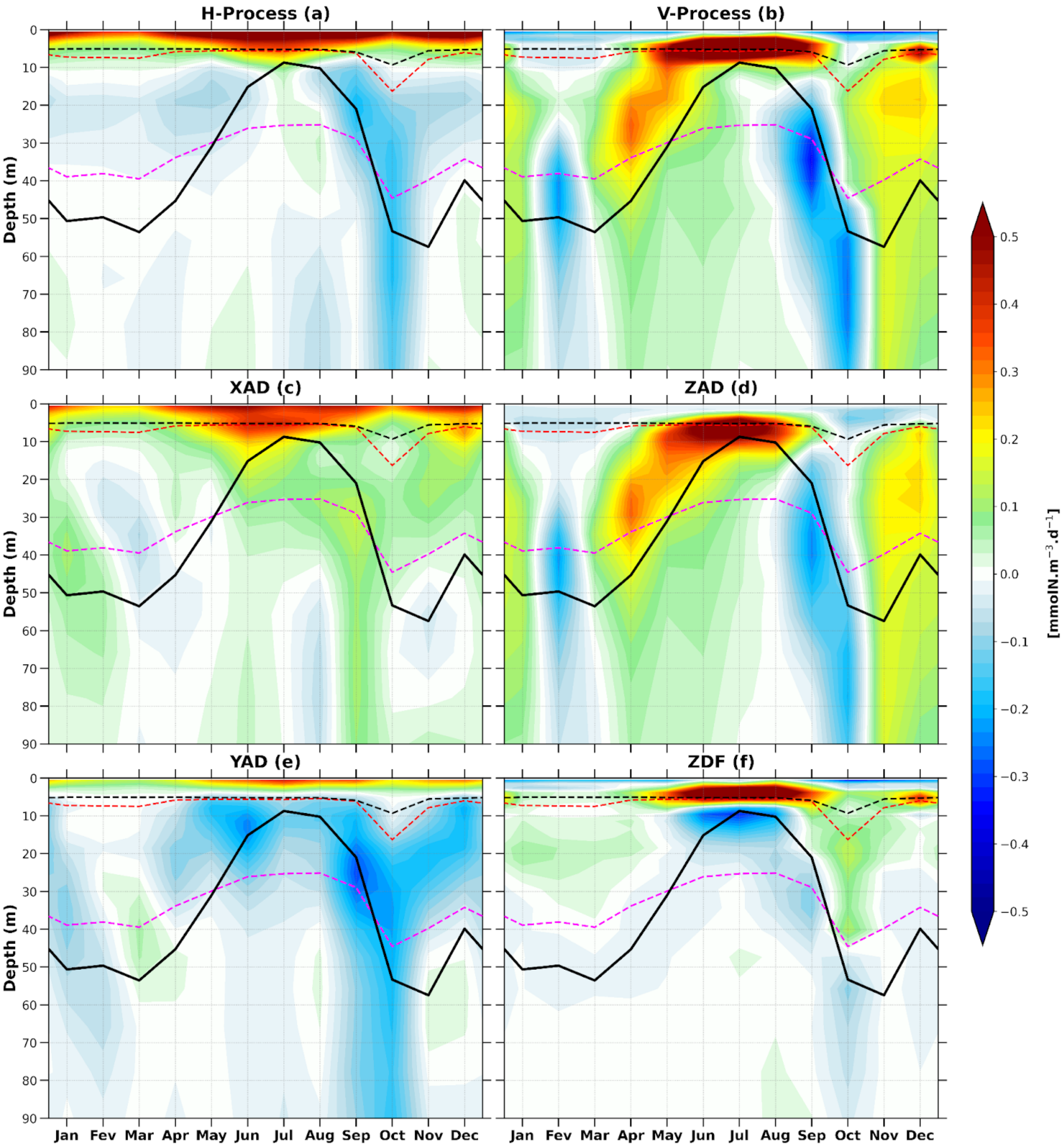


Fig. R19: Depth-time Hovmöller diagram of the model seasonal cycle of contributions to the nitrate budget of horizontal and vertical processes (a and b respectively), zonal, meridional, vertical advections (c, e and d respectively), vertical diffusion (f) along the Congolese coast (0°S-6°S and 1° width to the coast). Units are mmolN.m^{-3} for all of the plots. The black solid line represents the thermocline (20°C isotherm), while dashed magenta, red and black lines indicate the euphotic, isothermal and mixed layer depths, respectively.

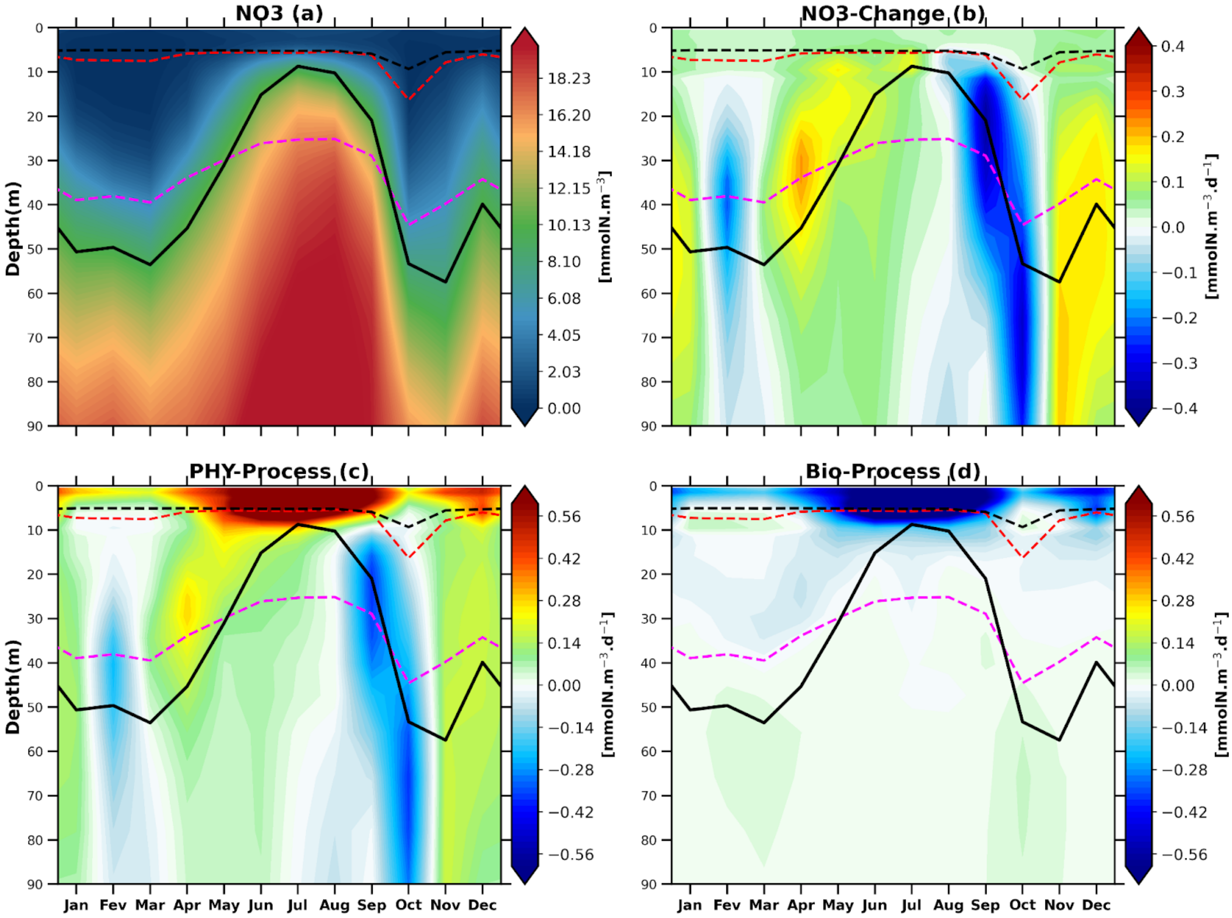


Fig. R20: Depth-time Hovmöller diagram of the seasonal cycle of the nitrate budget averaged within the Congolese coastal box (0°S–6°S, 1° wide coastal band, as shown in Fig. 1). (a) Nitrate concentration (mmolN.m−3), (b) nitrate rate of change, (c) physical process contribution, and (d) biological process contribution (mmolN.m^{-3}.d^{-1}). The black solid line represents the thermocline (20°C isotherm), while dashed magenta, red and black lines indicate the euphotic, isothermal and mixed layer depths, respectively.

MLD Nitrate Budget with MLD reference of 0.5 m (Scannel and McPhaden., 2018):

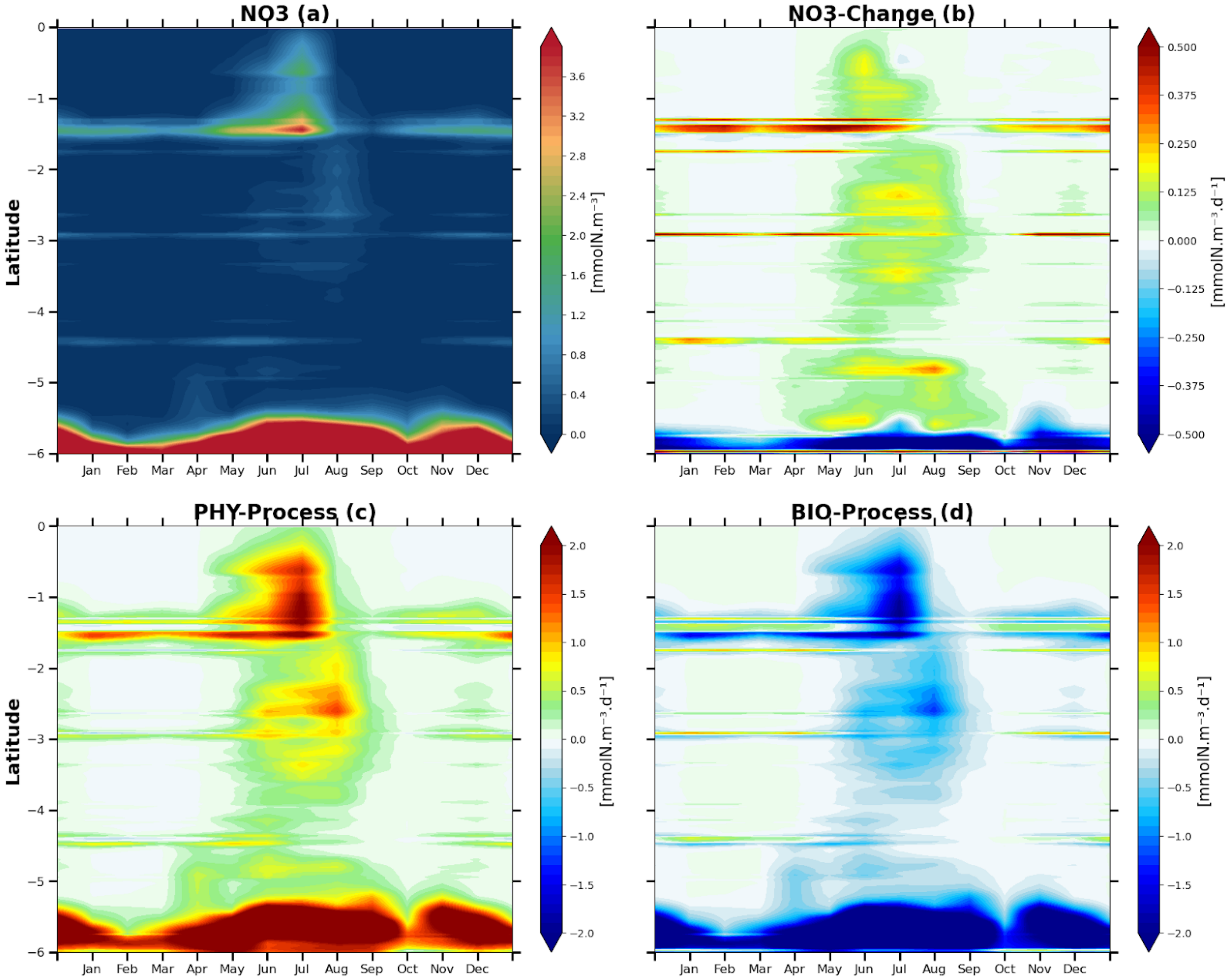


Fig. R21: Latitude-time Hovmöller diagram of the model seasonal cycle of Mixed Layer Nitrate (MLN) budget, a), the rate of the MLN change (b), the physical process contribution (c) and the biological process contribution (d) along the Congolese coast. Units are mmolN.m^{-3} and and mmolN.m^{-3}.d^{-1} for **Fig. R21**a and **Fig. R21**b,c,d, respectively.

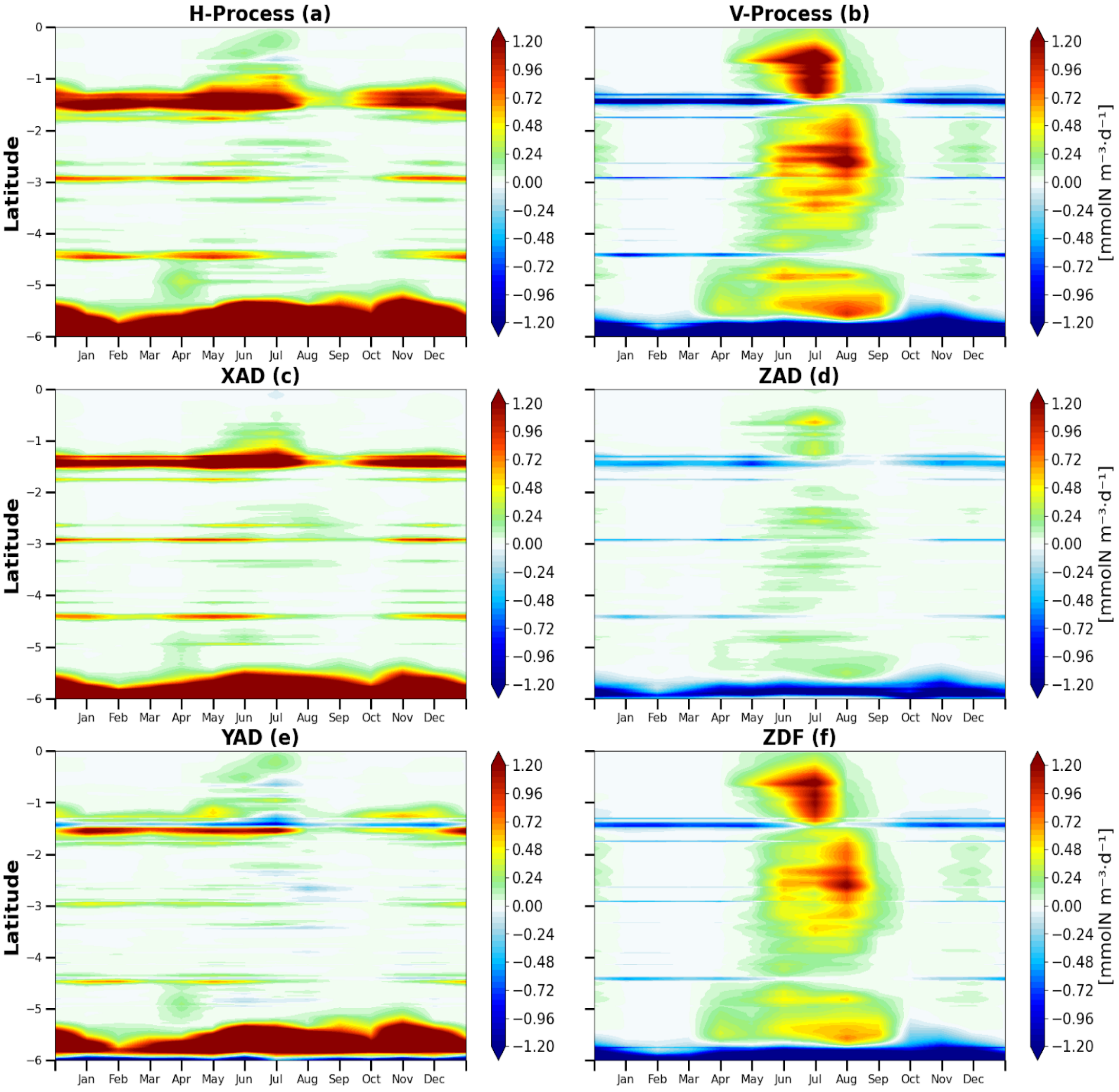


Fig. R22: Latitude-time Hovmöller diagram of the model seasonal cycle of horizontal (a) and vertical (b) process contributions , zonal (c), meridional (e), vertical (d) advections , vertical diffusion (f) averaged in the mixed layer along the Congolese coast. Units are mmolN.m^{-3}.d^{-1}.

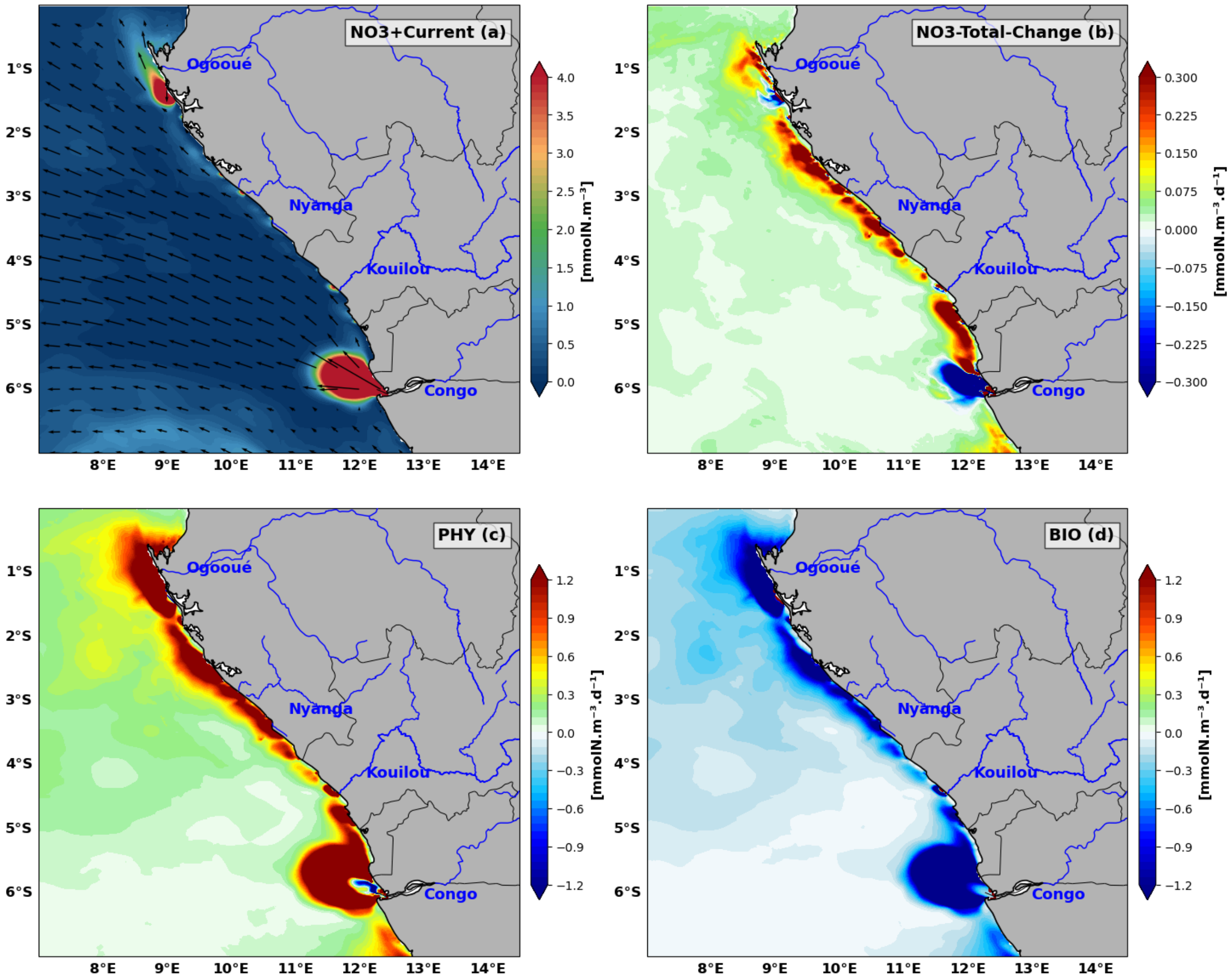


Fig. R23: Spatial distribution averaged over the main upwelling period of (a) nitrate, (b) nitrate tendency contributed by (c) physical processes and (d) biological processes, all averaged in the mixed layer in Austral winter. The mean current in the mixed layer is superimposed in (a). Nitrate concentration units are mmolN.m^{-3} and the tendency terms units are mmolN.m^{-3}.d^{-1}.

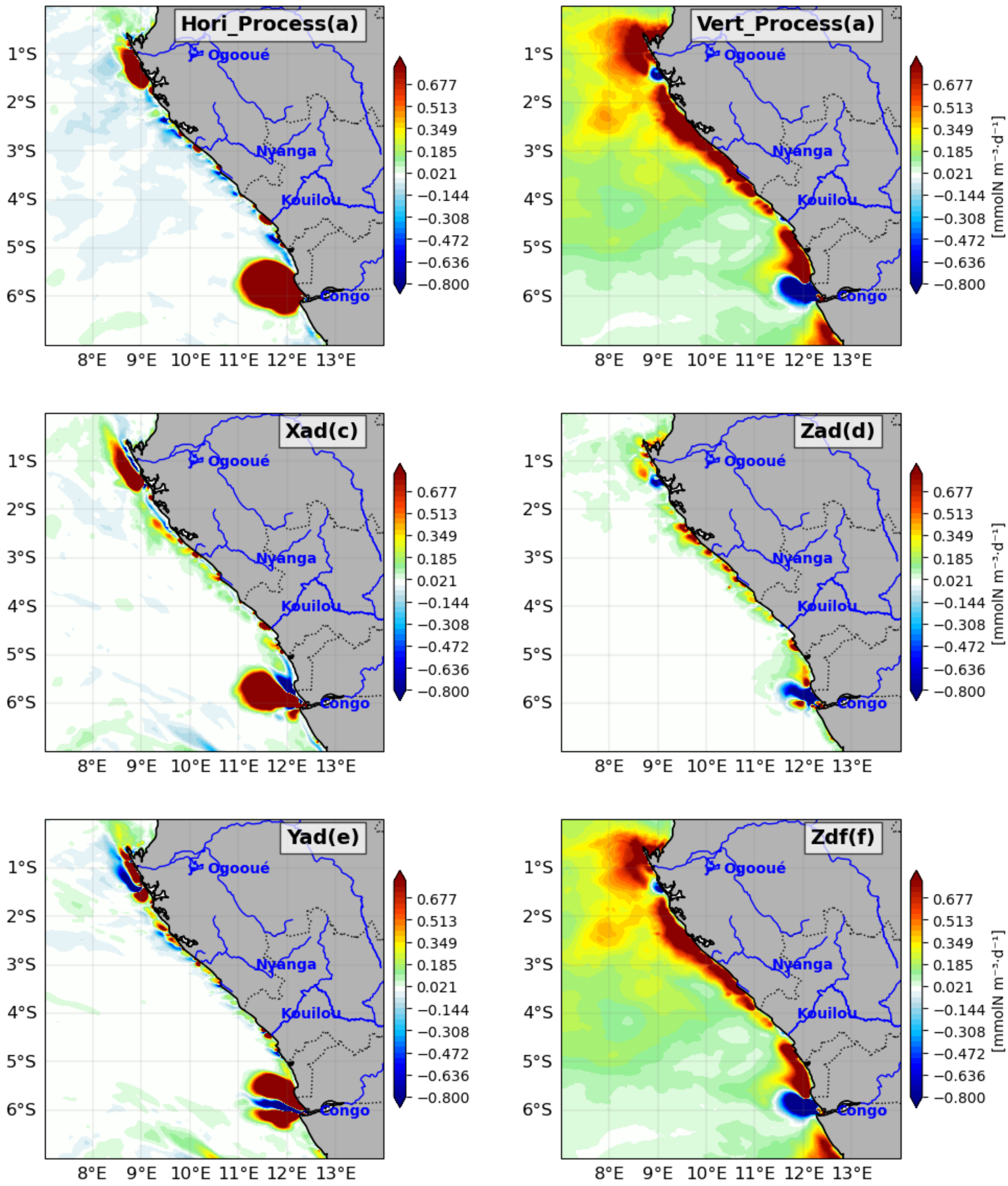


Fig. R24: Contribution of (a) the horizontal processes, including (c) zonal advection and (e) meridional advection, and (b) vertical processes, including (d) vertical advection and (f) vertical diffusion, to the nitrate budget averaged in the mixed layer during the austral winter. Units are mmolN.m^{-3}.d^{-1}.

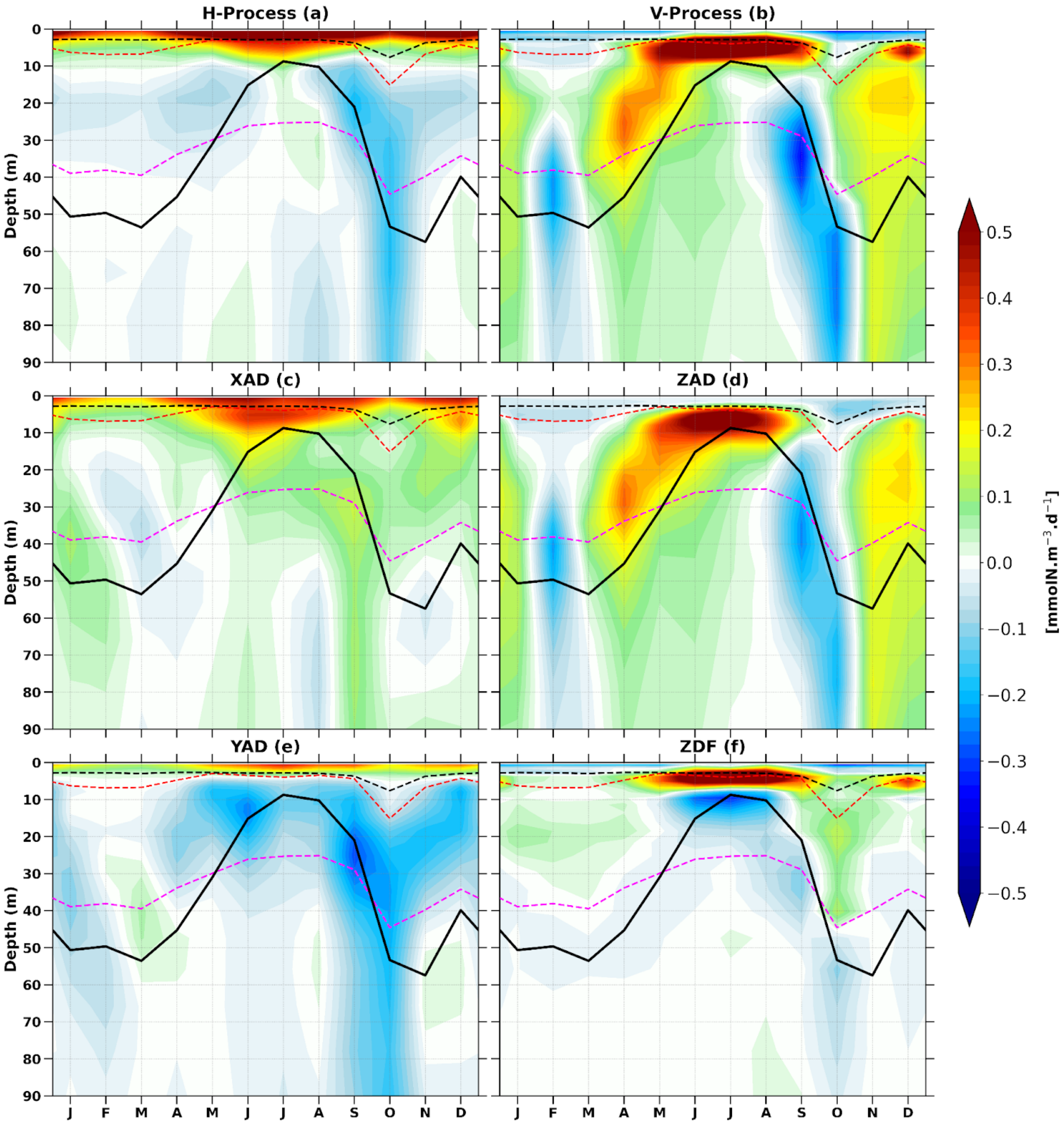


Fig. R25: Depth-time Hovmöller diagram of the model seasonal cycle of contributions to the nitrate budget of horizontal and vertical processes (a and b respectively), zonal, meridional, vertical advections (c, e and d respectively), vertical diffusion (f) along the Congolese coast (0°S-6°S and 1° width to the coast). Units are mmolN.m^{-3} for all of the plots. The black solid line represents the thermocline (20°C isotherm), while dashed magenta, red and black lines indicate the euphotic, isothermal and mixed layer depths, respectively.

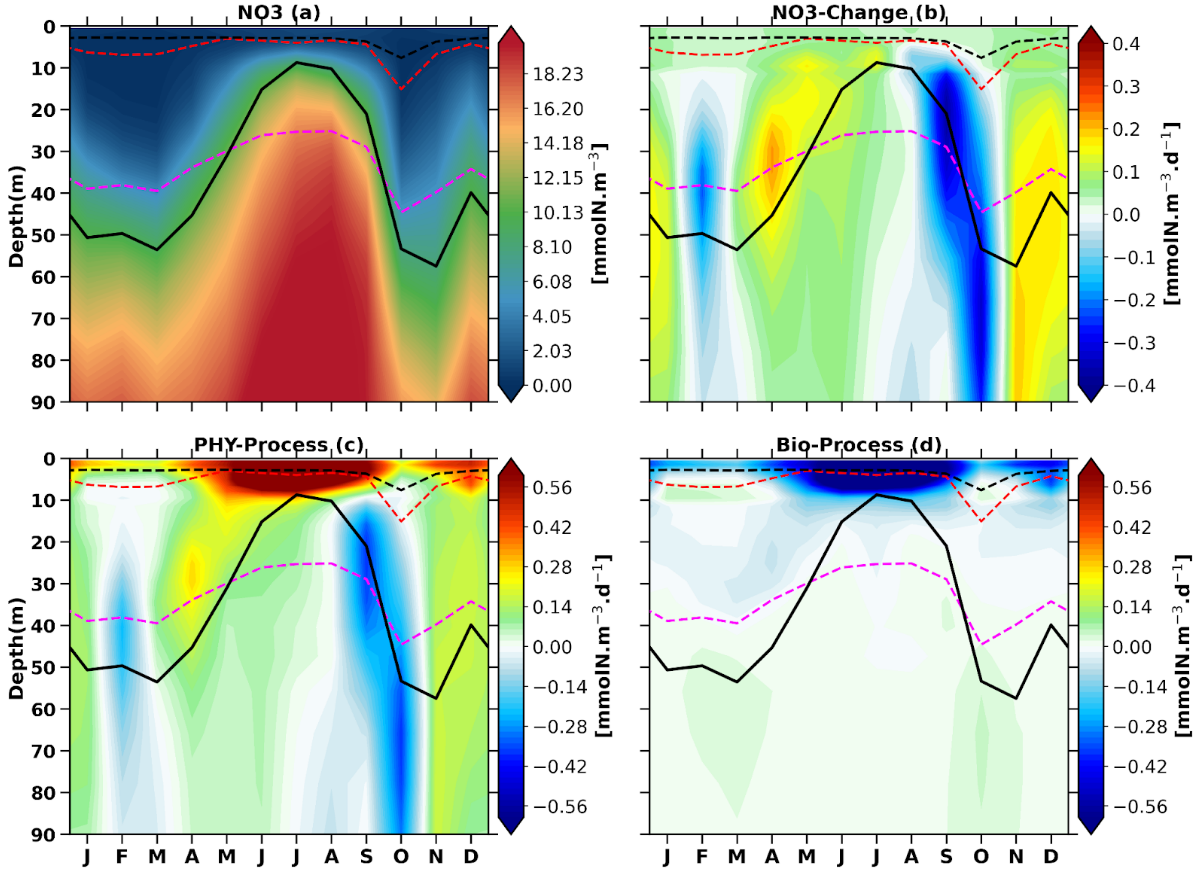


Fig. R26: Depth-time Hovmöller diagram of the seasonal cycle of the nitrate budget averaged within the Congolese coastal box (0°S–6°S, 1° wide coastal band, as shown in Fig. 1). (a) Nitrate concentration (mmolN.m−3), (b) nitrate rate of change, (c) physical process contribution, and (d) biological process contribution (mmolN.m^{-3}.d^{-1}). The black solid line represents the thermocline (20°C isotherm), while dashed magenta, red and black lines indicate the euphotic, isothermal and mixed layer depths, respectively.

We agree with the reviewer that the choice of a 10 m reference depth for mixed layer was probably not optimal. To ensure the robustness of our nitrate budget analysis, we performed sensitivity tests regarding the Mixed Layer Depth (MLD) definition, with two other criteria previously used in the literature for this region:

1. **Aroucha et al. (2025) criterion:** This method uses a reference depth of 3 m. The MLD is defined by a temperature threshold of 0.2°C relative to the temperature at 3 m, which corresponds to a density variation of approximately 0.06 kg·m^{-3}.
2. **Scannell and McPhaden (2018) criterion:** This method employs the same temperature and density thresholds but uses a much shallower reference depth of 0.5 m.

After a thorough examination of the resulting budget terms (see Figures R15 to R22 in the supplementary material provided for this response), we found that the criterion by **Aroucha et al. (2025)** is the most suitable for our study area.

Consequently, to accurately capture the seasonal dynamics of nitrate availability and biological productivity in the Congolese Upwelling System, we chose to use the **Aroucha et al. (2025)** criterion for all related figures in this paper (formerly figures 8-16, now figures 7-15).

Indeed our tests indicates that the **Scannell and McPhaden (2018)** criterion tends to significantly underestimate the intensity of the coastal upwelling. Specifically, when using a 0.5 m reference depth, the vertical nitrate supply to the surface mixed layer is nearly non-existent across the domain, except in the immediate vicinity of river mouths. This shallow definition appears to be overly sensitive to the strong haline stratification near the surface, thereby masking the physical signal of nutrient enrichment from deeper layers.

Figure13: Same as Fig.12, the mixed-layer depth looks constant.

Response : Already done **lines (604)**

Line 515-516: might be kind for readers if the author give a supplemental plot of CTW properties here. Even if the previous study using the same modeled data already studied the CTWs in this region, maybe better to show a plot in a different way as supplement. Otherwise, this statement is a bit unclear.

Response: We agree with the reviewer that the evidence for Coastal Trapped Waves (CTWs) is crucial for the understanding of the upwelling dynamics in this region. However, we believe that the signature and properties of these waves are already well-evidenced in the current manuscript through several complementary plots:

1. **Fig.4 (SLA panels):** The Sea Level Anomaly (SLA) seasonal cycle clearly shows the characteristic signature of CTWs, with positive and negative anomalies propagating along the coast, which are in phase with the upwelling and downwelling periods.
2. **Fig. 11, 12, and 15 (Hovmöller diagrams):** These figures illustrate the vertical migration of the thermocline (represented by the black line) and the nitracline. The upward and downward displacements shown in these budget analyses are the direct physical manifestation of the passage of CTWs, which regulate the nutrient supply from the subsurface to the euphotic zone.

Line531-533: I cannot grasp the fundamental philosophy why the advection term is subdivided into the components. (also mean <> and * what?). Need to clarify it more in this section. Therefore, a bit hard to follow the discussion in this subsection.

Response: We apologize for the lack of clarity regarding the objective and the notation of this decomposition. The "philosophy" of this analysis, often used in heat/salt budgets (i.e. Awo et al., 2018; Thiam et al., 2024, Topé et al., 2023), is to identify the **dynamical drivers** of the seasonal nitrate advection variability. Specifically, we aim to determine whether the seasonal pulses in nitrate transport are primarily caused by:

1. Fluctuations in the **ocean currents** (e.g., seasonal acceleration of the Angola Current).
2. Fluctuations in the **nitrate distribution** (e.g., seasonal enrichment/extension of the Congo River plume).

3. The **simultaneous variation** of both current and gradient (non-linear term).

Following the reviewer's suggestion, we have standardized the notation to follow conventional fluid dynamics:

- The annual mean of a variable A is now denoted as $\bar{A}$ (with an overbar).
- The seasonal fluctuation (anomaly) is denoted as **A'** (with a prime).
- The symbol **(·)** or juxtaposition is used for multiplication instead of the asterisk.

We have added a formal explanation and updated the equations at the beginning of Section 3.3.2 to make the discussion easier to follow. **Lines (294-305)**

$$(\mathbf{u}\cdot\nabla(\mathbf{NO_3}))' = \mathbf{u}'\cdot\overline{\nabla(NO_3)}+\bar{u}\cdot\nabla(\mathbf{NO_3})' + \mathbf{u}'\cdot\nabla(\mathbf{NO_3})'$$

- $\mathbf{u}'\cdot\overline{\nabla(NO_3)}$ **(Current variability):** This term quantifies the impact of current velocity anomalies acting upon a mean (steady-state) nitrate distribution. It isolates the effect of current acceleration or intensification (such as the SEUC or the Angola Current) on nutrient transport.
- $\bar{u}\cdot\nabla(\mathbf{NO_3})'$ **(Gradient variability):** This term represents the impact of seasonal changes in the nitrate concentration gradient under a mean circulation. It highlights the influence of seasonal water mass enrichment, particularly via the Congo River plume.

Line 544: not sure what is this term expresses.

Response : this term, which has been corrected to $\bar{u}\cdot\nabla(\mathbf{NO_3})'$ in the revised manuscript, represents the contribution of the seasonal anomalies of the zonal nitrate gradient to the advection, acting under a constant annual mean velocity.

Figure 14: Better to provide an equation that are shown in Fig.14.

Response : already done in the revised manuscript (**Line 294**)

$$(\mathbf{u}\cdot\nabla(\mathbf{NO_3}))' = \mathbf{u}'\cdot\overline{\nabla(NO_3)}+\bar{u}\cdot\nabla(\mathbf{NO_3})' + \mathbf{u}'\cdot\nabla(\mathbf{NO_3})'$$

Line 544: correlation with what?

Response: we clarify that the correlation coefficient (r=0.77) was calculated between the **seasonal anomaly of the specific component** (in this case, the mean current acting on the seasonal nitrate gradient anomalies:

$(\bar{u}\cdot\nabla(\mathbf{NO_3})')$ and the **total seasonal anomaly of zonal nitrate advection** ($((u\cdot\nabla \mathrm{NO3})')$). The objective of this correlation is to determine which of the decomposed terms is the primary driver of the total advection's seasonal variability. A high correlation of 0.77 indicates that the seasonal changes in the nitrate gradient are the main factor controlling the pulses of nitrate advection by the SEUC, rather than changes in the current velocity itself. **Lines (303-311)**

Line 629: greater=> warmer

Response:
Agreed. We have replaced the word "greater" with "**warmer**" to more accurately describe the temperature bias of the model compared to observations. **Line (698)**

Line630-631: any references?

Response: we have added several references to support the statement that the warm bias is a well-known and pervasive issue in ocean and climate models in the Eastern Tropical Atlantic. The added references include:

- **Richter (2015)**: Climate model biases in the eastern tropical Atlantic: causes, impacts and ways forward. **Line (700)**
- **Voldoire et al. (2019)**: *Role of wind stress in driving SST biases in the Tropical Atlantic*. **Line (701)**
- **Koseki et al. (2018)**: Air-sea interactions and the tropical Atlantic warm bias. **Line (706)**
- **Zuidema et al. (2016)**: Smoke and clouds above the southeast Atlantic: Upcoming field campaigns probe absorbing aerosol's impact on climate. **Line (700)**
- **Koubanova et al. (2018)**: Seasonal variability of the Atlantic cold tongue and its relationship with the Angola-Benguela upwelling system. **Line (707)**

- **Cabos et al. (2017)**: The coastal upwelling system of the southeast Atlantic as simulated by a high-resolution coupled model. **Line (705)**

These studies highlight that the bias is often rooted in atmospheric forcing errors (e.g., weak coastal jets) and the misrepresentation of stratocumulus clouds, which leads to excessive shortwave radiation reaching the ocean surface.

Line 633: but, XU et al. (2014) used a different coupled model. There are many causalities of the bias in this region.

Suggest see also
Voldire et al., 2019, https://link.springer.com/article/10.1007/s00382-019-04717-0
Koseki et al., 2018, https://link.springer.com/article/10.1007/s00382-017-3896-2
Koubanova et al., 2018, https://link.springer.com/article/10.1007/s00382-018-4197-0
Cabos et al., 2017, https://link.springer.com/article/10.1007/s00382-016-3319-9
Matched line 12: radiation (e.g. Xu et al., 2014). 633

Response: We thank the reviewer for this suggestion. We have expanded this section to acknowledge that the warm bias is multicausal. While we still mention the role of shortwave radiation, we now also discuss the impact of wind stress, coastal jets, and air-sea interactions, citing the suggested literature to provide a more comprehensive explanation. Lines (694-701)

Line 642: the CARS climatology.

Response: We have corrected the grammar by adding the definite article "the" before "CARS climatology". We have also replaced the conjunction "But" with "On the other hand" to provide a smoother transition between the two sentences. Line (714)

Line 642: But => better to replace with "however" or "on the other hand".

Response: We agree that a more formal transition improves the flow of the discussion. We have replaced "But" with "**However**" to better contrast the model's performance north and south of the Congo River mouth. **Line (721)**

Line 643: sounds a bit strange as here you refer to climatological distribution and seasonal cycle. maybe delete “Similarly”

Response: We agree that "Similarly" is not the most appropriate transition here, as the discussion is shifting from spatial distribution to temporal variability. We have followed the reviewer's suggestion and deleted the word to improve the clarity and flow of the paragraph. **Line (723)**

Line 648-652: not sure if this sentence is necessary.

Response: We agree with the reviewer that this detailed comparison between the WOA and CARS climatologies was somewhat redundant and distracted from the main discussion on model biases. Following your suggestion, we have removed these lines to streamline the paragraph and keep the focus on the lack of observational data in the region.

Line 657: underestimation.

Response: Agreed. We have corrected the spelling of the word "underestimation" throughout the manuscript to ensure consistency. **Line (732)**

Line 666: better to plot horizontal current in some figures as commented above.

Response: We agree. As noted in our response to your previous general comment and the similar suggestion regarding the visualization of circulation, we have now included horizontal current vectors in the relevant figures (e.g., **Figure 6** and **Figure 9**). These additions allow for a better understanding of the nitrate transport and the high-speed currents near the Congo River mouth. **Line (498)** see also **Fig.R4**

Line 668: CHLa.

Response: Agreed. We have updated "chlorophyll" to "**CHLa**" to be more precise and to ensure consistency with the acronym **CHLa** used throughout the manuscript. **Line (736)**

Line 673: budget

Response: Agreed. We have corrected the capitalization of "budget" (changing "Budget" to "budget") to maintain consistency with the rest of the manuscript and standard scientific English. **Line (745)**

Line 675-676: As commented, I am skeptical about the MLD in the plots (too constant). Be careful for plotting and corresponding arguements.

Response: We fully agree with the reviewer's skepticism. The previous use of the de Boyer-Montégut (2004) criterion, with a reference depth at 10 meters, was indeed too deep to capture the extreme stratification of the Congo River plume, leading to a depth that appeared artificially constant.
Following your advice, we have **reconsidered our MLD definition**. We now adopt the criterion described by **Aroucha et al. (2025)**, which uses a reference depth at **3 meters** and a density threshold of around 0.06 kg/m ^{3}. This new definition is much better suited for high-stratification coastal systems. Consequently, all budget calculations and figures (notably Figures 11, 12, and 13) have been updated.

This change allows for a more realistic representation of the seasonal variations of the mixed layer and its interaction with the river plume. **Line (260-263)**

Line 677-678 and 697-699: As commented, the estimated 10km MLD seems a barrier layer. What if a different definition of MLD is used?

Response: We agree with the reviewer that the 10m reference depth used in the original version was likely placing the MLD below the freshwater-induced barrier layer, leading to the "constant" appearance and potential errors in the budget analysis. As detailed in our previous response, we have **fully addressed this by adopting a new MLD definition** based on a shallower reference depth of **3 meters**, following **Aroucha et al. (2025)**.
This new definition allows us to accurately distinguish the actual mixed layer from the underlying barrier layer. All the budget calculations for nitrate, as well as the associated discussion, have been updated to reflect this more realistic physical representation of the Congolese surface waters.

Line 701-702: remove “In this section, we will….in the euphonic layer”

Response: We agree with the reviewer that this introductory sentence was redundant. We have removed it to improve the conciseness and flow of the section, allowing the discussion to begin directly with the analysis.

Figure A1: There is no lable in the y-axis. At the base of the puphotic layer (the pink dashed-line) the signals are quite weak, so I am not sure if the authors' argument here is reasonable.

Response: we understand the reviewer's concern regarding the signal strength at the base of the euphotic zone (pink dashed line). However, we argue that the physical consistency of these signals, even if their absolute magnitude is lower than at the surface, makes the interpretation robust.

1. **Light Limitation:** As noted by **Radenac et al. (2020)**, biological transformation rates and budget terms are naturally weaker at depth because light becomes the limiting factor for primary production. This explains the "weak" visual signal compared to the surface layers.
2. **Water Mass Properties (EUC/SEUC):** Based on the in-situ observations of **Nubi et al. (2016)**, the Equatorial Undercurrent (EUC) and its southern recirculation (SEUC) are characterized by waters that are relatively poor in nitrates compared to the surrounding tropical waters, but they still carry a specific signature of chlorophyll.
3. **Zonal Advection and Dilution (XAD_CHL):** In Figure A1b, we observe a loss of chlorophyll (blue signal) at the base of the euphotic zone during the downwelling period, which coincides with the intensification of the SEUC. The physical mechanism is as follows: the SEUC transports waters from the open ocean toward the coast. While these undercurrent waters contain some biomass, they are **significantly less loaded with chlorophyll than the nutrient-rich waters of the Congolese coastal strip** (which are fueled by river inputs and upwelling). Therefore, the zonal advection of these "cleaner" offshore waters toward the coast results in a local dilution effect, appearing as a loss in the chlorophyll budget.

Actions taken in the manuscript:

- We have added y-axis labels (**Depth in meters**) to Figure A1.
- We have **adjusted the color scale** (narrowed the range) for the subsurface panels to make these seasonal reversals (e.g., the blue signal in XAD_CHL) more visible to the reader.

- The text in Appendix A and the Discussion has been updated to explicitly include this "dilution" argument, supported by the findings of **Nubi et al. (2016)**. **Lines (928-936)**

Line 726: which box?

Response: We apologize for the ambiguity. The "box" refers to the **coastal strip defined in Section 3.1.2 and Section 3.2**, which corresponds to the area between the coastline and 1° of longitude offshore. Initially, this box was restricted to 3°S–6°S. However, following your general comment to extend the study area, this box now covers the coastal band from **0°N to 6°S**. We have updated the text to explicitly reference **Figure 1** (where the box is shown) and have specified its latitudinal and longitudinal boundaries to avoid any confusion. See Fig. 1b in the new version of manuscript **(Line 184)**

Line 731-732: Not only the nitrate meridional gradient, but also vertical motion's meridional gradient could be a source of nitrate frontogenesis: if vertical motion is more upward in the south than in the north, more nitrate is supplied in the south than in the north, consequently, the nitrate meridional gradient is negative like Fig.15b.

Response: We thank the reviewer for this very insightful physical suggestion. We agree that the meridional variation in the intensity of vertical velocity ($\partial w/\partial y$) is a significant driver of nitrate frontogenesis in the Congolese system. Near the Congo River mouth (around 6°S), the vertical upward motion is enhanced compared to the northern part of the domain (3°S–0°N), partly due to the coastal geometry and the specific impact of coastal trapped waves in this area. This differential vertical supply brings more nitrate to the surface in the south, which physically explains the establishment of the negative meridional nitrate gradient shown in Figure 14b. We have integrated this mechanism into the discussion to complement the advection-based arguments.

"This observation suggests that for the period from September to October, waters in the southern part of the box are richer in nitrate than waters to the north. Beyond horizontal transport, this frontogenesis is also driven by the meridional gradient of vertical motion ($\partial w/\partial y$). A stronger upward vertical velocity in the southern section (near 6°S) compared to the north leads to a higher vertical nitrate supply in the south, establishing the negative meridional nitrate gradient observed in Fig. 14b. This highlights the important role of vertical processes in the regional enrichment, as also emphasized by Nubi et al. (2016) for the equatorial band."

Line 732-733: Did the author show this plot? Same as CTWs, it would be helpful if any plots of connection to the equatorial part is shown.

Response: We agree that providing a visual and dynamical bridge between the equatorial forcing and the Congolese coastal response is essential. In the revised manuscript, we have strengthened this connection by following the approach of **Ngakala et al. (2025)** and integrating the physical framework established by **Illig & Bachèlery (2019)** and **Bachèlery et al. (2016)**.

The remote connection is now explicitly demonstrated through the following evidence:

1. **Direct SLA/TD Comparison (Fig. 3):** Following **Ngakala et al. (2025)**, we have included/highlighted **Figure 3**, which shows the monthly climatology of Sea Level Anomaly (SLA) and Thermocline Depth (TD) along both the equator (Panels a, c, e) and the Congolese coastal box (Panels b, d, f). This figure provides the visual proof requested: it shows that the

negative SLA and shallow TD signals originating at the equator in May–August propagate directly to the Congolese coast.

2. **Dynamical Mechanism:** As explained by **Illig & Bachèlery (2019)**, this connection is mediated by fast, first-mode Equatorial Kelvin Waves (EKW) that transform into Coastal Trapped Waves (CTW) upon reaching the eastern boundary. Our results show a phase consistency that matches their predicted propagation speeds (~5.5 $m.s^{-1}$).
3. **Biogeochemical Impact:** The transition from physical wave propagation to nutrient supply is supported by **Bachèlery et al. (2016)**, who demonstrated that remote equatorial forcing explains over 85% of the interannual and seasonal nitrate fluctuations in this region. The vertical uplift of the thermocline/nitracline seen in our **Figure 11** is the direct result of this equatorial-coastal wave connection.

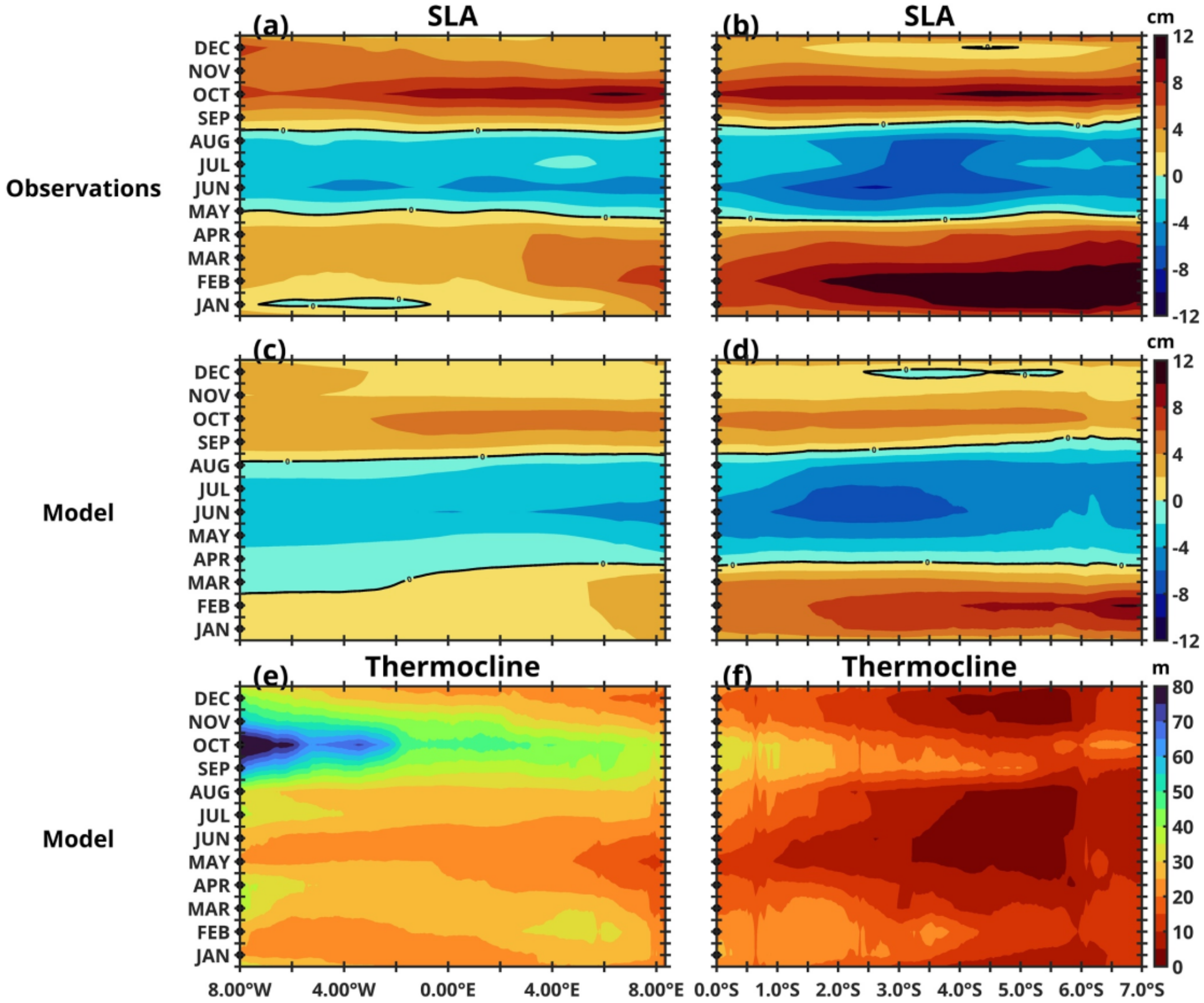


Fig. R27: Eastern equatorial (averaged within 1°S–1°N, panels a, c, and e) and coastal (averaged within the 1°-wide coastal band, panels b, d, and f) monthly climatology of altimetry (CMEMS satellite product, panels a and b) and model (panels c and d) sea level anomaly (SLA, cm). Panels e and f show the model monthly climatology of eastern equatorial and coastal thermocline depth (TD, m), respectively. **Ngakala et al. (2025)**

Line 734-737: I'm curious the horizontal map of this argument: subsurface budget plots could be shown here (as supplemental information)?

Response:

We thank the reviewer for this excellent suggestion. Indeed, a horizontal perspective at depth is valuable to confirm the spatial pathways of the currents (SEUC and Angola Current) and their role in the nutrient and chlorophyll balance.

Following your suggestion, we have included a new figure in the **Supplementary Information (Figure S1)** showing the horizontal distribution of the nitrate budget terms (zonal advection, meridional advection, and vertical diffusion) at a representative subsurface depth of **40 meters** during the main upwelling season (July).

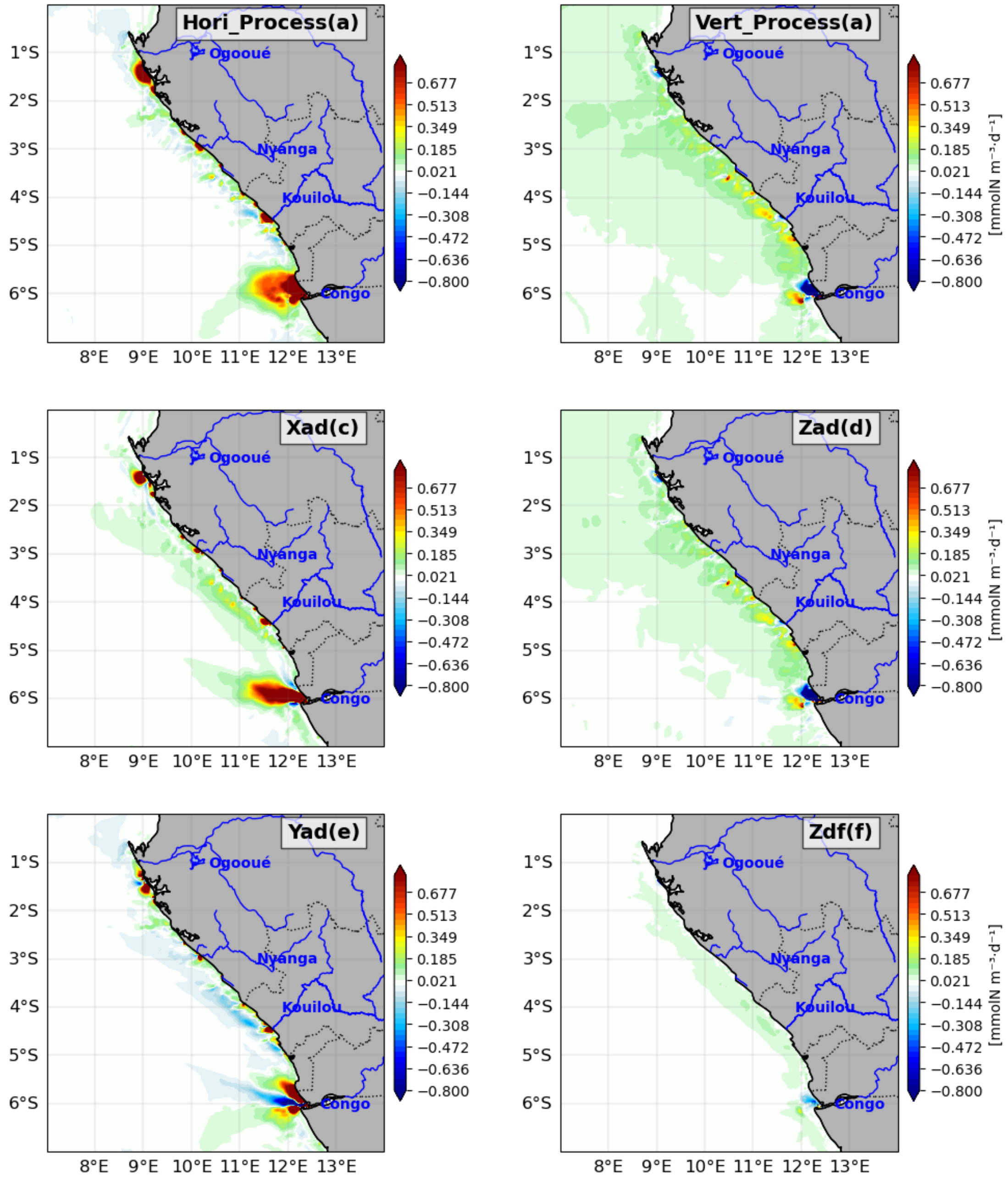


Fig. R28: Contribution of (a) the horizontal processes, including (c) zonal advection and (e) meridional advection, and (b) vertical processes, including (d) vertical advection and (f) vertical diffusion, to the nitrate budget averaged in the Euphotic layer during the austral Summer (December, January and February). Units are mmolN.m^{-3}.d^{-1}.

Line 742/743: Current.

Response: Agreed. We have capitalized the word "Current" throughout the manuscript when referring to specific, named ocean currents (e.g., Angola Current, Guinea Current, South Equatorial Counter Current) to adhere to standard oceanographic nomenclature. **Line (823)**

Line 746-748: From Fig.A1, it is not easy to see what the author mention here. As commented above, any horizontal plot at the subsurface might be helpful.

Line 754-792: It seems that the authors mix many words related to primary production (TPP, NPP, Net TPP, etc?). Therefore, it is hard to follow the statement in this part. Please be careful in re-wording.

Response: We have thoroughly revised this part (L754-792) to harmonize the vocabulary and ensure scientific consistency. Following the reviewer's suggestion, we have standardized the terms as follows:

1. **Net Primary Production (NPP):** Used to represent the total carbon fixation rate by both nanophytoplankton and diatoms. This replaces "TPP" and "Net TPP".
2. **New Production (NP):** Specifically refers to the fraction of NPP fueled by external nitrate inputs (upwelling and river discharge).
3. **Regenerated Production (RP):** Refers to the fraction of NPP fueled by recycled nutrients (ammonium).

   Consistency Check: We have verified that

   $$NPP=NP+RP$$

   across all figures and text. We also ensured that the units (either **mol C** $\mathbf{m^{-2}\ d^{-1}}$ for integrated production or **mmol N** $\mathbf{m^{-3}\ d^{-1}}$ for local rates) are correctly applied and consistent between the text and the colorbars of **Figure 17**.

Actions taken in the manuscript:
We have rewritten the entire Section 3.4 (Biological Productivity) to use this standardized terminology, starting with a clear definition of these terms. **Lines (846-880)**

Line 758: net primary production (NPP)

Response: Agreed. As part of our comprehensive revision of the terminology in Section 3.4, we have updated this line to use "**Net Primary Production (NPP)**". This ensures that the term is clearly defined and consistently used when referring to the total carbon fixation rate in our results. Line **847**

Line 771: Net TPP => NPP?

Response: Agreed. We have replaced "Net TPP" with "**NPP**" (Net Primary Production). This change is consistent with the standardization of biological terms throughout the revised manuscript, where NPP is defined as the sum of New Production (NP) and Regenerated Production (RP). Line (847)

Ligne 772 : fig.18 => Fig.18.

Response: Agreed. We have corrected the capitalization of the figure citation. We have also performed a global check to ensure that all figure references in the text use the capitalized format "**Fig.**" for consistency. Line (873)

Line 772-773: not sure what is “the difference between Net NPP and NP”

Response: We apologize for the confusion. In the biogeochemical framework of the PISCES model, **Net Primary Production (NPP)** is the sum of **New Production (NP)**, which is fueled by external nitrate, and **Regenerated Production (RP)**, which is fueled by recycled ammonium.
The "difference between NPP and NP" specifically refers to the **Regenerated Production (RP)**. We have clarified this definition in the revised manuscript (Section 3.4) and reworded the sentence to explicitly name the process of regenerated production.

Line 783-784: 10m looks like barrier layer

Response : Done

Physical and biological processes driving seasonal variability of Nitrate budget and biological productivity in the Gabon-Congo upwelling system

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REVIWER1

Dear Reviewers,

We would like to express our sincere gratitude for your constructive comments and insightful suggestions, which have greatly helped us improve the quality of our manuscript.

Please note the following points regarding the presentation of this document:

- **Color Coding:** For ease of reading, the reviewers' original comments are presented in **black**, while our detailed responses and the specific changes made to the text are highlighted in **blue**.
- **Figure Renumbering:** Following a specific recommendation from one of the reviewers, the **original Figure 3 has been removed**. As a result, the numbering of all subsequent figures has been updated throughout the revised manuscript. We apologize for any inconvenience this may cause when cross-referencing with the previous version.

Please find below our detailed responses to the comments.

Review comments:

Review of Landry Junior Mbang Essome et al. submitted to Ocean science.

"Physical and biological processes driving seasonal variability of Nitrate budget and biological productivity in the Congolese upwelling system."

The present manuscript is aimed at describing the relative contributions of physical and biological processes in modulating nitrate concentrations in the Congolese upwelling system. Although I found the manuscript quite well written, there are some points that need to be clarified (see my comments). Thus, I recommend major revisions to publish this manuscript.

General comments:

The paper is generally well written. However, the authors should provide more details and clearer descriptions in several sections (see comments below). I also find it unusual that the authors consistently use the present tense in the Introduction when referring to past studies. I would suggest using either the present perfect or past simple instead.

Response: We thank the reviewer for this relevant stylistic suggestion. We have thoroughly revised the Introduction to ensure that references to past studies and findings are now expressed in the **past simple** or **present perfect** tense, rather than the present tense. This improves the clarity and the chronological flow of the literature review. Lines (**101-183**)

In the Discussion and Conclusion sections, I recommend that the authors explicitly cite figures when recalling key results. This would improve the overall readability of the manuscript and be beneficial for readers. In addition, I suggest moving Figure 3 as a subplot within Figure 1 in order to better highlight the study area in the Introduction, and removing the red box currently shown in Figure 1.

Response: We thank the reviewer for these suggestions, which significantly improve the clarity of the manuscript.

1. We have thoroughly revised the **Discussion** and **Conclusion** sections to explicitly cite the relevant figures when recalling key results, helping the reader to easily connect the text with our numerical evidence.
2. As suggested, **Figure 3** (standard deviation of nitrate) has been moved and integrated as a subplot within **Figure 1**. This better highlights the regional variability of the Congolese Upwelling System right from the introduction. Line **(185)**
3. The red box in **Figure 1** has been removed to avoid cluttering, as the new multi-panel figure now clearly delineates the study area. **Line (185)**

2. Modifications in Discussion (Section 4)

- **Lines (699) : (Fig. 2a,b)** and **(Fig. 4c,d)**.

- **Line (721) : (Fig. 2c,d)**.
- **Line (745-747) : (Fig. 7c)** and **(Fig. 7d)**
- **Line (827): Appendix A, Fig. A1**

3. Conclusion Modifications (Section 5)

- **Lines (906) : Fig. 4e,f and Fig. 11a**
- **Line (910-911) : Fig. 10c , Fig. 10d and Fig. 10f**
- **Line (919) : Fig. 15**

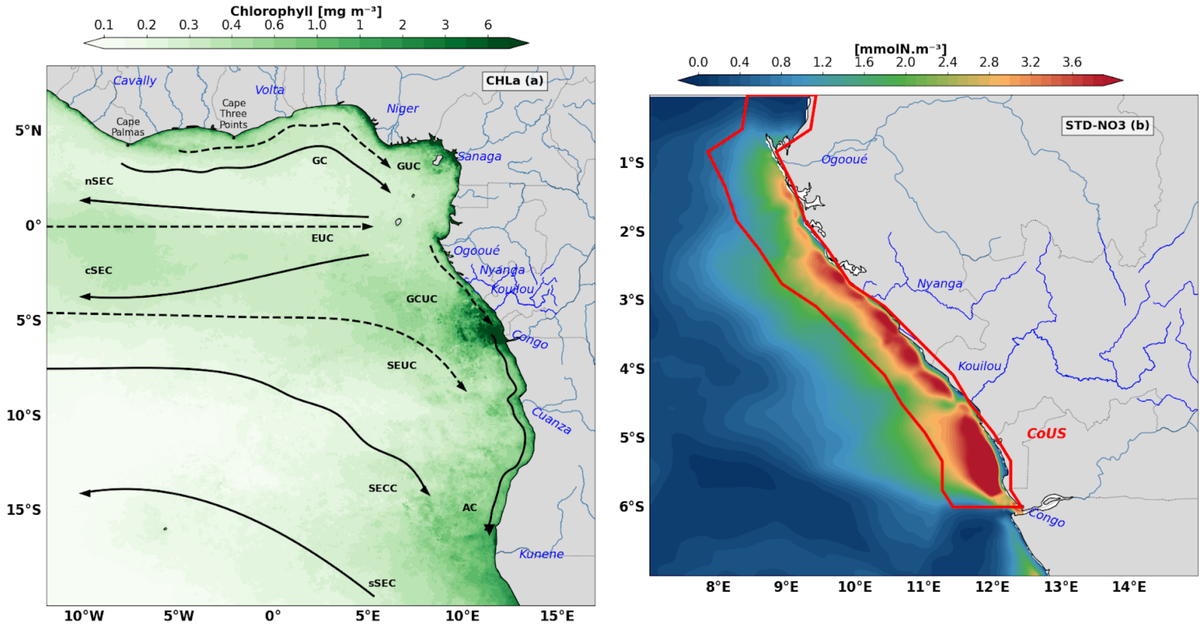

Fig. R1: Regional ocean circulation and spatial distribution of biological and nutrient tracers. (a) Annual mean surface Chlorophyll-a concentration (CHLa, [mg m^{-3}]). The map illustrates the spatial distribution of biological productivity across the Gulf of Guinea and the South Atlantic African margin. Black arrows and dashed lines indicate the major surface and subsurface currents: North South Equatorial Current (nSEC), Central South Equatorial Current (cSEC), South South Equatorial Current (sSEC), Equatorial Undercurrent (EUC), Guinea Current (GC), Guinea Undercurrent (GUC), Gabon-Congo Undercurrent (GCUC), South Equatorial Undercurrent (SEUC), South Equatorial Counter Current (SECC), and Angola Current (AC). (b) Standard deviation of Nitrate concentration (STD−NO3, [mmolN m^{-3}]). The color scale represents the variability of nitrates in the upper ocean. The red polygon delimits the coastal domain defined as the Congolese Upwelling System (CoUS), extending from the Congo River mouth (~6°S) to Cape Lopez (~1°S), which serves as the primary study area for the nutrient budget analysis. Blue labels highlight the discharge points of the Ogooué, Nyanga, Kouilou, and Congo rivers. Line (185)

The choice of the study area also requires clarification. Why did the authors restrict the domain to between 6°S and 3°S? Based on Figures 1 and 3, the northern boundary could be extended to 0°N, especially since the authors state that the region between 6°S and 0°N is poorly documented (L144). I would suggest that the authors extend the northern boundary to 0°N.

Response: We fully agree with the reviewer's suggestion. Initially, the study area (6°S–3°S) was chosen to focus on the core region where major river discharges (Congo and Kouilou rivers) occur and where the highest nitrate variability was observed. However, as noted by the reviewer, the entire region from 6°S to 0°N remains poorly documented. In the revised manuscript, we have **extended the study area box to 0°N** (covering the 6°S–0°N, 1° wide coastal strip). This extension allows for a more comprehensive analysis of the physical and biological interactions across the entire Congolese and Gabonese coastal systems. All figures (Hovmöller diagrams, budget maps, and time series) and associated calculations have been updated to reflect this new domain. Line (**185**)

Regarding the mixed-layer nitrate budget, I can understand the assumption that lateral diffusion term is negligible; however, what about the entrainment term at the base of the mixed layer? This contribution has not been shown or discussed in the analysis and should be addressed.

Response:

Regarding the entrainment term, we provide the following details:

1. **Model Calculation vs. Storage:** The entrainment term is indeed calculated internally by the NEMO-PISCES model at each time step (online). However, it was not included in the variables saved in the output files during this specific simulation.
2. **Methodological Precedent:** Our approach follows **Radenac et al. (2020)**, who performed a similar nitrate budget analysis in the tropical Atlantic with the NEMO-PISCES model. Their study demonstrated that the entrainment term is negligible in this region compared to the dominant roles of vertical advection and diffusion.
3. **Numerical Consistency:** To ensure the integrity of the budget, all terms presented in this study (advection, diffusion, and SMS) were computed *online* during the model run. Recalculating the entrainment term *offline* (using saved daily or monthly mean fields of MLD and nitrate) would introduce significant numerical errors and residuals due to time-sampling issues, potentially leading to a misleading interpretation.

Physical Justification: In the Congolese Upwelling System, the strong haline stratification induced by the Congo River plume maintains a very shallow and relatively stable mixed layer depth. Since entrainment is primarily driven by the rate of change of the MLD (dh/dt), its contribution remains very small in this specific high-stratification context.

Action taken in the manuscript:

We have added a clarification in **Section 2.3 (Methods)** to explain that the entrainment term, although calculated internally by the model, is not shown because it is negligible in this region, consistent with the findings of **Radenac et al. (2020)**. Line (**267-269**)

To avoid confusion, I recommend removing the acronyms NPP, PP, TPP, NP, RP, as well as AC, and using the full terms throughout the manuscript. These acronyms are used only sparsely and, in several instances, incorrectly (e.g., total PP in L281, new primary production (NPP) in L285, regenerated production (RPP) in L286, or in the title of Figure 18 where NP is used for new primary production, RP for regenerated production, and TPP for total primary production).

Response: We have thoroughly revised this part (L754-792) to harmonize the vocabulary and ensure scientific consistency. Following the reviewer's suggestion, we have standardized the terms as follows:

1. **Net Primary Production (NPP):** Used to represent the total carbon fixation rate by both nanophytoplankton and diatoms. This replaces "TPP" and "Net TPP".
2. **New Production (NP):** Specifically refers to the fraction of NPP fueled by external nitrate inputs (upwelling and river discharge).
3. **Regenerated Production (RP):** Refers to the fraction of NPP fueled by recycled nutrients (ammonium).

   Consistency Check: We have verified that
   NPP=NP+RP
   across all figures and text. We also ensured that the units (either **mol C m^{-2} d^{-1}** for integrated production or **mmol N m^{-3} d^{-1}** for local rates) are correctly applied and consistent between the text and the colorbars of **Figure 17**.

Actions taken in the manuscript:
We have rewritten the entire Section 3.4 (Biological Productivity) to use this standardized terminology, starting with a clear definition of these terms. Lines (**846-882**)

It would also be helpful if the authors clearly define how the standard deviation and correlation coefficients were calculated in the Methods section. Almost all figures need to be revised. Many figures lack clear boundaries or frames, and colorbars are often too close to the y-axis (e.g., Figures 9, 11, 13), making it difficult to distinguish between latitude/depth and colorbar values. Figures and colorbars should be clearly separated. In addition, I suggest using a finer color scale (more color levels) to better highlight differences.

Response:

To improve both the transparency of our methods and the quality of our visual results:

1. **Statistical Definitions:** We have added a dedicated paragraph in the **Methods section (Section 2.3, Lines (305-323)).** to explicitly define how the standard deviation (to quantify seasonal variability) and Pearson correlation coefficients (to evaluate relationships between physical drivers and nitrate concentrations) were calculated.

2. **Figure Revisions:** We have thoroughly updated almost all figures in the manuscript. Specifically:
    - We have added **clear frames and boundaries** to all panels.
    - **Colorbars** have been moved significantly further away from the y-axes to ensure that axis labels (latitude/depth) are clearly distinguishable from colorbar values.
    - We have adopted a **finer color scale** with more color levels to better highlight small-scale differences and gradients in the nitrate budget and biological production.

"The statistical analysis throughout this study relies on the standard deviation (SD) and Pearson correlation coefficients (r). The standard deviation was calculated to quantify the seasonal variability of the nitrate budget terms and chlorophyll-a concentrations across the coastal box. To evaluate the relationship between different physical and biological drivers, Pearson correlation coefficients were computed. For the budget decomposition analysis, the correlation was used to determine the contribution of seasonal anomalies (current or gradient) relative to the total advection term. All reported correlations are statistically significant at a 95% confidence level ($p<0.05$)." **Lines (303-311)**

From Figures 8, 10, and 12, it appears that there may be a discrepancy between the summed contributions of physical and biological processes and the total nitrate concentration tendency. Could the authors clarify this point? Is there a residual term in the budget?

Response: We thank the reviewer for this careful check. We would like to clarify that in our study, the **total nitrate tendency is indeed calculated as the exact sum of the physical processes and biological processes.**

The perceived discrepancy is purely a **visual effect related to the colorbar scales**, and we appreciate the opportunity to clarify this point:

1. **Large Compensation:** In highly productive systems like the Congolese upwelling, physical supply (positive) and biological uptake (negative) are the two dominant terms. They almost entirely compensate each other out.
2. **Order of Magnitude:** Because of this compensation, the resulting "Total Tendency" is **one order of magnitude smaller** than the individual physical or biological terms.
3. **Specific Color Scales:** To make the patterns of the Total Tendency visible, we used a much finer color scale (e.g., in Figure 8, the tendency scale is 10 times smaller than the physics/biology scales). If we were to use the same scale for all panels, the Total

Tendency would appear almost uniformly zero (white), masking the important seasonal signal of nitrate accumulation or depletion.

Some figures are not discussed anywhere in the manuscript (e.g., Figures 11c, 11e, 17, and Appendix B), and this should be corrected. I also suggest that the authors consistently use either “Figure” or “Fig.” throughout the manuscript when referring to figures.

Response: We apologize for these omissions. We have now fully integrated the discussion of all figures into the text: In the new manuscript, have removed Figure 3 so that figure number was reduced by 1 and caption figure was update in the whole manuscript. for instance, Fig. 11 is now Fig.10.

1. **Figures 10c and 10e:** These panels, representing the zonal and meridional nitrate advection in the mixed layer, are now explicitly discussed in **Section 3.2.1**, where we analyze the horizontal vs. vertical contributions to the nitrate budget. **Lines (524-531)**
2. **Figure 16:** This regional overview of annual nitrate and CHLa concentrations has been integrated into the beginning of **Section 3.4** (Biological Productivity) to provide a broader context for the study area compared to the wider Gulf of Guinea. **Lines (835-841)**

Appendix B: The decomposition of nitrate advection (Fig. B1) is now formally cited and discussed in **Section 3.3.2.1** to support the correlation analysis (r=0.77).

3. **Consistency:** We have standardized the citations throughout the manuscript. We now consistently use the abbreviation "**Fig.**" (e.g., Fig. 1) except when the word is at the beginning of a sentence, where we use "**Figure**". **Lines (945-947)**

Finally, there is a substantial number of missing references, both in the text and in the reference list, which must be addressed.

Response : We have corrected and add the missing reference

Other comments:

L3: I suggest that the list of affiliations start with the first author’s affiliation.

Response: Agreed. We have reordered the list of affiliations so that the first author's primary institution appears first. The superscripts in the author list have been updated accordingly to match this new order. **Lines (6-14)**

L79: CTWs abbreviation should be used first in L76.

Response: Agreed. We have introduced the acronym "**CTWs**" at its first occurrence in the Abstract (L76) and used the abbreviation consistently throughout the rest of the manuscript. **Line (76)**

L111 and L777: It should be: "…(Gutknecht et al., 2013…" otherwise, this reference is missing in the reference section.

Response: We thank the reviewer for noticing this omission. We have corrected the citation in the whole manuscript text at **Lines (111 and 878)**. Furthermore, the full reference has now been added to the reference section of the manuscript. **Lines (1041-1044)**

L115: I would suggest to add "South" after "eastern boundary of the …"

Response: Agreed. We have added "**South**" to specify that the discussion focuses on the South Atlantic eastern boundary, which improves the geographical precision of the introduction. **Line (117)**

L123: It should be: "… the Angolan coast"

Response: Agreed. We have changed "coasts" to singular "**coast**" to improve the grammatical accuracy and consistency of the sentence. **Line (125)**

L134: What do you mean by twhich? Did the authors want to write which?

Response: We apologize for this typographical error. "twhich" has been corrected to "**which**". **Line (137)**

L180: It should be: "The red box indicates…".

Response: We have corrected the subject-verb agreement in the caption of Figure 1. **Line (193)**

L229: It should be: "…surface wind vector SST dataset. They …"

Response: We have corrected the typographical error and clarified the sentence as suggested. **Line (246)**

L247-250: The authors should rewrite these sentences using the correct definitions for each term in the budget.

Response: We have thoroughly rewritten this section to ensure that each mathematical term in Equation 1 is correctly and rigorously defined according to standard oceanographic budget analysis. Specifically, we have clarified the distinction between vertical diffusion at the base of the mixed layer and the entrainment term. **Lines (260-271)**

L274: Equation 4 is missing in the manuscript.

Response: We sincerely apologize for this oversight. Equation 4, which details the Reynolds decomposition of the nitrate advection terms into mean and seasonal components, was indeed missing from the original submission. We have now inserted this equation in Section 2.3 (Methods) to support the analysis of the drivers of advection variability discussed in the results.

To understand the physical processes driving the seasonal variability of nitrate advection, we perform a decomposition of the advection anomaly. Any variable A (velocity u or nitrate gradient ∇NO3) can be expressed as the sum of its annual mean (A^{-}) and its seasonal fluctuation (A'). The total seasonal variation of the advection term is thus decomposed into three distinct contributions:

$$(\mathbf{u}\cdot\nabla(\mathrm{NO_3}))' = \mathbf{u}'\cdot\overline{\nabla(NO_3)} + \overline{u}\cdot\nabla(\mathrm{NO_3})' + \mathbf{u}'\cdot\nabla(\mathrm{NO_3})'$$

- $\mathbf{u}'\cdot\overline{\nabla(NO_3)}$ **(Current variability):** This term quantifies the impact of current velocity anomalies acting upon a mean (steady-state) nitrate distribution. It isolates the effect of current acceleration or intensification (such as the SEUC or the Angola Current) on nutrient transport.
- $\overline{u}\cdot\nabla(\mathrm{NO_3})'$ **(Gradient variability):** This term represents the impact of seasonal changes in the nitrate concentration gradient under a mean circulation. It highlights the influence of seasonal water mass enrichment, particularly via the Congo River plume.
- $\mathbf{u}'\cdot\nabla(\mathrm{NO_3})'$**(Non-linear term):** This term accounts for the simultaneous interaction between current fluctuations and gradient fluctuations.

This decomposition is essential for determining whether the "physical pump" (currents) or the "nutrient reservoir" (gradients) drives the seasonal variability of the nitrate budget within the Congolese upwelling system. **Line (294)**

L280: It should be: "… availability. Note …"

Response: We have corrected the punctuation and spacing at line 280. A period followed by a space has been added between "availability" and "Note" to improve the readability of the sentence. **Lines (318-319)**

L292: SSH not defined. Also, be consistent between SLA and SSH throughout the manuscript.

Response: Agreed. We have added the definition of **Sea Surface Height (SSH)** at its first occurrence in the results section. Furthermore, we have carefully reviewed the entire manuscript to ensure terminological consistency: we use **SSH** when referring to the absolute vertical position of the sea surface and **SLA** when discussing the seasonal variations and anomalies relative to the mean (e.g., signatures of Coastal Trapped Waves).

1. Corrected Text for (Results Section)

'The assessment of our model simulation was conducted using several observational products for physical variables, including Sea Surface Temperature (SST), **Sea Surface Height (SSH)**, and ocean currents, as well as biogeochemical tracers such as nitrate (NO3) and chlorophyll-a (CHLa)'. **Line (334)**

L293: I would suggest: "… regional distributions from observations …"

Response: We have updated the sentence at line 293 to follow the reviewer's suggestion, which more accurately describes the comparison between the observational datasets and the model results. **Line (336)**

In Figures 2a-b, what could explain the warm bias in the model west of 10ºE?

Response:
We thank the reviewer for this observation. While our model uses **ASCAT satellite data** for wind forcing (L199), which significantly improves the representation of momentum transfer and coastal upwelling, the **surface heat fluxes** (shortwave and longwave radiation) are derived from the JRA-55 reanalysis (**212-213**).

The warm bias of approximately 1°C observed offshore (west of 10°E) is primarily explained by:

1. **Overestimation of Shortwave Radiation:** JRA-55, like many atmospheric reanalyses, tends to underestimate the persistent low-level stratocumulus cloud cover characteristic of the South-East Tropical Atlantic. This leads to an excessive amount of downward solar radiation reaching the ocean surface, which cannot be corrected by the ASCAT winds alone.
2. **Heat Flux Feedback:** Since the heat fluxes are partly based on reanalysis, the thermodynamic coupling offshore might not perfectly capture the intense nighttime cooling or the specific diurnal cycle of the open ocean in this region.

L330-331: What could explain the strong nutrient depletion in the model compared to the observations in surface waters, as shown in Figure 4? In addition, Figure 4 shows that the maximum vertical nitrate gradient is shallower and more pronounced in the model than in the observations. Could the authors elaborate on this difference? Does it have any implications for the results or their interpretation?

Response:
We thank the reviewer for this technical question. The differences observed in **Figure 4** between the model and the CARS 2009 climatology are primarily due to the limitations of the observational dataset in this specific region:

1. **Data Scarcity and Interpolation:** CARS 2009 is built upon *in-situ* data that is notoriously sparse in the Gulf of Guinea, particularly in the Congolese coastal strip. Consequently, the product relies heavily on objective interpolation, which tends to smooth out extreme values and sharp transitions.
2. **Horizontal Resolution Mismatch:** CARS has a coarse horizontal resolution of **1/2° (~50 km)**, which is insufficient to capture the fine-scale structures of the Congo River plume and the coastal nitracline. In contrast, our model's **1/36° (~3 km)** resolution allows for a much more precise representation of these coastal features.
3. **Vertical Resolution Mismatch:** In the critical upper layers, CARS provides data at 5 m intervals between 0 and 20 m, and then at much coarser intervals (10 m to 30 m) beyond 20 m

depth. Our model uses a much finer vertical grid, with resolutions ranging from **0.5 m to 2.5 m within the first 20 meters**. This explains why the model nitracline is more "pronounced" and shallower: it resolves the intense stratification that the coarse observational grid "blurs" or "deepens" through vertical averaging.

4. **Temporal Mismatch:** CARS 2009 is a multi-decadal climatology (averaging decades of data), whereas our model analyzes a specific year (2011). Climatological averaging inevitably smooths the seasonal peaks of nutrient depletion that a high-resolution snapshot or year-specific simulation can capture.

Implications: These differences imply that the model is better equipped than coarse climatologies to study the high-frequency and fine-scale vertical processes (like wave-induced advection) that drive the Congolese upwelling. The sharpness of the model's gradient is a reflection of its superior resolution rather than a fundamental error in its interpretation.

The different parameters and panels described in the caption of Figure 5 do not correspond correctly to the figure. I suggest that the authors carefully check and revise this caption. The x-axis of Figure 6 seems to be cropped.

Response:

We thank the reviewer for their careful reading and for spotting these errors.

1. **Figure 4 Caption:** We have corrected the caption of Figure 4 to ensure that the panel letters (a–f) correctly correspond to the parameters shown in the plots. In the original version, the parameters were listed in the wrong order. **Lines (380-381)**
2. **Figure 5 X-axis:** We have adjusted the plot margins and the export settings for Figure 5 to ensure that the x-axis (representing the months of the year) is fully visible and no longer appears cropped. **Lines (430-431)**

L445: It should be: "… (a) and …" Spaces are needed between the figures and the different figures titles in Figures 9, 14, etc… .

Response: We have corrected the typo in the caption of **Fig. 8** by adding the word "and" and the necessary space. Furthermore, we have thoroughly reviewed the layout of all multi-panel figures (specifically **Figs. 8, 10, 12, 13, and 15**) to ensure that there is sufficient spacing between the figure panels and their respective titles and captions, as well as between the sub-panel labels (a, b, c, etc.). This significantly improves the clarity and readability of the budget analysis sections. Line **(490)**

L469-471: No possible to see with the actual colobars for Figures 10c-d.

Response:

We thank the reviewer for highlighting this visibility issue. We agree that the original colorbars for **Fig. 9c** (physical processes) and **Fig. 9d** (biological processes) were poorly optimized, leading to saturation and making the spatial gradients difficult to distinguish. **Lines (504)**

To address this, we have taken the following actions:

1. **Optimized Color Scales:** We have redrawn Figure 10 with wider and more precise colorbar ranges for panels (c) and (d). We adopted a **finer color scale** (more levels) to reveal the spatial variability within the Congo plume and the coastal upwelling strip without saturating the signal.
2. **Clear Separation:** Following your general recommendation, the colorbars have been moved further away from the figure panels to prevent interference with axis labels.

Terminology and Units: We have ensured that the units (mmolN.m−3.d−1) and the scale values are clearly legible. The text in **Section 3.2.2** has been updated to specifically guide the reader through these improved visualizations.

L480: It should be: "… to the processes …"

Response: Agreed. We have corrected the typographical error at line 480 by changing "process" to "**processes**" to ensure grammatical plural agreement, as multiple physical and biological drivers are discussed in this section. **Line (546)**

Are the euphotic layer depth and the nitrate budget in the euphotic layer computed online or offline? I suggest that the authors comment on that in the method section.

Response: We thank the reviewer for this request for clarification. To ensure maximum numerical precision and consistency, both the **euphotic layer depth and all nitrate budget terms were computed online** at each model time step (every 5 minutes) during the simulation. This approach, which is the same as the one used for the mixed-layer budget, avoids the significant sampling errors and residuals that occur with offline calculations based on daily or monthly averages. We have added this clarification to the **Methods section (Section 2.3)** as suggested.

L519: It should be: "…period (June, July, …)"

Response: Agreed. We have corrected the punctuation and spacing in the parenthetical list of months to improve readability. **Line (587)**

L526: I would suggest to remove "in the euphotic layer". It should be: "… (b) contributed by physical processes (c) and biological processes (d) …"

Response: Agreed. We have removed the redundant phrase "in the euphotic layer" from the caption of Figure 12 and revised the phrasing as suggested to improve conciseness and clarity. **Lines (593-594)**

L543: I suggest: “The seasonal cycle of zonal nitrate advection ...” instead of “The zonal nitrate advection seasonal cycle …”

Response: We have revised the phrasing as suggested to ensure a more standard and natural academic English structure. **Line (610)**

L544: “<” is missing. It should be “< u >”. Also Is the correlation (r=0.77) statistically significant? If yes, at which confidence level? I suggest to mention it for the other correlation coefficients too.

Response: We thank the reviewer for noticing the missing bracket in the mathematical notation; this has been corrected to ⟨u⟩. Regarding the statistical significance, we confirm that the correlation coefficient of r=0.77 is **statistically significant at the 95% confidence level (p<0.05)**. Following your suggestion, we have performed significance tests for all correlation coefficients mentioned in the manuscript (using a two-tailed Student's t-test). In the revised version, we now systematically provide the p -value or a statement of significance for every reported correlation to ensure full statistical transparency. **Lines (606 - 674)**

L547: It should be: “… the term. The …”

Response: We have corrected the sentence structure and punctuation at line 547 to remove the redundant phrasing ("the term The third component") and improve the clarity of the description. The text has been split into two distinct sentences as suggested. **Line (614)**

L551: I suggest: “… Undercurrent (SEUC), …”

Response: Agreed. We have updated the text at line 551 to correctly place the acronym for the South Equatorial Undercurrent (**SEUC**) in parentheses following its full name. This ensures a more standard and professional presentation of the oceanographic nomenclature. **Line (618)**

I suggest to write “zonal current”, “meridional current” and “verticial current” instead of “current” in the captions of Figures 14, 15, 16, respectively.

Response: Agreed. We have updated the captions of **Figures 13, 14, and 15** to explicitly specify the component of the velocity field being discussed (zonal, meridional, or vertical velocity). This clarification has also been applied to the text at lines 567 and 570 to ensure consistency. These changes help to avoid any ambiguity regarding which current component is driving the nitrate advection in each analysis. **Lines (Fig 13 (623), Fig 14 (668), Fig 15 (712))**

L567 and L570: I suggest to write “meridional current” instead of “current”

Response:

Agreed. We have updated the text at lines 567 and 570 to replace the general term "current" with the more precise "**meridional current**". This ensures full consistency with the specific advection component (meridional nitrate advection) being analyzed in this section. **Lines (634-637)**

L585: Rephrase the sentence since it is not only the vertical velocity variation term which is expressed in brackets.

Response:

We thank the reviewer for this correction. We agree that the term in brackets ($w^{'}.\overline{\nabla z\left(NO_3\right)}$) represents the **contribution of seasonal vertical velocity anomalies acting on the annual mean vertical nitrate gradient**, rather than just the velocity variation itself. We have rephrased the sentence at line 585 to accurately describe this physical interaction. **Line (653)**

L607: By using “consider” at the beginning of the sentence, do you mean “average”. If yes, I suggest: “However, if we average in the upper 100 m, …”

Response:

Agreed. We thank the reviewer for this clarification. We were indeed referring to the vertical average over the top 100 meters of the water column. We have replaced the term "consider" with "**average in**" as suggested, which is more scientifically precise. **Line (676)**

L620: It should be: “… budget drivers in the Congolese upwelling system …”

Response:

Agreed. We have updated the phrasing at line 620 as suggested. We now use the plural form "**budget drivers**" and the singular "**system**" to more accurately introduce the discussion on the primary mechanisms governing the nitrate balance in our study area. **Line (690)**

L628: It should be: “… surface currents, …”

Response:

Agreed. We have added the plural "s" and the missing comma to "**surface currents,**" at line 628 to ensure grammatical correctness and better sentence flow. **Line (697)**

L697: The year is missing in the reference Brandt et al.

Response:

Agreed. The year **2023** has been added to the citation of Brandt et al. to correctly identify the reference. **Line (771)**

L744: It should be: “toward” instead of “to ward”.

Response: We have corrected the typographical error at line 744, changing "to ward" to the single word "**toward**". **Line (818 and 824)**

L758-766: I am confused by the values and units used to describe primary production, which sometimes do not appear to be consistent with Figure 18, unless a colorbar is missing. For example, a maximum NPP value of 0.60 mol C m-2 d-1 is mentioned. What does NPP refer to here? Is this variable shown in Figure 18? If so, a corresponding colorbar with the appropriate unit (mol C m-2 d-1) should be included, but it is currently missing. Moreover, the value of 0.60 does not appear to be visible in Figure 18. I suggest that the authors carefully revise this section, remove all misleading acronyms (including those in Figure 18), and thoroughly check the consistency of the units.

Response:

We sincerely apologize for the confusion caused by the inconsistent use of units and terminology in the biological production section. We have thoroughly revised Section 3.4 and Figure 18 to ensure full consistency.

1. **Terminology Standardization:** Following your previous suggestion, we have removed misleading acronyms. We now consistently use the full terms: **Net Primary Production (NPP)**, **New Primary Production**, and **Regenerated Primary Production**.
2. **Units Harmonization:** The confusion regarding the value of **0.60** stemmed from a mix-up between carbon units (used in the text for comparison with literature) and nitrogen units (produced by the model and shown in the original figures). In the revised manuscript, we have standardized all primary production values to **mol C m^{-2} d^{-1}** to allow for direct comparison with other upwelling systems.
3. **Figure 18 Update:** We have updated Figure 18 with clear colorbars and explicitly labeled units (**mol C m^{-2} d^{-1}**). The peak value of 0.60 is now clearly visible and matches the description in the text.
4. **Consistency Check:** We have verified all calculations using the Redfield ratio (C:N=6.625) to ensure that the values cited in the text perfectly correspond to the visual data in the figures.

Lines (846-882)

Figure A1: The figure is unclear, the y-axes are missing, and the description provided in the caption does not match the different panels shown.

Response:

We have thoroughly revised **Figure A1** to ensure it meets the standard of the rest of the manuscript:

1. **Added Y-axes:** We have added clear **Depth (m)** labels and numeric scales (0 to 100 m) to the y-axes of all panels.
2. **Corrected Caption Mapping:** We have rewritten the caption to ensure that the panel letters (a–f) perfectly match the physical and biological processes shown in the figure. In the previous version, the description of the horizontal/vertical sums and individual advections was incorrectly assigned.

3. **Clarity Improvement:** We have increased the resolution and optimized the contrast of the figure to make the subsurface signals more distinguishable.

Lines (928-936)

References: Several references listed in the reference section are not cited in the text and should either be cited appropriately or removed. For instance:

- L871-872
- L890-891
- L896-898
- L902-904
- L915-916
- L948-949
- L950
- L968-969
- L989-919

Response:

We have thoroughly reviewed the bibliography and the text. For each reference identified, we have either integrated it into the relevant section of the manuscript to strengthen our arguments or removed it if it was redundant. Specifically:

- Removed references (**Gent and McWilliams, 1990; Monod, 1942;Carr, 2002; De Boyer Montégut et al., 2007)**
- **Added references (Aumont and Bopp, 2006**) have been added to the Methods section. **Line (210)**
- References regarding regional productivity and climatologies (**Ridgway et al., 2002**) have been added to the Method and Results. **Line (238)**
- References regarding stratification and the mixed layer (**Dossa et al., 2019**) have been integrated into the Discussion. **Line (774)**
- **Add Messié and Chavez, 2015:** Introduction . **Line (103-104)**

Citations in the text that are not written in the reference section:

4-

L124: Bachèlery et al. (2015)

L252: Körner (2023) L252

L155: Scannell and McPhaden (2018)

L189: Aumont et al. (1998)

L198: Kobayashi et al. (2015)

L206: Thiam et al. (2024)

L221: Dunn and Ridgway (2002)

L245: de Boyer-Montégut et al. (2004)

L365: Awo et al. (2023)

L400: Bourlès et al. (2004)

L655: Hardman-Mountford and McGlade (2002)

L695: Jouanno (2010)

L714: Johns et al. (2014)

L785: Zang et al. (2023)

Response:

We sincerely apologize for these omissions. We have performed a complete cross-check between the citations in the text and the reference section. All 14 missing references identified by the reviewer have now been added to the reference list. Furthermore, we have verified the entire bibliography to ensure that every study cited in the manuscript is correctly documented.

- **Aumont et al. (1998) : Line 988**
- **Awo et al. (2023) : Line 994**
- **Bachèlery et al. (2015) : Line 1004**
- **Bourlès et al. (2004) : Line 1007**
- **de Boyer Montégut et al. (2004) : Line 1026**
- **Dunn and Ridgway (2002) : Line 1038**
- **Hardman-Mountford and McGlade (2002) : Line 1051**
- **Johns et al. (2014) : Line 1063**
- **Jouanno (2010) : Line 1069**
- **Kobayashi et al. (2015) : Line 1071**
- **Körner et al. (2023) : Line 1078**
- **Scannell and McPhaden (2018) : Line 1123**
- **Thiam et al. (2024) : Line 1143**
- **Zeng et al. (2021) : Line 1160**