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

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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.

Regarding the Editor's comments:

many thanks for your thorough replies to the referees' comments and the revised version of your manuscript. Both referees have assessed the new version of the manuscript and agree that most concerns raised during the review process have been adequately addressed (see reports below). Yet, both referees suggest minor changes which should be considered before publication. I kindly invite you to address those.

Furthermore, I kindly invite you to revise the following points, which I identified after going through the manuscript:

- In the introduction there are a couple of sentences which are written in past tense, giving the impression that these are results, rather than references to previous work. Examples of this are l. 127–130 and l. 139.

- I noticed a few typos, missing spaces, etc. Here a list of examples (i.e. it should not be interpreted as an exhaustive list):
l.153 " (…) mixed layer.whereas (…)"
l.153 " (…) it play (…)"
l.369 " (…) August.black (…)"
l.455 " (…) Spetember (…)"
l.544 " (…) domain.. . (…)"
l.597 and ff.: The heading "Nitrate budget analysis" precedes each of the subordinate sections. As I see it, this is only necessary upon first usage, as the numbering makes it clear that these subsections refer to the overall topic on section 3.3.2.
l.727 " (…) area.. (…)"
l.877–878 Note that the upwelling area off Namibia is considered an integral part of the Benguela Upwelling System. Therefore, the distinction here is unnecessary.
l.889 " (…) e merges (…)"
l.919 " (…) input((…)"
l.923–926 I would recommend checking, as this sentence seems incomplete.
l.962 and ff.: Some of the links (e.g. in l.962–963 and l.976) are not valid anymore and should therefore be updated.
Figures: some of the labels and titles overlie the plots (e.g. in Figs. 7 and 8). I would recommend checking throughout.

Response

A. verbs (Introduction) , we have replaced :

- **L. 127-130 :** "It was characterized..." by **"It is characterized..."** and "there was a second warming" by **"there is a second warming"**.
- **L. 139 :** "was modulated" by **"is modulated"**.

B. Typos et orthographe :

- **L. 153 :** "mixed layer.whereas" by **"mixed layer, whereas"**.
- **L. 153 :** "it play" by **"it plays"**.
- **L. 369 :** "August.black" by **"August. Black"**.
- **L. 455 :** "Spetember" by **"September"**.
- **L. 544 :** "domain.. ." by **"domain."**.
- **L. 727 :** "area.." by **"area."**.
- **L. 889 :** "e merges" by **"emerges"**.
- **L. 919 :** "input(" by "input (".
- **L. 923-926 (incomplete sentences) :** by : *"In future works, the interannual variability will be studied, specifically in association with the interannual variability of the Congo river discharges..."*
- The distinction between Namibia and Benguela has been removed (l.877).
- **Section 3.3.2 :** we have suppressed the repetition of title "Nitrate budget analysis" in sub-section. we just keep it in the main title 3.3.2.

- Data links have been updated and verified : we have replaced **"CARS 2009** : http://apdrc.soest.hawaii.edu/datadoc/cars2009.php**" by "**https://portal.aodn.org.au/search?uuid=d9302a48-57b1-41c2-a0dc-78bd00dd5e4b**"**
- **L. 877-878 : we rewretted sentence such as :** ***"...differs from those of the Benguela Upwelling System (including the Namibian area)...***

Regarding Referee #1:

It seems that the authors responded to all my questions and comments sincerely and I am happy with their revisions, especially, they re-computed the ocean mixing layer, which is my biggest concern. One thing I am still a bit worried. Their Fig.R3 shows the ocean current of the model and observation. For me it looks like that the modelled Angola Current is totally missed. Isn't this critical for their scientific results and conclusions argued in this work? Perhaps, more justification is necessary here.

Response

Dear Reviewer,

Thank you for your constructive comments. We understand your concern regarding the representation of the Angola Current (AC) in the model. However, we would like to demonstrate that the apparent "miss" in the initial comparison (Fig. R3) is due to the inherent limitations of the satellite reference product rather than a failure of the NEMO model.

Below, we provide a multi-dataset validation to prove that NEMO accurately captures the regional dynamics.

1. Limitations of the OSCAR product near the coast

The initial comparison was made against **OSCAR satellite data**. It is well documented in the literature that OSCAR (and satellite altimetry-based products in general) suffers from significant **land contamination** within the first 50-100 km of the coast. Furthermore, OSCAR is a derived product that often misses ageostrophic components and high-frequency coastal dynamics. In our study area, the surface circulation is dominated by the narrow, coastal-trapped Angola Current and the high-momentum Congo River plume. OSCAR's coarse resolution is simply not suited to capture these small-scale, near-shore features, which explains the discrepancy seen in Fig. R3.

2. The general challenge of modeling the Angola Current (Fig. R1, Kopte et al., 2017)

To put our results into perspective, we refer to **Fig. R1** (from Kopte et al., 2017). This figure compares *in situ* observations (black lines) with several world-class reanalysis products (GODAS, ORAS4, SODA, NCEP).

- **Panel (a) and (c)** clearly show that even these state-of-the-art products struggle to perfectly replicate the vertical profile and the seasonal transport of the AC measured by buoys.
- There is a significant spread among the models, with many underestimating the core velocity or misplacing its depth.
  This demonstrates that the Angola Current region is a **highly complex dynamical system** where even the most recognized global models show deviations from observations. Expecting

a perfect match with a satellite product like OSCAR is therefore not a realistic benchmark for model validation in this area.

3. Validation with Scientific standard: NEMO vs. GLORYS (Fig. R2 and R3)

To further validate our configuration, we compared NEMO with **GLORYS12 (Mercator Ocean)**, which is widely considered one of the most reliable and highest-resolution global ocean reanalyses used by the scientific community.

- **Spatial Patterns (Fig. R2/R3 maps):** The comparison of zonal (U) and meridional (V) components during the main upwelling season (JJA) shows a very high degree of consistency between NEMO and GLORYS. Both models resolve the same core structures and flow directions.
- **Hovmöller Comparison (Fig. R2/R3 sections):** The latitude-time evolution of the currents is nearly identical in both products.
  Since GLORYS is an accepted standard for tropical Atlantic circulation, the fact that our NEMO configuration reproduces the same features confirms that our model's physics are sound and consistent with the best available reanalysis data.

4. NEMO vs. PIRATA Mooring and eOdyn (Fig. R4, Cardot et al., 2026)

Finally, to provide a more robust *in situ* validation, we have compared the NEMO outputs (which is the same simulation that have been used in this our study) with observations from the PIRATA mooring at 6°S–8°E and the eOdyn ship-drift product (Fig. R4). Unlike satellite-derived products, these datasets offer direct measurements of ocean currents at a fixed location, thereby allowing for a more rigorous assessment of the model performance.

- **Time Series Analysis (Fig. R4 c, d):** The green line (NEMO) follows the blue line (*in situ* buoy) and the red line (eOdyn) with remarkable precision for both the zonal (U) and meridional (V) components.
- The model correctly captures the **seasonal phase**, the **high-frequency variability**, and the **magnitude of the peaks** (reaching -0.4 m/s in U and +/- 0.3 m/s in V).
- This point-to-point validation at 6°S (the core of our study area) proves that **NEMO does not miss the currents**. On the contrary, it represents the real-world observations better than the large-scale satellite products.

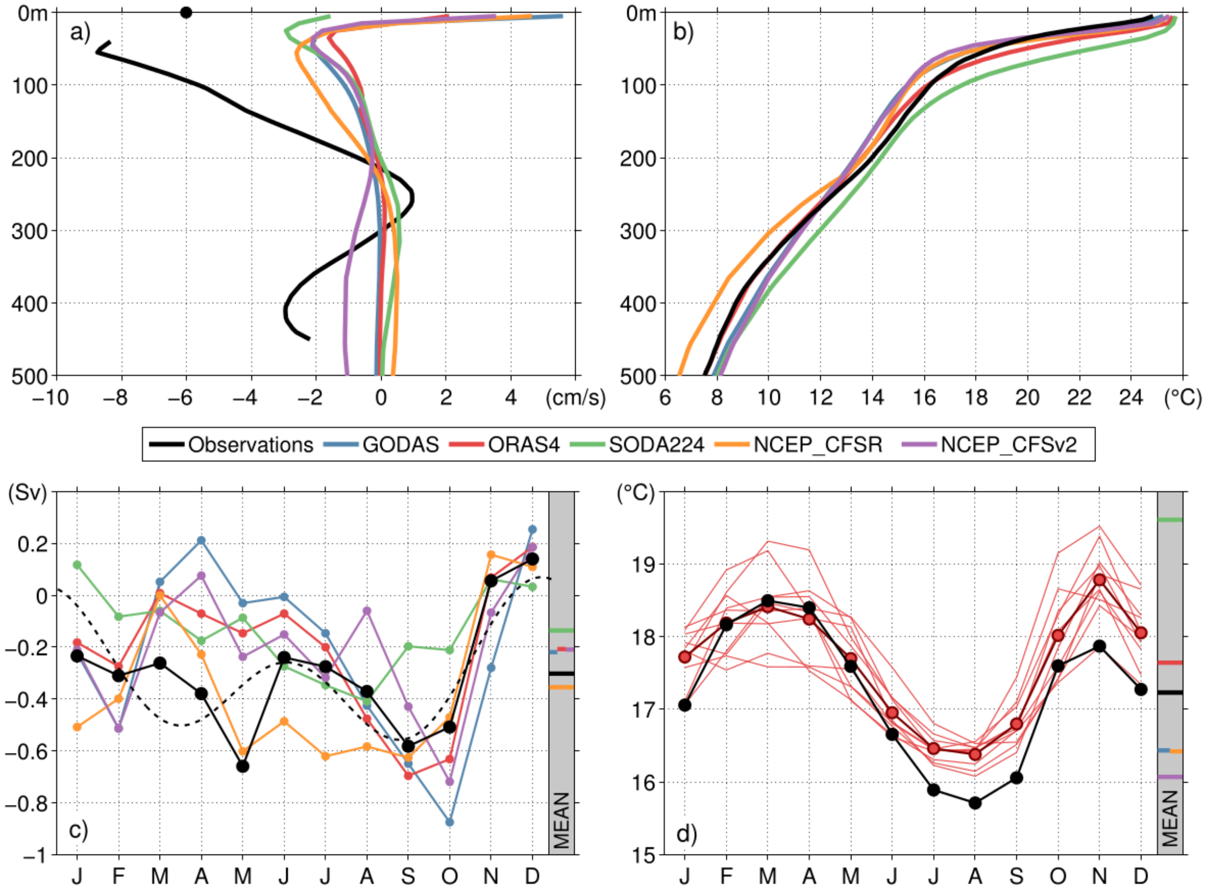

Fig.R1: Profiles of (a) mean alongshore velocity and (b) potential temperature profiles from observations (black) and various reanalysis products (colors). Seasonal cycle of Angola Current transport from observations (black solid) and reanalysis products (colors) is shown in (c). Black-dashed line shows the sum of semiannual and annual harmonics from Figure 3.5b). Total mean AC transport values are indicated to the right. In (d) the mean seasonal cycle of potential temperature averaged over 50–100 m depth is shown for observations (black) and ORAS4 reanalysis (red). Thin red lines correspond to seasonal cycles derived from individual 2 year segments, while the bold red line shows the mean seasonal cycle derived from the total time series (1995–2014). Corresponding layer-averaged total mean values for both observations and reanalysis products are indicated to the right. **(Kopte et al., 2017)**

The data sets presented in this study provide the opportunity for a first assessment of the performance of ocean reanalysis products upstream of the frontal region. Using the monthly output of five publically available reanalysis products (GODAS: 1995–2015, ORAS4: 1995–2014, SODA 2.2.4: 1995–2010, NCEP-CFSR: 1995–2010, NCEP-CFSv2: 2011–2015), we compare observed and simulated alongshore flow, AC transport, and temperature at the mooring array position at ~11 ◦ S (Fig.R1). The reanalysis products agree in showing a weak mean southward current of 1–3 cm s^{-1} at the AC core depth in about 50 m depth.

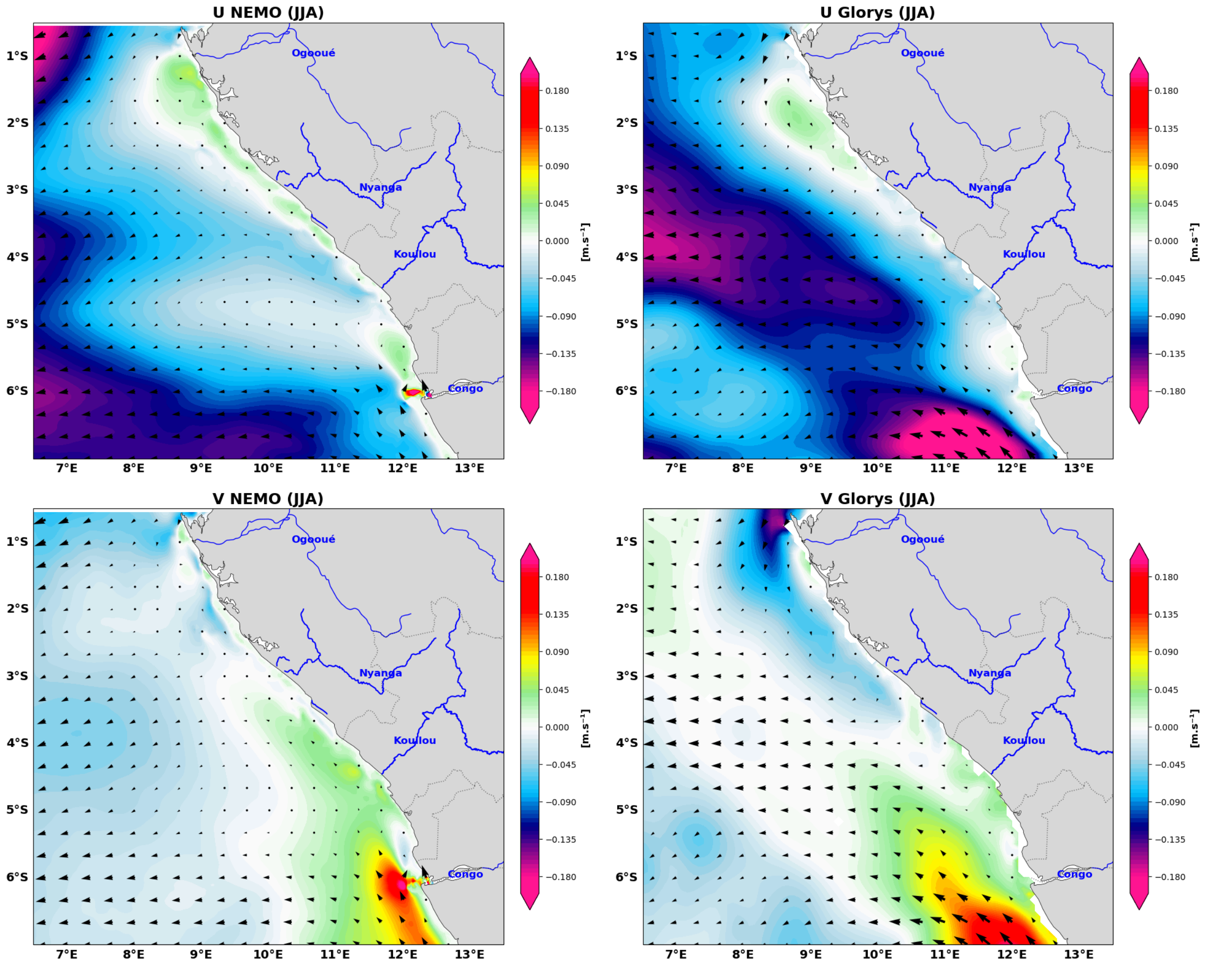

Fig.R2: Spatial distribution of the mean surface current components ($m.s^{-1}$) during the austral winter (June-July-August, JJA) averaged over the 2007–2016 period. Left panels (a, c) show NEMO model outputs and right panels (b, d) show the GLORYS12 reanalysis. Top row (a, b) displays the zonal velocity component (u) and the bottom row (c, d) shows the meridional velocity component (v). Black arrows represent the total current vectors. Both products resolve the narrow coastal-trapped Angola Current and the high-momentum Congo River plume with a high degree of spatial consistency.

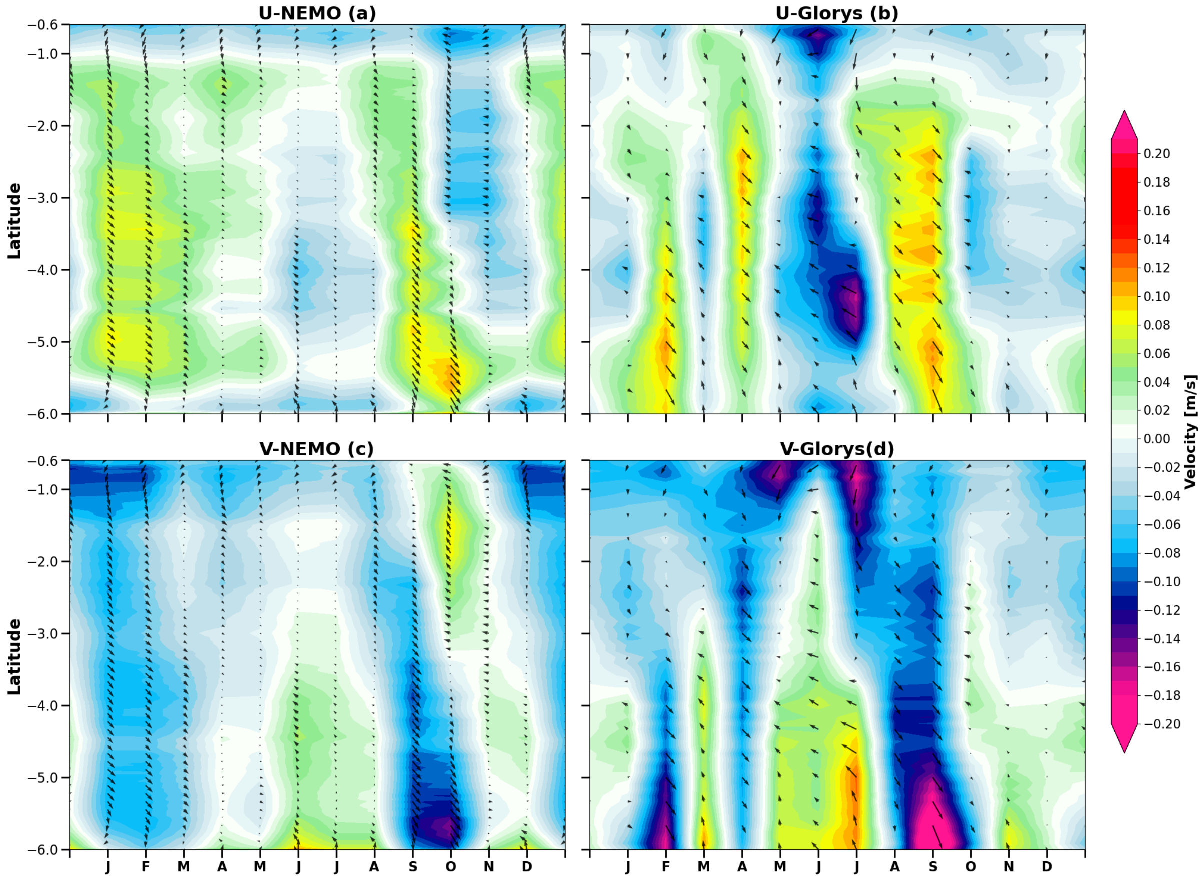

Fig.R3: Latitude-time Hovmöller diagrams of the 10-year mean (2007–2016) seasonal cycle of current components (m.s^{-1}) at 10 m depth. Data are averaged within the 1° wide coastal band along the Gabon-Congo margin (0.6°S–6°S). Panels (a, c) show NEMO model outputs and panels (b, d) show the GLORYS12 reanalysis. Top row (a, b) shows the zonal velocity (u) and the bottom row (c, d) shows the meridional velocity (v). The comparison demonstrates the model's ability to accurately capture the seasonal phasing of regional current branches, including the intensification of the South Equatorial Undercurrent (SEUC) and the Angola Current.

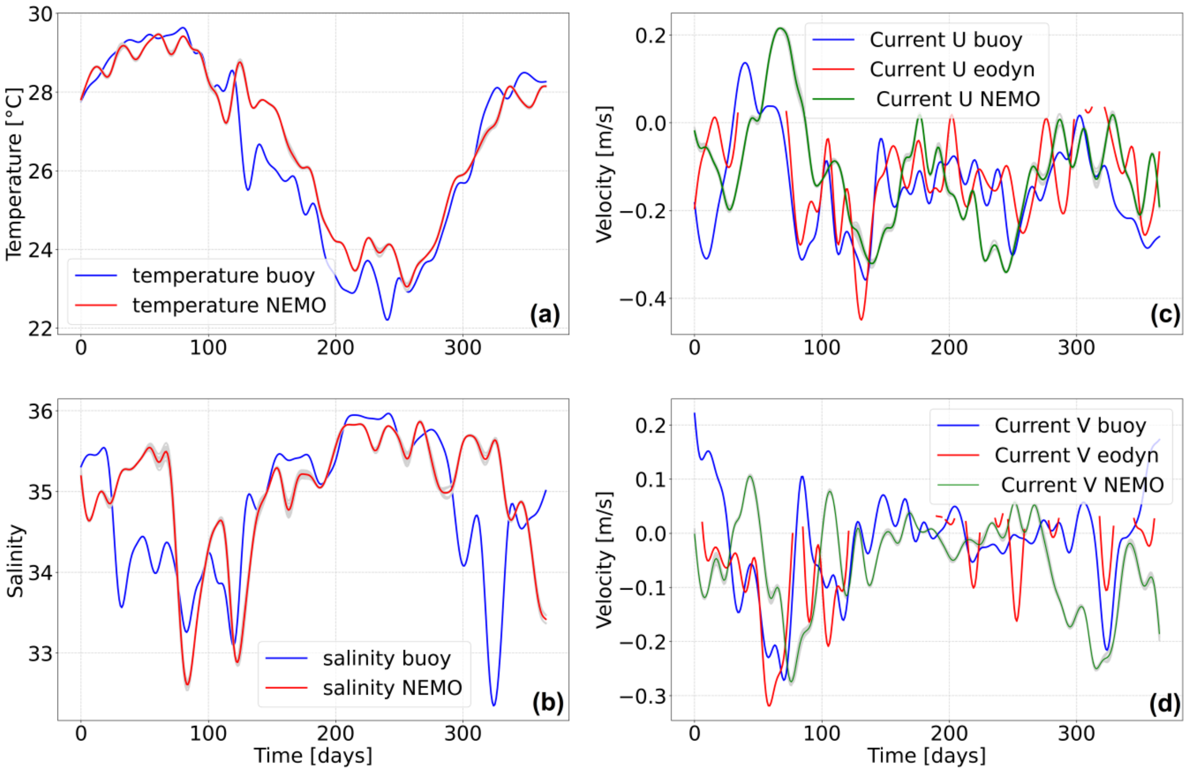

Fig.R4: Time series at 10 m depth of (a) temperature (°C), (b) salinity, and the (c) zonal u and (d) meridional v velocity components (m/s) at the PIRATA mooring (6°S-8°E). For temperature (a) and salinity (b), the red line represents model output and the blue line represents *in situ* mooring data. For the velocity components (c and d), the red line represents eOdyn current data, the blue line represents *in situ* mooring data, and the green line represents model output. **Cardot et al. (2026)**

Response regarding the representation of ocean subsurface currents:

To definitively address the concern regarding the representation of regional circulation, we have included a decadal vertical validation (2007–2016) comparing **NEMO** with the **GLORYS12** As shown in the climatological depth-time Hovmöller diagrams (Fig.R5), the agreement between the model and the reanalysis is striking:

1. **Seasonal Phasing:** NEMO perfectly captures the timing of current reversals for both the zonal (*u*) and meridional (*v*) components. For instance, the northward surface flow intensification in May–June and the southward return flow in September (Panels c and d) are identical in both timing and magnitude.
2. **Vertical Structure:** The model accurately reproduces the depth of the current cores (primarily within the top 40 meters) and the vertical shear observed in the assimilated GLORYS product.
3. **Statistical Robustness:** By showing a 10-year mean consistency, we demonstrate that the model's physics are stable and reliable over the long term, rather than being biased by a single anomalous year.

Combined with our point-to-point validation against **PIRATA** in-situ data and **eOdyn** ship-drift observations, this cross-platform comparison (Satellite-Assimilated Reanalysis vs. High-Resolution Model) provides the necessary evidence that NEMO's physical foundation is robust and fully suitable for the biogeochemical analysis presented in this study.

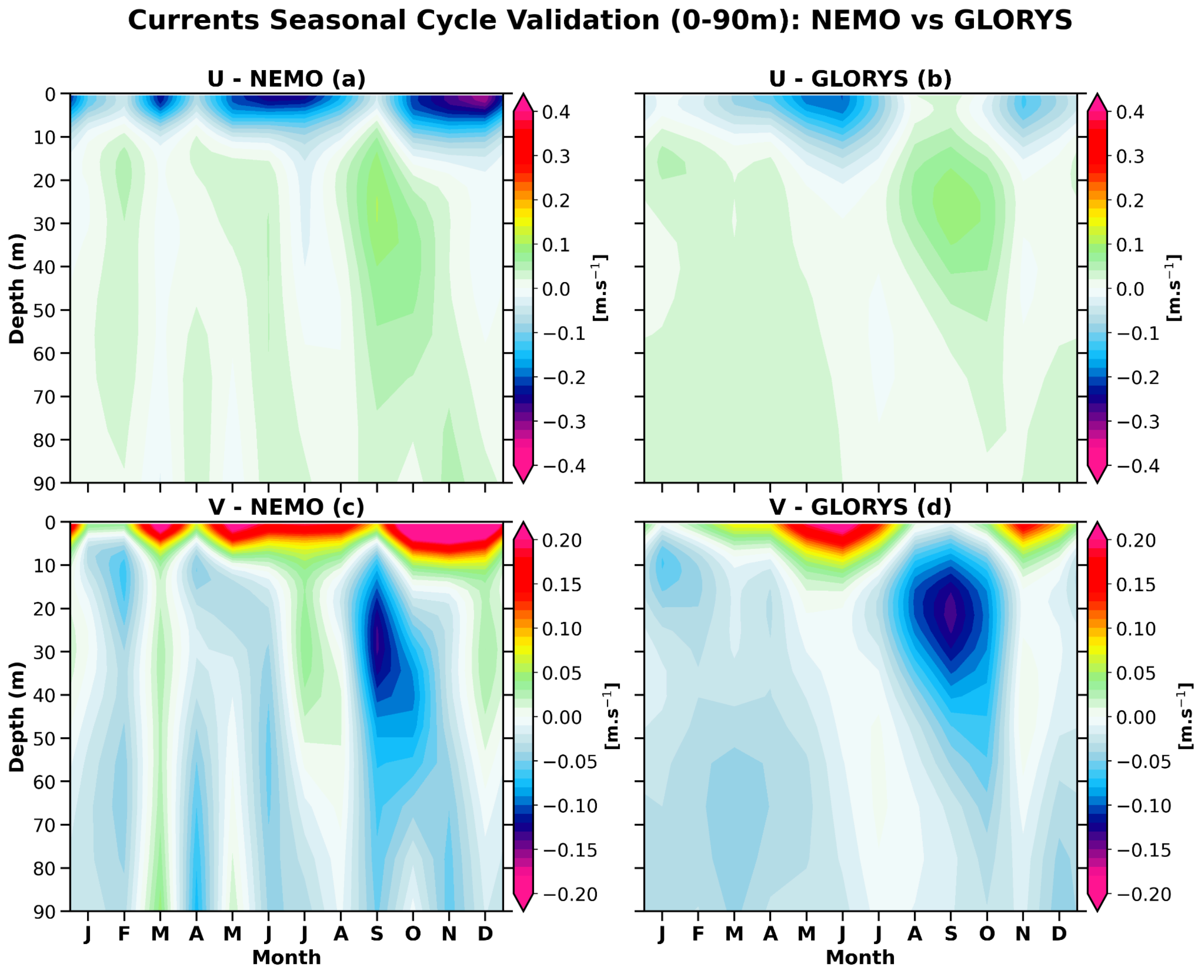

Fig.R5: Seasonal cycle validation of current velocity components (m.s^{-1}) along the Gabon-Congo margin (0–90 m). Climatological depth-time Hovmöller diagrams (averaged over the 2007–2016 period) within the coastal study area (5°E–14°E, 7°S–0°N). Panels (a) and (b) show the zonal velocity (u) for the NEMO model and GLORYS12 reanalysis, respectively. Panels (c) and (d) show the meridional velocity (v) for NEMO and GLORYS12, respectively. Positive values indicate eastward/northward flow (red), while negative values indicate westward/southward flow (blue). The comparison demonstrates a high degree of consistency in both the seasonal phasing and the vertical structure of the regional current system.

Regarding Referee #2:

Review report: Second round of review for 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.” I thank the authors for their detailed replies to my comments and questions. I am happy with the actual version of the manuscript and I recommend its publication after these minor comments are addressed by the authors. In the revised manuscript, the equations between lines 406 and 449 are not readable. I suggest that the authors carefully review and correct them.

Response to Referee #2:

We thank the reviewer for this remark. We would like to clarify that the readability issue mentioned (lines 406–449) was specifically due to the PDF conversion of the 'Track Changes' (markup) version of the manuscript, which often introduces formatting artifacts in mathematical equations.

We have verified that in the clean version of the revised manuscript, all equations are perfectly rendered, correctly indexed, and fully legible. We have performed a final check on the generated PDF to ensure that all symbols and fractions appear correctly for the final publication." **See Line (258 - 294) in the revised manuscript**

Reference adjustment to template recommendations.

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