Author's response

We thank both reviewers for the valuable feedback and have made significant revisions to the manuscript to improve its completeness and clarity.

- We rearranged the Introduction and figure labeling to enhance overall readability and clarity.
- We expanded the Results section to better describe the sources of NPP uncertainty at the EBUS scale and highlight the role of spatial heterogeneity.
- We have developed a more robust model evaluation and incorporated it into the Results section. We analysed the performance of individual CMIP6 models and observational products in capturing mean EBUS NPP values. We have also introduced new metrics, including the evaluation of models' ability to simulate historical NPP trends and key drivers such as nitrates and wind stress.
- We have conducted a more thorough investigation into inter-model differences by explicitly evaluating individual model behavior in both historical simulations and future projections, including a specific assessment of the CanESM5 model.
- We conducted a preliminary analysis to reduce projected EBUS NPP uncertainty and test potential relationships between historical and projected trends.
- We have addressed several specific points raised by the reviewers, paying particular attention to improving the description of sources of NPP uncertainty at the EBUS scale.
- We have expanded and reorganized the Discussion section to provide a more comprehensive examination of the role of key drivers such as geostrophic transport.

Below are the authors' point-by-point responses to the comments, with reviewer's comments in bold and author's responses in normal font.

Responses to Referee #1 :

Major Comments

1. Rearrangement of the Introduction section. In L53, the authors state "Alongside projected changes in vertical velocity," which may not be fully appropriate, as both changes in vertical velocity and in nutrient supply to the surface are discussed previously. Moreover, the subsequent paragraph focuses on the timing of the upwelling season, which could also be classified as changes in vertical velocity. I therefore suggest reorganizing the Introduction between L32-58. Specifically, the authors could first introduce the projected changes in different mechanisms that modulate the upwelling intensity and duration, and then present additional sources influencing nutrient supply to the surface beyond the physical drivers. L59 will follow just after this, summarizing how variations in upwelling itself and changes in biogeochemical properties of source waters together modulate nutrient supply in EBUSs. such a reorganization could improve the logical flow of the intro.

We agree, we have modified the manuscript according to these indications.

2. As the manuscript highlights regional differences in Fig. 3, additional evaluation would be valuable. For example, as shown in Fig. A2, most models project a weak positive

change in the CalCS, while fewer models project a strong negative change, particularly CanESM5. It would be useful to clarify whether CanESM5 exhibits mean NPP anomalies comparable to those of other models, or whether there are substantial spatial differences. Moreover, could these differences be related to model biases? For instance, does CanESM5 already exhibit biases in simulating NPP in the CalCS during the historical period? In addition, the model agreement showed in Fig. 3 raises further questions. In the CalCS, model agreement is weak and the projections remain highly variable, which is acceptable; and in the CanCS, model agreement is also modest, yet the projections show relatively high consensus.
The high uncertainty in the BCS can be explained by Fig. A3, where the poleward and equatorward regions show relatively consistent changes but in opposite directions. I believe adding this information to this section would be better. Therefore, the diversity of NPP projections warrants further evaluation to identify and discuss the potential sources of uncertainty that lead to this strong sensitivity to model choice, such as model biases, inter-model differences, or spatial heterogeneity.

We agree that a deeper investigation of inter-model differences, spatial patterns, and potential model biases is valuable. While a model-by-model evaluation of biases would be beyond the scope of the manuscript, the goal of which is to assess consensus in NPP projections and drivers across CMIP6 models, we have taken several steps to strengthen the analysis in this respect:

- We have expanded the Model Evaluation section and moved it to the Results section . We have assessed the ability of CMIP6 models to reproduce both the historical mean state and trends in NPP, using five observationally based products from Ryan-Keogh et al. (2023). This provides a more systematic evaluation of model performance;
- To better illustrate the diversity of projections, we included an additional figure in the Supplementary Information showing time series for each individual model, rather than only intermodel spread (Figure A of this document). This makes the number of models projecting increases versus decreases more explicit. In addition, we have moved the table currently shown in Fig. A2 into the main text to better highlight individual model behavior and inter-model differences;
- In response to your specific question on CanESM5, we have analyzed NPP anomalies in the CalCS for CanESM5 and compared them with the CMIP6 ensemble mean. We find that the spatial pattern of anomalies is broadly consistent with the ensemble mean, although the magnitude of both positive and negative anomalies is larger in CanESM5 (Fig. B of this document).
- Regarding the model agreement in the CanCS, we argue the signal is more robust than it first appears. While strict thresholds suggest lower consensus, the projected changes in CalCS-P align with the consistent, large-scale decreasing patterns observed across CMIP6. Furthermore, sensitivity tests indicate that lowering the agreement threshold to 70% yields strong consensus, and at 60%, nearly the entire CanCS region exhibits significant robustness (indicated by stippling on Fig. C of this document).
- We agree that the contrasting responses between poleward and equatorward regions, as shown in Fig. A3, help explain the high uncertainty in the BenCS. We have improved the clarity of section 3.1 to better highlight the role of spatial heterogeneity in driving inter-model spread.

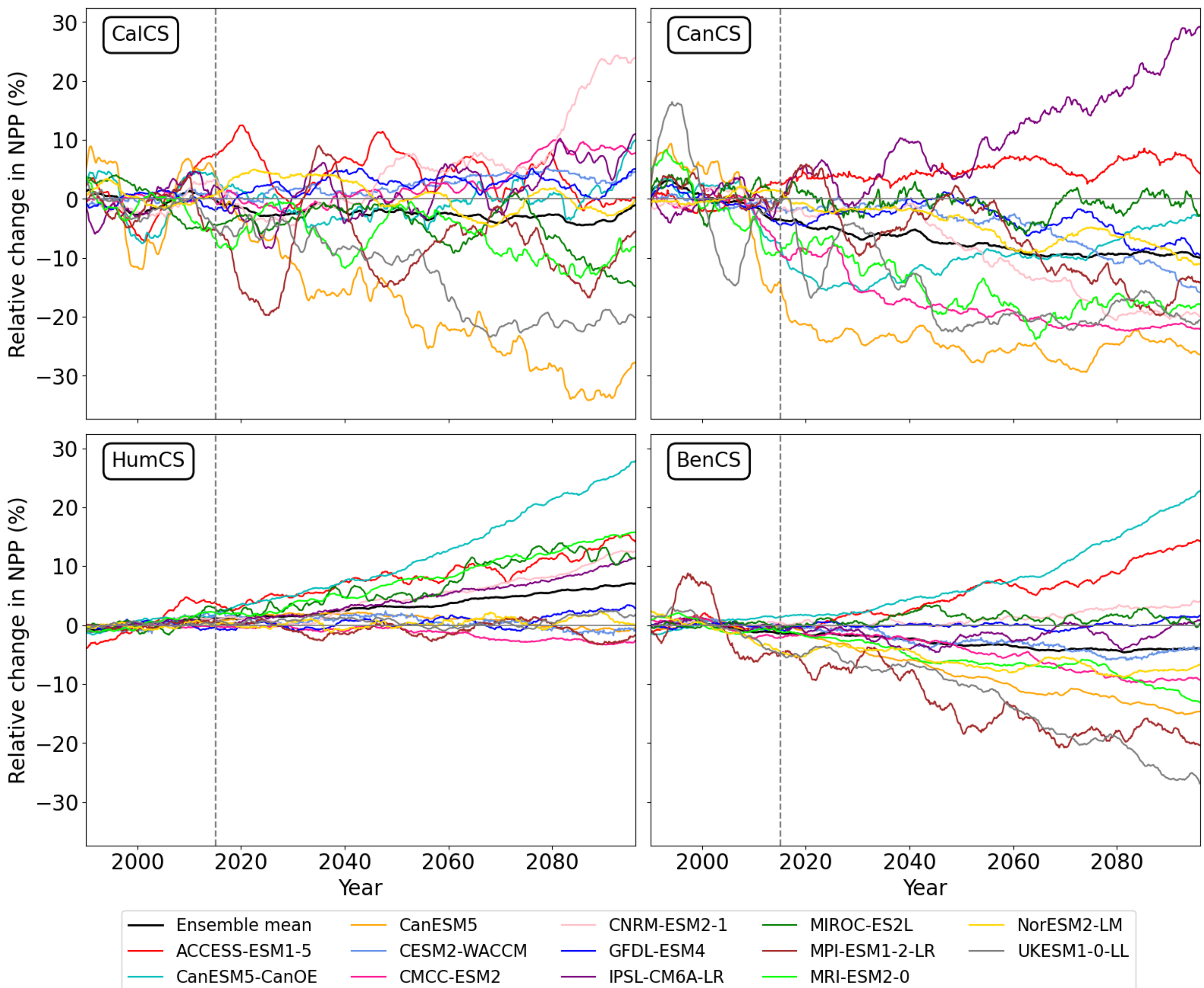


Fig. A) Historical and SSP5-8.5 projected time-series of relative change in NPP for CMIP6 models in the EBUSs.

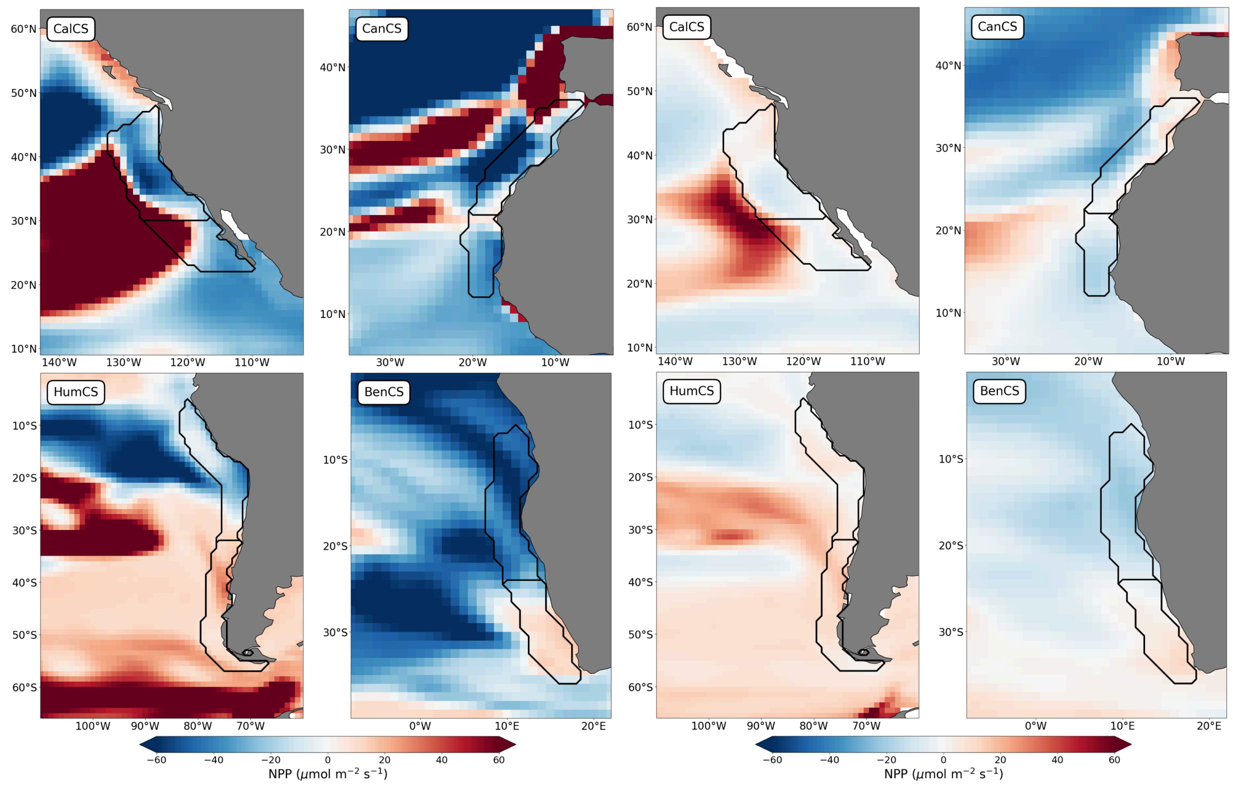
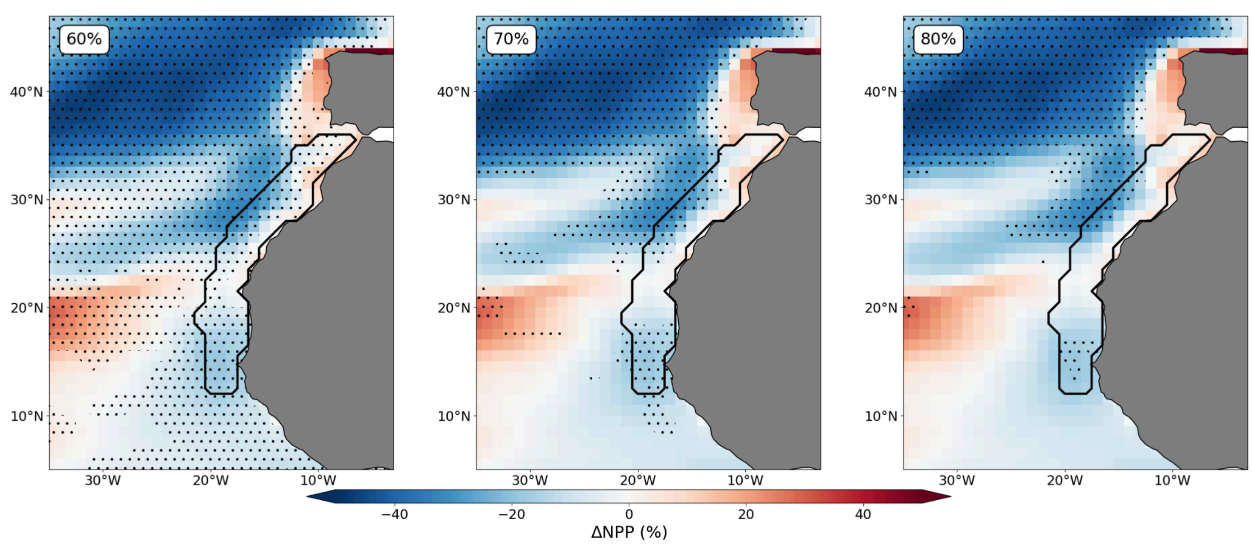


Fig. B) CanESM5 (left) vs. ensemble mean (right, 13 models) NPP anomalies (2071–2100 relative to 1985–2014) under SSP5-8.5 in the four eastern boundary upwelling systems.



Fic. C) Ensemble mean (13 models) NPP anomalies (2071–2100 relative to 1985–2014) under SSP5-8.5 in the CanCS. Areas of high model agreement are indicated by stippling, based on different thresholds of agreement on the sign of change: at least 60% (left), 70% (middle), and 80% (right).

3. Some rearrangement of the Discussion section is recommended. I found that Section 4.1 is somewhat repetitive, covering material similar to the Introduction. Some of the content could be interspersed into the preceding text. This section also does not present any additional analysis. I therefore suggest deleting Section 4.1 and incorporating any necessary statements into Sections 3 and 5. Section 4.2 is somewhat unclear and abrupt. It appears to discuss the mismatch between wo60 and tau, possibly attributing it to contributions from wind stress curl, but geostrophic transport is also mentioned without clear connection. I suggest integrating the discussion of wind stress curl, together with Figure A10, into Section 3.2 for a clearer and more coherent presentation. Additionally, the role of geostrophic transport requires further explanation.

We revised the Discussion section to improve both clarity and completeness following your suggestions. In particular:

- We removed Section 4.1 and incorporate its relevant content into Sections 3 and 5;
- We expanded Section 4.2 to improve its integration within the overall analysis. Specifically:
    - We provided a more detailed explanation of the processes already illustrated in Fig. A12 (Appendix), the previous description was perhaps too concise.
    - To strengthen the analysis, we included an additional “four-color” EBUS map (similar to Fig. 4 in the manuscript), showing the relationships between projected anomalies in Ekman and geostrophic transports (Fig. D of this document). This additional analysis shows that in the central HumCS and BenCS-P regions, Ekman and geostrophic transports tend to vary in opposite directions, likely contributing to the weak correspondence between wind changes and vertical velocity in these regions. This helps explain the projected changes in wo_{60} in the BenCS-P region, but it provides limited additional insight for the HumCS, where vertical velocity remains highly variable.

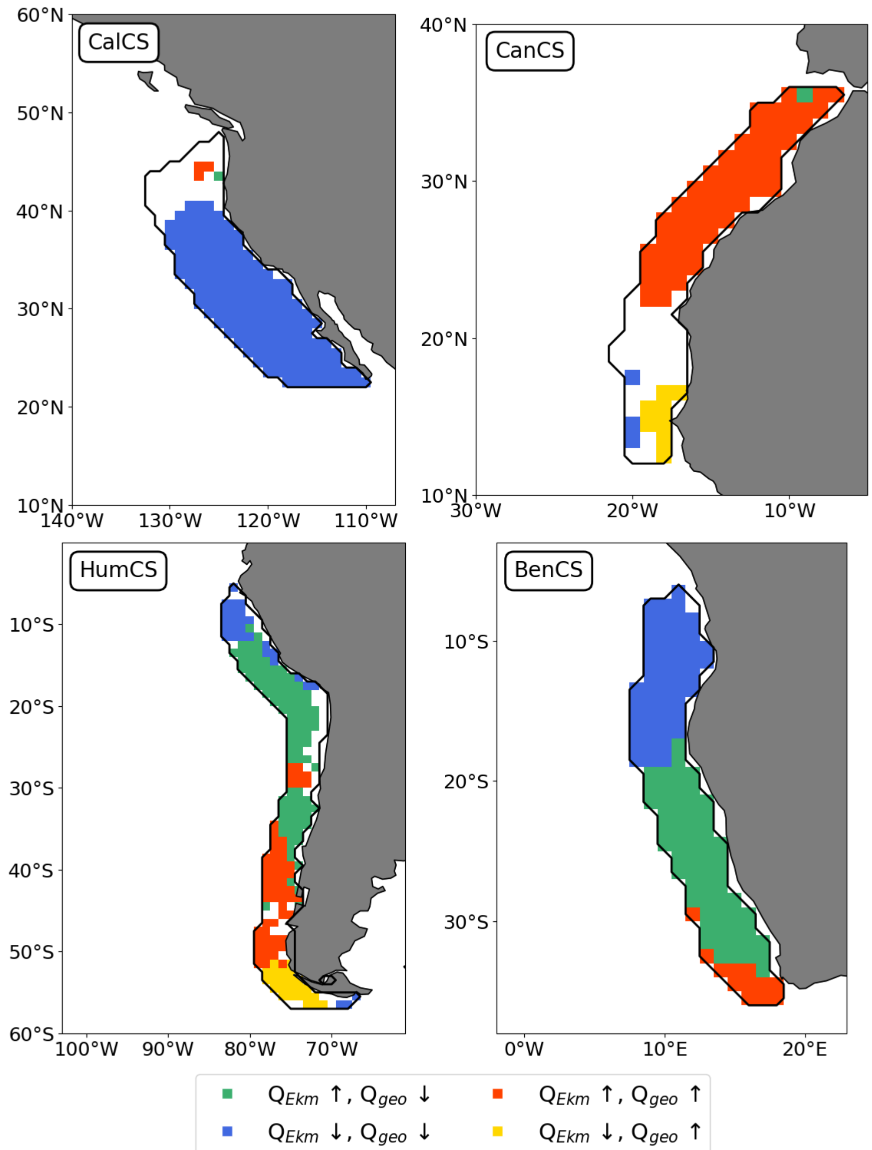


Fig. D) Ekman and Geostrophic transport changes are reinforcing each other in some regions (blue and red), offsetting in others (green and yellow). Signs of twenty-first century colocalized anomalies in Ekman and Geostrophic transport under SSP5-8.5 (2071-2100). Grid cells are colored if there is ≥ 50 % model agreement.

4. The manuscript includes many different regions and numerous subplots that are frequently cross-referenced in the text. However, in several places the relevant figures or panels are not explicitly specified, making it difficult for readers to follow. I recommend labeling multi-panel figures with clear identifiers (such as Fig. 5; e.g., a, b, c, d) and explicitly referring to these labels in the text to improve clarity and readability.

Yes, we modified the manuscript.

Detail Comments:

1. There are some errors in the line numbers on page 6 and 7. A large section of text between lines 115 and 120 is missing line numbers.

Yes, we modified the manuscript.

2. L25-29 should include appropriate references not only for the “other physical processes”, but also for the broader statements made in this part of the text.

Yes, we modified the manuscript.

3. In L67-74, the influence of decadal and multidecadal climate variability on NPP should be introduced in greater depth to reinforce the importance of the limited duration of the observational records.

Yes, we modified the manuscript.

4. L105: The authors use the variables “tauu/tauv” to represent the surface wind stress. These variables originate from the atmospheric model on its native grid, which differs from the ocean model grid. Could the authors please clarify whether these fields were first interpolated onto the ocean grid and then regridded to the common 1-degree resolution, or whether they were directly regridded from the atmospheric grid to the 1-degree grid? This distinction is important because wind stress is interpolated to the ocean grid to drive coastal upwelling, and CMIP also provides the “tauuo/tauvo” variables on the ocean grid.

In our analysis, we used the tauu/tauv as direct model outputs from the atmospheric grid, and we have directly regridded to the 1-degree resolution grid. To assess the robustness of this choice, we compared results obtained using tauu/tauv with those derived from the ocean-grid variables tauuo/tauvo, and we found generally very small differences. In particular, the spatial patterns, as well as the sign and magnitude of projected anomalies, are highly consistent between the two datasets. Thus, we opted to use tauu/tauv, as these variables were for us more readily available across the full ensemble considered.

5. What is the relative width (200 km?) of the LME mask?

Masks identifying these domains were obtained from the ISIMIP repository, and have variable extents in longitude (widths from 4 to 9°) and latitude (lengths from 25 to 50°).

6. L157 Stating the exact number of models projecting positive versus negative changes would provide useful quantitative information.

Yes, we modified the manuscript.

7. L207-208 Please specify which figure is being referred to, the second left column in Fig 5?

We are referring to the second column of Fig.5, we modified the manuscript to clarify better.

8. L272 “While nitrates are projected to increase around 200 m in this region (Appendix Fig. A15), these waters do not reach the typical source depth (60 m)” can this be attributed to enhanced stratification?

Yes this could be an explanation, we added this hypothesis in the manuscript.

Responses to Referee #2 :

First, the “model evaluation” section (2.4) is wholly insufficient. The only evaluation presented compares mean NPP from all CMIP6 models to mean NPP from five data products. This is problematic on several levels: (1) each CMIP6 model should be evaluated separately instead of evaluating their mean (this will be important for the comment in the next paragraph); (2) the data NPP products should be used separately and not averaged; (3) other metrics beyond mean bias should be considered. Regarding (2), NPP satellite algorithms are known to display contrasting patterns and trends, and averaging products of likely varying quality is difficult to justify. I suggest the authors read the comment by Toby Westberry on the paper by Ryan-Keogh et al. (2023, https://doi.org/10.5194/essd-15-4829-2023) at https://essd.copernicus.org/articles/15/4829/2023/essd-15-4829-2023-discussion.html. Also note that the authors of that paper themselves analyzed the NPP products separately in their subsequent paper (Ryan-Keogh et al. 2025, https://doi.org/10.1038/s43247-025-02051-4 - I have no affiliation with either paper) with a discussion of this in the section “Assessing the merits of the different remote sensing algorithms”. Regarding (3), I would suggest looking at other metrics beyond the mean, in particular the 1998-2014 trend – before assessing the model trends in the future, it would be useful to evaluate their trend in the reference period. Other metrics could be used (eg standard deviation) if the authors think they are pertinent to evaluating how likely models are to be “right” in the future.

We agree that a more robust model evaluation would be valuable in grounding our analysis. We have therefore expanded the Model Evaluation section and moved it to the Results section. We have developed the following main points:

- We kept Figure 1 as it is in the current manuscript, as we believe it effectively demonstrates the models' general ability to simulate the historical mean state of NPP and provides a straightforward entry point for readers.
- We have assessed the ability of individual models to simulate the historical mean state of NPP. We added in the Supplementary Information a new figure (Figure E of this Document) displaying a scatter plot of the mean NPP for each individual CMIP6 model alongside each of the five observational products (Ryan-Keogh et al., 2023) across the four EBUSs. This explicitly shows model-specific biases and spread within the observational data products.
- We investigated historical NPP trends (1998–2014) by comparing the CMIP6 models with the five observational products. We included a box-and-whisker plot in the main manuscript, comparing the historical normalised trends of the observational products versus the CMIP6 models at the sub-EBUS scale (Figure F of this document). This illustrates that the CMIP6 models are generally capable of capturing the trends, as in most regions, the simulated trends fall within the range of observational values. In some sub-systems, the interquartile range is even greater for the observational data.
- We extended the model evaluation to two key drivers of NPP:
    - Equatorward wind stress $\boldsymbol{\tau}$: we added an evaluation of both mean states and normalised trends using box-and-whisker plots (Figure G of this document), over the historical period (1998–2014). We compared the CMIP6 models with the ERA-Interim reanalysis (data available at https://esgf.nccs.nasa.gov/thredds/catalog/bypass/CREATE-IP/reanalysis/ECMWF/IFS-Cy31r2/ERA-Interim/mon/atmos/catalog.html) and found that they generally reproduced the mean state well, while the trends are more variable, potentially due to the important role of interannual variability over the considered period.

- Nitrates: we added an evaluation of climatological states of both surface and subsurface (200 m) NO_3 using box-and-whisker plots (Figure H of this document), comparing CMIP6 models with World Ocean Atlas 2018 climatological data (Garcia et al., 2019) for the period 1900–2017 (WOA) and 1900–2014 (CMIP6 models). Our results show that the models effectively capture the nutrient fields at the EBUS scale

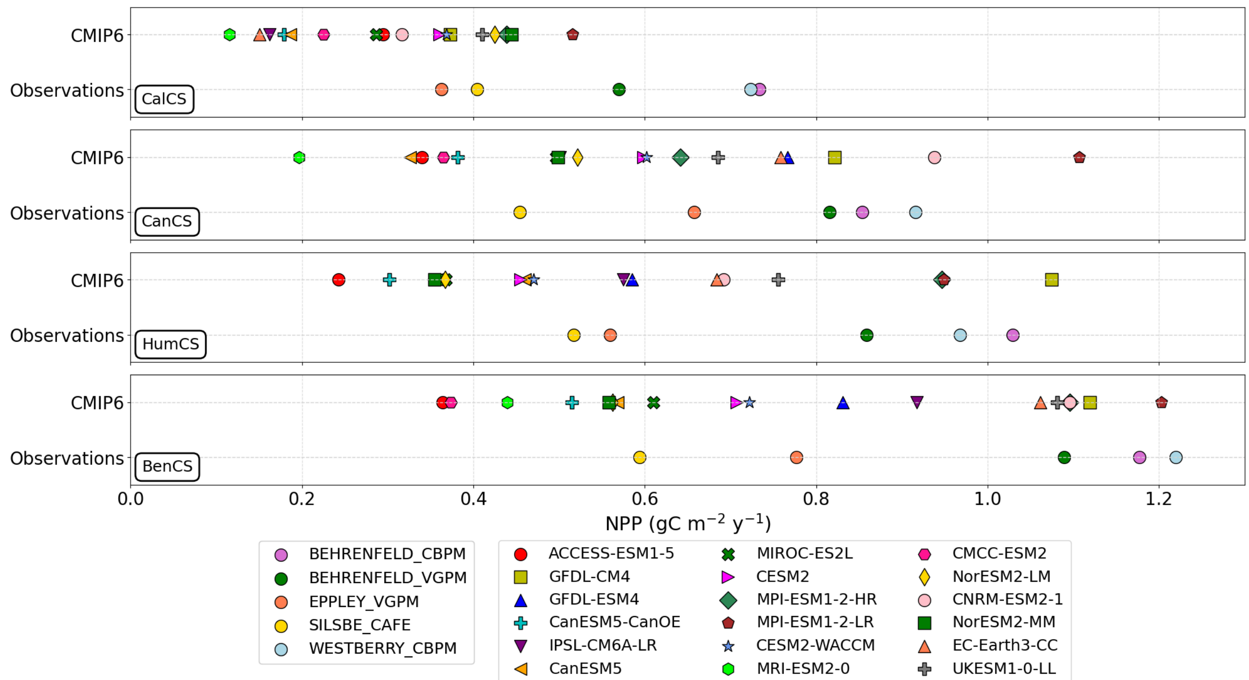


Fig. Fig. E) Evaluation of 18 CMIP6 models versus different data products of observations. Each colored marker represents the temporal (1998-2014) and spatial (EBUS-scale) average of NPP.

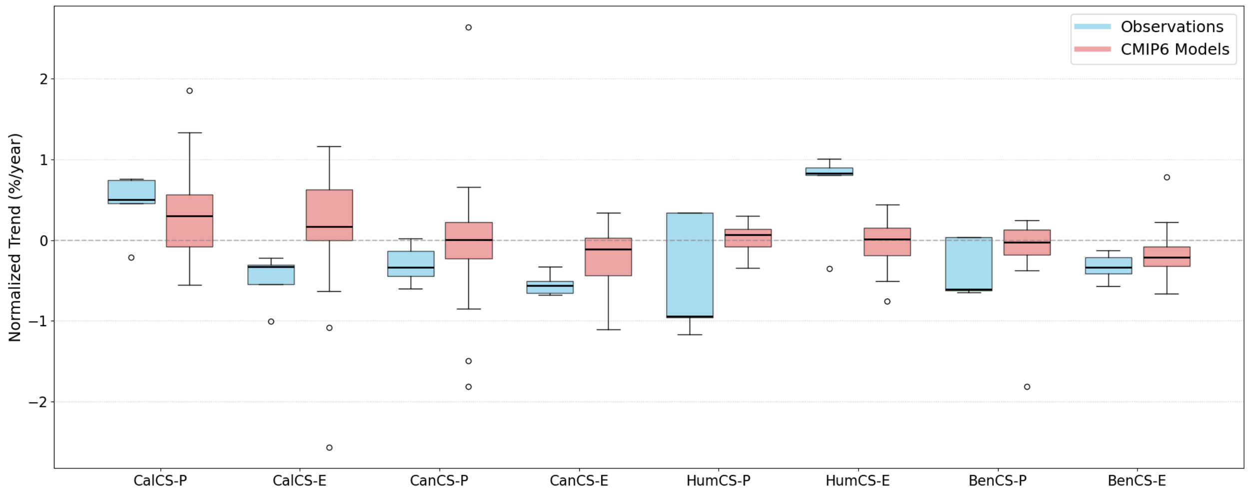


Fig. F) Box-and-whisker plots showing the distribution of observational data products and CMIP6 model estimates of historical (1998-2014) NPP trends across sub-EBUSs. For each region, boxes represent the interquartile range (IQR), whiskers extend to 1.5×IQR, and the median is shown as a thick black line, in blue for observations (five data products obtained combining ESA OC-CCIv4.1 ocean color observations with five different algorithms) and salmon for CMIP6 models.

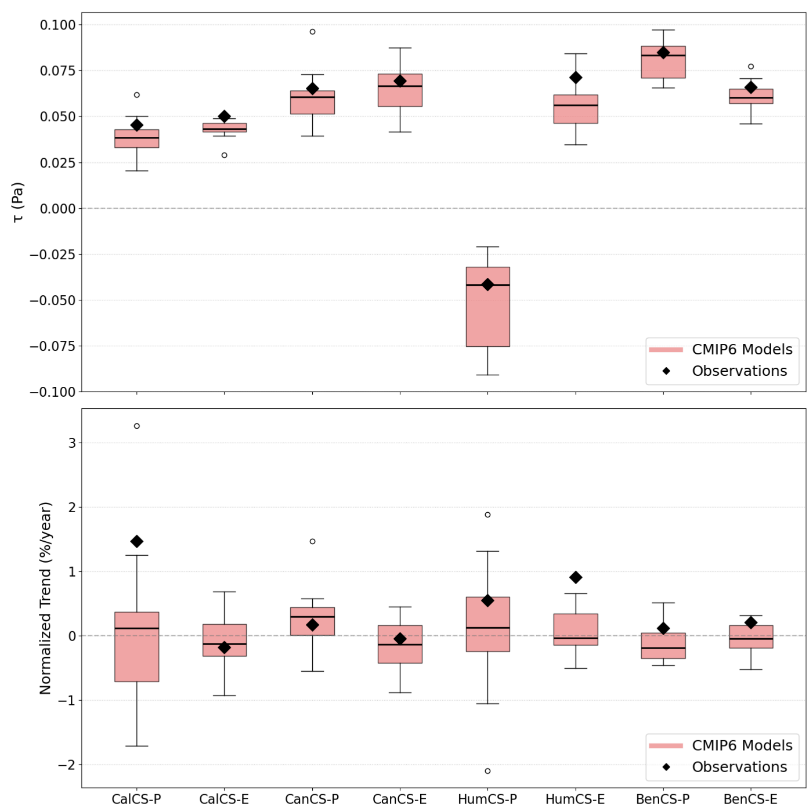


Fig. G) Box-and-whisker plots showing the distribution of observational data (ERA-Interim reanalysis) and CMIP6 model estimates of historical (1998-2014) τ mean values (upper figure) and trends (lower figure) across sub-EBUSs. For each region, boxes represent the interquartile range (IQR), whiskers extend to 1.5×IQR, and the median is shown as a thick black line, with the black diamond being observational data.

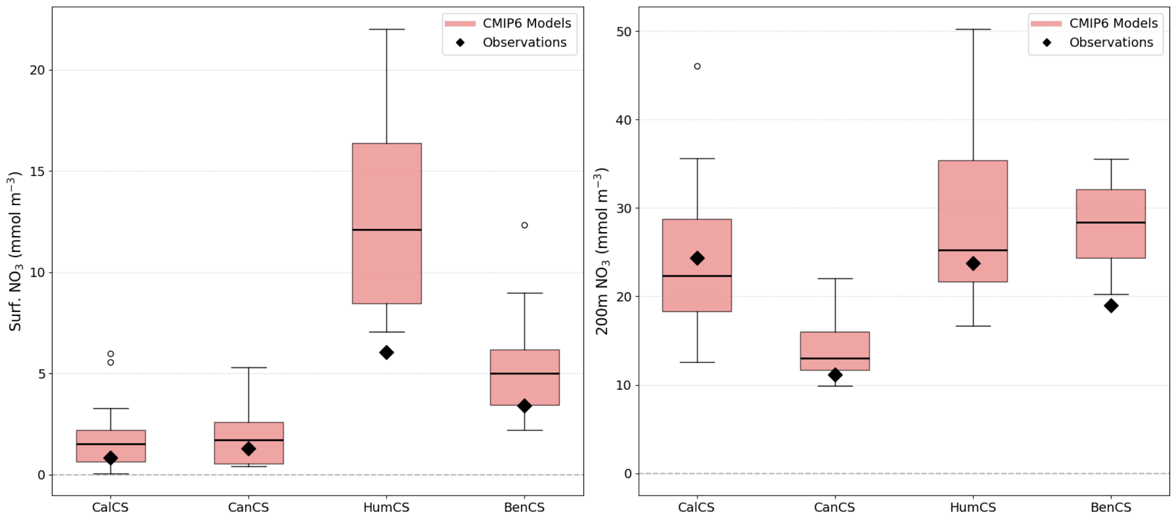


Fig. H) Box-and-whisker plots showing the distribution of observational data (from World Ocean Atlas 2018, Garcia et al., 2019) and CMIP6 model estimates of climatological (1900-2017 for observations, 1900-2014 for CMIP6 models) NO_3 at the surface (left figure) and at 200 m depth (right figure) across EBUSs. For each region, boxes represent the interquartile range (IQR), whiskers extend to 1.5×IQR, and the median is shown as a thick black line, with the black diamonds being observational estimates.

Second, I think there is a missed opportunity to narrow the projection uncertainty by considering the accuracy of each CMIP6 model in representing historical NPP (related to point (1) in the previous paragraph). I realize that most CMIP analyses only consider model ensembles, and this approach is valid for physical parameters that are well constrained by first principles equations. However, BGC model formulation can be highly variable and, even if BGC models similarly perform globally, their performance can be variable in specific regions (here EBUS) and for specific variables (here NPP). Moreover, the different models have an horizontal resolution varying from 0.25° to 1.5° in the 13-model subset, and resolution has a strong impact on upwelling representation and model accuracy in EBUS (see above). It would be very useful to define a "score" for each CMIP model that defines how well they perform during the historical period, and to see if the standard deviation of future projection decreases by only keeping the top X% performing models (half?). This is conceptually similar to the method used by Ryan-Keogh et al. (2025) although a simpler ranking scheme could be used based on model evaluation.

We believe that the proposed approach may prove useful in reducing uncertainties in NPP projections. Following the reviewer's suggestion, we conducted a preliminary analysis to verify whether there is a relationship between historical trends and SSP5–8.5 projections across the model ensemble (Fig. I of this document). However, we found no significant emergent relationship in the vast majority of sub-EBUS regions. This suggests that the historical NPP projections of these models are not linearly reflected in future sensitivities in a way that allows for a simple classification scheme, which prevents us from pursuing this specific study further. Although previous studies have succeeded in reducing uncertainties regarding NPP, for example by using emerging constraints (Kwiatkowski et al., 2017) or a model classification system based on the similarity of linear responses (Ryan-Keogh et al., 2025), any such approach would require significant additional work in this case, and we are not certain that this is fully in line with the objective of the present study, namely to understand, across the entire CMIP6 scale, the consistent future changes in NPP and its determining factors. Furthermore, given the high variability of observational data products at the EBUS scale, the selection of a subset of models could inadvertently introduce arbitrary choices that may not necessarily be optimal.

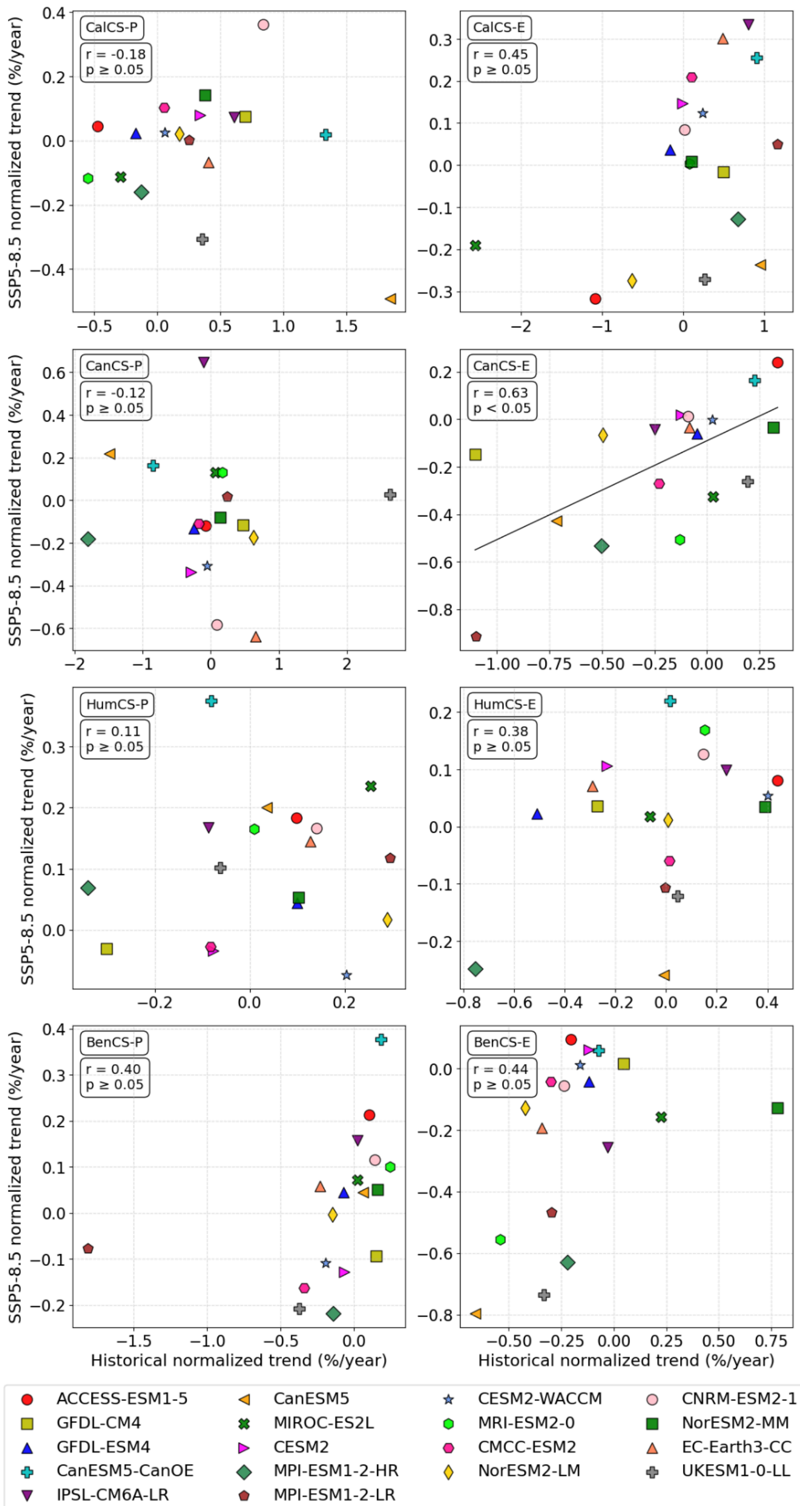


Fig. I) Relationship between historical and future normalized NPP trends across sub-EBUS for CMIP6 models. In each sub-EBUS, individual markers represent models, the x-axis indicates the historical normalized trend (1998-2014), the y-axis shows the corresponding future trend under the SSP5–8.5 scenario (2015-2100). The Pearson correlation coefficient (r) and its significance level are displayed in each panel, and a linear regression line is shown only where the relationship is statistically significant ($p < 0.05$).

Third, some of the hypotheses in the discussion could be easily tested or at least explored further. For instance, if geostrophic transport and wind-stress curl are important contributor to NPP changes, there should still be agreement between w60, surfNO3 and NPP in regions where there is no agreement between tau, surfNO3 and NPP (section 4.2). Similarly, agreement between subsurface nitrate, surfNO3 and NPP could be tested (section 4.3).

We revised the Discussion section to improve both its clarity and completeness. In particular, following the reviewer's suggestions, we have undertaken the following:

- We expanded Section 4.2 to improve its integration within the overall analysis. Specifically:
  - We provided a more detailed explanation of the processes already illustrated in Fig. A12 (Appendix), whose current description is quite concise.
  - To strengthen the analysis, we included an additional "four-color" EBUS map (similar to Fig. 4 in the manuscript), showing the relationships between projected anomalies in Ekman and geostrophic transports (Fig. L of this document). This additional analysis shows that in the central HumCS and BenCS-P regions, Ekman and geostrophic transports tend to vary in opposite directions, likely contributing to the weak correspondence between wind changes and vertical velocity in these regions. This helps explain the projected changes in wo_{60} in the BenCS-P region, but it provides limited additional insight for the HumCS, where vertical velocity remains highly variable and noisy.
- We have analysed combined changes in NPP, surface and subsurface (200 m) NO_3 to test further potential relationships and investigate whether there are consistent concurrent changes in such variables. However, the results (Fig. M of this document), show only limited regions of consistent changes (CanCS-E and BenCS-E). We have therefore preferred not to include this additional figure in the Manuscript, as we believe that this result does not add much to our current analysis and consider it sufficient to retain only Figures A13–A16.

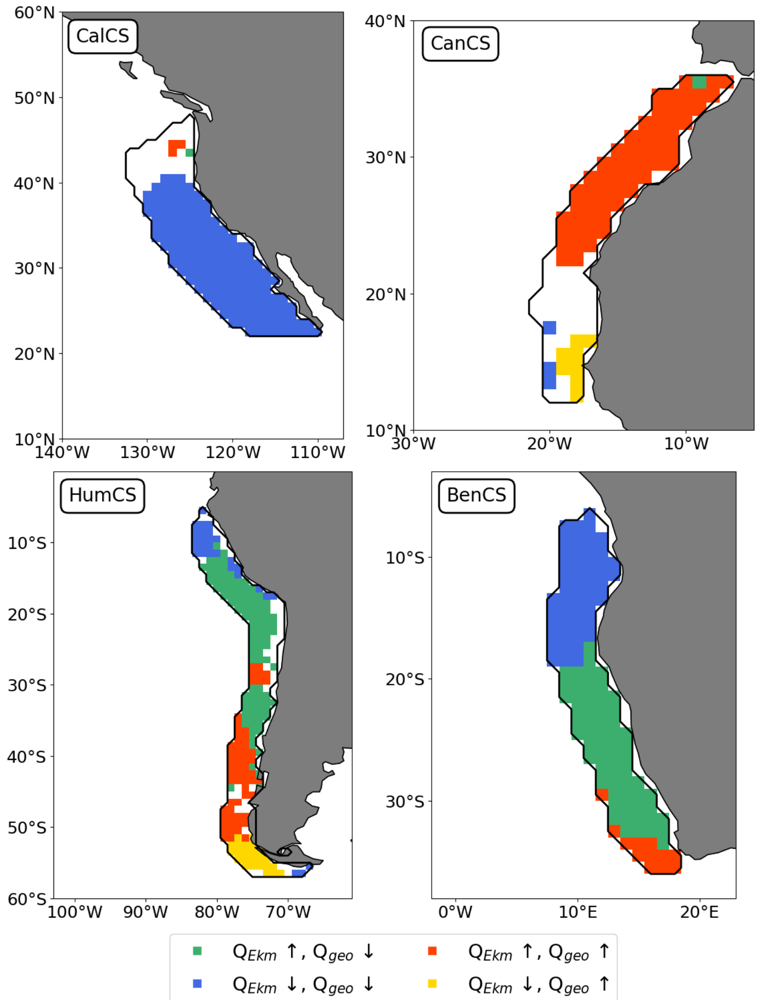


Fig. L) Ekman and geostrophic transport changes are reinforcing each other in some regions, offsetting in others. Signs of twenty-first century colocalized anomalies in Ekman and geostrophic transport under SSP5-8.5 (2071-2100). Grid cells are colored if there is ≥ 50 % model agreement.

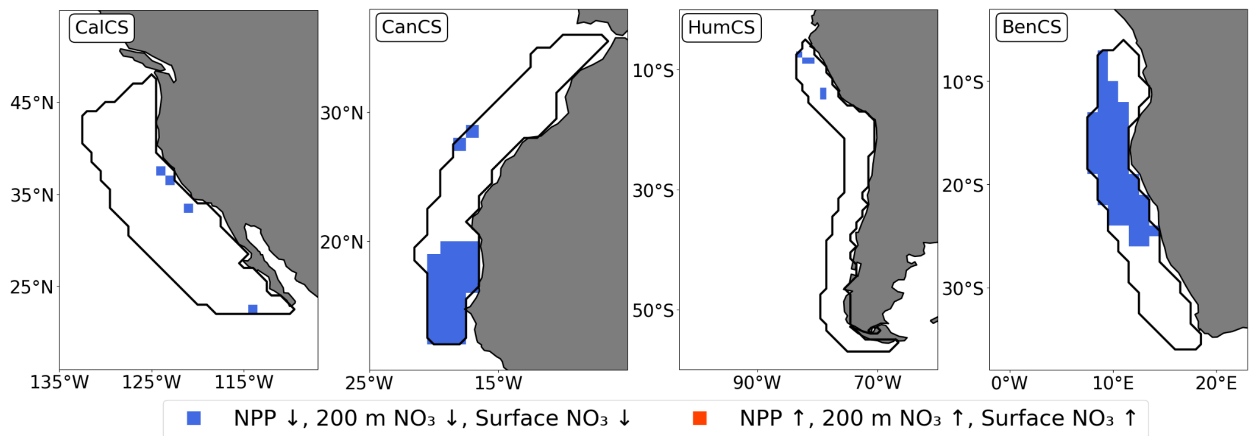


Fig. M) Signs of twenty-first century co-localized anomalies among key variables under SSP5-8.5 (2071–2100). Grid cells are colored if there is ≥ 50 % model agreement on the relationship between anomalies of NPP, surface and 200 m NO_3 combined.

Minor comments

Abstract "This uncertainty partially results from compensating positive and negative NPP anomalies within individual systems, with consistent multi-model responses only emerging at subsystem scales." and similar statements elsewhere (l. 159-172): I don't really understand what you mean. Are you referring to anomalies compensating between models (some models are positive, other negative) or regions (some subregions are positive, other negative)? In either case, that suggests higher variability in subregions than when considering entire EBUS, so I am unclear why this explains part of the uncertainty in projections. Also consistent multi-model responses are not very common according to Fig. 3 (1/3 of the coastal area perhaps? Should be quantified) so "consistent patterns projected across models" (caption) is contradicted by the figure, from what I see.

We acknowledge that this explanation could be made clearer, and we revised the results section (l. 159–172) to improve clarity. The key point is that, while the high uncertainty at the EBUS scale is primarily linked to differences between models in certain regions (e.g., CalCS-E), in others (BenCS-E, BenCE-P, CalCS-P), it is also associated with contrasting and compensating trends within individual systems that are not apparent at the aggregated EBUS scale. When examining projected time series at the sub-EBUS scale, these spatially heterogeneous but internally consistent signals emerge and uncertainty is reduced (e.g., in BenCS, there is an offset between positive (in the poleward portion) and negative (in the equatorward portion) NPP anomalies).

Statements l. 36 "Most past studies have focused on (…) wind-induced upwelling" and l. 75 "we reevaluate the standard perspective that perturbations to upwelling favorable winds (…)" are somewhat contradicted by l. 45-66 that highlight a rich literature supporting other drivers (stratification, geostrophic transport, subsurface nitrate etc). These statements should be rephrased.

We rephrased these sentences.

l. 125-127: did you use the products by Ryan-Keogh et al. (2023), or calculated your own? In the first case this paper needs to be cited. In the second case, more details are needed since the authors only cite OC-CCI which, as far as I know (and found on the website) is only chlorophyll.

We used the Ryan-Keogh et al., 2023 products, we modified the manuscript by citing the paper.

l. 280: do all CMIP6 models include iron limitation? If not it could be useful to see if model performance in regions where it may matter most (CanCS) depends on iron inclusion in BGC models.

Except for two models (MRI-ESM2-0 and CanESM5), all CMIP6 members include a representation of the iron cycle (Séférian et al., 2020), although the level of complexity varies across models. We agree that a deeper investigation of how these different representations influence primary productivity would be valuable, but we recognize that such an analysis would require a substantial additional effort that goes beyond the scope of this study. For this reason, we consider our current approach, which focuses on nitrate as the primary limiting macronutrient, to be appropriate for the objectives of this work.

l. 120: the 30m approximation has only been shown to be valid in the CalCS system; is it valid for other systems too? Also please note that this is defined from the mixed layer depth (as described in Jacox et al., 2018) rather than Ekman layer depth.

We recognize that using a fixed 30 m depth is a simplification, as the Ekman layer depth varies spatially and seasonally and does not strictly correspond to the mixed layer depth, from which this approximation has been defined (Jacox et al., 2018). As pointed out, this approximation has been used in the California Current System (Jacox et al., 2018; Ding et al., 2021), but has also been applied to the BenCS (Veitch et al., 2010). However, there is limited consensus on how Ekman layer depth across different EBUSs. To account for potential differences (and considering that the 30 m approximation is derived from the MLD), we also computed geostrophic transport using spatially and temporally varying MLD fields from the models (Figure N of this document). This approach yielded results that are broadly consistent with those obtained using a fixed 30 m depth, however, in the HumCS-P, the MLD is substantially deeper, which complicates the interpretation of the results. For these reasons, we opted to retain the fixed 30 m depth, as it provides a more interpretable framework for inter-system comparison.

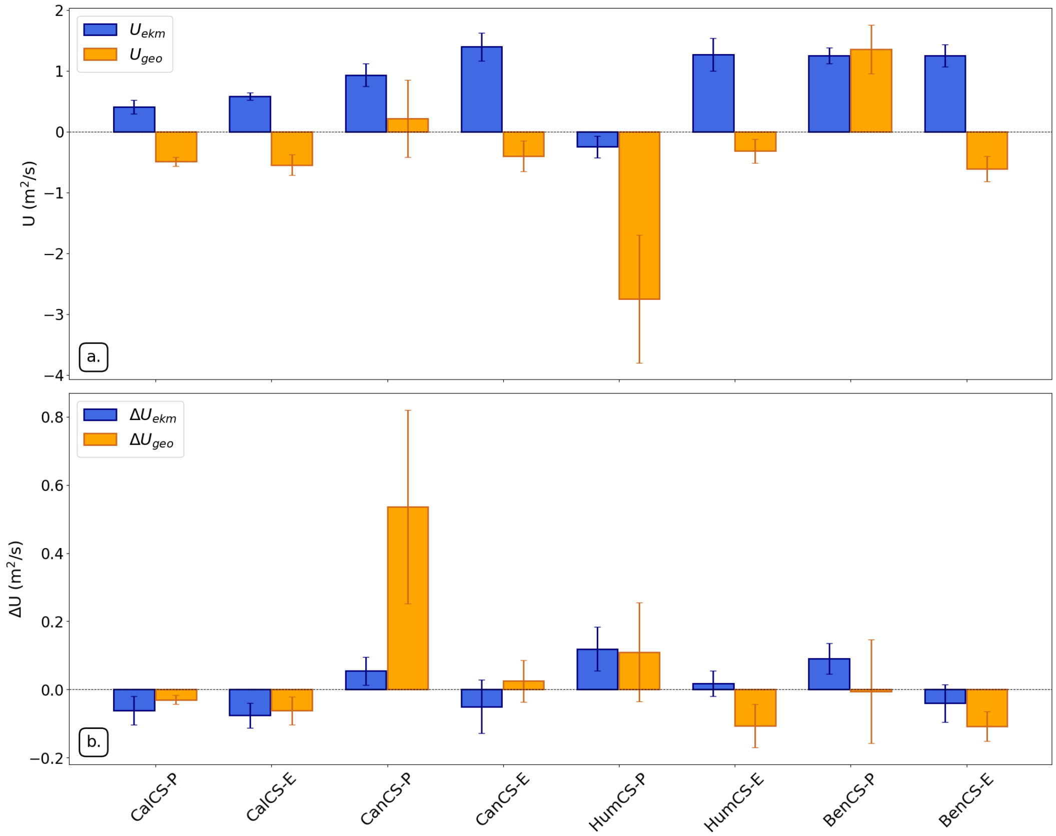


Fig. N) Relative contributions of Ekman and geostrophic transport in EBUS. Ensemble mean (13 models) Ekman and geostrophic transport in the sub-EBUS computed according to equations (1) and (2) respectively (using MLD as Ekamn depth rather than the fixed 30 m), for historical (1985-2014) (a), and anomalies (2071–2100 relative to 1985–2014) (b).

Technical comments

l. 105 what do you mean by "equatorward and downward component of surface wind stress"? Did you just mean equatorward?

In the model outputs, tauv and tauu are officially defined as 'surface downward northward stress' and 'surface downward eastward stress', where the specification 'downward' is used to specify that the stress is applied from the atmosphere to the ocean.

l. 110, 207, 209 and elsewhere "nitrate" is a more common spelling than nitrates.

Yes, we modified the manuscript.

l. 227-229 it would be useful to refer to Fig. 5 right column (that supports this statement)

Yes, we modified the manuscript.

l. 354 cite the Biogeoscience paper rather than Biogeoscience Discussions

Yes, we modified the manuscript.

References:

Ryan-Keogh, T. J., Thomalla, S. J., Chang, N., & Moalusi, T. (2023). A new global oceanic multi-model net primary productivity data product. Earth System Science Data, 15(11), 4829-4848.

Garcia, H. E., Weathers, K. W., Paver, C. R., Smolyar, I. V., Boyer, T. P., Locarnini, R. A., ... & Reagan, J. R. (2019). World Ocean Atlas 2018, volume 4: Dissolved inorganic nutrients (phosphate, nitrate and nitrate+ nitrite, silicate).

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