

Response to the editor

We sincerely thank the Editor for her patience and for giving us the opportunity to further improve our manuscript. We are truly grateful for the careful and thorough evaluation by the reviewers, as well as for the Editor's guidance throughout this process.

We have carefully addressed all the points raised by the reviewers, including the discussion of the new figure showing the deep SCM and its integration with the rest of the manuscript. We therefore changed the order of the figures.

Furthermore, we changed several figures (1 and 4) with wrong units.

We have also corrected all typos and technical errors highlighted by the reviewers and performed a final check to ensure no additional issues remain. All changes are visible in the Author's track-changes file.

Response to the reviewer 1

Second Review of *Heterogeneous future of Arctic Ocean primary productivity changes projected in CMIP6* by Champiot-Bayard et al.

General Comments:

The authors have done a good job of addressing my questions and comments from the first round of review. Significant changes were made to the manuscript, and I am especially pleased to see the extra analysis considering changes over the upper mixed layer. I appreciate that this required a considerable amount of extra evaluation that went beyond simply justifying use of the 100m threshold for consistency with Vancoppenolle et al. (2013), but I believe it has strengthened the paper. The parts of the paper that do make use of surface values for direct comparison are now well-justified.

Additionally, considering seasonal analysis gives a more comprehensive view of the projected changes in Arctic productivity and I am pleased to see these additional analyses have added further detail to the original conclusions of whether/when oligotrophic conditions are reached in the CMIP6 ensemble.

I have a few minor comments on the updated manuscript that I would like to see addressed, but otherwise I am satisfied with the response to my comments and with the changes to the manuscript.

1. Most importantly, thank you for the figures showing the depth of CHL maxima in the CMIP6 ensemble! The projected changes in the depth at which the maximum occurs are interesting, but I think **the key point here is assessing whether the deep CHL max (in the historical part of the run) is better simulated by CMIP6 than CMIP5, as this was a known limitation with some CMIP5 models.**

The analysis done for the new Figure 3a should be sufficient to make a comment on this. I would like to see an addition to the discussion section where these results are compared to, for example, the Steiner et al. paper (<https://doi.org/10.1002/2015JC011232>) that I mentioned in my original comment. **I would argue that an important question for understanding how Arctic NPP has changed between the current generation of models compared to the previous generation of models is understanding whether simulation of the observed deep CHL maxima has improved.**

Given that the analysis of the depth CMIP6 CHL maxima is already in the results section now, a short paragraph in the discussion about how these results compare to papers that analyse the depth of CHL maxima in CMIP5 would tie this part of the story together well.

Response:

We thank the reviewer for raising this point. We agree that the new insights on the depth of the chlorophyll maximum should be discussed. We have added this in the results describing multi-model uncertainty and additional text in the discussion.

In the Results: “Models largely disagree on the depth of the SCM, particularly in future projections where deepening is observed. In some regions, the uncertainty is nearly as large as the SCM depth, possibly indicating that while some models predict a deep chlorophyll maximum, others do not, consistent with findings from CMIP5 models (Steiner et al., 2016). »

In the discussion:

« In addition to this projected NPP increase, in CMIP6 models, the Subsurface Chlorophyll Maximum (SCM) deepens in CMIP6, consistent with CMIP5 (Steiner et al. 2016). However, the uncertainty surrounding this deepening remains high and the modeled historical SCM depth is still far from observational estimates. »

2. There are a few minor style corrections/typos to correct in some of the edits:

- The new Figure 2 is currently captioned as just “Fig 2” rather than “Figure 2”

Response:

We have corrected this.

- Typo on P2 line 25: (“region” should be changed to “regional”)

Response:

We have corrected this.

- P2 line 32: “Arctic Ocean NPP is projected to experience a continued increase in NPP” reads oddly. “The Arctic Ocean is projected to...”?

Response:

We have corrected this.

- P7 L2: “We did more individual model and regional analysis...” – consider rephrasing to make more formal.

Response:

We changed the sentence to: “Several additional figures on individual model and regional analysis are provided in the appendix.”

- P7 L14: “Nitrate concentrations were extracted over the full water column, representing the upper 100m of the ocean” – it is unclear from this whether you used the full water column or just the upper 100m; please rephrase to clarify.

Response:

This was unclear. It has been clarified to: "Observed nitrate concentrations were extracted over the upper 100m of the ocean. Depending on analysis, depth-averaging was done consistently with model output."

- P9 L3: check reference to "upper-100m NO₃". I believe this now averaged over the MLD instead?

Response:

This has been corrected to: "NO₃ concentration in the MLD".

- P21 L19: "...CMIP6 projections point a reorganization..." should be "...CMIP6 projections point to a reorganization..." (This is not intended as an exhaustive list, double check for minor typos.)

Response:

We have corrected this.

Technical Comments:

There are a few instances where changes to the manuscript have not appeared highlighted as edits in the track changes version. These are mostly on the first two pages of the document. The additions to the manuscript detailed in the Author Response are present in the new manuscript, just not highlighted as edits in the track changes version. I haven't found any problems with these edits other than that they're not flagged, but it may be worth double-checking that no intended extra changes have been missed.

Response:

Apologies for the oversight, these were minor text changes. These have been double-checked and all edits are now in the tracked changes.

Response to the reviewer 2

Second Review of *Heterogeneous future of Arctic Ocean primary productivity changes projected in CMIP6* by Champiot-Bayard et al.

General response:

We would like to thank the reviewer 2 for the time spent on this second version of the manuscript, with constructive spirit and willingness to improve it.

P2L4 “in these regions”

Response:

We have reworded this.

P2L9 “ocean circulation patterns , I don't think AMOC is a current”

Response:

We have reworded this.

P2L18 “reducing the”

Response:

We have reworded this.

P2L25 “the carbon pump”

Response:

We have reworded this.

P2L25 “regional contribution?”

Response:

We have reworded this.

P2L32 Suppress: « in NPP »

Response:

We have removed this.

P2L38 on the driving mechanisms

Response:

We reworded.

P3L1 an

Response:

We reworded.

P3L7 but a systematic

Response:

We reworded.

P4L22 Suppress: « (MLD). »

Response:

We removed it.

P4L25 An additional figure is shown in the appendix, where NO₃

Response:

We reworded.

P7L2 Additional individual.. analysis are provided..

Response: This sentence has been modified to "Several additional figures on individual model and regional analysis are provided in the appendix." to make it more formal as suggested by the reviewer 1.

P7L14 This sentence does not make sense to me. Did you extract the full watercolumn, but only assess the upper 100m? please clarify

Response: We agree that it is unclear. Indeed, we meant that the dataset represents only the first 100m of the water column and we took this whole water column provided. We changed the sentence as follows: "Observed nitrate concentrations were extracted over the upper 100m of the ocean. Depending on analysis, depth-averaging was done consistently with model output."

P7L16 any newer ref here, given that you are using a 2018 climatology?

Response: We changed the citation for Gibson et al.

P8L16 How are Feb, July and annual mean differentiated. There seems to be only one line per model in the figure ????

ah I notice only for the MMM all three are shown, please clarify what the colored ones show March, july or annual mean?

Each color-symbol combination one color actually represents 3 models

ah I notice only for the MMM all three are shown, please clarify what the colored ones show March, july or annual mean?

Response:

The upper black line one represents the winter concentration, the middle one the mean concentration and the line below represents the summer concentration. We will add the information in the caption as follows: "Only winter NO₃ concentrations are shown for individual models."

P9L5 over the

Response:

We reworded.

P9L6 Suppress: « over which »

Response:

We reworded.

P9L7 repeated

Response:

We reworded.

P9L24 move note on drivers from below to here

P10L5 While I really like to see the SCM in this analysis, I am missing the context, why is it shown here and how is it connected to the rest of the study? I suggest providing some info in the introduction - general info on the SCM and why it is relevant, clarify how it relates to the results/story line and bring it up in the discussion/conclusion if it is there to provide an additional message or strengthen the message. Also, why is it part of the model evaluation ??? seems like a better fit with the projection section, unless you evaluate it with observations without additional information it is just a nice figure, but we don't know why it is here which means it may better be removed.

Response:

We added this figure in response to Reviewer 1 that said that it could be interesting to have an insight of the becoming of the SCM, to compare its evolution with CMIP5 (Steiner et al., 2016) and we appreciated the idea.

*However, we agree that we did not integrate a part in the introduction to better connect this study to our paper. We therefore added some information in the introduction: "The Arctic Ocean NPP is projected to experience a continued increase in NPP under climate change (Tagliabue et al., 2021). Future sea ice retreat will further extend the open-water season duration, enhance light availability and stimulate phytoplankton growth. However, the melting of sea ice will also introduce large volumes of freshwater, which may further stratify the water column, reducing nutrient transport from deeper waters and potentially modifying NPP dynamics (Pabi et al., 2008; Popova et al., 2010) **and the distribution of the phytoplankton in the water column (Steiner et al., 2016).**"*

We also include a paragraph in the discussion as it was proposed by the reviewer 1 as follows: "In addition to this projected NPP increase, in CMIP6 models, the Subsurface Chlorophyll Maximum (SCM) continues to deepen throughout the simulation, consistent with trends observed in the previous CMIP5 models (Steiner et al., 2016). However, the uncertainty surrounding this deepening remains high and the modeled historical SCM depth is still far from observational estimates."

We did indeed move the figures because they weren't in the right section. They are now in the next section and are therefore numbered 5 and 6.

P10L8 why in contrast if it is also deepening? or do you mean is "only" slightly deepening?

Response:

We meant that this is "only" slightly deepening. We suppressed the "In contrast".

P11L3 Suppress: « according to »

Response:

We reworded.

P11L9 This paragraph seems to disrupt the flow of the evaluation and doesn't really fit here. It should be with the projection discussion further up (before SCM/CHL figure, indicated by comment). Also suggest to better connect by rephrasing: "The drivers of these projected changes are .." Not sure what "providing continuity with" means in this context: confirming earlier assessments? consistent with earlier assessment? strengthening the results from ..???

Response:

Indeed, we didn't put the paragraph in the right section. We moved it next to figure 1, in the section "Model evaluation".

We changed the sentence for: "The drivers of these projected changes are changing in the same direction across all Arctic subregions : NO₃ and September sea ice decrease and SST increases for all models and regions, consistent with earlier CMIP-based assessments (Vancoppenolle et al., 2013)"

P12L3 values for coastal

Response:

We reworded.

P12L3 basin, it .. (no new sentence, otherwise the "While" does not make sense

Response:

We reworded.

P12L4 the coast itself is land, I assume this should be the coastal regions or the coastal shelves

Response:

It have been changed for "The coastal shelves ..."

P12L4 of the

Response:

We reworded.

P12L13 suggest adding to caption that timeseries for subregions are shown in the appendix

Response:

We added in the caption that "Additional figures representing the timeseries for subregions are shown in the appendix."

P12L13 for the

Response:

We reworded.

P12L14 represents the value or represent the values

Response:

We reworded. to "represents the value".

P13L6 is there an explanation for this mismatch?

P13L8 5d shows temperature, is the wrong reference?

Response:

Yes, it is Fig5c. We reworded.

P14L5 does this apply for all 4 panels? i.e for the other variables 80% agreement across the Arctic?

Response:

Yes, it is applied on every map.

We added that in the caption.

P14L9 sign

Response:

We reworded.

P14L10 This may be a good place for the SCM figure, but it would still need better description on how it is connected

Response:

Yes, we are going to put the figure about the SCM here.

P15L8 should this be Arctic Basin subregion or does it refer to the Arctic Ocean average????

Response:

It refers to the Arctic Ocean average. We changed the sentence to: "The Pan-Arctic Ocean NPP..."

P16L10 over time in SSP..

Response:

We reworded.

P16L10 driver?

Response:

We reworded.

P16L12 phytoplankton growth functions ? or temperature functions affecting growth?

Response:

We reworded. We now use: "via temperature-dependency of phytoplankton physiology (i.e., Tf)".

P16L16 consistent across models ?

Response:

We reworded.

P17L5 This kind of presentation (Figure10) is not intuitive, I suggest adding a sentence on the goal of this type of presentation, before jumping into the figure description. E.g. To better understand the spatial pattern and causes for modeled NPP uncertainties across the Arctic we present.. (if that is the goal, otherwise clarify)

Response:

We clarified this with this sentence: "To better understand NPP uncertainties, their causes and their distribution across the Arctic, we represented the multi-model standard deviation of anomalies in NPP and each limitation term in Figure 10."

P18L5 This may be semantics, but I would suggest if your discussion refers to miscellaneous phytoplankton to show the percentage of the miscellaneous phytoplankton, or vice versa, if you show the diatom, then refer the discussion to the diatoms. This would help with clarity

*Response: You are correct. We changed the sentence and now talk about diatoms and not misc. phytoplankton as you suggest: "In the two decades 1995-2014, **diatoms** are **not** the dominant contributor to total NPP across the majority of the Arctic Ocean with the exception of the coastal East Siberian Sea where diatom NPP is particularly important"*

P19L5 Suppress: « 12Figure a »

Response:

We reworded.

P19L12 The light limitation

Response:

We reworded.

P21L19 point at a reorganization

Response:

We reworded.

P21L19 dynamics

Response:

We reworded.

P21L20 Suppress: « in »

Response:

We reworded.

P21L22 the magnitude

Response:

We reworded.

P21L23 This is interesting as usually we expect more replenishment with expanded open water in fall as more storms can impact the water column, but your figures show otherwise suggesting that the whole nutrient inventory is lower that even storms can't mix up more, or wind becomes lower. I suggest adding a sentence in the discussion of the seasonal plots above, pointing out that delayed replenishment.

Response:

We added a paragraph in the discussion as follows: *“Contrary to expectation, fall is not showing nutrient replenishment despite the expansion of the open water areas. Under usual conditions, the reduced sea ice cover in this season would increase fetch and, which could allow stronger storm-driven mixing and entrain nutrient-rich deep waters into the surface layer (citation with zotero to add). However, our analysis suggests that this phenomenon is inefficient”*

P21L23 nutrients

Response:

We reworded.

P22L18 Suppress: « public »

Response:

In this sentence, the word “public” is useful to refer to health, not at the individual scale but at the community-scale. We referred to the social impact that is associated with this change in marine resource, including food, but also the mental health linked to cultural and environmental transformation. Using “health” alone would narrow this meaning toward an individual health outcome. “Public health” is more accurately reflecting the collective dimension we wanted to discuss.

P23L5 a longer

Response:

We reworded.

P23L5 This sentence does not make sense and should be separated. As is, it suggests a correlation between the NPP increase and the shift toward smaller species, however as indicated even in this sentence, the shift to smaller species is driven by lower nutrients. Please make clear that even though CMIP6 has higher nutrients than CMIP5 the nutrients are still projected to decline, driving increased dominance of smaller species over time.

Response:

We agree that we were trying to say too many things at the same time, and that we did not specify the role of declining nutrients clearly enough. We split the sentence into two parts.

“The NPP increase is accompanied by a shift toward smaller phytoplankton species, driven by projected nutrient decline over the 21st century — despite CMIP6 models simulating higher absolute nutrient levels than CMIP5. This community shift has implications for higher trophic levels, biogeochemical cycling, and carbon export.”

P25L1 averaged over the pan-Arctic

Response:

We reworded.

P25L5 suggest use region or subregion here as not all of those regions are basins - change throughout

Response:

We changed the word "basin" for "subregion" throughout the whole paper when it was adapted.

P26L8 I am missing the data acknowledgments & links for obs and CMIP, but maybe I overlooked them, I assume they are added somewhere as per journal requirements ?

Response:

We added the section "Code data and availability" before the acknowledgements.