Light absorption by marine cyanobacteria affects tropical climate mean state and variability

Reply to Reviewer 2

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We thank the reviewer for the positive feedback and for the helpful and constructive comments. A point-to-point reply is given below. The referee's comments are in red color, and our reply in black color.

Paulsen et al. implement light absorption by cyanobacteria in the MPI ESM and discuss its impact on the mean climate as well as on the seasonal SST cycle and interannual SST variability. They suggest that cyanobacteria lower SST due to a shading effect: the sub-surface water cool because they receive less sunlight, and the upwelling of these sub-surface waters lead to a SST decrease. Changes in SST gradients induce changes in ocean currents, thus slightly altering the mean climate state. Light absorption by cyanobacteria also leads to a greater seasonal SST cycle in the tropics.

Paulsen et al., implement a new effect, that is neglected in most models I believe. The parametrization implemented makes sense and the MPI model is well tested. The impact on sub-surface temperature seem justified. The manuscript is clear and well written. I thus recommend publication after the comments below are addressed.

1) This new implementation affects the oceanic and atmospheric circulations with effects reaching the mid latitude. Explaining some of these changes is not straight forward, and the authors suggest changes in the Hadley cells and the Walker circulation. In the present state of the manuscript it is not possible to check whether this is really the case. Changes in the Hadley cells and the Walker circulation would need to be shown: figures of the atmospheric circulation are needed. Figures showing changes in ocean surface currents would also help as they are discussed in the text.

Figures of the Hadley circulation (zonal global mean meridional mass flux), surface wind, wind stress on the ocean, and ocean surface currents – as well as their respective anomalies – are provided at the end of this document (Figures R 1-4). They are discussed in more detail below.

If the Walker circulation is stronger (p11, L.17), shouldn't the upwelling in the Eastern equatorial pacific be stronger (p10, L.18)? From Fig. 6, I can see that the upwelling in the EEP and EEA are indeed weaker, and that the barotropic stream-function seems weaker almost everywhere. This is consistent with weaker wind-driven circulation as mentioned p13, l12. I can see that in other parts of the text the authors suggest the strengthening is mostly restricted to the western side of the Pacific basin. Please make sure your description of the Walker circulation changes are accurate. The northward shift of the Gulf Stream is consistent with Fig.6b, however the change in the Kuroshio is less clear.

As stated correctly by the reviewer, the strengthening of the Walker circulation is restricted to the western Pacific (visible in the strengthening of the westward equatorial winds, Figure R 2). At the same time, the transition between convection and subsidence is shifted towards the west (see Figure 5c of the manuscript). That means, the region of convection is more confined to the western part of the Pacific basin. Related to that, the strengthening of the windstress on the ocean (Figure R 3) and the strengthening of the equatorial upwelling (Figure 6d of the manuscript) is also restricted to the western equatorial region. In the eastern tropical Pacific, on the other hand, the weakening of the trade winds (Figure R 2) due to the weaker meridional SST gradient rather causes a decrease in upwelling strength (Figure 6d of the manuscript). We modified the respective text passages in the manuscript to be more precise about the changes in the Walker circulation (page 11 lines 14-20, page 13 lines 1-2). Furthermore, we included figures of the wind field and its anomaly (Figure R 2) in the manuscript (Figure 5a,b).

The northward shift of the subtropical gyre (and the western boundary current) is indeed more pronounced in the North Atlantic than in the North Pacific, as seen in the barotropic streamfunction (Figure 6b of the manuscript). Although a slight northward shift is also visible in the North Pacific (better visible in experiment PHY_CYAx2 than in PHY_CYA, see Figure R 5), the dominant cause of the cold anomaly in the western subtropical Pacific is probably the decrease in the northward transport of warm tropical surface water (Figure R 4) related to the changes in the wind field (Figure R 2). We modified the respective passage in the manuscript to make this more clear (page 12 lines 32-33, page 14 lines 1-2).

Although the additional figures (Figures R 1-4 of this document) generally underline what is described in the text, we decided to add only one additional figure to the manuscript, showing the wind field and its anomaly (Figure R 2 of this document, Figure 5a,b in the manuscript, respectively). The other properties (wind stress on the ocean and ocean surface currents) mainly follow the patterns of the surface wind field and hence do not need to be additionally shown in our opinion. Following the reviewer comments, we improved the descriptions in the text regarding the changes in Hadley and Walker circulation.

P13, L.1: It is stated that the Hadley cells are expanded: is it in both hemispheres?

Figure R 1 shows the global zonal mean meridional mass flux Ψ visualizing the Hadley circulation. In both hemispheres, the anomaly patterns indicate a slight shift of the boundaries of the Hadley cells polewards. The expansion is, however, rather small. Furthermore, in the southern hemisphere, the subtropical gyres do not show a poleward shift in the barotropic streamfunction (Figure 6b of the manuscript) which one would expect from an expansion of the Hadley cells. We modified the respective text passages in the manuscript and stress the weakening of the Hadley circulation rather than the expansion of its cells (page 1 line 8, page 13 line 6, page 24 line 5).

P13, L. 19-20: This sentence is really confusing. Are the authors really talking about the Northwest Pacific Ocean? Is there really southerly winds dominating there (I would have thought it would have been westerlies)? Latitude and an East-West location are needed to really understand this sentence. As mentioned above a figure of winds and wind anomalies would really help to understand.

Winds and wind anomalies are shown in Figure R 2 and are added to the manuscript (Figure 5a,b). The description in the manuscript was indeed not very clear about the geographical location of the described changes. The location that is meant is in the tropical Pacific north of the equator along the coast of Southeast Asia (10-30°N, ∼120°E). In this region, a southwestward wind is prevailing on the climatological mean (Figure R 2a). In PHY_CYA and PHY_CYAx2, this wind is enhanced (Figure R 2b,c), subsequently enhancing the windstress on the ocean (Figure R 3b,c). This southwestward windstress acts in the opposite direction than the flow of the northeastward western boundary current (Figure R 4a) and hence reduces its transport. This, together with the slight northward shift of the northern boundary of the subtropical gyre (Figure 6b of the manuscript and Figure R 5 of this document), results in the cold SST anomaly in the northwestern Pacific subtropical gyre. We modified the respective text passage in the manuscript to make the location of the described changes of winds and ocean transport more clear (page 13 lines 26-29).

2) Section 5: seasonal dynamics. It might help to mention at which time the cyanobacteria blooms occur. The timing of the blooms will most likely significantly impact the seasonal changes. Is the timing of the blooms in agreement with observations?

As shown in Figure 9 of the manuscript, the timing of the blooms affects the seasonal cycle of SST in the model. The seasonal cycle of cyanobacteria concentrations is regionally quite different and depends on several factors such as temperature, ocean circulation, and phosphate and iron availability. Not many long-term observations of the seasonality of cyanobacteria concentrations and N_2 fixation rates are available. Exceptions regarding N_2 fixation are the stations ALOHA and BATS. An evaluation of the timing for ALOHA and BATS for N_2 fixation is given in Paulsen et al., 2017. The modeled seasonality of N_2 fixation roughly reproduces the observed seasonal cycle. We added some more information on the seasonality of N_2 fixation in the manuscript (page 6 line 29-30).

3) Figures: Figure 1: Add Latitude in plot 1b as it is different from a, c and d. It would be nice to add the satellite estimate of Chla for comparison.

We thank the reviewer for pointing this out. We modified the latitudinal range in Figure 1b so that it is identical with a,c,and d.

In this study, we specifically investigate the sensitivity of the climate system to light absorption by cyanobacteria. Satellite products of chlorophyll only provide an approximation of total chlorophyll concentrations. There is no satellite product available providing separate chlorophyll data for cyanobacteria. We, instead, evaluate the simulated distribution of cyanobacteria via its biomass (see Paulsen et al., 2017). Chlorophyll is only used as a measure of strength of light absorption. It is not a prognostic variable but depends linearly on cyanobacteria concentrations. The applied C:Chl ratio is based on observations. A sensitivity experiment was performed to assess the sensitivity to this parameter. We think that the distribution of cyanobacteria and their chlorophyll concentrations are evaluated to the extent possible. The model's ability to simulate large scale patterns of phytoplankton in general has been shown elsewhere (e.g., Wetzel et al., 2006). We therefore refrain from including a figure of satellite-derived chorophyll *a* in this study.

Figure 2: why are the plots cut at 50deg? It might help to see what's happening poleward of 50deg, particularly for the change in Kuroshio and Gulf Stream.

Figure R 6 of this document shows Figure 2 of the manuscript, but with extended latitudinal range up to 90°S and 90°N. There are indeed also anomalies in higher latitudes. However, since this paper focuses on the effects on low and mid-latitudes, we decided to keep the figures in the manuscript unchanged.

Extending the latitudinal range does not help a lot to explain the changes in the Kuroshio Current and the Gulf Stream. Thus, instead of showing a larger latitudinal range, we improved the descriptions in the text to make the changes – and its causes – more clear.

Figure 11: Should the authors also plot PHY_ONLY-CTRL? In that way in one figure one can see the impact varying light attenuation, and the impact of the cyanobacteria. This would be particularly useful as the high latitude regions are not shown in Figure 2.

Figure R 7 shows the difference in SST between PHY_ONLY and CTRL. The differences between this plot and Figure 11b of the manuscript (showing the difference between PHY_CYA and CTRL) are difficult to see since the anomalies between the experiments with and without feedback included (PHY_ONLY and CTRL, and PHY_CYA and CTRL, respectively) are larger than the anomalies between the experiments with and without cyanobacteria (PHY_ONLY and PHY_CYA). The applied color scale is hence not suitable to show both impacts – the impact of varying light attenuation, and the impact of the cyanobacteria. Thus, we decided not to include this additional figure in the manuscript.

4) Minor and typos: P6, L. 13: "Furthermore, we" P6, L. 33: "For comparison" (remove the) P10, L.19: "surface warming." (remove effect) P11, L. 4-5: Rephrase "Here, it is probably the changes in the circulation system that is causing the anomalies instead of the local heat absorption effect." P13, L.3: "There" instead of "Here" P13, L. 21: "Interior"

We modified all of the respective text passages according to the suggestions.

Section 6: Many sentences have a weird structure. It would be worth trying to improve the flow of the section

We reworked the structure of a number of sentences of Section 6 to improve their readability (pages 18-23).

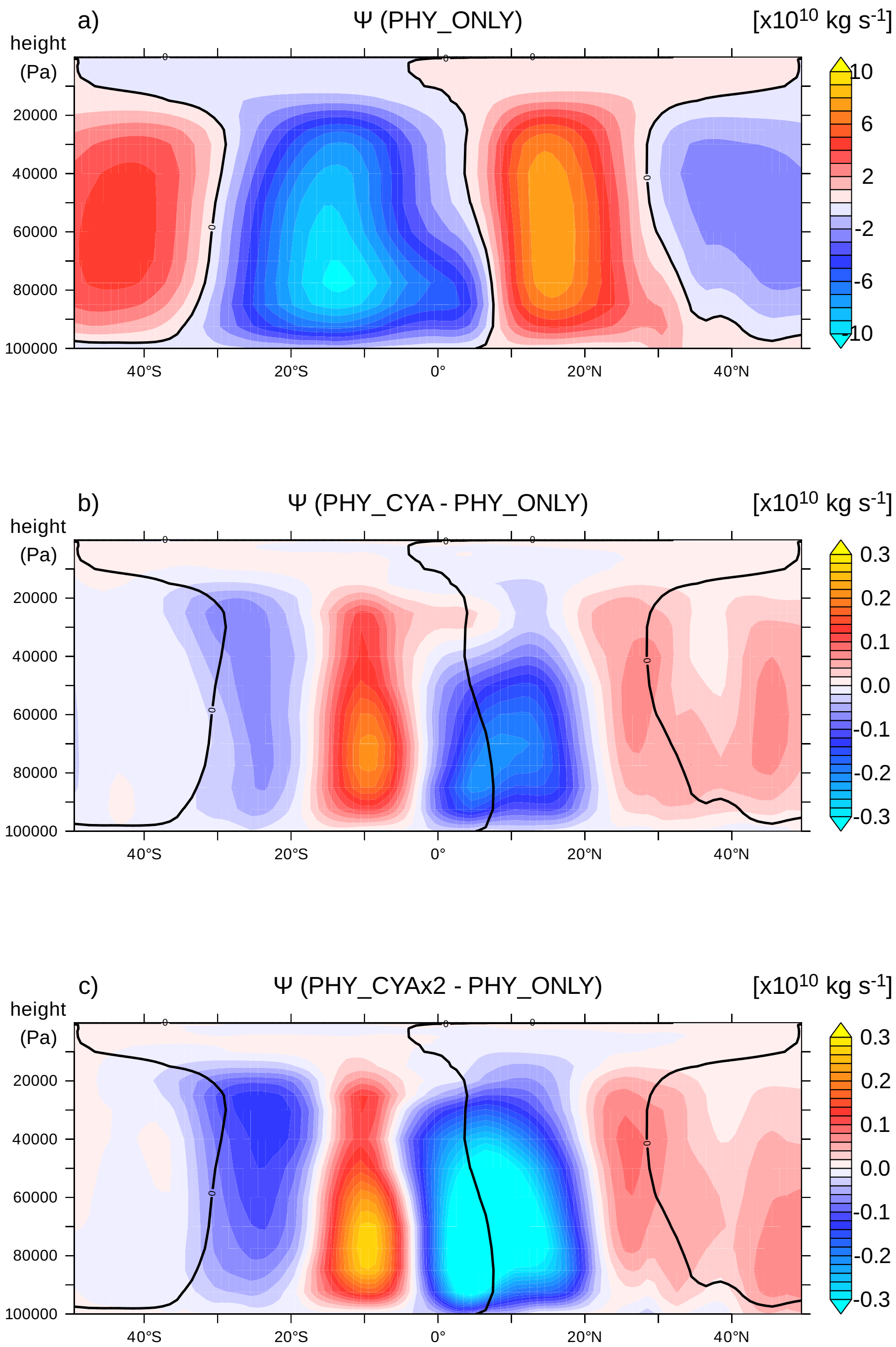

Figure R 1: a) Climatological global zonal mean meridional mass flux Ψ [10^{10} kg s^{-1}] in PHY_ONLY. The zero-isoline is overlaid in black. b) The difference in the climatological zonal mean meridional mass flux [10^{10} kg s^{-1}] between PHY_CYA and PHY_ONLY. The zero isoline of PHY_ONLY is overlaid in black. c) The difference in the climatological zonal mean meridional mass flux [10^{10} kg s^{-1}] between PHY_CYAx2 and PHY_ONLY. The zero isoline of PHY_ONLY is overlaid in black.

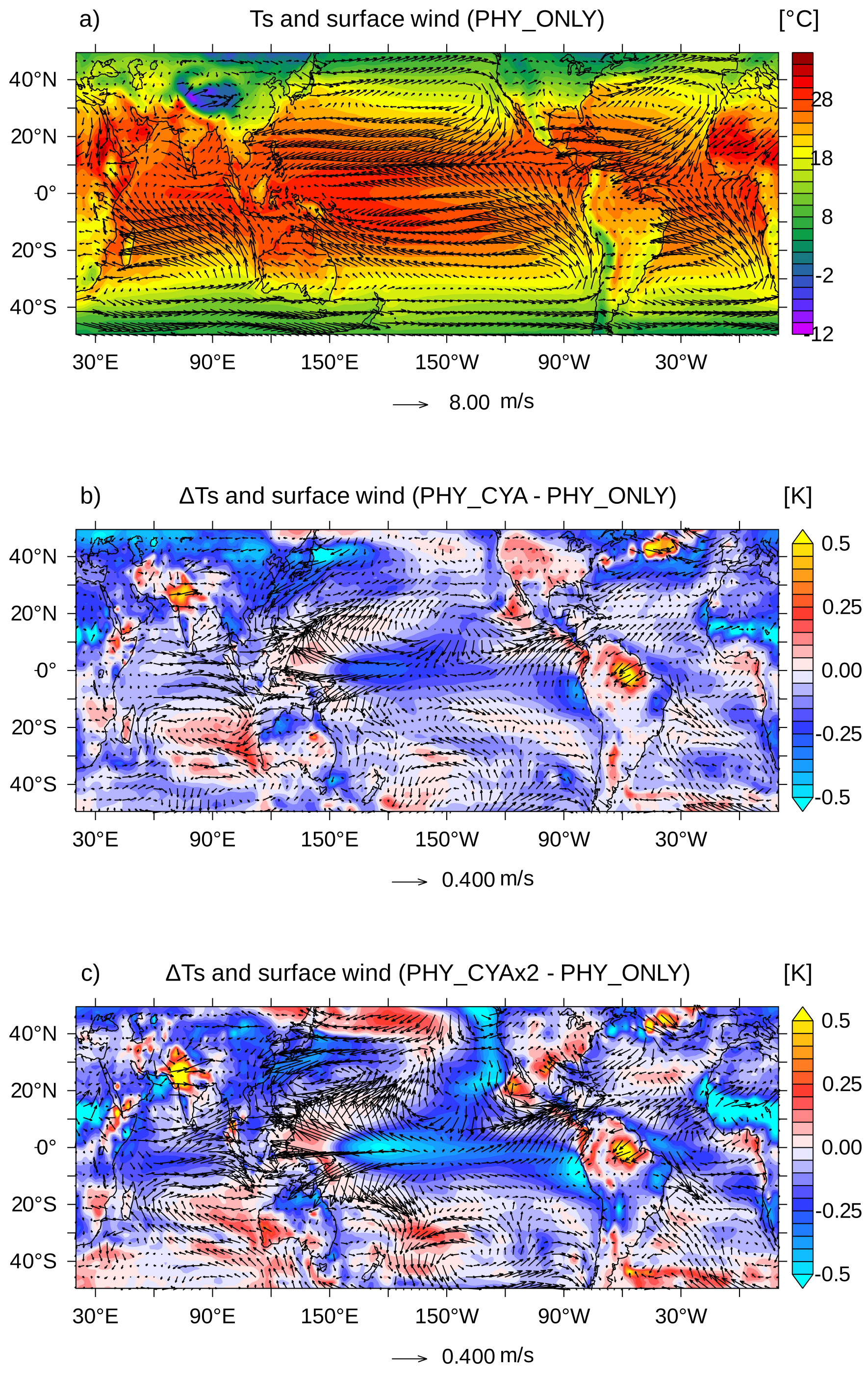

Figure R 2: a) Vectors: Climatological annual mean wind vectors in PHY_ONLY (the reference vector refers to 8 m s^{-1}). Colors: Climatological annual mean surface air temperature [K]. b) analogous to a) but for the anomalies between PHY_CYA and PHY_ONLY (the reference vector refers to 0.4 m s^{-1}). c) analogous to a) but for the anomalies between PHY_CYAx2 and PHY_ONLY (the reference vector refers to 0.4 m s^{-1}).

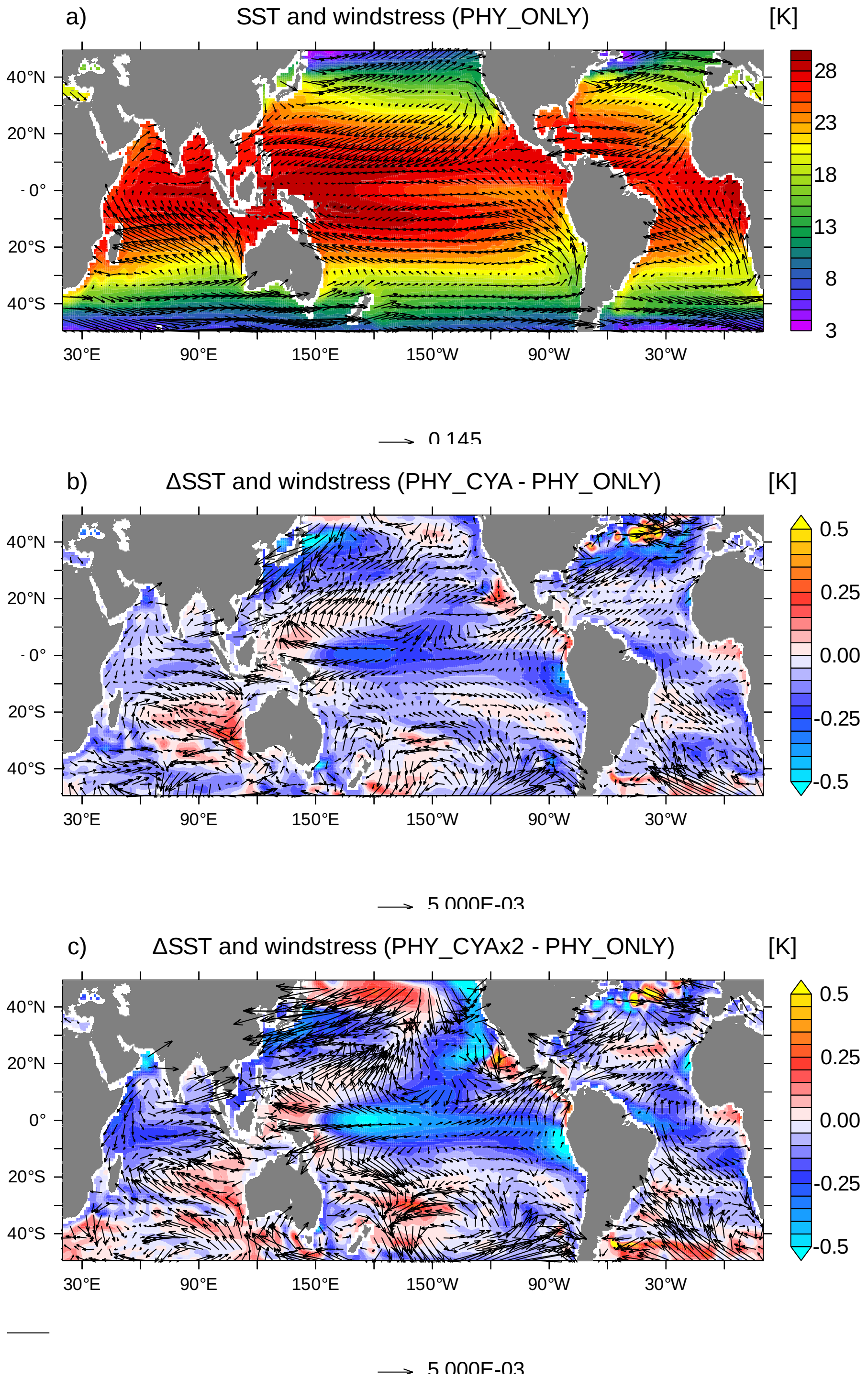

Figure R 3: a) Vectors: Climatological annual mean windstress on the ocean in PHY_ONLY (the reference vector refers to 0.145 N m^{-2}). Colors: Climatological annual mean SST [K]. b) analogous to a) but for the anomalies between PHY_CYA and PHY_ONLY (the reference vector refers to 0.005 N m^{-2}). c) analogous to a) but for the anomalies between PHY_CYAx2 and PHY_ONLY (the reference vector refers to 0.005 N m^{-2}).

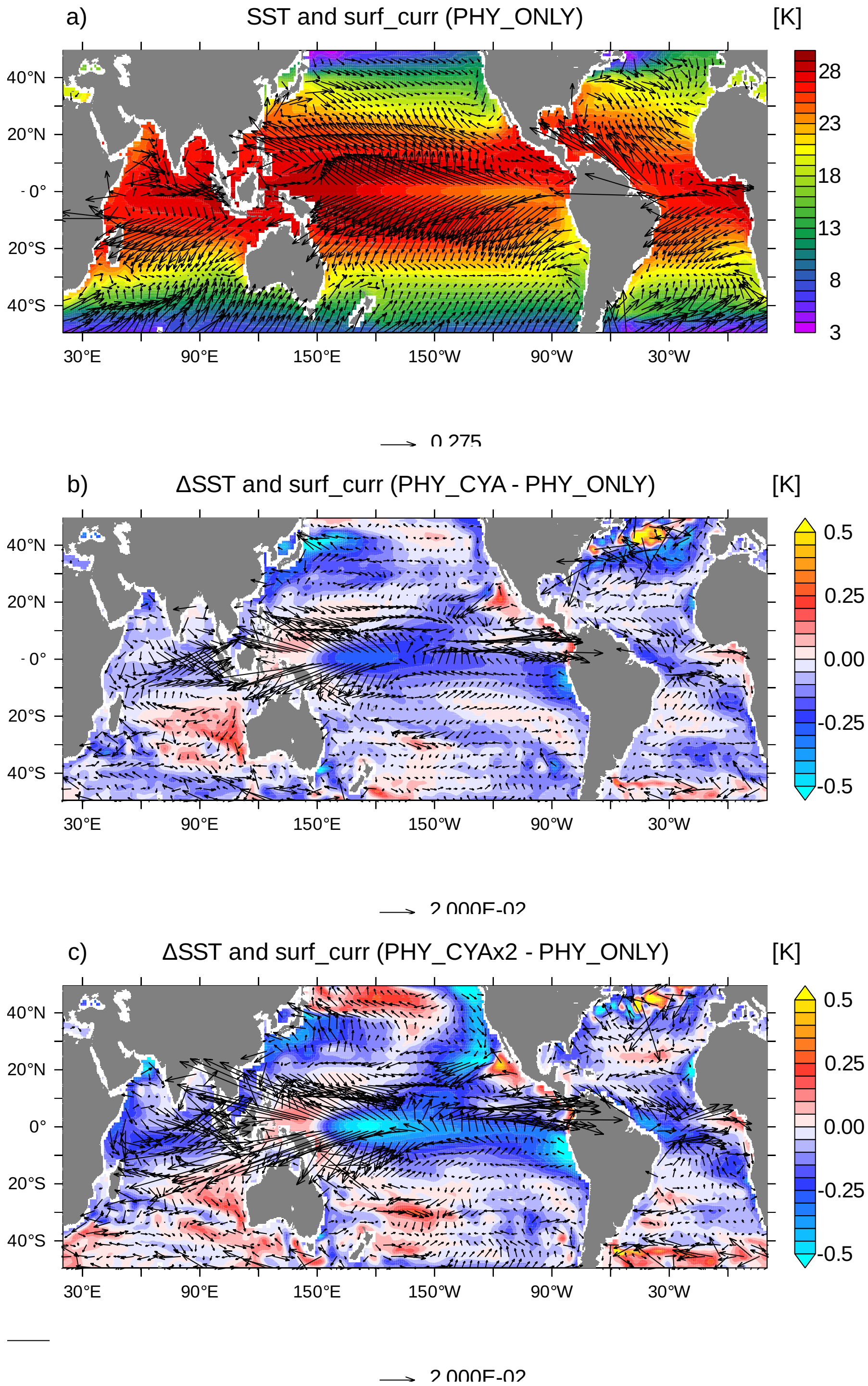

Figure R 4: a) Vectors: Climatological annual mean ocean surface currents in PHY_ONLY (the reference vector refers to 0.275 m s^{-1}). Colors: Climatological annual mean SST [K]. b) analogous to a) but for the anomalies between PHY_CYA and PHY_ONLY (the reference vector refers to 0.02 m s^{-1}). c) analogous to a) but for the anomalies between PHY_CYAx2 and PHY_ONLY (the reference vector refers to 0.02 m s^{-1}).

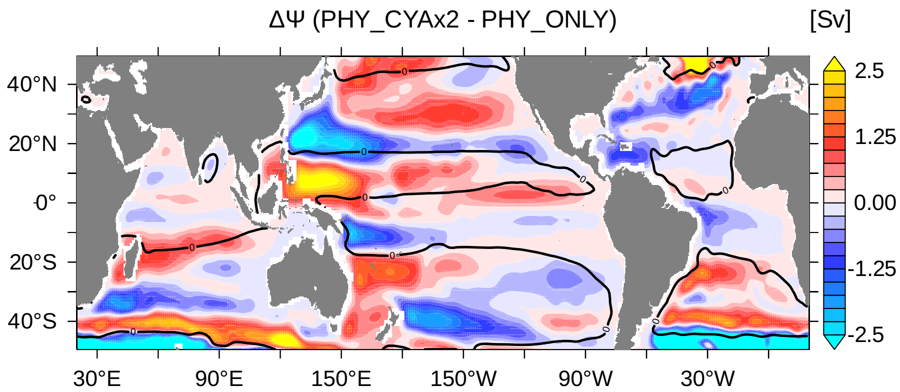

Figure R 5: Difference in the barotropic streamfunction Ψ [Sv] between PHY_CYAx2 and PHY_ONLY.

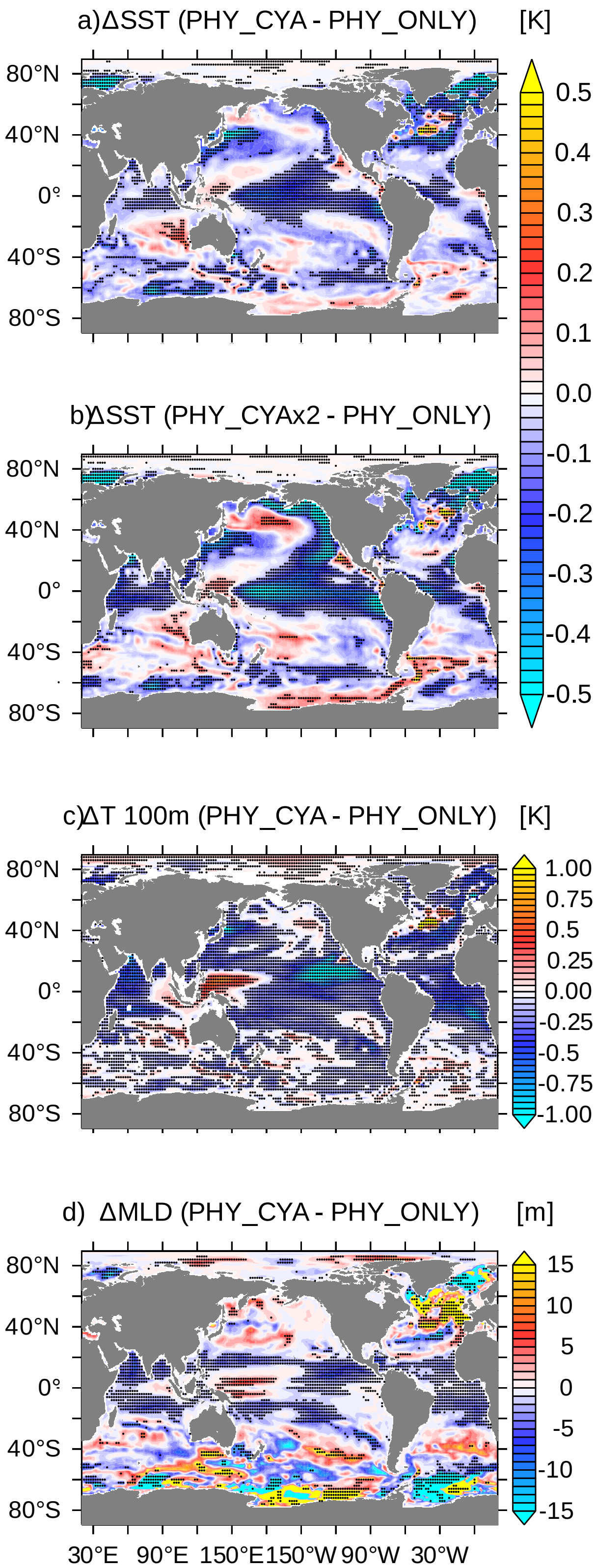

Figure R 6: a) Difference in the climatological annual mean SST [K] between PHY_CYA and PHY_ONLY and b) between PHY_CYAx2 and PHY_ONLY. c) Difference in the climatological annual mean temperature at a depth of 100 m [K], and d) mixed layer depth [m] between PHY_CYA and PHY_ONLY. Dotted areas show anomalies larger than 90 % significance (Student's *t*-test).

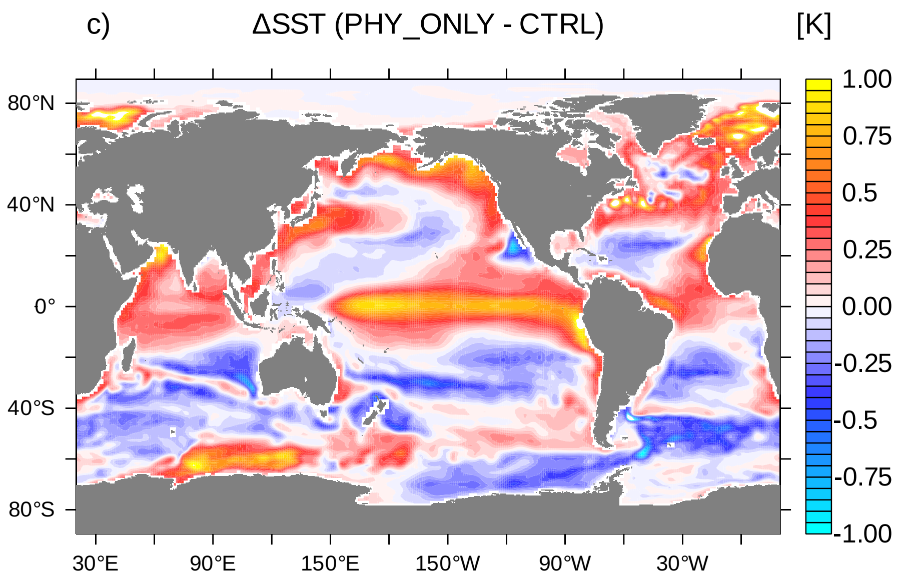

Figure R 7: Difference in SST [K] between PHY_ONLY and CTRL.

References

Paulsen, H., T. Ilyina, K. D. Six, and I. Stemmler (2017). Incorporating a prognostic representation of marine nitrogen fixers into the global ocean biogeochemical model HAMOCC. *Journal of Advances in Modeling Earth Systems 9*(1), 438–464.

Wetzel, P., E. Maier-Reimer, M. Botzet, J. Jungclaus, N. Keenlyside, and M. Latif (2006). Effects of ocean biology on the penetrative radiation in a coupled climate model. *Journal of Climate 19*(16), 3973–3987.