First reviewer

I have completed the review of the manuscript and the replies to my comments by Asselot et al. I would like to thank the Authors for taking into account my comments. The manuscript is now more clear and scientifically soundings. I'm happy to suggest its publication in present form.

We thank the reviewer for its comments that improve the science behind our article.

Review of "**A missing link in the carbon cycle: phytoplankton light absorption under RCP emissions scenarios**"

by Rémy Asselot, Philip Holden, Frank Lunkeit and Inga Hense

General comments

Following the conclusions of Asselot et al (2022) who demonstrate that phytoplankton light absorption (PLA) mainly affects the climate system via air-sea CO2 exchange, the present study of Asselot and co-authors analyse the effect of activating the PLA in an earth system model (ESM) of intermediate complexity under emissions-driven (for CO2) scenarii of climate change.

Thanks to their framework with freely-evolving atmospheric CO2 concentrations, the authors show that the consideration of the PLA is critical, as it leads to an enhanced greenhouse gas effect in climate forecasts. Indeed it increases by 8 to 20% the global atmospheric CO2 concentrations. This result has great implications for climate forecasts: it highlights the importance of PLA-induced climate changes that a large proportion of current ESM do not consider, and proposes a quantification of this missing part of the atmospheric CO2 content under different climate scenarii (it identifies the PLA-induced changes as a function of climate change itself).

We thank Sarah Berthet for her review and her valuable comments.

However, two points need clarifications from my perspective:

- What implications has the use of an EMIC compared to a classical ESM in terms of feedbacks between the ocean and atmosphere ? This would give some clues on how your main results are generalizable.

Due to the simplified nature of EMICs, they simulate fewer climate feedbacks and simplified dynamics relative to high complexity ESMs. The largest simplification in our setup is the loss of atmospheric dynamics through the use of a 2D EMBM atmosphere, in which the surface wind-stress forcing is prescribed and fixed through time and between simulations. In the "Limitations" section we rephrased by:

"Additionally, if wind stress could evolve freely, as in classical high complexity ESMs, we suppose that the increase in atmospheric temperature would lead to increased wind stress. As a result, upwelling dynamics would be altered."

- One of the main result of this study is that PLA increases the surface net primary production in mid-latitude and upwelling regions due to a higher availability of nutrient concentrations, which is in turn driven by a higher remineralization at the ocean surface (and a reduced export efficiency). While this result is important, I would expect to understand to what perturbations of the oceanic physical conditions the higher remineralization is due.

Phytoplankton light absorption directly increases the surface oceanic temperature; promoting environmental conditions that increase surface remineralization (see equations in Ward et al. (2018)). Consequently, surface nutrient concentrations increase, leading to enhanced surface chlorophyll. Via the phytoplankton light absorption mechanism, the higher chlorophyll allows more heat to be trapped in the ocean surface.

Specific comments by section

Abstract

L.9 "This biogeophysical mechanism increases the surface chlorophyll": based on your Table 2, your net primary production (globally integrated) in 2500 increases by less than 2% for all RCPs when activating the PLA. Of course this is not comparable with the order of changes you cited in your introduction part (e.g. "chlorophyll concentration has declined over more than 62% of the ocean surface from 1890 to 2010", "between 1998 and 2006, low surface chlorophyll areas have expanded by 15%"...), but I would highlight that point in the abstract by giving the percentages of changes, because your results show that, by triggering NPP changes of less than 2%, the PLA may perturb the global atmospheric CO_2 content by 8 to 20%.

We rephrased to "this biogeophysical mechanism increases the surface chlorophyll by ~2%, the sea surface temperature by 0.2 to 0.6°C, the atmospheric CO_2 concentrations by 8-20% and the surface air temperature by 0.3 to 0.9°C".

L.15 "that may be" or "that are maybe" ?

We rephrased to "may be".

2 Methods

From the legend of figure 1, I understood that what differentiates your EMIC from what you call an "ESM of high complexity" here is mainly the use of a simplified atmospheric module ("EMBM") which is not a fully 3D atmospheric model…? Please, could you clarify that aspect in the text of section 2, and explain with one sentence what is EMBM: if not a 3D model, is it a slab layer of atmosphere ?

Yes the atmospheric component, EMBM is not a fully 3D atmospheric model. In the revised manuscript, we revised to:
"The atmospheric component is an Energy Moisture Balance Model (EMBM), which is closely based on the UVic Earth system model (Weaver et al., 2001). It is a 2D slab layer of the atmosphere".

L.72-74 the authors wrote "EcoGEnIE is an ESM of intermediate complexity (EMIC) (Claussen et al., 2002) and due to the limitations of such a model, we focus on the quantification of the large-scale impacts of phytoplankton light absorption but we do not quantify the components or drivers of those large-scale impacts".
I am wondering how could we trust the large-scale impacts of PLA analyzed here if we do not trust what cause them ? I understand from this sentence that, due to the limitations inherent to an EMIC, the authors do not trust the drivers of the PLA large-scale impacts. Please reformulate.

It is not that we do not trust the drivers, only that we do not attempt to quantify them, which is a layer of complexity deeper than our analysis has gone. The limitation to large-scale impacts is primarily the result of low resolution together with simplified dynamics which cannot address local-scale processes. We have omitted the clause which was causing misunderstanding and have rephrased to:

“EcoGEnIE is an ESM of intermediate complexity (EMIC) (Claussen et al., 2002) and due to the limitations of such a model, in particular its low resolution, we focus on the quantification of the large-scale impacts of phytoplankton light absorption”.

L.75-77 “We chose to conduct our study with an EMIC because we are interested on the effect on particular climate mechanism (e.g. phytoplankton light absorption) and it would have been difficult to isolate this effect with an ESM of high complexity, due to numerous climate feedbacks implemented in high complexity ESM.”
In their analysis of many ESM “of high complexity”, Séférian et al (2020) decomposed the Earth system interactions represented in ESM involving marine biogeochemistry into 4 main feedbacks: climate-carbon cycle feedbacks (F1), biogenic aerosol-cloud feedbacks (F2), non-CO2 biogeochemical cycle feedbacks (F3) and phytoplankton-light feedbacks (F4). It is not straithforward to me to see how climate feedbacks F1 to F3 would have perturb your analyses of the PLA-induced effects. Please, be more specific : give examples of the numerous feedbacks that would hinder the identification of PLA-induced effects. Don’t you mostly think here to ocean-atmosphere interactions (not existing in your case due to the use of a simplified atmosphere with EMBM) ? If true, please mention it.

Séférian, R., Berthet, S., Yool, A. et al. Tracking Improvement in Simulated Marine Biogeochemistry Between CMIP5 and CMIP6. Curr Clim Change Rep 6, 95–119 (2020). https://doi.org/10.1007/s40641-020-00160-0

As stated by the reviewer, we mainly think about ocean-atmosphere interactions. We added the sentences “For instance, in our model setup, the wind is prescribed and doesn’t change between simulations. Consequently, the effect of wind on ocean circulation is unchanged between the simulations and through time.”

2.1 Ocean, atmosphere and sea-ice representation

L.95 “However, on a global scale, Marsh et al. (2011) show that the model simulates realistic upwelling.”
With an horizontal resolution smaller than 3° in latitude (and not specified in longitude... but Ward et al., 2018 declare that they have 10° of longitudinal increments: what about yours ?…) and a minimum vertical spacing of 29 m, I guess “upwelling” refers to equatorial convergence, and not to coastal upwelling regions which have widths < 100 km, associated to very specific coastal dynamics needing quite fine horizontal and vertical resolutions to be represented. But even for equatorial regions, I find a bit inappropriate the expression “the model simulates realistic upwelling” as we know that your model represents only the very large-scale ocean dynamics. Could you describe in the text the dynamical conditions favoring these “realistic” upwellings in your model ?

We used the same horizontal grid as Ward et al. (2018) with a 10° longitudinal increment. Although we did not state that local scale upwelling is realistically modelled - only global scale upwelling - given the reviewer’s concerns, and the fact that there are different wind field forcing between Marsh et al. (2011) model setup and our model setup, we have deleted this sentence.

L.96-107 Again, could you clarify why this 2D atmospheric model was a more suitable choice than the fully 3D atmospheric model PLASIM in your framework ? Could you add a sentence explaining how the use of this simplified atmosphere may help revealing the PLA effects ?

The simplified atmospheric component simplifies climate feedbacks, such as ocean-atmosphere interactions. We refer the reviewer to our answer to her comment l.75-77. We note that the use of the EMBM is well suited for ocean model development given the run time of PLASIM-GOLDSTEIN (50 model years per CPU day) increases the computational demand by several orders of magnitude relative to the EMBM-GOLDSTEIN version (5000 years per model day).

2.3 Ecosystem community component

l.126 “messy feeding” ?

Corrected

l.145 “so the rate”

Corrected

2.8 Model inter-comparison

l.225 comparison with an other EMIC (“an ESM of intermediate complexity”) model: but more generally the reader is curious to know what would give the comparison with a high-complexity ESM?

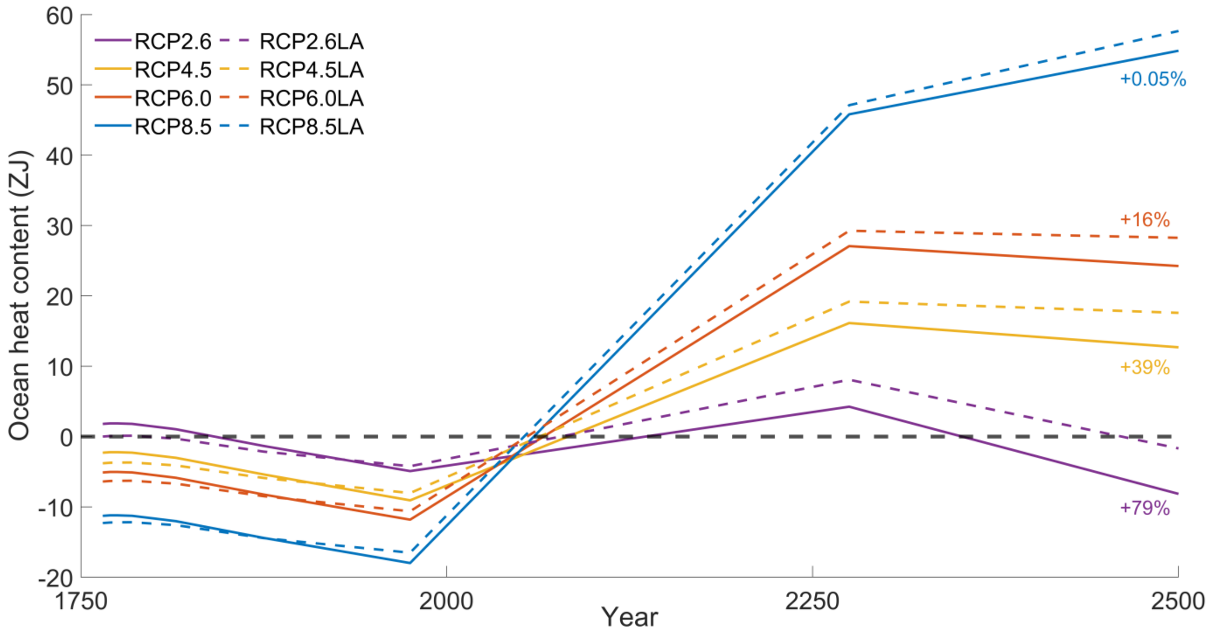
Thank you for this suggestion. We have now revised Fig 3 to also include a comparison with the CMIP5 ensemble. Independently of the RCP scenario, our increases in SAT are in close agreement with the ensemble mean warming of the EMIC and CMIP5 inter-comparisons, and comfortably within the ensemble ranges.

More generally, I understand that this first comparison focused on surface atmospheric temperature (SAT) because it allows to validate the use of a simplified atmospheric model in this study...? But back to the main goal of this study (effect of the PLA), I would expect here some elements characterizing how the ocean compartment absorbs heat without PLA (ocean heat content or at least ocean temperature). This would allow to discuss later the true PLA effect added by your equation (3). If Zickfeld et al (2013) have no ocean heat data, I suggest you to insert a small paragraph (and figure) characterizing the ocean heat content changes (or time series: see for example Figure 1 of Berthet et al, 2023) for each of your RCPs without and with PLA. Based on eq. (3), the first effect PLA will have on climate before any feedbacks on the biological pump/CHL/atmospheric CO2/SAT, will be to perturb the oceanic temperature, no ? So the first question for me is: how much ocean heat content is altered by the activation of your PLA parameterization ? Could you elaborate a bit on that point ?

Berthet, S., Jouanno, J., Séférian, R., Gehlen, M., and Llovel, W.: How does the phytoplankton–light feedback affect the marine N2O inventory?, Earth Syst. Dynam., 14, 399–412, https://doi.org/10.5194/esd-14-399-2023, 2023.

As requested by the reviewer, we have now computed the time-series of ocean heat content for all the simulations. The ocean heat content anomalies are computed with respect to the mean of the time-series. Independently of the RCP scenario, phytoplankton light absorption increases the ocean heat content in the top 2000m of the water column (see figure below). However, the relative changes in ocean heat content strongly vary between the scenarios. For instance, ocean heat content increases by 79% for RCP2.6 while it only increases by 0.05% for RCP8.5. This is in agreement with our findings, where phytoplankton light absorption has a reduced effect on the climate under RCP8.5 compared to the other RCP scenarios.

We added the figure below in appendix and reported the values of the relative ocean heat content changes in the result section. In the main text, we added the sentences “Phytoplankton light absorption warms the surface of the ocean and increases the ocean heat content (Appendix C1). For the scenarios RCP2.6, RCP4.5 and RCP6.0, ocean heat content in the top 2000 m increases by 16-79%. For RCP8.5, this increase is strongly reduced to 0.05% reflecting the lower increase in global surface chlorophyll under this scenario.”.



3 Results

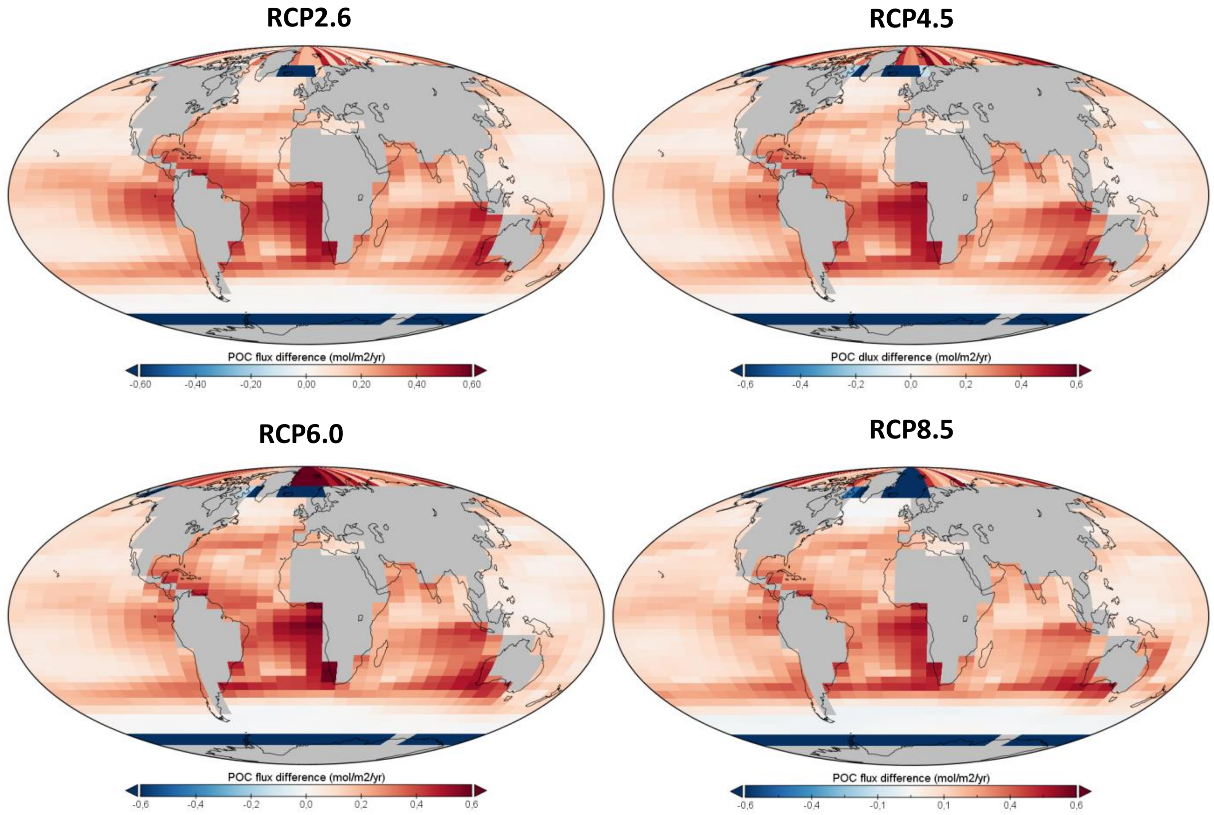
3.1 Oceanic properties

l.240 I would suggest to reformulate: “when PLA is activated” or “represented”, rather than “simulated” ; this is only a suggestion, as my english is far from being perfect.

We changed to “activated”.

L.241 How is the spatial pattern of this POC flux reduction ? Do you observe a reduction over the entire globe ? Or is it consistent with the patterns you described for the chlorophyll (l.266-270), i.e. mainly marked in upwelling and mid-latitude regions ?

We plotted the difference of surface POC flux between the simulations (see below). The maps represent the simulation without minus with phytoplankton light absorption. Red colours represent a higher POC flux for the simulations without phytoplankton light absorption while blue colours represent a lower POC flux without phytoplankton light absorption compared to the corresponding simulation with this biogeophysical mechanism.
The patterns of POC flux reduction is consistent with the patterns described for chlorophyll. The reduced surface POC flux is mainly marked in the upwelling and mid-latitude regions.



L.242 “independently of the RCP scenario”: by activating the PLA, the oceanic temperature increases in sub-surface in all scenarii, but with different intensities, no ?

Phytoplankton light absorption leads to an increase in temperature along the whole water column (Figure C1 in Appendix and the figure about ocean heat content above).

l.245 “Indeed, the surface net primary production increases with phytoplankton light absorption”: could you explain why ? To what perturbations of the physical conditions is it due (see my general comment on section 2.8) ? Please elaborate on that.

Phytoplankton light absorption increases oceanic temperature, promoting environmental conditions that increase surface remineralization (Ward et al., 2018), increasing nutrient concentration and thus surface net primary production. We added the sentence:
“Indeed, phytoplankton light absorption increases the oceanic temperature (see below), promoting environment conditions that increase the surface remineralization (Table 2). Consequently, the nutrient concentration (Table F1) and thus the net primary production in the surface ocean layer is enhanced.”

3.1.2 Surface chlorophyll

L.266 Unlike the results of Paulsen (2018), who reports a decline in chlorophyll concentrations in the upwelling regions with PLA (L.46), you find a higher chlorophyll (CHL) concentration in the upwelling and mid-latitude regions with PLA in your model and framework: could you explain why Paulsen obtained an opposite feedback with its “Earth system model of high complexity” ? By which mechanism ? Does your EMIC represent this mechanism ? Or is this different behaviour attributable to the fact that Paulsen run its ESM under prescribed future atmospheric CO2 concentrations rather than freely-evolving emissions: in this case could you explain by which mechanism the atmospheric CO2 concentration may constrain the CHL to decrease locally in upwelling regions ?

Paulsen et al. (2018) reports a decline in chlorophyll in the upwelling regions with PLA because her ESM simulates a decline in the strength of the upwelling (see section 4.5.3 of Paulsen et al. (2018)). The reduced upwelling strength is caused by a shoaling of the oceanic mixed layer depth and a decrease of the trade winds (Paulsen et al., 2018). In contrast, our results show an increase in chlorophyll in upwelling regions because, in these regions, the upward vertical velocity is enhanced by phytoplankton light absorption (increased upwelling strength).
We apologize for the confusion here because in the previous version of the manuscript we wrote that "Paulsen et al. (2018) reports an enhanced circulation in the upwelling regions", which is not true. We rephrased by:
"With phytoplankton light absorption, Paulsen et al. (2018) reports a decline in chlorophyll concentrations in the upwelling regions due to a reduced upwelling strength. However, this local effect is outweighed by advective process such as the upward transport of warmer subsurface water originating off-equator, leading a local oceanic warming of up to 0.7°C."

3.1.3 Sea surface temperature

L.273 "Due to changes in surface chlorophyll, we expect variations in SST".
What do you mean exactly here ? Due to changes in 1) surface chlorophyll concentration or 2) in absorption properties of surface chlorophyll ? This does not imply the same chain of causality:
– case 1) describes the fact that PLA activation directly affects CHL concentration and, then, indirectly affects the SST due to the CHL concentration changes. However, in this case, could you clarify what mechanism triggers the initial perturbation of your CHL concentration ? In other words, how the PLA activation affects your CHL concentration ?
– case 2) describes the fact that activating PLA has first a direct effect on ocean temperature. And that the other effects on CHL/export/remineralization arise from that one.

We meant that we expect variations in SST because activating phytoplankton light absorption has a direct effect on oceanic temperature (case 2). To avoid confusion, we removed this sentence.

3.2.1 Atmospheric CO2 concentration

L.293 I am a bit puzzled about these runs driven by CO2-emissions that do not match the target. I am not sure to fully understand the implications that could have on your analyses. Could you elaborate on it ?

Generating a tuned version of a new climate-carbon-cycle model coupling is highly demanding. We chose to tune the model's primary production to generate realistic plankton biomass and export production. We focus on the relative changes between simulations with and without phytoplankton light absorption and so are less interested in the absolute climate state. Although a differently tuned model would (by definition) exhibit differences in any state-dependent feedbacks, we demonstrate in Figure 3 that the carbon cycle response is largely insensitive to this background state, and the model reflects the responses to a wide range of emissions shown by EMIC and CMIP5 ensembles. We rephrased:
"We are interested in relative changes between our simulations rather than the absolute values, so the specifics of the background state are unlikely to affect the qualitative findings of the study, especially given that the carbon-cycle response to a range of emissions is consistent with IPCC model intercomparison projects (Figure 3)."

L.302 "For the RCP8.5 scenario, the atmospheric CO2 concentration increases by 8% only, which is due to the lower increase in chlorophyll and SST".

To demonstrate this assertion it would be interesting to see maps of atmospheric and oceanic CO2 partial pressure, as well as DpCO2 for all RCPs. Because in the current state I am not sure you have enough elements to directly conclude what you wrote. For me, you need to disentangle here 1) how the PLA activation changes your ocean CO2 content, from 2) how the CO2 atmospheric content in RCP8.5 allows to absorb new oceanic outgassing compared to the other RCPs. Your results in figures 7 and 8 show a non-linear behaviour of RCP8.5 compared to the other three RCPs, which is most likely attributable to a non-linear effect of the increased atmospheric CO2 concentrations.

Due to the 2D atmospheric component of our model, the atmospheric pCO2 is uniform over the whole world. Rather than showing maps, we report here and in appendix the changes in oceanic CO2 concentration and in atmosphere-ocean CO2 fluxes. The table below summarizes these results; negative values in the second column indicate a lower oceanic CO2 concentration in the simulations with phytoplankton light absorption while positive values in the third column indicate a higher outgassing of CO2 with phytoplankton light absorption. The decrease in oceanic CO2 concentration and the increase in air-sea CO2 flux are reduced under RCP8.5 scenario compared to the other scenarios. This result shows, again, the non-linear behaviour of RCP8.5 compared to the other three RCPs. We rephrased by:
"For the RCP8.5 scenario, the atmospheric CO2 concentration increases by only 8%. This lower increase in atmospheric CO2 concentration is due to the lower decrease in oceanic CO2 content and lower increase in air-sea CO2 flux (Appendix D1). These reduced changes in between the different CO2 reservoirs are due to the lower increase in chlorophyll and SST."

	Oceanic CO2 concentration	Air-sea CO2 flux
RCP2.6	-14.0%	+17.4%
RCP4.5	-12.1%	+15.6%
RCP6.0	-11.4%	+14.8%
RCP8.5	-2.0%	+1.3%

From my perspective you did not dig deep enough into this aspect, because it was one of the main conclusions of your work: the effect of PLA activation is not linear and depends on the climate scenario. You may show that RCP8.5 crossed a tipping point (due to an extensive ice melt and other effects) what changes the way the ocean-atmosphere system manages the CO2 exchanges and finally, modulates the effect/amplitude the PLA activation may have on climate.

In the general discussion section we added the sentence:
"Our results show that there is the potential of a tipping point (which is crossed in RCP8.5 in our model) at which changes in the climate system modulate the effect of phytoplankton light absorption."

4.1 General discussion

L.334 "Our results show that phytoplankton light absorption affects water temperature and nutrient concentrations."
Please see my related comment in section 3.1.3.

We rephrased by:
"Our results show that phytoplankton light absorption has a direct effect on oceanic temperature, affecting, in consequences, the biogeochemical properties of the ocean."

L.335 "The increase in surface nutrient concentrations (Appendix D1) is driven by a reduced export efficiency of organic matter and enhanced remineralization at the ocean surface (Table 2)."

While I found the result of more remineralization in surface very interesting, I still have the feeling that something is missing in your analyses. You did not explain (or I missed it, so maybe it would be great to clarify it) by what mecanisms does the PLA activation affect your modelled remineralization and export ? This will possibly also help understand why RCP8.5 does not react proportionally to the other RCPs when activating the PLA.

The modelled remineralization and export depend on the oceanic temperature (Ward et al., 2018). The activation of phytoplankton light absorption increases oceanic temperature, increasing in turn the surface remineralization and reducing the POC export flux. We rephrased to:
"Activating phytoplankton light absorption directly increases the oceanic temperature, which reduces export efficiency of organic matter and enhanced remineralization at the ocean surface. Consequently, the surface nutrient concentration increases, which leads to a higher chlorophyll. Via the phytoplankton light absorption mechanism, this higher chlorophyll creates a feedback loop, leading to a warmer ocean."

L.336 "The increased surface nutrient concentrations leads to higher surface chlorophyll, which in turn leads to a warming of the ocean surface."
Here I interpreted that you choose the case (1) of my comment in section 3.1.3.

Phytoplankton light absorption has a direct effect on oceanic temperature, which in turn affects the biogeochemical properties of the ocean (case 2). See answer to comment L.335 (just above).

4.2 Limitations

L. 384 "Our results highlight that phytoplankton light absorption itself increases chlorophyll leading to more heat being trapped in the ocean surface."
My guess is that PLA promotes environmental conditions in ocean surface temperature that allow an increase in remineralization in surface, what triggers an increase in nutrients concentrations and, thus, an increase in CHL concentrations allowing more heat to be trapped: is that what you mean ? Please clarify

We agree with the reviewer and rephrased by:
"Our results highlight that phytoplankton light absorption increases ocean surface temperature, allowing an increase in surface remineralization and triggering an increase in nutrient concentrations. As a consequence, chlorophyll increases allowing more heat to be trapped in the ocean surface."