Review of "How does the phytoplankton-light feedback affect the marine N_2O inventory?" by Berthet et al.

Reviewer #2: Anonymous Referee #2, 16 Sep 2022

OVERVIEW

The authors study the effect of light absorption by phytoplankton on the heat content of the ocean and subsequently on N20. They run simulations with full/partial representation of this process and study its effect. They demonstrate that indeed the biooptical coupling influences N20 and the heat content of the ocean. I propose some modification to this manuscript prior to publication, which are given below.

We appreciate your thoughtful review of our manuscript. We have addressed all points you raised in our revised manuscript, and we hope that the manuscript is now ready for publication. Please find below our detailed response (blue text) to your comments (black text). In our responses, changes to the manuscript are indicated by ***bold italicized*** text and lines numbers are relative to the new manuscript.

GENERAL COMMENTS

1. The model was spun up considerably longer than the simulation runs. Please elaborate as to why not use longer simulation runs?

Our framework shows that a period of 20 years is long enough to highlight that the 3 numerical solutions diverge (see Figure 1). We choose the period 1999-2018, as it corresponds to the last 20 years of the JRA55 atmospheric forcing which is the most realistic forcing we currently have. In addition, this period is of interest because it is well covered by observations: for example, observations of ocean heat content really started in 2005 with a massive Argo deployment.

In the first version of the manuscript we mentioned that the model was spun-up for 2000 years. This correspond to the accumulated spin-up of all the simulations that we started from the older ones in our modelling group. We mentioned it in the first draft to certify that our model was in quasi-steady state. But we agree that the protocol was not very understandable for the reader. To clarify our spin-up protocol we rewrote this part as follows (lines 184-190):

"***JRA55-do atmospheric reanalysis (Tsujino et al., 2018; Tsujino et al., 2020) provided the atmospheric forcings of the ocean. The global domain was first spun-up under preindustrial conditions during several hundred years ensuring that all fields approached a quasi-steady state. The historical evolution of atmospheric CO_2 and N_2O concentrations was prescribed since 1850. To avoid the warming jump between the end of the spin-up and the onset of the reanalyses in 1958, the first 5 years of JRA55-do forcings were cycled, followed by the complete period of JRA55-do atmospheric forcing from 1958 to 2018.***"

2. The overall text seems to be missing a thread and has too many shorthand notations. While familiar to the authors and others in the field, this hampers the flow of the paper

substantially. I suggest reducing the usage of shorthand notation and move some of the technical parts to the supplement.

We reduced the use of shorthand notation by suppressing six of them (SW, SST, OMZ, ORCA1, T/S and WOA09). We only kept the ones that we use all along the text: PLF (phytoplankton-light feedback), OHC300 (ocean heat content of the upper 300 meters depth), CHL (chlorophyll), Dpn2o (N2O partial pressure difference across the air-sea interface) and chemical names (N2O/CO2/O2). NEMO, PISCESv2 and CNRM-ESM2-1 are model names. CMIP and OMIP are acronyms very used in climate sciences, but to clarify we added the definition of CMIP6 in the abstract at lines 16: " Only one third of the Earth system models contributing to ***the 6th phase of the Coupled Model Intercomparison Project (CMIP6)*** includes a complete representation of the PLF."

As requested section 2b presenting the N2O parameterization has been moved to the supplementary material.

3. Given the paper deals with the effect of the biooptical coupling I suggest the authors add exact mathematical expressions which describe this process. It is described somewhat shortly in lines 218 to 224. For example: please state the exact equations which model how phytoplankton affects light penetration.

Please see how we reorganize section 2 ("Methodology"). While the subsection presenting the N2O parameterization has been moved to the supplementary material, a new subsection (2b) is now dedicated to the formulation of the PLF, in which we describe it as follows (starting at line 192):

"b) Experimental design: three representations of the PLF

The control simulation (hereafter REF) together with the spin-up both account for a fully interactive PLF: the penetration of shortwave radiation into the ocean surface is constrained by the CHL concentration ([CHL]) produced by the PISCESv2 biogeochemical component ***(Figure S1, REF)***.

PISCESv2 simulates prognostic 3D distributions of nanophytoplankton and diatom concentrations. The evolution of phytolankton biomasses is the net outcome of growth, mortality, aggregation and grazing by zooplankton (Aumont et al., 2015). Light absorption by phytoplankton depends on the waveband and on the species (Bricaud et al., 1995). A simplified formulation of light absorption by the ocean is used in our experiments to calculate both the phytoplankton light limitation in PISCESv2 and the oceanic heating rate (Lengaigne et al., 2007). In this formulation, visible light is split into three wavebands: blue (400–500 nm), green (500–600 nm) and red (600–700 nm); for each waveband, the CHL-dependent attenuation coefficients, $\boldsymbol{k_R}, \boldsymbol{k_G}$ and $\boldsymbol{k_B}$, are derived from the formulation proposed in Morel and Maritorena (2001):

$$k_{WLB} = \sum_{\lambda_1}^{\lambda_2} \left(k(\lambda) + \chi(\lambda) [CHL]^{e(\lambda)} \right) \qquad \textbf{(1)}$$

where WLB means the wavelength band associated to red (R), green (G) or blue (B), and bounded by the wavelengths λ_1 and λ_2 as detailed above. $k(\lambda)$ is the attenuation coefficient

for optically pure sea water. $\chi(\lambda)$ and $e(\lambda)$ are fitted coefficients which allows to determine the attenuation coefficients due to chlorophyll pigments in sea water (Morel and Maritorena, 2001).

At year 1999 two sensitivity experiments were branched off (**Error! Reference source not found.**). Both simulations climZCST and climZVAR account for an incomplete and external PLF, as they consider an observed climatology of surface [CHL] from ESACCI (Valente et al., 2016) in order to compute the light penetration into sea water (***Equation 1; Figure S1***). These two simulations differ from each other by the "realism" of the vertical profile derived in each grid point from the surface value of the ESACCI CHL climatology to the level of light extinction (Table 1). ***climZCST uses constant profiles of CHL spreading uniformly in the vertical direction (Figure 2, b and d-f). climZVAR uses variable vertical profiles computed following Morel and Berthon (1989) (Figure 2, c and d-f)***. This set of simulations is representative of the several configurations used in the case of CMIP intercomparison project.

[...]"

Subsequently, how does this affect the rate of phytoplankton growth, rate of heating at depth, and so on. I consider this to be of high value for non-experts. Also, it would make the model more easily reproducible.

As shown by equation 1 the PLF has only one direct effect, on the quantity of light penetrating the water column. By modulating the quantity of light reaching the subsurface, the chlorophyll-light interaction will effectively change the ocean heat content and the photosynthesis. However, as explained in the introduction, the net effect of PLF is a mix between direct thermal (local and remote) and indirect dynamical effects. This is why there is no simple quantification of the perturbation that the PLF exerts on phytoplankton growth or rate of heating at depth. To quantify these effects our only solution is to integrate a 3D model of ocean physics and marine biogeochemistry.

4. Please state the governing equations for phytoplankton dynamics: in particular the growth term of phytoplankton as a function of light, nutrients and temperature. What limits growth? How is the loss term parametrized? Does light penetration feedback onto the growth rate? Does temperature effect the growth rate? Is the model time step adequate to resolve this?

PISCESv2 (Pelagic Interactions Scheme for Carbon and Ecosystem Studies volume 2) is a 3D biogeochemical model which simulates the lower trophic levels of marine ecosystems (nanophytoplankton, diatoms, microzooplankton and mesozooplankton), the biogeochemical cycles of carbon and of the main nutrients (P, N, Fe, and Si). The revised section 2b clarifies this as follows (lines 199-201):

"***PISCESv2 simulates prognostic 3D distributions of nanophytoplankton and diatom concentrations. The evolution of phytoplankton biomasses is the net outcome of growth, mortality, aggregation and grazing by zooplankton (Aumont et al., 2015).***"

Aumont et al. (2015) give a complete description of this complex biogeochemical model which represents the evolution of 24 prognostic variables (see Figure R1) and in which 5 pages are dedicated to phytoplankton dynamics. We cannot reproduce them here, but we give you a short overview below:
PISCESv2 considers that biomasses of nanophytoplankton and diatoms experience growth, mortality, aggregation and grazing by micro- and mesozooplankton (see attached Figure R1). The 3 latter processes compose what you called "the loss term". Growth rate mainly depends on the length of the day, the depth of the mixed layer and the depth of the euphotic zone (defined as the depth at which there is 1‰ of surface photosynthetic available radiation). Light absorption by phytoplankton depends on the waveband and on the species. Nanophytoplankton growth depends on the external nutrient concentrations in N and P (Monod-like parameterizations of N and P limitations), and on Fe limitation which is modeled according to a classical quota approach. The production terms for diatoms are defined as for nanophytoplankton, except that the limitation terms also include Silicate. Nutrient half-saturation constants vary with the phytoplankton biomass of each compartment because the observations show that the increase in biomass is generally due to the addition of larger size classes of phytoplankton. The aggregation term depends on the shear rate, as the main driver of aggregation is the local turbulence. The diatoms aggregation term is increased in case of nutrient limitation because it has been shown that diatoms cells tend to excrete a mucus which increases their stickiness. As a consequence, collisions between cells yield to a more efficient aggregation process.

Modulating light penetration through the PLF is expected to change light availability for biogeochemical cycles (labelled "Photosynthetic Available Radiation" on Figure R1) as well as physical properties of the ocean waters (what we show in our manuscript). That would indirectly change the conditions for CHL production. However, our set of experiments show no marked perturbations in terms of CHL production in climZCST and climZVAR compared to REF (Figure R2). As shown by our manuscript, main biogeochemical perturbations arise from those of temperature, ocean heat content, dynamics and stratification.

Finally, yes, the time step is adequate to resolve the processes mentioned above on a spatial grid at 1 degree of horizontal resolution: our oceanic configuration of the NEMO model had a timestep of 1800 seconds (30 min) and marine biogeochemistry (PISCESv2) has been called at every timestep of the ocean physics.

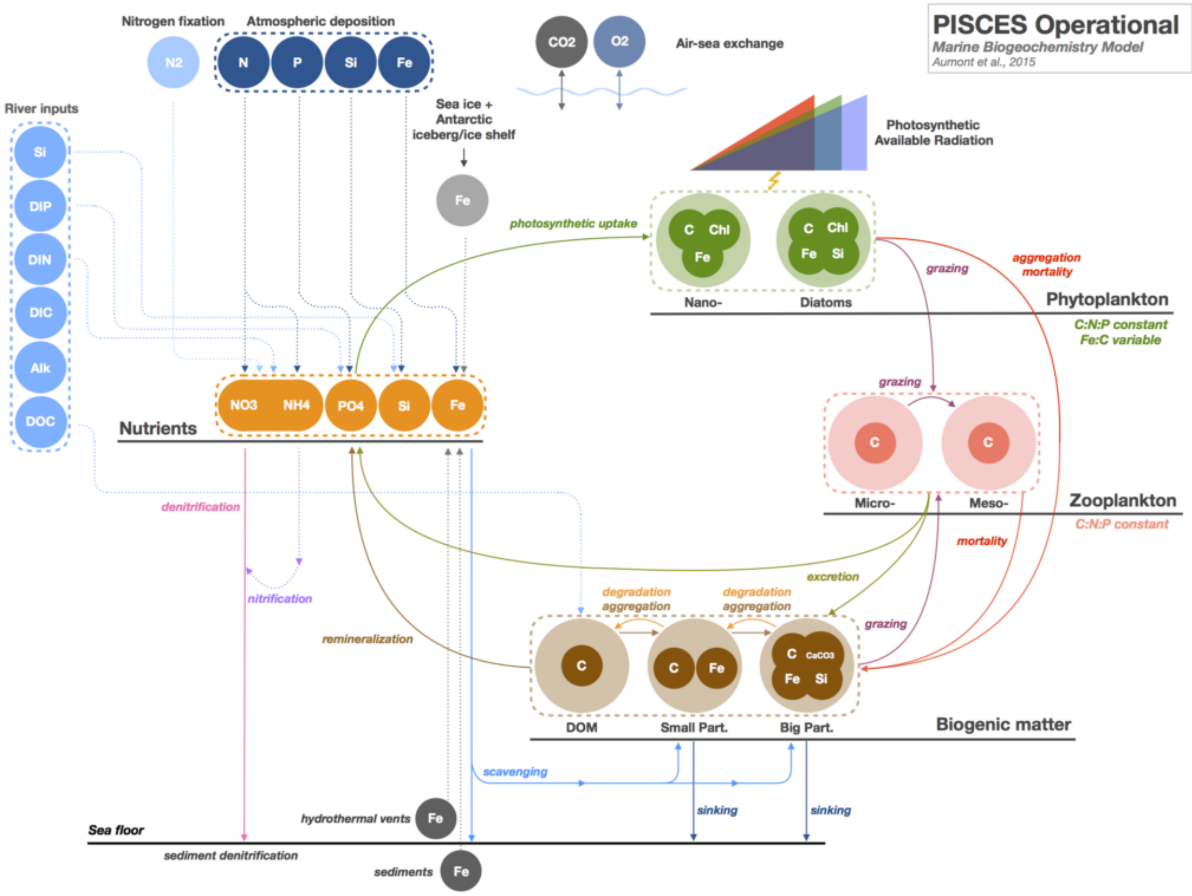

Figure R1: Schematic diagram of the standard version of PISCESv2 describing the nutrients, carbon and oxygen cycles and processes modelled.

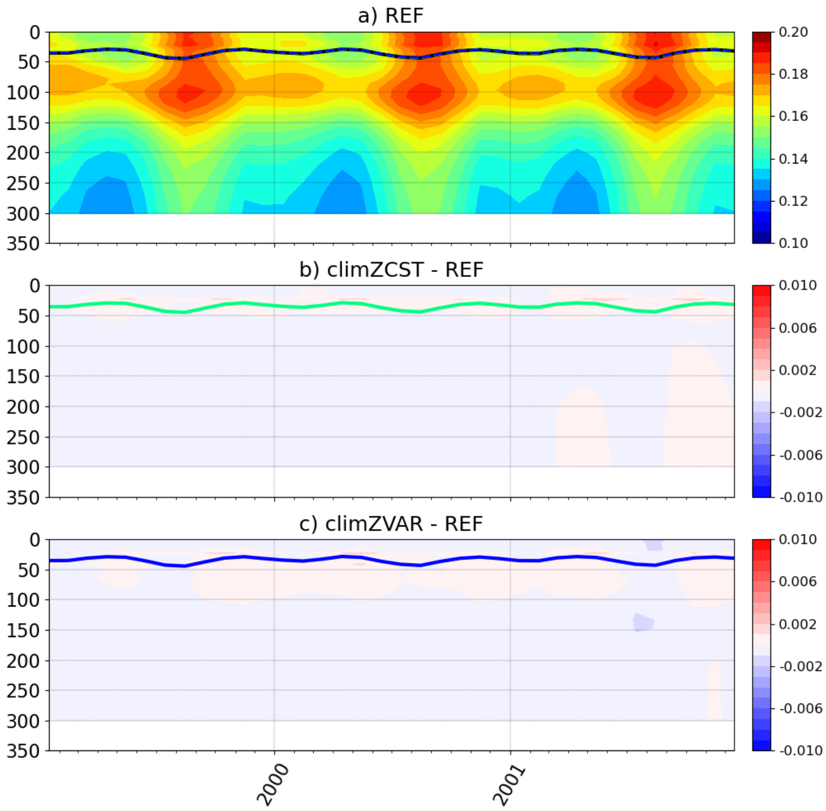

Figure R2: Time versus depth diagram of the mean chlorophyll (mg/m^3; shading) and mixed layer thickness (m; color line) averaged over the tropical area [35S-35N; 0-360E].

Note that for our study the marine N2O cycle (now described in the supplementary material on your request) has been added in PISCESv2.

5. Please add a figure displaying the model structure, highlighting the part related to biooptical coupling and the link to nitrous oxide, as it is the core of the paper.

Figure R3 below has been added in the supplementary material, as Figure S1. We choose to not add it in the main text.

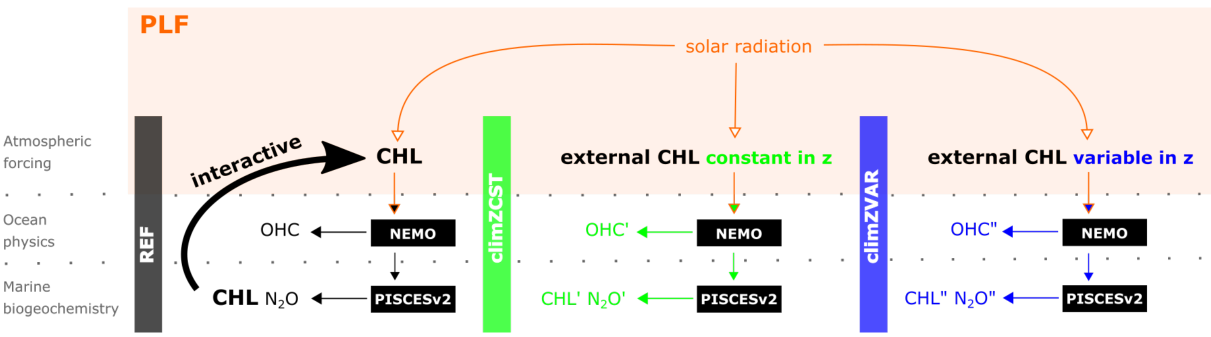

Figure R3: Schematic diagram of the numerical set. The phytoplankton-light feedback (PLF) encompasses the interaction between the incoming solar radiation (identical among the 3 simulations) and the CHL concentration used to filter its penetration into the water column. Different representations of the PLF are distinguished in function of the CHL used to filter the incoming radiation: it is either computed from PISCESv2 model (REF) or externally prescribed from an observed climatology (climZCST and climZVAR). We show that the nature of the CHL chosen to interact with light determines different states of the ocean physics (e.g. OHC, temperature, dynamics, stratification) that drive different states of the marine biogeochemistry (e.g. N_2O, CHL, O_2).

6. The effect of phytoplankton on the mixed layer depth is mentioned in line 447 (I assume the authors mean heating due to the biooptical feedback). Here the effect of wind is stated to alter the mixed layer depth more strongly than phytoplankton. However, it is known since Platt et al. (2003) that the phytoplankton change their biomass so that the Critical depth (Sverdrup, 1953) matches the mixed layer depth. This occurs due to the biooptical coupling that the authors explore. Please elaborate more on this.

The winds and air-sea fluxes are expected to control the mixed-layer depth and more generally the thermal stratification more strongly than phytoplankton. The point we wanted to raise in the passage between line 395 and 399 was that the differential heating is expected to have a major impact in regions with low mixing conditions (in region with high mixing the effect of differential heating between the surface and subsurface layers is almost instantaneously mixed and is not expected to have some impact on the stratification). This interpretation is in line with Figure 5 that shows a major impact on the pycnocline depth in the low wind subtropical regions.

The corresponding sentence has been modified as follows: « ***As stressed by Sweeney et al. (2005), small changes in CHL concentration (Figure 2) may have important effects on the mixed layer depth in these subtropical gyres due to low local wind speeds and low mixing conditions. This is thought to explain the large sensitivity we observe in terms of pycnocline depth (Figure 5) and ocean heat content in these regions."***

Regarding the attraction of the critical depth to the mixed-layer depth. A first point we want to raise is that the CHL produced by the biogeochemical model PISCESv2 is poorly impacted by the change of PLF representation (Figure R2; and we show that N_2O concentration is much more sensitive than CHL to these changes). This suggests that in average the critical depth is weakly impacted by the PLF. But we did not check whether the attraction of the critical depth to the mixed layer depth may be locally modulated by the winds/mixing conditions. This could be interesting but we think that it is out of the scope of our study.

REFERENCES

Sverdrup, H. U. (1953). On conditions for the vernal blooming of phytoplankton. *Journal du Conseil International Pour lExplorationde la Mer*, 18: 287–295.

Platt, T., Broomhead, D. S., Sathyendranath, S., Edwards, A. M., Murphy, E. J. (2003). Phytoplankton biomass and residual nitrate in the pelagic ecosystem. Proceeding of the Royal Society A, 459: 1063–1073.

SPECIFIC COMMENTS

L14 Please rephrase the sentence starting with "Considering…".

Done, see lines 14-15: "***The PLF allows to simulate differential heating across the ocean water column as a function of the phytoplankton concentration.***"

L65 Change "into" to "through".

The sentence has been reformulated (line 65): "***It implies that the chlorophyll (CHL) produced by the biogeochemical model is used to determine the fraction of shortwave radiation penetrating ocean surface waters.***"

L67 Please remove "(because the same)".

Done.

L72 – L109 Suggested references on this effect from the literature:

Edwards, A. M., Wright, D. G., Platt, T. (2004) Biological heating effect of a band of phytoplankton. *Journal of Marine Systems*, 49, 89-103. doi: 10.1016/j.jmarsys.2003.05.011.

Edwards, A. M., Platt, T., Wright, D. G. (2001) Biologically induced circulation at fronts. *Journal of geophysical research*, 49, 89-103. doi: 10.1016/j.jmarsys.2003.05.011.

Thanks for that interesting papers. We added the references to your papers at line 79 as follows:

"Enabling a phytoplankton-light interaction ***modifies the hydrodynamics of the water column (Edwards et al., 2001; Edwards et al., 2004)***, the intensity of the spring-bloom in subpolar regions (Oschlies, 2004), the maintenance of the Pacific Cold Tongue (Anderson et al., 2007), the seasonality of the Arctic Ocean (Lengaigne et al., 2009), the strength of the tropical Pacific annual cycle, as well as the ENSO variability (Timmermann and Jin, 2002; Marzeion et al., 2005), the northward extension of the meridional overturning circulation (Patara et al., 2012) and the cooling of the Atlantic and Peru-Chili upwelling systems (Hernandez et al., 2017, Echevin et al., 2022)."

L152 Please rephrase the sentence starting with "In that perspective…".

We changed the sentence as follows (line 157): "***Here we investigate*** how an incomplete representation of the ***PLF leads to uncertainties in N_2O projection*** in an up-to-date global ocean-biogeochemical model making up the current generation of Earth system models."

L209 Table 1 should be on top of the table. Suggest renaming chl_inter, clim_zcst, clim_zvar so as to drop the "_".

The legend of Table 1 has been moved to the top of the table.

We renamed our simulations and drop the underscore. Our control experiment which uses an interactive CHL to infer the PLF is now called "REF". Our two sensitivity experiments are now called climZCST and climZVAR. "clim" refers to the use of an externally prescribed climatology, and "ZCST" or "ZVAR" denote the nature of the vertical profile z that we respectively impose constant or variable.

L231 – L317 Please move to the Introduction.

Following your suggestion to move the technical parts to the supplementary, we moved section 2b regarding N2O parameterization to the supplementary material.

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