

## Answer to referee #2:

We thank referee #2 for taking the time to provide valuable comments and suggestions that have helped to improve our manuscript.

Below, we include our detailed answers to all comments and questions.

### Answers to general comments (GC):

“ [...] a few additional sentences might help that discuss

**GC1:** *The choice of food preferences and feeding parameterization of zooplankton. What I could find in preceding papers of the BEC model is that zooplankton is parameterized via fixed feeding preferences. However, other biogeochemical models have applied zooplankton grazing formulations that saturate with the total amount of food, or even employ a switching behaviour of zooplankton (see, e.g., Appendix A of the classic paper by Fasham et al., 1990, J. Mar. Res., 591-639). A few notes on that could complement the discussion; also, given that this process seems to be of importance, it might be helpful for the reader to have a brief explanation of the grazing formulation (and the preferences) in the methods description (so that the reader does not have to look up earlier papers).*

We thank the reviewer for raising this point. The reviewer is correct in that BEC currently assumes fixed feeding preferences, which are set by differences in the maximum grazing rate  $\gamma_{g,max}$  across the PFTs. Here, based on size assumptions, we assume a preferential feeding of the single zooplankton grazer in ROMS-BEC on smaller phytoplankton (higher  $\gamma_{g,max}$  for small phytoplankton and coccolithophores than larger ones like diatoms and *Phaeocystis*, see table 1 in manuscript). Similarly, we assume preferential feeding on diatoms relative to *Phaeocystis* colonies (see section 2.1 of the original version of the manuscript).

Admittedly, by only including a single grazer that includes characteristics of both micro- and macrozooplankton (see **Moore et al., 2002**, but especially **Sailley et al., 2013**), the grazing formulation in ROMS-BEC is likely overly simplistic (e.g. **Le Quéré et al. 2016**). Furthermore, not accounting for adaptive feeding preferences or for total biomass to saturate zooplankton feeding at high total biomass levels are major shortcomings of the current parametrization (**Vallina et al. 2014; Vallina and Le Quéré, 2011**). These can be expected to significantly alter the interactions of the zooplankton with each PFT over the course of the growing season by e.g. temporarily alleviating the grazing pressure on all or single phytoplankton PFTs. The inclusion of multiple zooplankton functional types in ROMS-BEC is planned in current and ongoing work in our lab, but goes beyond the scope of this paper. Rather, the action of the zooplankton FT upon its prey should be viewed as a closure term, with phyto- and zooplankton biomass tightly coupled in space and time.

To clarify for the reader what parametrizations are currently used in ROMS-BEC, we have included a full description of the model equations describing growth and loss rates of phytoplankton biomass, including the equation for grazing, in the appendix of the revised version of the manuscript (see also our answer to reviewer #1):

The single zooplankton grazer  $Z$  [ $\text{mmol C m}^{-3}$ ] feeds on the respective phytoplankton  $P^i$  [ $\text{mmol C m}^{-3}$ ] at a grazing rate  $\gamma_g^i$  [ $\text{mmol C m}^{-3} \text{ day}^{-1}$ ] that is given by:

$$\gamma_g^i = \gamma_{max}^i \cdot f^Z(T) \cdot Z \cdot \frac{P^i}{z_{grz}^i + P^i} \quad (\text{B12})$$

with

$$f^Z(T) = 1.5 \cdot \exp\left(\frac{T - T_{ref}}{10^\circ\text{C}}\right) \quad (\text{B13})$$

In the discussion section 4.1, we have modified the text to mention the shortcomings of the grazing parametrization in ROMS-BEC more explicitly:

“Additionally, as discussed in Nissen et al. (2018), the lack of multiple zooplankton groups in the SO model (Le Quéré et al. 2016), and the parametrization of the single zooplankton grazer using fixed prey preferences and separate grazing on each prey using a Holling Type II function (Holling et al., 1959), which thus precluding a saturation of feeding at high total phytoplankton biomass, are major limitations of ROMS-BEC.”

**GC2: Aggregation:** *To my opinion, this term is somehow loosely defined in the present paper. Sometimes it is referred to as "mortality" (Table 1), sometimes as aggregation. Do phytoplankton become detritus after aggregation? But why? Theoretically, this process only describes that the cells or colonies collide and stick together - will they instantaneously stop being "green", i.e. cease photosynthesis and growth and become detritus? I assume that this is the case in the model, possibly with the argument that in this case they sink out of the euphotic quickly. However, given that in many cases aggregates ("marine snow") sink rather slowly, or not at all, this does not have to be the case. As for (a), given the large importance of this loss term for the simulated biogeochemistry, I would recommend some more in depth model description and discussion of this assumption”*

We thank the reviewer for this point and apologize for any confusion. Yes, phytoplankton biomass in ROMS-BEC immediately becomes detritus after aggregation, thus immediately stops being “green”. We agree with the reviewer in that this is likely not what happens for small aggregates in the real ocean, which do not sink out of the euphotic zone rapidly, suggesting that current model formulations in ROMS-BEC and other models are overly simplistic (see e.g. **Laufkötter et al., 2016**).

Assuming that aggregation is less effective in quickly removing the smaller phytoplankton cells from the upper ocean, aggregation is formulated to be more effective for larger phytoplankton in ROMS-BEC (in our case diatoms and *Phaeocystis* colonies). Still, once formed, no differentiation is made in the model in how quickly the particles are transferred to depth between POC originating from aggregated small phytoplankton cells and those from larger phytoplankton types. We note, however, that this differentiation is prevented by the currently used single POC class in the model (see also section 4.3 in the originally submitted manuscript, L. 657ff). Furthermore, ideally, aggregation losses of each PFT should be calculated based on total biomass rather than based on the biomass of each PFT separately and should additionally consider larger detritus particles (POC) of different size classes. Since the ROMS-BEC set-up we use currently uses an implicit sinking formulation in which POC is directly redistributed and remineralized across the water column upon its formation, this precludes a tracking of aggregates and their fate in space and time (**Lima et al., 2014**).

Overall, we fully agree with the reviewer that our model (and other models, see discussion in **Laufkötter et al., 2016**) would benefit from an increased complexity regarding the fate of biomass losses and the resulting particles, and quantitative relationships should be established as more observations become available to guide model parametrizations (see e.g. **Guidi et al., 2015**).

In direct response to the reviewer’s comment, we have revised the text in the manuscript to make a clearer distinction between non-grazing mortality and aggregation. In particular, we have revised the respective part of method section 2.1, which now reads:

“Furthermore, based on the assumption that for a given biomass concentration, larger cells are more likely than smaller cells to form aggregates and to subsequently stop photosynthesizing and sink as POC, we use a higher quadratic loss rate for *Phaeocystis* ( $0.005 \text{ d}^{-1}$ ) than for diatoms ( $0.001 \text{ d}^{-1}$ ) in the model (see  $\gamma_{a,0}$  in Table 1).“

In Table 1 of the revised manuscript, we refer to the constant  $\gamma_{a,0}$  as “quadratic loss rate in aggregation” in the revised manuscript:

**Table 1.** BEC parameters controlling phytoplankton growth and loss for the five phytoplankton PFTs diatoms (D), *Phaeocystis* (PA), coccolithophores (C), small phytoplankton (SP), and diazotrophs (N). Z=zooplankton, P=phytoplankton, PI=photosynthesis-irradiance. If not given in section 2.1, the model equations describing phytoplankton growth and loss rates are given in Nissen et al. (2018).

Parameter	Unit	Description	D	PA	C	SP	N†
$\mu_{\max}$	$\text{d}^{-1}$	max. growth rate at 30° C	4.6	‡	3.8	3.6	0.9
$Q_{10}$		temperature sensitivity	1.55	‡	1.45	1.5	1.5
$k_{\text{NO}_3}$	$\text{mmol m}^{-3}$	half-saturation constant for $\text{NO}_3$	0.5	0.5	0.3	0.1	1.0
$k_{\text{NH}_4}$	$\text{mmol m}^{-3}$	half-saturation constant for $\text{NH}_4$	0.05	0.05	0.03	0.01	0.15
$k_{\text{PO}_4}$	$\text{mmol m}^{-3}$	half-saturation constant for $\text{PO}_4$	0.05	0.05	0.03	0.01	0.02
$k_{\text{DOP}}$	$\text{mmol m}^{-3}$	half-saturation constant for DOP	0.9	0.9	0.3	0.26	0.09
$k_{\text{Fe}}$	$\mu\text{mol m}^{-3}$	half-saturation constant for Fe	0.15	0.2	0.125	0.1	0.5
$k_{\text{SiO}_3}$	$\text{mmol m}^{-3}$	half-saturation constant for $\text{SiO}_3$	1.0	-	-	-	-
$\alpha_{\text{PI}}$	$\frac{\text{mmol C m}^2}{\text{mg Chl W s}}$	initial slope of PI-curve	0.44	0.63	0.4	0.44	0.38
$\gamma_{\text{g,max}}$	$\text{d}^{-1}$	max. growth rate of Z grazing on P	3.8	3.6	4.4	4.4	3.0
$Z_{\text{grz}}$	$\text{mmol m}^{-3}$	half-saturation constant for ingestion	1.0	1.0	1.05	1.05	1.2
$\gamma_{\text{m},0}$	$\text{d}^{-1}$	linear non-grazing mortality	0.12	0.18	0.12	0.12	0.15
$\gamma_{\text{a},0}$	$\frac{\text{m}^3}{\text{mmol C d}}$	quadratic loss rate in aggregation	0.001	0.005	0.001	0.001	-
$r_{\text{g}}$	-	fraction of grazing routed to POC	0.3	0.42	0.2	0.05	0.05

† Compared to Nissen et al. (2018), the  $k_{\text{Fe}}$  of diazotrophs in ROMS-BEC is higher than for all other PFTs, consistent with literature reporting high Fe requirements of *Trichodesmium* (Berman-Frank et al., 2001). Furthermore, the maximum grazing rate on diazotrophs is lowest in the model (Capone, 1997). Still, diazotrophs continue to be a minor player in the SO phytoplankton community, contributing <1% to domain-integrated NPP in ROMS-BEC.

‡ The temperature-limited growth rate of *Phaeocystis* is calculated based on an optimum function according to Eq. 1 (see also Fig. A1a).

Furthermore, in order to make the differences between all the loss terms in the model more apparent, we have added a full description of the model equations as an appendix in the revised version of the manuscript (see also our response to reviewer #1). There, we have also included a sentence stating that phytoplankton in the model stop photosynthesizing upon aggregation:

Phytoplankton  $P^i$  [ $\text{mmol C m}^{-3}$ ] aggregate at an aggregation rate  $\gamma_{\text{a}}^i$  [ $\text{mmol C m}^{-3} \text{ day}^{-1}$ ] which is computed with the quadratic mortality rate constants  $\gamma_{\text{a},0}^i$  [ $\text{m}^3 (\text{mmol C})^{-1} \text{ d}^{-1}$ ], Table 1) and :

$$\gamma_{\text{a}}^i = \min(\gamma_{\text{a,max}}^i \cdot P^{i^2}, \gamma_{\text{a},0}^i \cdot P^i \cdot P^i) \quad (\text{B15})$$

$$\gamma_{\text{a}}^i = \max(\gamma_{\text{a,min}}^i \cdot P^i, \gamma_{\text{a}}^i) \quad (\text{B16})$$

In ROMS-BEC,  $\gamma_{\text{a,min}}^i$  is  $0.01 \text{ day}^{-1}$  for small phytoplankton and coccolithophores and  $0.02 \text{ day}^{-1}$  for *Phaeocystis* and diatoms, and with  $\gamma_{\text{a,max}}^i$  being  $0.9 \text{ day}^{-1}$  for *Phaeocystis*, diatoms, coccolithophores, and small phytoplankton. Note that phytoplankton immediately stop photosynthesizing upon aggregation and that aggregation losses do not occur for diazotrophs in ROMS-BEC.

As an important caveat of this study, we have added the following sentences regarding the current formulation of aggregation in ROMS-BEC in section 4.1 of the revised manuscript:

«Here, our findings suggest an important role for biomass loss processes in controlling the relative importance of *Phaeocystis* and diatoms in ROMS-BEC, but very little quantitative information exists to constrain model parameters (see section 2.1) or to validate the simulated non-grazing mortality, grazing, or aggregation loss rates of *Phaeocystis* and diatoms over time. **Certainly, the simulated aggregation rates in the model and their impact on spatio-temporal distributions of PFT biomass concentrations and rates of NPP are associated with substantial uncertainty due to the immediate conversion of biomass to sinking detritus in the model, the equal treatment of POC originating from all PFTs, the neglect of disaggregation, and due to the calculation of aggregation rates based on the biomass concentrations of individual PFTs rather than all PFTs or even particles combined (see e.g. Turner, 2015).**»

## **Answers to specific comments (SC):**

**SC1:** *Table 1 and line 175: The unit of quadratic mortality (aggregation) is given as 1/d. Shouldn't it be 1/((mmol N/m<sup>3</sup>)\*d), given that it will be multiplied with the squared concentration?*

We thank the reviewer for this comment. The unit of the constant  $\gamma_{a,0}$  given in Table 1 should indeed be 1/(mmol C m<sup>-3</sup> d<sup>-1</sup>) and we have corrected this in the revised version of the manuscript (see also the revised Table 1 on the previous page). Furthermore, in response to a comment by reviewer #1, we have provided a full description of the model equations describing phytoplankton growth and loss in the appendix of the revised version of the manuscript.

**SC2:** *Line 184: "we use monthly climatological fields for all tracers" - For all nutrients? Dissolved inorganic tracers? Please specify.*

Yes, we use monthly climatological fields for all nutrient tracers. We used climatological data from World Ocean Atlas 2013 for all macronutrients (Garcia et al., 2013), data from GLODAP for DIC and alkalinity (Lauveset et al., 2016), and climatological output fields from a global simulation with CESM-BEC for ammonium, dissolved inorganic Fe, and all dissolved organic phases of the nutrients (DOC, DOP, DOPr, DON, DONr, DOFe, Yang et al., 2017).

**SC3:** *Lines 197-214, spin up procedure of the coupled model: here a simple diagram of the spinup procedure could help a lot! E.g. (if I understood correctly), ...30y physics.....10yBEC...10yBaseline (5 yr analysis)..10ySensitivity (5 yr analysis)*

Indeed, the reviewer has understood our procedure of the model simulations correctly. Given that the results presented in this study are not qualitatively dependent on the exact years analyzed (due to the climatological forcing applied in the simulations) and in light of the length of the manuscript, we refrain from adding another figure after careful consideration of the issue. However, we have slightly modified the description of the setup of the sensitivity experiments to make things even clearer:

“All sensitivity experiments use the same physical and biogeochemical spin-up as the *Baseline* simulation and start from the end of year 10 of the coupled ROMS-BEC spin-up.”

**SC4:** *Line 275: "phytoplankton biomass ... is the balance" - I suggest to rephrase this as "phytoplankton biomass ... is determined by the balance"*

We have rephrased as suggested.

**SC5:** *Line 320 and elsewhere: "In ROMS-BEC" - I assume what is referred to here is the baseline experiment? If so, I'd suggest to use "Baseline", to not confuse this simulation with the earlier non-Phaeocystis model and simulation.*

We have modified the indicated sentence to start by “In the 5-PFT *Baseline* simulation of ROMS-BEC, [...]”. Furthermore, for the revised version of the manuscript, we have double-checked the whole text and clarified wherever we thought confusion was possible.

**SC6:** *Figure 4: The upper and lower panels would be easier to compare if in the lower panels the x- and y-axis were swapped (i.e., to have always temperature on the x-axis).*

We thank the reviewer for this excellent suggestion regarding Fig. 4. We have adopted this in the revised version of the manuscript (see Figure below). Furthermore, in response to a comment by reviewer #1, we have additionally moved the panels showing the ecological niches of coccolithophores to the supplementary material, in order to focus the manuscript earlier on the competition between *Phaeocystis* and diatoms.

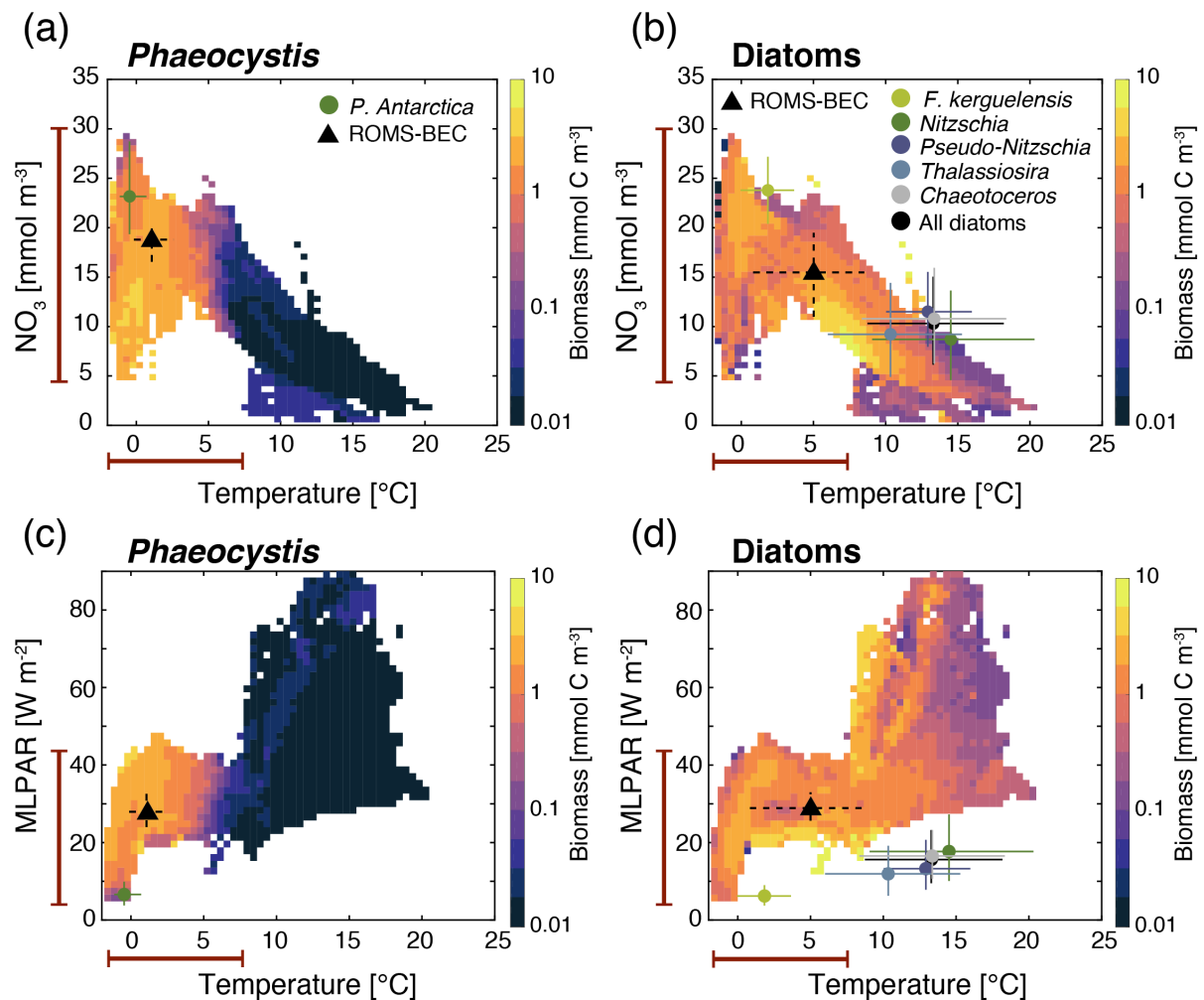


Fig. 1: Revised version of Fig. 4 in the manuscript.

SC7: Figure 5: The caption could also note over what depth these terms were calculated.

We have modified the figure caption to state that Fig. 5 only shows the quantities at the surface:

“For all metrics, the left panels are surface averages over 60-90° S and those on the right for the Ross Sea.”

We note that this choice is mainly motivated by the higher available temporal frequency in the necessary output variables. Overall, the dynamics of the seasonal competition between diatoms and *Phaeocystis* also broadly hold (at least qualitatively) for averages over the mixed layer over the growing season (not shown).

SC8: Figure 6: If I add up the different contributions to POC formation in the right panel (60- 90S) I end up with  $(6+17+4(\text{blue arrow})+0.2+0.1+13+9=49.3\%$  but the p-ratio is given as 45%. Does the blue arrow not contribute to the total flux? If so, then in the left panel the p-ratio should be  $3+19+0.8+3+5+2=32.8\%$  (and not 37%). Please clarify.

We thank the reviewer for spotting this inconsistency of the numbers, as there was indeed a mistake in the figure in the submitted manuscript regarding the individual pathways leading to POC production (i.e., the indicated p ratio was correct). As a result of correcting the respective factor applied in the post-processing of the model output, the fraction of grazing on *Phaeocystis* leading to POC production

are now corrected down to 3.4% (5% before) and 9.2% (13% before) for 30-90°S and 60-90°S, respectively (see corrected Fig. 6 below).

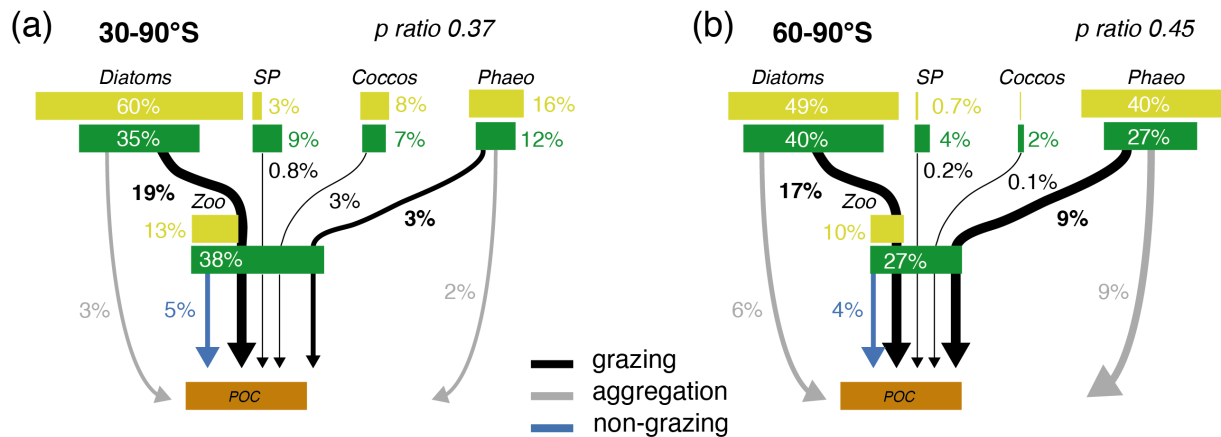


Fig. 2: revised Fig. 6 of the manuscript.

While this does not affect the general conclusion from this analysis, we note that this affects the discussion in the text (see below). While grazing remains the main POC production pathway for *Phaeocystis*, the difference to aggregation is now minor at high latitudes (9.2% for grazing, 8.9% for aggregation).

Accordingly, we reformulate the corresponding part of the manuscript, which now reads:

“For both diatoms and *Phaeocystis*, grazing by zooplankton (i.e., the formation of fecal pellets) is the most important pathway of POC production in ROMS-BEC (black arrows in Fig. 6, 9%/52% and 20%/37% of total POC production for *Phaeocystis*/diatoms between 30-90° S and 60-90° S, respectively). Yet, at high latitudes (60-90° S), aggregation of *Phaeocystis* biomass contributes *equally* to POC formation.”

Furthermore, we corrected a minor mistake in the caption of Fig. 6, where we falsely stated that the numbers describing the importance of the respective POC production pathway relative to total NPP were rounded to the nearest integer if they were >0.5%. Instead, this is only the case if the contribution of a respective pathway is >1%.



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