

Answer to referee #1:

We thank referee #1 for reviewing our manuscript. His/Her valuable comments and suggestions have significantly improved the quality of our manuscript.

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

Answers to general comments (GC):

General Comment #1:

*Nissen and Vogt present a model study on the relative importance of the colonial form of *Phaeocystis* for ecosystem processes and biogeochemical fluxes; they evaluate their results with observations from different data sources. A comparable study (Nissen et al 2018) had been performed with a focus on coccolithophores instead of *Phaeocystis* with similar analyses. In that respect this work is not overly innovative nor are original ideas presented. More critical is, however, that there is no thread in this manuscript; a clear goal is missing. A number of topics (e.g. phenology, competition, carbon and DMS-fluxes) are touched but not thoroughly permeated. It is unclear whether the authors would like to study the success of *Phaeocystis* compared to other phytoplankton functional groups or the importance of *Phaeocystis* for carbon export fluxes. Either way, no comprehensible motivation for either of these broad themes is provided. Some aspects of the methodology also need to be revised with consequences for the model analyses. Last but not least, recent work on this topic has been ignored. Overall this manuscript is premature and the authors must clarify their focus before publication. To sharpen the focus maybe it helps to look at the unpublished, recent modelling work on Southern Ocean *Phaeocystis* and PFTs (Losa et al. 2019) that has been put up for discussion in Biogeosciences Discussion.*

Answer to GC1:

We thank reviewer 1 for his/her constructive criticism on our work, regarding the focus, the motivation, the novelty, the methodology, and the presentation of our study. We address the concerns of the reviewer 1 with regard to these aspects in the revised manuscript through the following changes:

- 1) We have changed the title of the manuscript to “Factors controlling the competition between *Phaeocystis* and diatoms in the Southern Ocean and implications for carbon export fluxes” so that it better reflects the focus of the study, namely the links between the variability in phytoplankton community structure and downward carbon fluxes in the high-latitude Southern Ocean throughout the year.
- 2) We have entirely revised the introduction which now clarifies the focus and novelty of the study and includes additional recent literature.
- 3) We have restructured the result section and adjusted the relative weighting of the individual sections to have a more balanced representation of the different aspects of the study, especially regarding the drivers of the competition between *Phaeocystis* and diatoms and its biogeochemical implications.
- 4) Ultimately, within the discussion section of the revised version of the manuscript, we have adopted the same structure of subsections as in the result section, making it easier for the reader to follow. Furthermore, we have adjusted the lengths of the discussion of the individual aspects, in order to better represent the main focus of the study.

For the comment regarding the methodology (i.e., the temperature sensitivity of phytoplankton growth), we refer the reviewer to our detailed answer to SC4 and SC5 below.

In our study, we set out for a comprehensive assessment of the link between plankton biogeography and biogeochemical cycling in the Southern Ocean over the course of the year. Since we consider the comprehensiveness as a key strength and key aspect of novelty of the current paper as compared to previous work, the emphasis of our revision has been to (1) clarify the aims of the study in the revised version of the introduction, (2) highlight the current gaps in our understanding with regard to the

missing link between plankton biogeography and ecosystem function in terms of global biogeochemical cycling, and (3) improve upon the presentation of our study in the manuscript. Previous studies have often only presented snapshots of the factors controlling the relative importance of *Phaeocystis* and diatoms at high SO latitudes and its implications for downward carbon fluxes at a specific location and/or point in time (e.g. Arrigo et al., 1998, Garcia et al., 2009, Wang et al., 2011, but see the introduction of the manuscript for a comprehensive overview), meaning that the biogeochemical implications of the seasonally varying phytoplankton community remain under-explored, especially on larger spatial scales. We clarify these issues in the revised version of the manuscript, as detailed in the sections below.

In the following, we will address the individual concerns raised by the reviewer in more detail and summarize how we have addressed them in the revised version of the manuscript.

Focus/Novelty/Motivation

In this paper we set out to assess the link between the spatio-temporal variability in high-latitude Southern Ocean phytoplankton community structure and the variability in downward carbon fluxes. To that aim, we extended the work by Nissen et al., 2018 to develop a model which would include all major biogeochemical actors of this region, a prerequisite to address this research question. Hence, with this tool, we were able to provide a first comprehensive assessment of the spatio-temporal variability of pathways leading to downward fluxes of carbon, which are inherently linked to the overlying phytoplankton community structure.

To clarify the focus of the study, we have changed the title of the manuscript to “Factors controlling the competition between *Phaeocystis* and diatoms in the Southern Ocean and implications for carbon export fluxes”, so that it sets up the reader for the link between phytoplankton community structure and the implications for the carbon cycle.

Furthermore, we have substantially rewritten the introduction, to better highlight the focus, the novelty, and the motivation of our study. In this context, we apologize for the omission of certain recent papers in our initial submission. In response to the reviewer’s comment, we have performed an additional extensive literature research and included the identified novel work in the revised version of our manuscript. We identified the following additional 7 papers that are of relevance for the current paper, and that were not included in the reference list of the initial submission:

Papers describing the succession from *Phaeocystis* to diatoms throughout the season in the Ross Sea (Ryan-Keogh et al., 2017) and off the Western Antarctic Peninsula (Arrigo et al. 2017):

Ryan-Keogh, T. J., DeLizo, L. M., Smith, W. O., Sedwick, P. N., McGillicuddy, D. J., Moore, C. M., & Bibby, T. S. (2017). Temporal progression of photosynthetic-strategy in phytoplankton in the Ross Sea, Antarctica. *Journal of Marine Systems*, 166, 87–96. <https://doi.org/10.1016/j.jmarsys.2016.08.014>

Arrigo, K. R., van Dijken, G. L., Alderkamp, A., Erickson, Z. K., Lewis, K. M., Lowry, K. E., ... van de Poll, W. (2017). Early Spring Phytoplankton Dynamics in the Western Antarctic Peninsula. *Journal of Geophysical Research: Oceans*, 122(12), 9350–9369. <https://doi.org/10.1002/2017JC013281>

Paper describing the impact of Fe concentrations on colony formation by *Phaeocystis Antarctica*:

Bender, S. J., Moran, D. M., McIlvin, M. R., Zheng, H., McCrow, J. P., Badger, J., ... Saito, M. A. (2018). Colony formation in *Phaeocystis antarctica*: connecting molecular mechanisms with iron biogeochemistry. *Biogeosciences*, 15(16), 4923–4942. <https://doi.org/10.5194/bg-15-4923-2018>

Papers on recent modeling of *Phaeocystis Antarctica*, focusing either on interactions between light and temperature on growth rates (Moisan & Mitchell, 2018) or functional type modeling in the Southern Ocean (Losa et al., 2019):

Moisan, T. A., & Mitchell, B. G. (2018). Modeling Net Growth of *Phaeocystis antarctica* Based on Physiological and Optical Responses to Light and Temperature Co-limitation. *Frontiers in Marine Science*, 4(February), 1–15. <https://doi.org/10.3389/fmars.2017.00437>

Losa, S. N., Dutkiewicz, S., Losch, M., Oelker, J., Soppa, M. A., Trimborn, S., Xi, H., and Bracher, A.: On modeling the Southern Ocean Phytoplankton Functional Types, *Biogeosciences Discuss.*, <https://doi.org/10.5194/bg-2019-289>, 2019.

Papers discussing the role of aggregates (especially those from *Phaeocystis Antarctica*) as a vector for carbon transfer to depth in the Southern Ocean (relative to that of e.g. fecal pellets):

Asper, V. L., & Smith, W. O. (2019). Variations in the abundance and distribution of aggregates in the Ross Sea, Antarctica. *Elem Sci Anth*, 7(1), 23. <https://doi.org/10.1525/elementa.355>

Ducklow, H. W., Wilson, S. E., Post, A. F., Stammerjohn, S. E., Erickson, M., Lee, S., ... Yager, P. L. (2015). Particle flux on the continental shelf in the Amundsen Sea Polynya and Western Antarctic Peninsula. *Elementa: Science of the Anthropocene*, 3, 000046. <https://doi.org/10.12952/journal.elementa.000046>

The analysis of this body of work reveals that these more recent findings are complementary to our results, and their inclusion into the introduction and discussion sections of our paper increases the quality of the discussion in the revised version of the manuscript.

In particular, we have included the references on the role of aggregates for POC export in the discussion section 4.2. of the revised manuscript (section on biogeochemical implications) and have added the study by **Losa et al. (2019)** in the discussion section 4.3 (Limitations & Caveats), discussing the complexity in marine ecosystem models:

“The transition from solitary to colonial cells is a function of the seed population and light and nutrient levels (Verity, 2000; Bender et al., 2018), and transition models have been applied in SO marine ecosystem models (e.g. Popova et al., 2007; Kaufman et al., 2017; Losa et al., 2019). For example, in their higher complexity, self-organizing ecosystem model (Follows et al., 2007), Losa et al. (2019) include both life stages of *Phaeocystis* and two types of diatoms to simulate phytoplankton competition at high SO latitudes. While our model results suggest that this is not required to reproduce the observed SO biogeography of *Phaeocystis* and diatoms in ROMS-BEC, it nevertheless highlights the need for further research on the impact of the chosen marine ecosystem complexity on the modeled biogeochemical fluxes (Ward et al., 2013).”

In the revised version of the manuscript, the introduction section now reads:

1 Introduction

Phytoplankton production in the Southern Ocean (SO) regulates not only the uptake of anthropogenic carbon in marine food-webs, but also controls global primary production via the lateral export of nutrients to lower latitudes (e.g. Sarmiento et al., 2004; Palter et al., 2010). The amount and stoichiometry of these laterally exported nutrients is determined by the combined action of multiple types of phytoplankton with differing ecological niches and nutrient requirements. Yet, despite their important role, the drivers of phytoplankton biogeography and competition and the relative contribution of different phytoplankton groups to SO carbon cycling are still poorly quantified. Today, the SO phytoplankton community is largely dominated by silicifying diatoms that efficiently fix and transport carbon from the surface ocean to depth (e.g. Swan et al., 2016) and have been suggested to be the major contributor to SO carbon export (Buesseler, 1998; Smetacek et al., 2012). However, calcifying coccolithophores and dimethylsulfide (DMS) producing *Phaeocystis* have been found to contribute in a significant way to total phytoplankton biomass at subantarctic (Balch et al., 2016; Nissen et al., 2018) and at high latitudes, respectively (Smith and Gordon, 1997; Arrigo et al., 1999; DiTullio et al., 2000; Poulton et al., 2007), thus suggesting that the succession and competition of different plankton groups governs biogeochemical cycles at the (sub)regional scale. As climate change is expected to differentially impact the competitive fitness of different phytoplankton groups and ultimately their contribution to total net primary production (NPP; IPCC, 2014; Constable et al., 2014; Deppeler and Davidson, 2017), with a likely increase in the relative importance of coccolithophores and *Phaeocystis* in a warming world at the expense of diatoms (Bopp et al., 2005; Winter et al., 2013; Rivero-Calle et al., 2015), the resulting change in SO phytoplankton community structure is likely to affect global nutrient and carbon distributions, ocean carbon uptake, and marine food web structure (Smetacek et al., 2004). While a number of recent studies have elucidated the importance of coccolithophores for subantarctic carbon cycling (e.g. Rosengard et al., 2015; Balch et al., 2016; Nissen et al., 2018; Rigual Hernández et al., 2020), few estimates quantify the role of present and future high-latitude SO phytoplankton community structure for ecosystem services such as NPP and carbon export.

Phaeocystis blooms in the SO have been regularly observed in early spring at high SO latitudes (especially in the Ross Sea, see e.g. Smith et al., 2011), thus preceding those of diatoms (Green and Sambrotto, 2006; Peloquin and Smith, 2007; Alvain et al., 2008; Arrigo et al., 2017; Ryan-Keogh et al., 2017), and *Phaeocystis* can dominate over diatoms in terms of carbon biomass at regional and sub-annual scales (e.g. Smith and Gordon, 1997; Alvain et al., 2008; Leblanc et al., 2012; Vogt et al., 2012; Ben Mustapha et al., 2014). Nevertheless, *Phaeocystis* is not routinely included as a phytoplankton functional type (PFT) in global biogeochemical models, possibly a result of the limited number of biomass validation data (Vogt et al., 2012) and its complex life cycle (Schoemann et al., 2005). In particular, *Phaeocystis* is difficult to model because traits linked to biogeochemistry-related ecosystem services, such as size and carbon content, vary due to its complex multi-stage life cycle. Its alternation between solitary cells of a few μm in diameter and gelatinous colonies of several mm to cm in diameter (e.g. Rousseau et al., 1994; Peperzak, 2000; Chen et al., 2002; Bender et al., 2018) directly impacts community biomass partitioning and the relative importance of aggregation, viral lysis, and grazing for *Phaeocystis* biomass losses, its susceptibility to zooplankton grazing relative to that of diatoms (Granéli et al., 1993; Smith et al., 2003), and ultimately the export of particulate organic carbon (POC; Schoemann et al., 2005). With *Phaeocystis* colonies typically dominating over solitary cells during the SO growing season (Smith et al., 2003), *Phaeocystis* biomass loss via aggregation possibly increases in relative importance at the expense of grazing as more colonies are formed and colony size increases (Tang et al., 2008). Altogether, this implies a complex seasonal variability in the magnitude and pathways of carbon transfer to depth as the phytoplankton community changes throughout the year, which is difficult to comprehensively assess through in situ studies and therefore calls for marine ecosystem models.

Across those marine ecosystem models including a *Phaeocystis* PFT, the representation of its life cycle differs in terms of complexity (Pasquer et al., 2005; Tagliabue and Arrigo, 2005; Wang and Moore, 2011; Le Quéré et al., 2016; Kaufman et al., 2017; Losa et al., 2019). While some models include rather sophisticated parametrizations to describe life cycle transitions (accounting for nutrient concentrations, light levels, and a seed population, see e.g. Pasquer et al., 2005; Kaufman et al., 2017), the majority includes rather simple transition functions (accounting for iron concentrations only, see Losa et al., 2019) or only the colonial life stage of *Phaeocystis* (Tagliabue and Arrigo, 2005; Wang and Moore, 2011; Le Quéré et al., 2016). Despite these differences, all of the models see improvements in the simulated SO phytoplankton biogeography as compared to observations upon the implementation of a *Phaeocystis* PFT. In particular, Wang and Moore (2011) find that *Phaeocystis*

60 contributes substantially to SO integrated annual NPP and POC export (23% and 30% south of 60° S, respectively; Wang and Moore, 2011), implying that models not accounting for *Phaeocystis* possibly overestimate the role of diatoms for high-latitude phytoplankton biomass, NPP, and POC export (Laufkötter et al., 2016). Overall, the link between ecosystem composition, ecosystem function, and global biogeochemical cycling in general (e.g. Siegel et al., 2014; Guidi et al., 2016; Henson et al., 2019) and the contribution of *Phaeocystis* to SO export of POC in particular are still under debate. While some have found 65 blooms of *Phaeocystis* to be important vectors of carbon transfer to depth through the formation of aggregates (Asper and Smith, 1999; DiTullio et al., 2000; Ducklow et al., 2015; Asper and Smith, 2019), others suggest their biomass losses to be efficiently degraded in the upper water column through bacterial and zooplankton activity, making *Phaeocystis* a minor contributor to SO POC export (Gowing et al., 2001; Accornero et al., 2003; Reigstad and Wassmann, 2007). This demonstrates the major existing uncertainty in how the high-latitude phytoplankton community structure impacts carbon export fluxes.

70 In general, the relative importance of different phytoplankton types for total phytoplankton biomass is controlled by a combination of top-down factors, i.e. processes impacting phytoplankton biomass loss such as grazing by zooplankton, aggregation of cells and subsequent sinking, or viral lysis, and bottom-up factors, i.e. physical and biogeochemical variables impacting phytoplankton growth (Le Quéré et al., 2016). The observed spatio-temporal differences in the relative importance of *Phaeocystis* and diatoms in the SO are thought to be largely controlled by differences in light and iron levels, but the relative importance 75 of the different bottom-up factors appears to vary depending on the time and location of the sampling (Arrigo et al., 1998, 1999; Goffart et al., 2000; Sedwick et al., 2000; Garcia et al., 2009; Tang et al., 2009; Mills et al., 2010; Feng et al., 2010; Smith et al., 2011, 2014). Concurrently, while available models agree with the observations on the general importance of light and iron levels, differences in the dominant bottom-up factors controlling the distribution of *Phaeocystis* at high SO latitudes across models are possibly a result of differences in how this phytoplankton type is parametrized (Tagliabue and Arrigo, 2005; 80 Pasquer et al., 2005; Wang and Moore, 2011; Le Quéré et al., 2016; Kaufman et al., 2017; Losa et al., 2019). Besides bottom-up factors, some observational studies suggest that top-down factors are important in controlling the relative importance of *Phaeocystis* and diatoms as well. For instance, van Hilst and Smith (2002) suggest grazing by zooplankton to be an important factor explaining the observed distributions of these two phytoplankton types in the SO, likely resulting from the generally lower grazing pressure on *Phaeocystis* colonies than on diatoms (Granéli et al., 1993; Smith et al., 2003). Yet, further evidence 85 suggests a role for other biomass loss processes such as aggregation and subsequent sinking (Asper and Smith, 1999; Ducklow et al., 2015; Asper and Smith, 2019). Altogether, this calls for a comprehensive quantitative analysis of the relative importance of bottom-up and top-down factors in controlling the competition between *Phaeocystis* and diatoms over the course of the SO growing season and its ramifications for carbon transfer to depth.

In this study, we investigate the competition between *Phaeocystis* and diatoms and its implications for carbon cycling using a 90 regional coupled physical-biogeochemical-ecological model configured at eddy-permitting resolution for the SO (ROMS-BEC, Nissen et al., 2018). To address the missing link between SO phytoplankton biogeography and the global carbon cycle, we have added *Phaeocystis* colonies as an additional PFT to the model, so that it includes all major identified biogeochemically relevant phytoplankton types of the SO. We then assess the relative importance of bottom-up and top-down factors in controlling the relative importance of *Phaeocystis* colonies and diatoms over a complete annual cycle in the high-latitude SO. We show that 95 a correct representation of SO phytoplankton biogeography leaves a distinct imprint on upper ocean carbon cycling and POC export across the SO.

Structure

In response to the reviewer's comments, we have revised the results and the discussion section of the manuscript to make the order and relative weighting of individual sections clearer to the reader, and to better align the presentation of results with the core questions this paper aims to address.

In particular, we have merged the result sections 3.3 & 3.4 of the original version of the manuscript into a single section in the revised manuscript, which is entitled "Drivers of SO phytoplankton biogeography, phenology, and succession patterns". This section was shortened in the merging process, with the aim to make it more readable and to better balance the amount of text spent on the description of a) simulated patterns of biogeography, phenology, and succession, b) the drivers of the competition, and c) its biogeochemical implications. Please see our answer to SC8 for the new result section 3.3.

Furthermore, in order to make it easier for the reader to follow, we have adjusted the order of subsections within the discussion section to reflect their order in the result section, i.e., swapped discussion section 4.1 & 4.2 of the original manuscript. In the revised manuscript, the discussion of the

drivers of the competition of *Phaeocystis* and diatoms (section 4.1) is now followed by the discussion of its biogeochemical implications (section 4.2). In addition, in the latter, we have modified the paragraph on the implications of Southern Ocean *Phaeocystis* biogeography for DMS fluxes. In particular, we have shortened the paragraph on DMS from the method section 2.3.1 and moved it to section 4.2 in the revised manuscript, so that the manuscript is more clearly focused on carbon fluxes up until this point. Please see our answer to SC14 for the new paragraph on DMS.

Answers to specific comments (SC):

SC1: *title: the title only partly reflects the content of this study*

We thank the reviewer for this important comment, as it made us aware of imbalances in terms of content in the original version of the manuscript. As the analysis regarding the implications of the variability in phytoplankton community structure on high-latitude carbon fluxes is an important, novel aspect of the study, which has been highlighted even more in the revised version of the manuscript (see also answer to GC 1 above), the revised version of the manuscript will be entitled “Factors controlling the competition between *Phaeocystis* and diatoms in the Southern Ocean and implications for carbon export fluxes”. Thereby, the content of the manuscript is better reflected by its title, helping the reader to follow.

SC2: *abstract and entire manuscript: it is unclear which research gap the authors want to fill. What is currently unclear - which open question in this research field are attempted to be answered with ROMS-BEC?*

In response to the reviewer’s comments, we have substantially reworked the manuscript, in order to more clearly highlight the knowledge gap filled with this study. After having added *Phaeocystis* as a functional type to ROMS-BEC, we were able to provide a first comprehensive assessment of the spatio-temporal variability of pathways leading to downward fluxes of carbon at high Southern Ocean latitudes, which are inherently linked to the overlying phytoplankton community structure, especially the competition between *Phaeocystis* and diatoms. We kindly refer the reviewer to our response to GC1 above for more details.

SC3: *the manuscript should stand alone. Currently important parts of the model description are missing. The prognostic equation for *Phaeocystis* with all source and sink terms as well as all functional dependencies of rates to environmental drivers need to be provided.*

We fully agree with the reviewer on this point and apologize for not having included a full description of growth and loss terms for phytoplankton biomass in the original version of the manuscript. In the revised version, we have included a full description of the relevant model equations of BEC in Appendix B and added corresponding references to this section in the method section 2.1 and throughout the text:

Appendix B: BEC equations: Phytoplankton growth & loss

Any change in phytoplankton biomass P [mmol C m⁻³] of phytoplankton i ($i \in \{PA, D, C, SP, N\}$) over time is determined by the balance of growth and loss terms:

$$\frac{dP^i}{dt} = \text{Growth} - \text{Loss} \quad (\text{B1})$$

$$= \mu^i \cdot P^i - \gamma^i(P^i) \cdot P^i \quad (\text{B2})$$

$$= \mu^i \cdot P^i - \gamma_g^i(P^i) \cdot P^i - \gamma_m^i \cdot P^i - \gamma_a^i(P^i) \cdot P^i \quad (\text{B3})$$

In the above equation, γ_g denotes the loss by zooplankton grazing, γ_m the loss by non-grazing mortality, and γ_a the loss by aggregation.

B1 Phytoplankton growth

The specific growth rate μ^i [day⁻¹] of phytoplankton i ($i \in \{D, C, SP, N\}$, i.e., all but *Phaeocystis*) is determined by the maximum growth rate μ_{\max}^i (Table 1) and modifications due to temperature (T), nutrients (N) and irradiance (I), following:

$$\mu^i = \mu_{\max}^i \cdot f^i(T) \cdot g^i(N) \cdot h^i(I) \quad (\text{B4})$$

The temperature function $f(T)$ is an exponential function, which is modified by the constant Q_{10} specific to every phytoplankton i (Table 1):

$$f^i(T) = Q_{10}^i \cdot \exp\left(\frac{T - T_{\text{ref}}}{10^\circ\text{C}}\right) \quad (\text{B5})$$

Note that for *Phaeocystis* in ROMS-BEC, an optimum temperature function is used (Eq. 1), as this PFT is parametrized to only represent *Phaeocystis Antarctica* in the SO application of this study (see section 2.1).

First, the limitation of growth of phytoplankton i ($i \in \{PA, D, C, SP, N\}$) by the surrounding nutrient $L^i(N)$ is calculated individually for each nutrient (nitrogen, phosphorus, iron for all phytoplankton, silicate for diatoms only) following a Michaelis-Menten function (see Table 1 for half-saturation constants k_N^i). Accordingly, the limitation factor is calculated as follows for iron (Fe) and silicate (SiO₃):

$$L^i(N) = \frac{N}{N + k_N^i} \quad (\text{B6})$$

For nitrogen and phosphorus, the combined limitation by nutrient N and M (nitrate (NO₃) and ammonium (NH₄) for nitrogen, phosphate (PO₄) and dissolved organic phosphorus (DOP) for phosphorus) is accounted for following:

$$L^i(N, M) = \frac{N}{k_N^i + N + M \cdot (k_N^i/k_M^i)} + \frac{M}{k_M^i + M + N \cdot (k_M^i/k_N^i)} \quad (\text{B7})$$

In the model, the phytoplankton growth rate is then only limited by the most limiting nutrient:

$$g^i(N) = \min(L^i(\text{NO}_3, \text{NH}_4), L^i(\text{PO}_4, \text{DOP}), L^i(\text{Fe}), L^i(\text{SiO}_3)) \quad (\text{B8})$$

The light limitation function $h^i(I)$ includes the effects of photoacclimation by including the chlorophyll-to-carbon ratio θ^i and the growth of the respective phytoplankton i ($i \in \{PA, D, C, SP, N\}$) limited by nutrients and temperature:

$$h^i(I) = 1 - \exp\left(-1 \cdot \frac{\alpha_{PI}^i \cdot \theta^i \cdot I}{\mu_{\max}^i \cdot g^i(N) \cdot f^i(T)}\right) \quad (\text{B9})$$

Here, same as in Nissen et al. (2018), growth by coccolithophores is set to zero at PAR levels <1 W m⁻² (Zondervan, 2007) and is linearly reduced at temperatures <6°C following:

$$\mu^C = \mu^C \cdot \frac{\max(T + 2^\circ\text{C}, 0)}{8^\circ\text{C}} \quad (\text{B10})$$

Coccolithophore calcification amounts to 20% of their photosynthetic growth at any location and point in time in ROMS-BEC.

Diazotroph growth is zero at temperatures <14°C.

B2 Phytoplankton loss

In ROMS-BEC, the corrected phytoplankton biomass P^i is used to compute loss rates of phytoplankton biomass, to prevent phytoplankton biomass loss at very low biomass levels:

$$P^i = \max(P^i - c_{\text{loss}}^i, 0) \quad (\text{B11})$$

In this equation, c_{loss}^i is the threshold of phytoplankton biomass P^i below which no losses occur ($c_{\text{loss}}^{\text{N}} = 0.022 \text{ mmol C m}^{-3}$ and $c_{\text{loss}}^{\text{PA,D,C,SP}} = 0.04 \text{ mmol C m}^{-3}$).

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

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

with

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

The non-grazing mortality rate γ_m^i [$\text{mmol C m}^{-3} \text{ day}^{-1}$] of phytoplankton i [mmol C m^{-3}] is the product of a maximum mortality rate m_0^i [day^{-1}] scaled by the temperature function $f^i(T)$ with the modified phytoplankton biomass P^i :

$$\gamma_m^i = m_0^i \cdot f^i(T) \cdot P^i \quad (\text{B14})$$

with m_0^i being 0.15 day^{-1} for diazotrophs and 0.12 day^{-1} for all other phytoplankton.

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

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

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

In ROMS-BEC, $\gamma_{a,\text{min}}^i$ is 0.01 day^{-1} for small phytoplankton and coccolithophores and 0.02 day^{-1} for *Phaeocystis* and diatoms, and with $\gamma_{a,\text{max}}^i$ being 0.9 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.

SC4: *the newly introduced formulation of the temperature dependent growth for the PFT Phaeocystis is fundamentally different from the description of the PFTs of the original BEC model. The former is a “Gauss-like” temperature dependent growth function with a temperature optimum. Any deviation from the optimum is a limitation, varying between 0...1. In contrast, the Q10-approach with different Q10 values that is applied to the other PFTs denotes the “sensitivity” in the exponential growth towards temperature - in these cases the higher the temperature, the higher the growth. Even if a relatively high reference temperature of 30 degrees Celsius is given (which is likely not reached in the Southern Ocean), there is no such thing as an optimum in the Q10 approach. Thus, the “limitation” values used in the analyses cannot easily be compared.*

[Generally the question arises whether the Q10 approach should be applied to PFTs at all. Introduced by Eppley it is valid and a good description for bulk phytoplankton but as soon as the bulk is divided into groups, “Gauss-like functions” with a clear optimum seem to be more adequate.]

We thank the reviewer for raising this important point. First of all, we completely agree with the reviewer in that the two approaches (“optimum” vs “Q10”) to model the temperature-limited growth rates of phytoplankton are fundamentally different. However, we think that a comparison of the temperature-limited growth rates of *Phaeocystis* (“optimum”) to that of diatoms (Q10) is still valid in our model, for reasons outlined in the following.

In lab experiments, individual phytoplankton species typically show an optimum temperature for growth, above and below which its growth is slowed down (see Fig. 1 below). Yet, in models, the Q10-approach describes the temperature-limited growth as an exponential function without a temperature optimum (see black lines in Fig. 2 below or Fig. A1 in our manuscript). Since models typically represent the whole phytoplankton community by a set of plankton functional types (PFTs,

Le Quéré et al., 2005), thereby combining multiple species into a single PFT, this Q10-function can hence be interpreted as the overlap of numerous optimum curves of numerous individual species.

In the 5-PFT setup of ROMS-BEC presented here, the PFT “*Phaeocystis*” only represents the single species of *Phaeocystis* present in the SO, namely *Phaeocystis antarctica* (Schoemann et al., 2005). This species has been shown to stop growing above temperatures of $\sim 8^{\circ}\text{C}$ (Buma et al., 1991), thus an optimum curve applies. At the same time, within the model PFT “diatoms”, we do not model a specific species of diatoms, but the whole diatom community (typical PFT approach; Le Quéré et al., 2005). This means that with increasing temperatures towards lower latitudes, diatom growth will be less and less temperature-limited (relative to the prescribed maximum growth rate at 30°C), as we assume that there is always a species that can cope with these higher temperatures (see also blue dots in Fig. 2 below). Yet, this is not the case for *Phaeocystis antarctica*, which is not observed northwards of approximately 60°S (Schoemann et al., 2005). At latitudes north of 60°S , other bloom-forming species of *Phaeocystis* are typically found (Schoemann et al., 2005 and Fig. 3 below). While these are *not* included in our study, there is no reason not to include these other species in global models, thus suggesting that the applicability of a temperature optimum curve to describe the growth of *Phaeocystis* in global models may be limited (see also black line in the lower panel of Fig. 2 below). Yet, the literature review of available growth rates of all *Phaeocystis* species presented in Schoemann et al. (2005) is best fit by using a temperature optimum curve despite multiple species being included in the analysis (see Fig. 3 below; compare to the fit Fig. 2), suggesting that the Q10 approach may be unsuitable – at least for the bloom-forming species of this phytoplankton type.

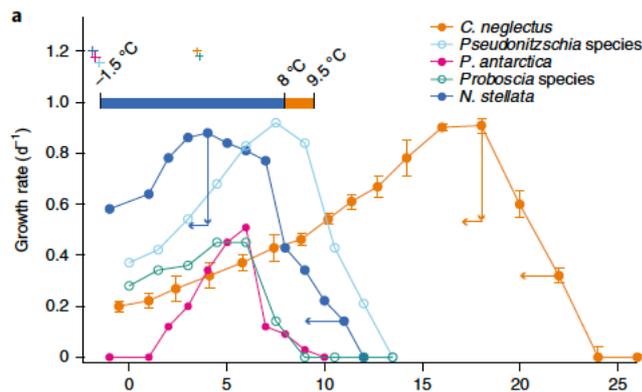


Fig. 1: Growth rates as a function of temperature for example high-latitude SO species of diatoms and *Phaeocystis* (Boyd 2019).

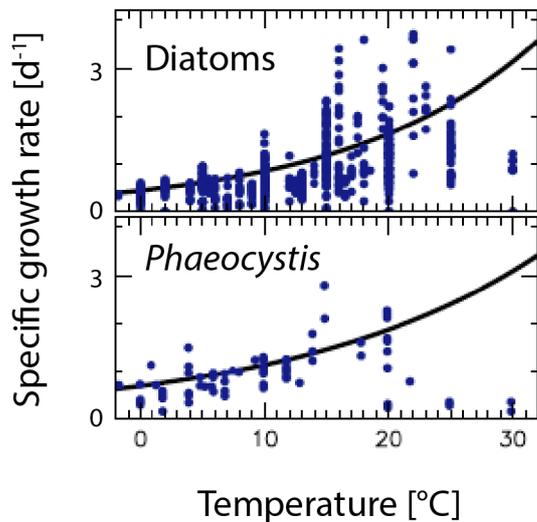


Fig. 2: Global compilation of diatom (top) and *Phaeocystis* (bottom) growth rates as a function of temperature by [Le Quéré et al. \(2016\)](#). Black lines are Q10-functions fit to the data with $Q_{10}=1.93$ and $Q_{10}=1.66$ for diatoms and *Phaeocystis*, respectively., as used in the PlankTOM10 model.

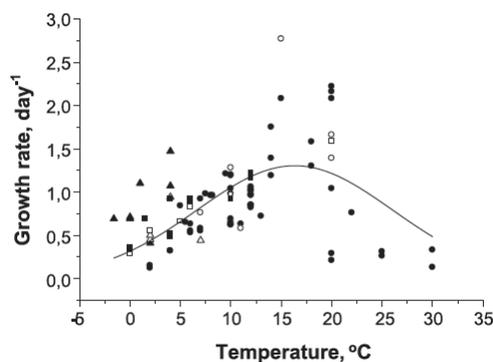


Fig. 3: Global compilation of *Phaeocystis* growth rates as a function of temperature by [Schoemann et al. \(2005\)](#). Triangles represent *Phaeocystis Antarctica*, filled triangles its colonial stage.

To account for the different formulations to describe the temperature-limited growth rates of *Phaeocystis* and diatoms in ROMS-BEC in our analysis of their competition over time (section 3.4 of the manuscript), we directly compare the temperature-limited growth rates (in d^{-1}) rather than the growth limitation by temperature of these two phytoplankton types (see Eq. 2 of the manuscript).

SC5: *temperature-dependent growth functions of any organism group usually have a negatively skewed thermal reaction norm. This is also true for Phaeocystis antarctica. Since there already exists a mathematical description for the temperature- & light-dependent growth function of Phaeocystis antarctica (Moisan and Mitchell 2018), I wonder why the authors have not used it. In fact there are more recent observation-based publications on Phaeocystis antarctica that may be of interest for this study.*

We thank the reviewer for pointing us to the manuscript by [Moisan and Mitchell \(2018\)](#), which we had not been aware of. In comparison to the formulation used in ROMS-BEC ([Geider et al., 1998](#)), the equations presented in [Moisan & Mitchell \(2018\)](#) include the possibility for photoinhibition at high light intensities (expressed by beta; [Platt et al. 1980](#)) and a temperature dependent initial slope of the photosynthesis-irradiance-curve (alpha), but do not explicitly account for all effects of photoacclimation in their equations that are included in ROMS-BEC (e.g., the local chlorophyll:carbon ratio of phytoplankton and the nutrient limitation of its growth, see Eq. 3a-3d in

Moisan & Mitchell, 2018 and Eq. B9 of the revised manuscript for ROMS-BEC). As a result, the set of equations provided by **Moisan & Mitchell (2018)** and the ones currently used in ROMS-BEC predict different temperature-light-limited net growth rates of *Phaeocystis antarctica* for any given temperature and PAR level (see Fig. 4 below). Furthermore, the ratio of the growth rate predicted by ROMS-BEC and that obtained with **Moisan & Mitchell (2018)** varies substantially across temperatures and light levels (see Fig. 4d).

Overall, as a result of the differences between the formulation in **Moisan & Mitchell (2018)** and that in **Geider et al. (1998)**, the light limitation of growth by *Phaeocystis* is generally lower in ROMS-BEC than that predicted with the equations by **Moisan & Mitchell (2018)**, leading to substantially higher net growth rates in the current model than would be predicted if we were to apply the parameterization in **Moisan & Mitchell (2018)** to describe temperature and light-limited growth of *Phaeocystis* in ROMS-BEC (especially at low PAR levels, see Fig. 4d below). Due to the impact of nutrient limitation and chlorophyll:carbon ratios on the simulated net growth rates in ROMS-BEC, implementing the formulation by **Moisan & Mitchell 2018** would lead to substantially lower *Phaeocystis* biomass south of 60°S and would require a major retuning in the model to facilitate any substantial biomass accumulation of *Phaeocystis antarctica* colonies relative to diatoms in the high-latitudes, where these two phytoplankton types have been shown to locally and temporarily reach equally high biomass concentrations (**Vogt et al., 2012; Leblanc et al., 2012**).

A further issue with the parameterization that we encounter is its applicability within the temperature regime that constitutes the ecological niche of *Phaeocystis* in ROMS-BEC. We note that the parametrization by **Moisan & Mitchell (2018)**, being derived from laboratory experiments conducted at temperatures between -1.5-4°C, is currently only defined for temperatures below 6.8°C, above which the predicted growth rate becomes ecologically meaningless due to a negative alpha value (whereas this value should be >0, as it describes the sensitivity of photosynthetic rates of phytoplankton to increases of irradiance levels at low light). Altogether, given that the equations by **Moisan & Mitchel (2018)** do not account for all effects of photoacclimation which are accounted for in ROMS-BEC for all phytoplankton types and given that the alphaPI currently used in ROMS-BEC is backed up by the literature review in **Schoemann et al. (2005)**, we refrain from implementing the formulation by **Moisan & Mitchell (2018)** at this stage.

Nevertheless, taken together, this highlights the uncertainty still associated with model formulations describing the growth of phytoplankton functional types in general and *Phaeocystis* in particular. In response to the reviewer, we have modified section 4.3 (Limitations & Caveats) and added the following statement in the revised version of the manuscript:

“Furthermore, other functional relationships than those used in ROMS-BEC exist to describe the light and temperature dependent growth of *Phaeocystis* (e.g. Moisan and Mitchell, 2018). In comparison to the equations used in ROMS-BEC (see appendix B), the ones suggested by Moisan and Mitchell (2018; based on laboratory cultures of *Phaeocystis antarctica* grown under continuous blue light and at 4 different temperatures between -1.5°C and 4°C) lead to generally lower *Phaeocystis* growth rates, especially at $PAR < 50 \text{ W m}^{-2}$, suggesting that our biomass estimates at high latitudes and early/late in the season are associated with substantial uncertainty.”

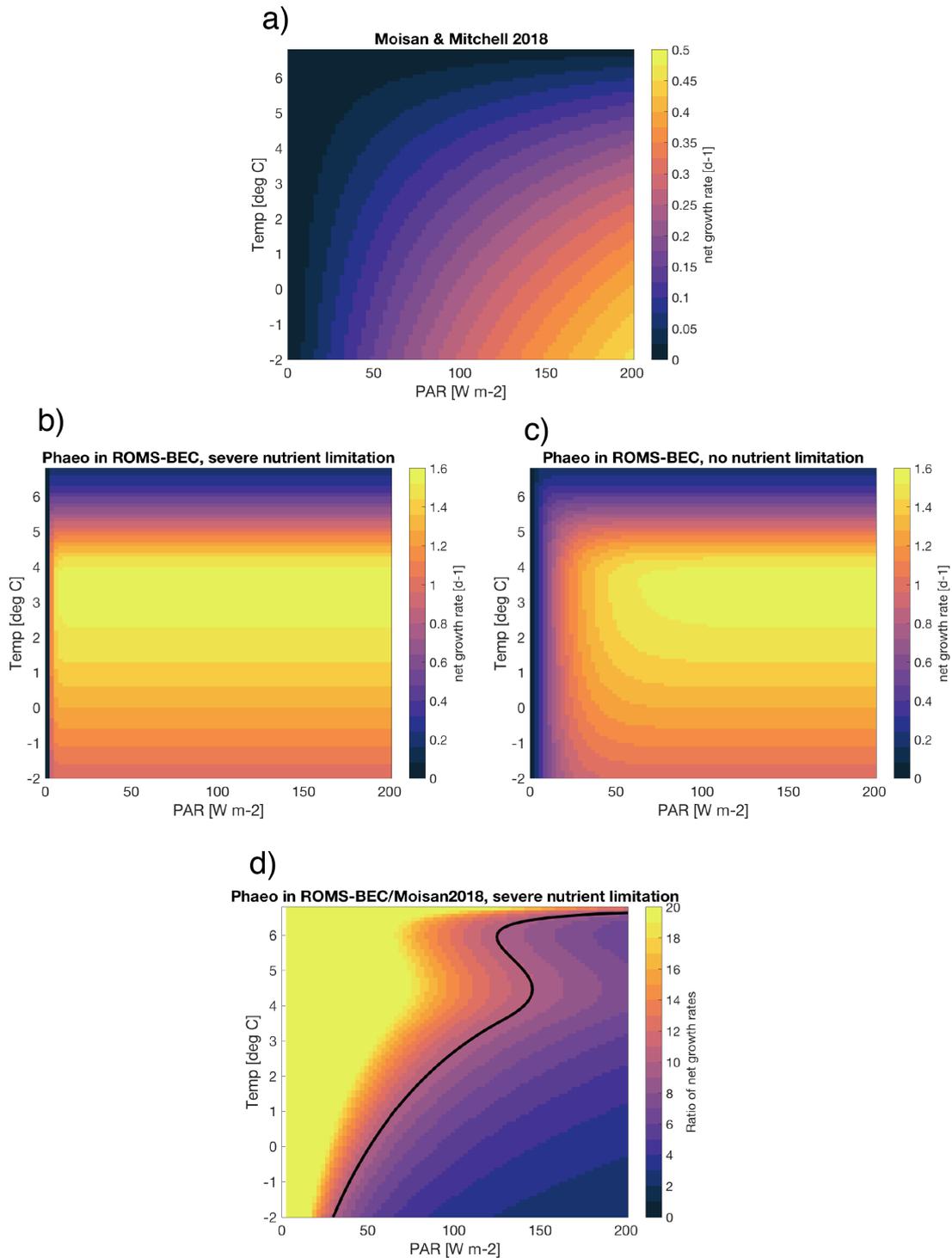


Fig. 4: a) Net growth rate of *Phaeocystis antarctica* as a function of temperature and light levels based on the equations in **Moisan & Mitchell (2018)**, assuming no photoinhibition (same as in ROMS-BEC), i.e., $\beta=0$. b) & c) Same plot as a) obtained with the equations used in ROMS-BEC (see appendix B of revised manuscript and answer to SC3 above). Panel b) and c) show the resulting net growth rates for different nutrient conditions, with “severe nutrient limitation” in panel b) using $g(N)=0.1$ in Eq. B9 of the revised manuscript and “no nutrient limitation” in panel c) using $g(N)=1$. For both cases, we have here taken the surface annual average chlorophyll:carbon ratio of *Phaeocystis* in the *Baseline* simulation of the model (0.1434 mg chl / mmol C). Note that the formulation by **Moisan & Mitchell (2018)** does not account for the nutrient conditions or the chlorophyll:carbon ratio. Panel d) shows the ratio of panel a) and b), with the black contour denoting a 10-times higher growth rate in panel a) as compared to panel b).

SC6: *please specify which atmospheric forcing fields have been used.*

We refer the reviewer to L. 185/186 of the original version of the manuscript, where we state “At the ocean surface, the model is forced with a 2003-normal year forcing for momentum, heat, and freshwater fluxes (Dee et al., 2011).”

SC7: *model results: there is a mixture of model results, model evaluation, model comparison with results from previous experiments which makes it difficult to read and to follow the arguments; the entire results section needs to be revised.*

We thank the reviewer for this helpful comment, which made us reassess the chosen structure in the result section of the original version of manuscript, leading to changes in the revised version as outlined in the following. As we consider the addition of a new phytoplankton functional type a major change in the complexity of ROMS-BEC, we have decided to first present a thorough model evaluation of this new model setup by comparing to available observational data sets (sections 3.1 & 3.2). For the purpose of this study, a realistic representation of the high-latitude phytoplankton community structure in both space and time is essential to address the competition of *Phaeocystis* and diatoms throughout the year on the one hand and the implications for downward carbon fluxes on the other. This part of the result section therefore also had the purpose to highlight model improvements compared to the earlier version of the model without *Phaeocystis*, in order to stress why the 5-PFT setup was essential for the questions at hand. Thereafter, we first present a detailed analysis on the drivers of the competition between *Phaeocystis* and diatoms (sections 3.3 & 3.4 of the original manuscript) and secondly on the implications for downward carbon fluxes (section 3.5 of the original manuscript).

To increase the clarity of the result section and to overall better reflect the focus of the manuscript, sections 3.3 & 3.4 of the original manuscript are merged into a single section called “Drivers of SO phytoplankton biogeography, phenology, and succession patterns” in the revised version of the manuscript. This new section 3.3 was shortened in the merging process (see also SC8 & SC10), in order to better balance the two aspects of the study, namely the drivers of the competition between *Phaeocystis* and diatoms and the implications for high-latitude carbon cycling. Furthermore, the title of section 3.2 was changed in the revision process (now: “Patterns of phytoplankton phenology and seasonal succession”), so that the reader is more clearly guided throughout the result section, starting with a description of the simulated biogeography (section 3.1) and succession patterns (section 3.2) and ending with a description of the drivers of these spatial and temporal patterns (section 3.3) and their implications for carbon cycling (section 3.4). Please see also our answer to SC8-SC10 for more details.

SC8: *the sections about the ecological niches, bottom-up and top-down effects are tedious to read and questionable with respect to temperature (see my comments above).*

In the revised version of the manuscript, we tried to improve upon the readability of sections 3.3 and 3.4. In particular, we have moved the part on coccolithophores from section 3.3 of the original manuscript to the supplement, in order to focus more clearly on the main topic of this study, namely the competition between *Phaeocystis* and diatoms (see also our response to the reviewer’s comment SC10). Furthermore, we have merged the sections 3.3 & 3.4 of the original manuscript into a single section in the revised version of the manuscript and revised its content in the process, in order to improve the readability (see also SC7). The revised section 3.3 of the manuscript reads:

390 3.3 Drivers of SO phytoplankton biogeography, phenology, and succession patterns

Relating the observed or simulated PFT biomass concentrations to the concurrent environmental conditions allows for an assessment of the ecological niche of the PFT in question. In ROMS-BEC, *Phaeocystis* and diatoms occupy distinct ecological niches in the *Baseline* simulation, in agreement with their distinct geographic distributions in summer (Fig. 1c-d). Between 40-90° S, the niche center of DJFM average *Phaeocystis* biomass is simulated at a nitrate concentration of 18.8 mmol m⁻³ (inter quartile range (IQR) 16.6-20.5 mmol m⁻³), a temperature of 1.1° C (IQR -0.2-2.6° C), and MLPAR of 27.8 W m⁻² (IQR 24.3-32 W m⁻², Fig. 4a & c). Since the diatom PFT in ROMS-BEC represents multiple species (in contrast to the *Phaeocystis* PFT), diatoms occupy a wider niche in temperature (IQR 0.8-8.5° C, niche center at 5° C) and nitrate (IQR 11-19.5 mmol m⁻³, niche center at 15.5 mmol m⁻³) in the model, which is in agreement with the ecological niches of important SO diatom and *Phaeocystis* species derived by Brun et al. (2015) based on presence/absence observations and species distribution models (Fig. 4a & b). In ROMS-BEC, the niche center is only at marginally higher MLPAR for diatoms than for *Phaeocystis* (28.9 W m⁻² compared to 27.8 W m⁻², respectively, Fig. 4c & d) and is at higher MLPAR for both PFTs than available observations for important SO species suggest (~10 W m⁻² and ~20 W m⁻² for *Phaeocystis* and diatoms, respectively, see Fig. 4c & d). While this bias in the MLPAR niche is consistent with the mixed layer depth bias in ROMS-BEC (~10 m; Nissen et al., 2018), the small difference in the MLPAR niche center between *Phaeocystis* and diatoms implies a minor role for MLPAR in controlling the differences in DJFM average biomass concentrations of these two PFTs (Fig. 1c-d). With regard to iron, the two PFTs do not occupy distinct ecological niches in ROMS-BEC (niche centers at 0.32 μmol m⁻³ for both PFTs, see Fig. S9). Yet, as all simulated phytoplankton growth is limited by iron availability in the high-latitude SO (Fig. S1), this suggests that the spatio-temporal averaging applied for the niche analysis here potentially precludes the assessment of the role of iron in the competition between *Phaeocystis* and diatoms, especially on a sub-seasonal scale. We conclude that the simulated ecological niches of *Phaeocystis* and diatoms are largely in agreement with available observations, but acknowledge the difficulties in comparing the ecological niche of a model PFT to those of individual phytoplankton species or groups, a sampling bias towards temperate and tropical species/strains and the overall low data coverage in the high-latitude SO in Brun et al. (2015), and the limitation of this niche analysis to inform about the role of top-down factors and sub-seasonal environmental variability in controlling the simulated biogeography of phytoplankton types.

415 The temporal evolution of the relative growth ratio, i.e., the ratio of the specific growth rates of diatoms and *Phaeocystis*, informs about the competitive advantage of one PFT over the other throughout the year due to bottom-up factors and can be broken down into the different environmental contributors for each phytoplankton type at any point in time (Eq. 2). In the 5-PFT *Baseline* simulation of ROMS-BEC, the relative growth ratio is only positive ($\mu^D > \mu^{PA}$) between early December and early February between 60-90° S (μ^D is on average 5% larger than μ^{PA} in summer, but 5-6% smaller in the other seasons, Fig. 5a & c) and only between mid-December and mid-January in the Ross Sea (μ^{PA} is up to 38% larger than μ^D in spring, Fig. 5b & d). Hence, bottom-up factors promote the accumulation of *Phaeocystis* relative to diatom biomass over much of the year, particularly in the Ross Sea. In both areas, as expected from the chosen half-saturation constants ($k_{Fe}^{PA} > k_{Fe}^D$; Table 1), the iron limitation of *Phaeocystis* growth is stronger than that of diatoms in the model, and iron availability is an advantage for diatoms at all times ($\beta_{Fe} > 0$; up to 14% stronger iron limitation of *Phaeocystis* in both areas in summer, blue areas in Fig. 5a-d). Yet, the two subareas differ in the simulated temperature and light limitation of growth of *Phaeocystis* and diatoms. Overall, temperature is limiting diatom growth more than *Phaeocystis* growth in both subareas throughout the year ($\beta_T < 0$), but this difference is rather small in summer between 60-90° S (5%, but up to 19% stronger growth limitation in the Ross Sea, red areas in Fig. 5a-d, see also Fig. A1). Similarly, the difference in light limitation between diatoms and *Phaeocystis* is rather small between 60-90° S (3-4% throughout the year, yellow areas in Fig. 5a & c), implying that their differences in α_{PI} (43% higher for *Phaeocystis*, see Table 1) are balanced by differences in photoacclimation in ROMS-BEC in this area (see Eq. B9 and Geider et al., 1998). In contrast, in the Ross Sea, differences in light limitation between diatoms and *Phaeocystis* are large, especially in spring (the growth of diatoms is 32% more light limited; Fig. 5b & d). Therefore, the difference in light limitation predominantly controls the seasonality of the relative growth ratio (Fig. 5b) and promotes the dominance of *Phaeocystis* over diatoms early in the growing season in this area in our model (Fig. 5j), which is not simulated when averaging over 60-90° S (Fig. 5i). Nevertheless, acknowledging the sensitivity of the simulated *Phaeocystis* and diatom biomass levels to all chosen model parameters describing the growth of the respective PFT (the annual mean biomass changes by >17% and >14% for *Phaeocystis* and diatoms, respectively, in the experiments TEMPERATURE, ALPHA_{PI}, and IRON, Fig. A2 & Fig. S11), the sensitivity simulations support the importance of light in controlling the annual mean high-latitude phytoplankton community structure for both subareas, as the elimination of the differences in α_{PI} between the PFTs results in the largest biomass changes both between 60-90° S (-76% and +52% for *Phaeocystis* and diatoms, respectively) and in the Ross Sea (-87% and +86%, Fig. A2). Altogether, in ROMS-BEC, differences in growth between diatoms and *Phaeocystis* are mostly controlled by seasonal differences in iron/temperature (60-90° S) and iron/light conditions (Ross Sea), respectively. Still, given the simulated growth

advantage of *Phaeocystis* throughout much of the growing season in both subareas, bottom-up factors alone cannot explain why *Phaeocystis* only dominates over diatoms temporarily (Fig. 5i & j), implying that top-down factors need to be considered to explain their biomass evolution in our model.

In both subareas, the simulated relative total loss ratio is positive throughout spring and summer, implying that the specific total loss rate of *Phaeocystis* is higher than that of diatoms ($\gamma_{\text{total}}^{\text{PA}} > \gamma_{\text{total}}^{\text{D}}$, see Eq. 6), which favors the accumulation of diatom biomass relative to that of *Phaeocystis* (Fig. 5e-h). In fact, the total loss rate of *Phaeocystis* is on average 17%/38% (60-90° S) and 18%/40% (Ross Sea) higher than that of diatoms in spring/summer (Fig. 5g & h), despite the higher prescribed maximum grazing rate on *Phaeocystis* in ROMS-BEC (Table 1). In the model, the relative total loss ratio is only negative in early fall in both subareas ($\gamma_{\text{total}}^{\text{D}} > \gamma_{\text{total}}^{\text{PA}}$, Fig. 5e & f), but the difference between diatoms and *Phaeocystis* in their specific total loss rates is rather small in this season (9% and 3% between 60-90° S and in the Ross Sea, respectively, Fig. 5g & h). In all top-down sensitivity experiments, the simulated change in *Phaeocystis* biomass levels is larger than for the bottom-up experiments (>20% for experiments GRAZING, AGGREGATION, and MORTALITY, see Fig. A2), and the dominance of *Phaeocystis* over diatoms increases in magnitude and duration both between 60-90° S and in the Ross Sea if disadvantages of *Phaeocystis* in the loss processes are eliminated (Fig. S11). The simulated seasonality of the total loss ratio is the result of the interplay between losses through grazing, aggregation, and non-grazing mortality of each phytoplankton type in ROMS-BEC (Eq. 6, colors in Fig. 5e-h). Of all three loss pathways, differences in aggregation losses in the *Baseline* simulation are largest between *Phaeocystis* and diatoms both between 60-90° S (up to 200% higher aggregation losses for *Phaeocystis* in summer, yellow in Fig. 5e & g) and in the Ross Sea (up to 250% higher in summer, Fig. 5f & h). In comparison, differences between *Phaeocystis* and diatoms in grazing (up to 16% and 14% between 60-90° S and in the Ross Sea, respectively) and mortality losses (50% everywhere) are considerably smaller (see blue and red areas in Fig. 5e-h, respectively), suggesting that aggregation losses predominantly contribute to the simulated differences in the total loss rates between *Phaeocystis* and diatoms.

In summary, between 60-90° S, the simulated growth advantage of *Phaeocystis* early in the season (facilitated by advantages in the temperature limitation of their growth) are not large enough to outweigh the disadvantages in iron limitation of their growth and in the biomass losses they experience. As a result, in spring and summer, *Phaeocystis* do not accumulate substantial biomass relative to (or even dominate over) diatoms in this subarea in ROMS-BEC. In the Ross Sea, however, the simulated growth advantages of *Phaeocystis* (resulting from advantages in the light and temperature limitation of their growth) are large enough to outweigh the disadvantages in iron limitation and specific biomass loss rates, allowing them to dominate over diatoms early in the growing season in our model and explaining the simulated succession from *Phaeocystis* to diatoms close to the Antarctic continent (see also section 3.2). Ultimately, this simulated spatio-temporal variability in the relative importance of *Phaeocystis* and diatoms has implications for SO carbon cycling, which we will assess in the following.

Regarding the importance of temperature, the reviewer is kindly referred to our answer to SC4.

SC9: *the section about carbon cycling arises out of sudden.*

We thank the reviewer for this important comment. We fully agree with the reviewer in that the parts on the cycling of carbon were not motivated thoroughly enough in the original version of the manuscript. In response, we have added this aspect to the title of the revised manuscript, so that it now better reflects the content of the study (see also SC1). Further, we have substantially rewritten the introduction, so that it now better reflects and motivates the aspects covered in the result section and discussed thereafter, in particular the implications of variability in phytoplankton community structure for downward fluxes of carbon at high SO latitudes. The reviewer is referred to our answer to GC1 for more details.

SC10: *figures: some of the selected figures are not convincing. Why focus sometimes on Phaeocystis and diatoms, sometimes on Phaeocystis, diatoms and coccolithophores and sometimes on all PFTs?*

In general, we decided to show all PFTs in the model validation (Fig. 1 & 2). Furthermore, we chose to show the whole phytoplankton community whenever showing averages/integrals over 30-90°S (Fig. 6 & 7), where coccolithophores and small phytoplankton are non-negligible members of the community. In the manuscript, Fig. 3 & 5 directly concern the competition of diatoms and *Phaeocystis* at high latitudes. In these areas, these two phytoplankton types contribute >90% of the simulated NPP, which is why no other PFT is included in these figures (see Table 3 and Fig. 2 of the manuscript).

The only exception to the above reasoning in the original manuscript is Figure 4, where we had decided to show coccolithophores in addition to diatoms and *Phaeocystis*, but not the small phytoplankton PFT. The choice “pro coccolithophores” and “contra small phytoplankton” was motivated by the fact that coccolithophores do occupy a niche that is distinct from that of diatoms and *Phaeocystis*, whereas small phytoplankton do less so and are therefore not shown. Yet, we thank the reviewer for pointing out that this choice might be confusing for the reader. In order to make the focus of the paper clearer, we changed Fig. 4 so that the new version of this figure shows diatoms & *Phaeocystis* only in the revised version of the manuscript, thus moving the niche plots for coccolithophores to the supplement (new Fig. S8, see Figure below). This way, Fig. 3-5 of the revised manuscript include only diatoms and *Phaeocystis*. Together with the substantial revisions of result sections 3.3 & 3.4 of the original manuscript (see SC7 & SC8), the result section of the revised version of the manuscript is thereby now more clearly divided into a descriptive part of the simulated patterns in space and time (partly including coccolithophores and small phytoplankton, sections 3.1 & 3.2), a section describing the drivers of the competition of *Phaeocystis* and diatoms at high latitudes (section 3.3) and its implications for carbon cycling (section 3.4).

In the method section 2.3.1 of the revised manuscript, we have added the following statement: “In section 3.3 of this manuscript, only the results for *Phaeocystis* and diatoms will be shown, the corresponding figures for coccolithophores can be found in the supplementary material (Fig. S8 & S9).”

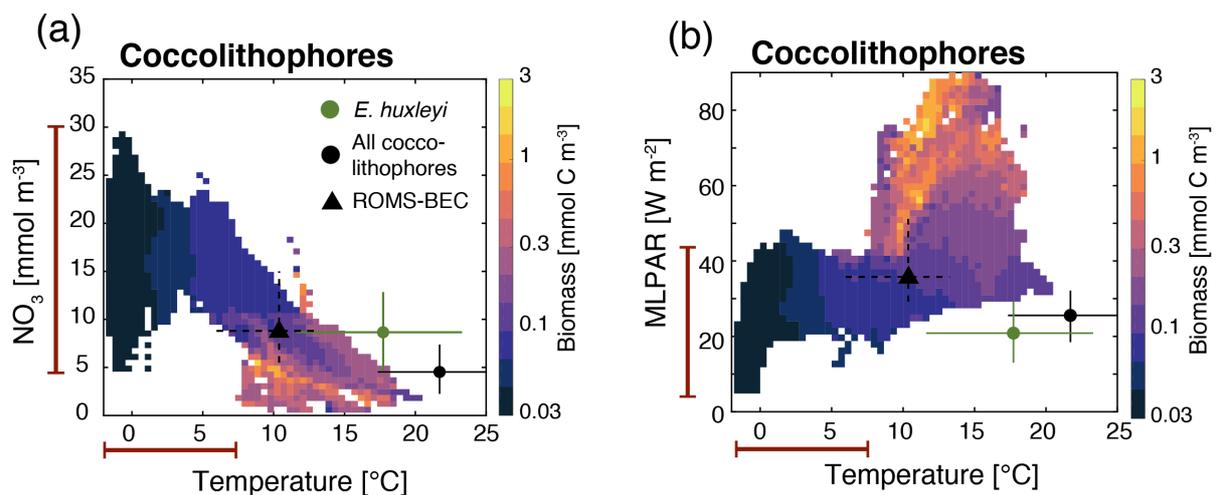


Fig. 5: Fig. S8 in the revised version of the manuscript

SC11: Fig. 2 presents a rather artificial classification of the phytoplankton community. Why is the 25% used for *Phaeocystis* and coccolithophores but 75% for diatoms (Fig 2a)? Is “Mixed” (Fig. 2a) the same as “Others” (Fig. 2b-d)?

Admittedly, the chosen thresholds are rather arbitrary and were chosen with the sole goal to indicate broad patterns of phytoplankton biogeography across the SO. The different thresholds for diatoms on the one hand and *Phaeocystis* and coccolithophores on the other hand were motivated by their different relative importance in their main region of occurrence. E.g., coccolithophores never dominate over diatoms, but still, we can define a clear SO coccolithophore biogeography – simply based on where they contribute most to NPP across the SO. If the 75% threshold was used for all PFTs, it would only be “diatoms” or “mixed”. In this context, “mixed” denotes areas where diatoms do not contribute >75%, but neither coccolithophores nor *Phaeocystis* contribute >25%, e.g. if diatoms contribute 60% and coccolithophores and *Phaeocystis* 20%, respectively.

Consequently, “mixed” in panel a is not the same as “other” in panels b-d. As indicated in the method section 2.3.1 (L 224-226 of the original manuscript): “The CHEMTAX analysis splits the

phytoplankton community into diatoms, nitrogen fixers (such as *Trichodesmium*), pico-phytoplankton (such as *Synechococcus* and *Prochlorococcus*), dinoflagellates, cryptophytes, chlorophytes (all three combined into the single group "Others" here), and haptophytes (such as coccolithophores and *Phaeocystis*)."

In order to clarify this, areas, that were labeled "mixed" in the original version of Fig. 2a, are now labeled "co-existence" and we changed the figure caption accordingly. Furthermore, we added a statement in the figure caption in the revised version of the manuscript defining "others" in the panels including CHEMTAX information: "[...] "others" in the CHEMTAX fractions corresponds to dinoflagellates, cryptophytes, and chlorophytes [...]"

SC12: how does the annual or climatological "relative contribution of the five PFTs" looks like (and not the seasonal contribution as in Fig. 2b-c)? If such a figure were shown the statements in the paragraph l. 348–354 might be more comprehensible.

We decided to only give the annual mean/integral numbers for NPP (see Table 3) and focus on the seasonal evolution for chlorophyll in Figure 2, which we can directly compare to HPLC-based estimates. The annual mean contribution to mixed layer chlorophyll levels of *Phaeocystis*/diatoms/coccolithophores amounts to 12.2/64.5/9.8 (30-90°S) and 31.1/54.8/2.4 (60-90°S) in our model, in rather close agreement with the estimates for NPP (15.3/53/14.6 between 30-90°S and 45.8/49.1/0.7 between 60-90°S, see Table 3).

Furthermore, we want to highlight the data scarcity in general and especially in all seasons besides summer in this context (see numbers printed below upper pie charts in Fig. 2), preventing a meaningful comparison of *annual mean* community structure in the model with the CHEMTAX data, which is why no annual mean figure is shown for the CHEMTAX data.

SC13: Fig. 4 - why is silicate not chosen as an important factor for diatoms? At least in the northern part of the SO (south of ~40°S) diatoms are limited by silicate.

As shown in Fig. S1, the reviewer is correct in pointing to a growth limitation of diatoms by silicic acid close to 40°S. Yet, as the focus of this paper is the competition between diatoms and *Phaeocystis*, which mainly takes place south of 60°S in ROMS-BEC, we chose not to show silicic acid as one of the environmental variables here, as the availability of silicic acid does not limit diatom growth in the focus area of this study. In fact, across Si levels, diatom biomass varies substantially south of 40°S (see Figure below), indicating that it is not a major control on diatom biomass levels in the area. For completeness, we add the figure below to the supplementary material (Fig. S8 in original manuscript, S9 in revised version) in the revised version of the manuscript.

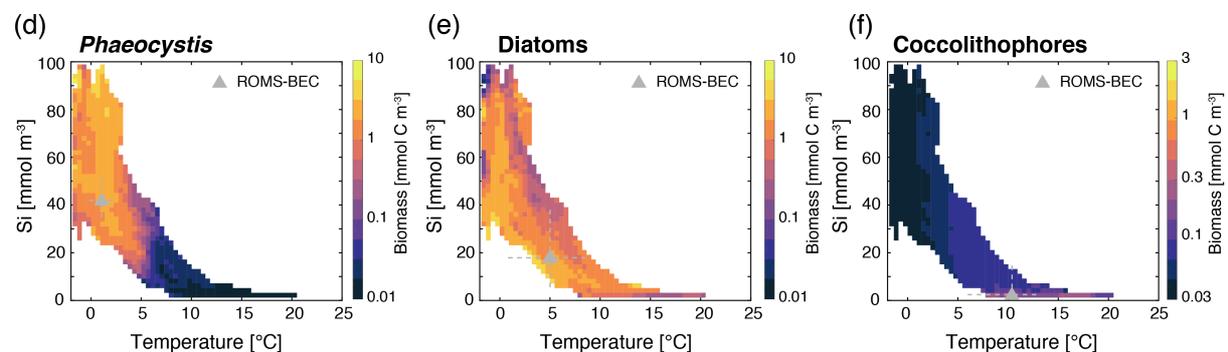


Fig. 6: Same as the ecological niche plots in Fig. 4 of the manuscript, but showing phytoplankton biomass as a function of silicic acid concentrations [mmol m⁻³]. This figure will be added as Fig. S9 to the revised manuscript.

SC14: the discussion and conclusion sections suffer from what I commented above. The authors must make clear what the paper is about in the first place. I am confident that also the discussion and conclusion section will then be easier to write.

We thank the reviewer for this comment, in direct response to which we have made several modifications to the manuscript. Besides small modifications to the text of all discussion sections and the conclusion section to improve upon the clarity of the text and to better reflect the focus of the study, we have changed the order of discussion sections 4.1 & 4.2 in the revised version of the manuscript, so that it reflects the order in which these aspects are described in the result sections (first drivers, then biogeochemical implications).

Furthermore, we have moved the part about DMS from the method section 2.3.1 in the original version of the manuscript to the new discussion section 4.2, to more clearly focus the method section on aspects regarding carbon cycling, which is the main focus of the paper.

The part about DMS was shortened in the process, and the new paragraph reads:

Besides its impact on the carbon cycle, *Phaeocystis* is the major contributor to the marine sulphur cycle in the SO through its production of DMSP (Keller et al., 1989; Liss et al., 1994; Stefels et al., 2007). Though not explicitly including the biogeochemical cycling of sulphur, we can nevertheless use model output from ROMS-BEC to obtain an estimate of DMS production by *Phaeocystis* through a simple back-of-the-envelope calculation. Integrating the modeled *Phaeocystis* biomass loss rates via zooplankton grazing and non-grazing mortality over the top 10 m, assuming a molar DMSP:C ratio for *Phaeocystis* of 0.011 (Stefels et al., 2007), and a DMSP-to-DMS conversion efficiency between 0.2-0.7 (the DMS yield depends on the local sulphur demand of bacteria, Stefels et al., 2007; Wang et al., 2015), our estimated annual DMS production by *Phaeocystis* in ROMS-BEC amounts to 3.3-11.5 Tg S and 1.8-6.4 Tg S south of 30° S and 60° S, respectively. Consequently, assuming that all of this DMS production quickly escapes to the atmosphere, our estimates correspond to 11.6-40.1% (30-90° S) and 6.5-22.7% (60-90° S) of the global flux of DMS to the atmosphere previously estimated by Lana et al. (2011, 28.1 Tg S yr⁻¹). Our estimate is an upper bound, however, as not all DMS produced in seawater is readily released to the atmosphere. In fact, a fraction is likely broken down by bacteria, by photolysis, or is mixed down in the water column (see e.g. Simó and Pedrós-Alló, 1999;

Stefels et al., 2007). Still, given that other phytoplankton types also produce DMS(P) (Keller et al., 1989; Stefels et al., 2007), the ROMS-BEC-based contribution of SO *Phaeocystis* alone (3.3-11.5 Tg S yr⁻¹) to the global flux of DMS to the atmosphere is in agreement with the flux suggested in Lana et al. (2011, 8.1 Tg S yr⁻¹ south of 30° S, i.e., 29% of their global estimate), and the substantial contribution of SO *Phaeocystis* underpins its major role for the global cycling of sulphur.

Cited literature

- Arrigo, K. R., Schnell, A., & Lizotte, M. P. (1998). Primary production in Southern Ocean waters. *Journal of Geophysical Research*, 103(C8), 15587–15600. <https://doi.org/10.1029/98JC00930>
- Boyd, P. W. (2019). Physiology and iron modulate diverse responses of diatoms to a warming Southern Ocean (supplement). *Nature Climate Change*, 9(2), 148–152. <https://doi.org/10.1038/s41558-018-0389-1>
- Brun, P., Vogt, M., Payne, M. R., Gruber, N., O'Brien, C. J., Buitenhuis, E. T., ... Luo, Y.-W. (2015). Ecological niches of open ocean phytoplankton taxa. *Limnology and Oceanography*, 60(3), 1020–1038. <https://doi.org/10.1002/lno.10074>
- Buma, A. G. J., Bano, N., Veldhuis, M. J. W., & Kraay, G. W. (1991). Comparison of the pigmentation of two strains of the prymnesiophyte *Phaeocystis* sp. *Netherlands Journal of Sea Research*, 27(2), 173–182. [https://doi.org/10.1016/0077-7579\(91\)90010-X](https://doi.org/10.1016/0077-7579(91)90010-X)
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system.

Quarterly Journal of the Royal Meteorological Society, 137(656), 553–597.
<https://doi.org/10.1002/qj.828>

- Garcia, N., Sedwick, P., & DiTullio, G. (2009). Influence of irradiance and iron on the growth of colonial *Phaeocystis antarctica*: implications for seasonal bloom dynamics in the Ross Sea, Antarctica. *Aquatic Microbial Ecology*, 57(2), 203–220. <https://doi.org/10.3354/ame01334>
- Geider, R. J., MacIntyre, H. L., & Kana, T. M. (1998). A dynamic regulatory model of phytoplanktonic acclimation to light, nutrients, and temperature. *Limnology and Oceanography*, 43(4), 679–694. <https://doi.org/10.4319/lo.1998.43.4.0679>
- Leblanc, K., Arístegui, J., Armand, L., Assmy, P., Beker, B., Bode, A., ... Yallop, M. (2012). A global diatom database – abundance, biovolume and biomass in the world ocean. *Earth System Science Data*, 4(1), 149–165. <https://doi.org/10.5194/essd-4-149-2012>
- Le Quéré, C., Harrison, S. P., Colin Prentice, I., Buitenhuis, E. T., Aumont, O., Bopp, L., ... Wolf-Gladrow, D. (2005). Ecosystem dynamics based on plankton functional types for global ocean biogeochemistry models. *Global Change Biology*, 11, 2016–2040. <https://doi.org/10.1111/j.1365-2486.2005.1004.x>
- Le Quéré, C., Buitenhuis, E. T., Moriarty, R., Alvain, S., Aumont, O., Bopp, L., ... Vallina, S. M. (2016). Role of zooplankton dynamics for Southern Ocean phytoplankton biomass and global biogeochemical cycles. *Biogeosciences*, 13(14), 4111–4133. <https://doi.org/10.5194/bg-13-4111-2016>
- Nissen, C., Vogt, M., Münnich, M., Gruber, N., & Haumann, F. A. (2018). Factors controlling coccolithophore biogeography in the Southern Ocean. *Biogeosciences*, 15(22), 6997–7024. <https://doi.org/10.5194/bg-15-6997-2018>
- Platt, T., Gallegos, C. L., & Harrison, W. G. (1980). Photoinhibition of Photosynthesis in Natural Assemblages of Marine Phytoplankton. *Journal of Marine Research*.
- Schoemann, V., Becquevort, S., Stefels, J., Rousseau, V., & Lancelot, C. (2005). *Phaeocystis* blooms in the global ocean and their controlling mechanisms: a review. *Journal of Sea Research*, 53(1–2), 43–66. <https://doi.org/10.1016/j.seares.2004.01.008>
- Vogt, M., O'Brien, C., Peloquin, J., Schoemann, V., Breton, E., Estrada, M., ... Peperzak, L. (2012). Global marine plankton functional type biomass distributions: *Phaeocystis* spp. *Earth System Science Data*, 4(1), 107–120. <https://doi.org/10.5194/essd-4-107-2012>
- Wang, S., & Moore, J. K. (2011). Incorporating *Phaeocystis* into a Southern Ocean ecosystem model. *Journal of Geophysical Research*, 116(C1), C01019. <https://doi.org/10.1029/2009JC005817>