Response to Reviewer 1 comments

In this document, the reviewer's comments are in black, our responses are in brown, the old original text is in light blue, the new/updated text is in dark blue.

Review of "Drivers of Phytoplankton Bloom Interannual Variability in the Amundsen and Pine Island Polynyas" by Guillaume Liniger et al.

The manuscript presents a valuable study of the phytoplankton blooms and their drivers in the Amundsen and Pine Island Polynyas. Satellite-derived Chl-*a* and NPP maps were used to characterize phytoplankton abundance and primary productivity in the years 1998 – 2017. Overall, the manuscript is well-written, well-organized, and the main points are clearly articulated. The determination of phenology metrics followed the standard methodologies described in the literature, and the use of Principal Component Analysis (PCA) and the Mann-Kendall test demonstrates good statistical practices. I especially appreciate the application of non-parametric statistical metrics in this study.

I see, however, a few issues that when fixed, could improve the final version of the paper. I present them in the points below:

We are grateful for the reviewer's positive feedback. We answer the reviewer's concerns below.

1. The study compares the Amundsen and Pine Island Polynyas, highlighting several differences that appear to arise from variations in local topography, sediment resuspension, and currents (as mentioned in lines 519-520). While these factors were discussed, they were overlooked in the study area's section. To improve the brief description and make it easier for readers to follow the discussion, it would be beneficial to add the following: (a) the bathymetry of the area, which is an important aspect in the analysis of sediment resuspension; (b) contrasts between the polynyas regarding circulation patterns; (c) a brief description of the glaciers analyzed in the study with a particular focus on the differences between them; and (d) information on phytoplankton composition, which determines the demand for nutrients, sensitivity to iron shortages (notably different for diatoms and small flagellates), and the potential for using recycled nutrients. Recent research has indicated changes in the phytoplankton community structure on Antarctica's shelf, including a decline in diatoms sensitive to iron shortages, so I would expect at least a brief characterization of these communities.

We thank the reviewer for their suggestions, following them, we have:

a. Added a map of the bathymetry with a schematic of ocean circulation as new Figure 1a, and the mixed-layer depth (MLD; ECCO Consortium version 4 release 4) climatology as subpanel Figure 1b to give more context to our study. We use the new MLD product later in our analysis.

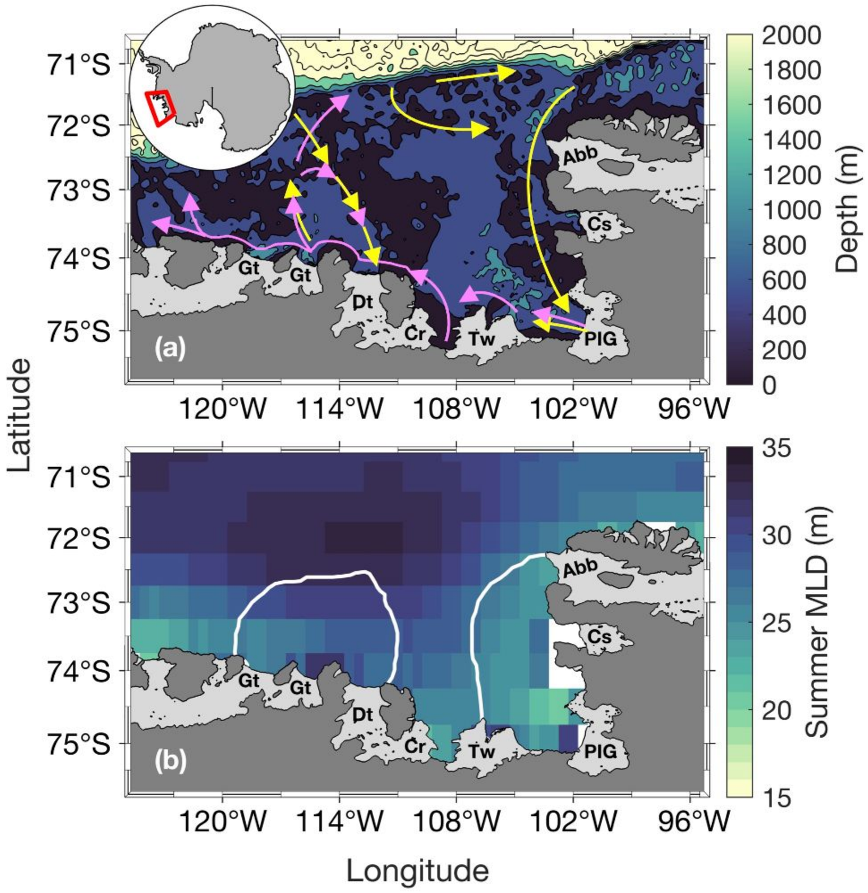

Figure 1. Study area. Panel 1a shows the bathymetry (from ETOPO1; Amante & Eakins, 2009) and panel 1b shows the climatological summer mixed-layer depth (MLD) from 1998 to 2017. Panel 1a shows a simplified schematic of the local deep ocean circulation (~ below 400m, yellow arrows) and upper glacial meltwater/sediments/circumpolar deep water sourced dFe pathways (magenta arrows), which follows the local upper ocean circulation. Schematic adapted from St-Laurent et al. (2017). The white lines in panel (b) represent the climatological summer polynya boundaries for the Amundsen Sea polynya (left) and Pine Island polynya (right). The dark grey area is mainland Antarctica. Light grey areas indicate floating ice shelves and glaciers: Abbot (Abb), Cosgrove (Cs), Pine Island Glacier (PIG), Thwaites (Tw), Crosson (Cr), Dotson (Dt) and Getz (Gt).

b. Added a brief description of the circulation in the embayment in the method section of the updated manuscript. We also added arrows showing the local ocean circulation and pathways of glacial meltwater and sediments in the embayment in the new Figure 1a.

In the ASE, the ice sheet loss is mainly through enhanced basal melting of the ice shelves. This is attributed to an increase in wind-driven Circumpolar Deep Water (CDW) fluxes and ocean heat content intruding onto the continental shelf through deep troughs such as Pine Island and Dotson-Getz, flowing into the ice shelf cavities (Dotto et al., 2019; Jacobs et al., 2011; Pritchard et al., 2012). There, warm waters fuel intense basal melt of the Pine Island, Thwaites, and Getz ice shelves, and returns as a fresher, colder outflow that can strengthen stratification (Jenkins et al., 2010; Ha et al., 2014). The PIP and ASP differ in their exposure to CDW and in local circulation: the ASP is more strongly influenced by upwelled modified CDW (mCDW) and glacial meltwater inputs, while the PIP is typically more stratified and less directly ventilated by deep waters (Assmann et al., 2013; Dutrieux et al., 2014). These hydrographic contrasts can shape the timing and magnitude of phytoplankton blooms and nutrient dynamics across the two polynyas."

c. Added a brief description of the relative importance of the glaciers and ice shelves in the area in the updated manuscript

We focus on the PIP and ASP in the ASE embayment in West Antarctica (Figure 1). The ASE embayment is comprised of several ice shelves and glaciers, including Abbot (Abb), Cosgrove (Cs), Pine Island (PIG), Thwaites (Tw), Crosson (Cs), Dotson (Dt) and Getz (Gt). The PIG and Thwaites have received significant attention in recent years due to their potentially large contribution to sea level rise (Rignot et al., 2019; Scambos et al., 2017). Along with the Crosson and Dotson ice shelves, the PIG and Thwaites are undergoing the highest melt rate, which is expected to increase under climate change scenarios (Naughten et al., 2023; Paolo et al., 2023). The mean MLD in the ASP is deeper (Figure 1b), indicating that it may better entrain deeper sources of nutrients into the upper waters. The polynya boundaries were determined using a 15% sea-ice concentration (SIC) mask (Moreau et al., 2015; Stammerjohn et al., 2008) for every 8-day period from June 1998 to June 2017 to accurately represent the size of the polynya through time.

d. Added information about the phytoplankton composition in the Amundsen embayment, in the introduction section in the updated manuscript.

The phytoplankton community in the ASE is generally dominated by *Phaeocystis antarctica* (Lee et al., 2012; Lee et al., 2017; Yager et al., 2016), which is adapted to low iron availability and variable light conditions, and forms large summer blooms (Alderkamp et al., 2012; Yager et al., 2016). Diatoms like *Fragilariopsis sp.* and *Chaetoceros sp.* are also present, often becoming more important near the sea-ice edge or under shallow, stratified mixed layers where silicic acid (Si) and iron (Fe) are more available (Mills et al., 2012). In exceptional years, such as 2020, diatoms like *Dactyliosolen tenuijunctus* replaced *P. antarctica* as the dominant taxon, driven by anomalously shallow mixed layers and sufficient Fe–Si supply (Lee et al., 2022). This dynamic balance highlights how light, nutrient supply, and stratification control community composition in these highly productive and complex Antarctic systems.

2. The role of ligands, which are mentioned late in the discussion, seems significant for the availability of iron to phytoplankton. Information in lines 568-570 seems to suggest a possible feedback loop between the biological activity, ligands and the bioavailability of iron, which could be an interesting aspect to consider when analyzing bloom cycles. It might be worth adding a short comment on this topic in the model description around line 190.

We agree with the reviewer. We mentioned in the original version that ligands may be important in the feedback loop "The production of ligands by phytoplankton would increase the stock of bioavailable Fe and further fuel the phytoplankton bloom in the polynyas".

Regarding how ligands are constrained in the model, in the original version of the manuscript, we specified that every iron particle in the model is bound to a ligand, implying that all of the dissolved iron is made available at any time for phytoplankton to use. We have added a reference that showed that when dFe is bound to ligands, it remains bioavailable for phytoplankton.

"This is parameterized in the model as all iron molecules being bound to a ligand, and therefore remaining in solution in a bioavailable form (Gledhill & Buck, 2012). For a detailed and complete explanation of the model, see Dinniman et al. (2020)."

3. There are at least two GlobColour L3 chl-a products that differ by the averaging method. It would be helpful to provide an ID or DOI number for the dataset. On a similar note, it would be interesting to see a discussion on the strong connection between net primary production (NPP) and chl-a, as chl-a is a key parameter for estimating NPP.

We have specified which chla algorithm/dataset we used in section 2.2 in the updated manuscript.

"We obtained level-3 satellite surface chlorophyll-a (chla) concentration with spatial and temporal resolution of 0.04° and 8 days from the European Space Agency (ESA) Globcolor project (https://www.globcolour.info/). We used the CHL1-GSM (Garver–Siegel–Maritorena) (Maritorena and Siegel, 2005) standard Case 1 water merged products consisting of the Sea-viewing Wide Field-of-view (SeaWiFS), Medium Resolution Imaging Spectrometer (MERIS), Moderate Resolution Imaging Spectroradiometer (MODIS-A) and Visible Infrared Imaging Suite sensors (VIIRS)."

We also added sentences about the relationship between chla and NPP in the method and discussion section in the updated manuscript, and elaborate more on this in #Reviewer2 response.

"The VGPM model is a chlorophyll-based approach and relies on the assumption that NPP is a function of chlorophyll, influenced by light availability and maximum daily net primary production within the euphotic zone."

"The Vertically Generalized Production Model (VGPM) relates chla to depth-integrated photosynthesis through empirical relationships with light and temperature (Behrenfeld & Falkowski, 1997)."

"We also note as a limitation that satellite-derived chla and VGPM NPP estimates lack the vertical resolution needed to resolve sub-plume stratification and mixing processes (e.g. fine-scale vertical gradients in iron or nutrient fluxes), so our interpretations of surface chla vs. depth-integrated productivity decoupling must be taken with caution."

4. Under high-nitrate low-iron conditions, literature reported significant variations in the carbon-to-chlorophyll (C_{phyto}:Chl) ratio from those assumed globally, due to phytoplankton adaptations to iron shortages. Additionally, low-light conditions can alter the carbon-to-chlorophyll ratio. It would be worth including these elements in the discussion as a potential source of uncertainty. Might these differences explain the significant correlation with chl-a in Figure 3 and the lack of correlation with NPP at the same time?

In the original version of the manuscript, we briefly mentioned that the decoupling between chla and NPP in the ASP could be due to the bloom being dominated by *P. antarctica*. In the updated version, we elaborate more about why we observe such differences in chla/NPP response to the environmental factors. We added some text related to the role of light and iron co-limitation, and ligands. We also added some data about the mixed-layer depth and how those could impact the phytoplankton bloom community and the relationship observed between chla, NPP and the environmental parameters throughout the text in the different section, where we hypothesize that:

a. More meltwater can drive stronger overturning, deepening the mixed layer, decreasing light availability → Potentially favoring *P. antarctica.*

The summer MLD is deeper in the ASP (Figure 1b), which would decrease light availability, despite higher PAR compared to the PIP. Previous studies report that the small prymnesiophyte *P. antarctica*, a low-efficiency primary producer (Lee et al., 2017), is better adapted to deeper mixed layer and therefore lower light condition (Alderkamp et al., 2012; Mills et al., 2010) and could contribute to high surface chla decoupled from NPP, as observed in the ASP.

b. More ligands can favor *P. antarctica*, which can access organically bound Fe more efficiently than many diatoms.

The production of ligands by phytoplankton may increase the stock of bioavailable Fe and further fuel the phytoplankton bloom in the polynyas, potentially highlighting the dominance of *P. antarctica*, which uses iron-binding ligands more efficiently than diatoms (Thuróczy et al., 2012), even under low light conditions.

c. *P. antarctica* is adapted to a low light environment + deeper MLD, compared to diatoms. Therefore, a strong light relief + warmer temperature create an ideal stratification environment for diatom blooms to happen, which is what we suggest may be happening in the PIP based on our results.

While *P. antarctica* is usually the main phytoplankton species dominating in both polynyas, the combination of light-limitation relief and higher SST may create better conditions for a stratified and warmer environment that would favor diatoms (Arrigo et al., 1999; van Leeuwe et al., 2020), as recently observed in the ASP (Lee et al., 2022). The positive association of PAR, SST and chla with MLD likely reflects conditions around sea-ice retreat (all negatively associated with IRT), when enhanced wind mixing deepens the mixed layer and replenishes surface nutrients at the same time that light availability and SST increases. This nutrient–light co-limitation phase supports high biomass accumulation, likely from diatoms.

d. We also added some text about the potential effect of shifting community:

Our results suggest potential long-term changes in the phytoplankton community, specifically a shift towards diatoms in the ASE coastal regions during phytoplankton bloom. Hayward et al. (2025) reported a decline in diatoms from 1997 to 2017 in the PIP. However, they observed an increase in diatoms after 2017, linked to regime shift in sea ice. Their study also indicates that diatoms are competitively disadvantaged under iron-depleted conditions, whereas in the ASP, *P. antarctica*, which relies on dFe supplied by ocean circulation, tends to dominate. Such shifts in phytoplankton composition are likely to affect carbon export, grazing, and higher trophic levels. Additional long-term data on inter-annual variability in phytoplankton composition and physiology will be essential to fully understand these relationships.

5. Lastly, a small editorial note: lines 274-277 contain a repeated sentence

Thank you for pointing it out. Corrected.