

# **Interactive comment on « Southern Ocean biological pump over the last glacial cycle from new diatom transfer functions » by Rembauville and Pichat.**

## **Authors response to Reviewer 2**

We thank the anonymous reviewer #2 for reviewing our manuscript and the constructive comments that helped us improving the manuscript. All the modifications appear on the new version of the manuscript and the supplementary information attached as a supplement to this answer.

**R2-Cx:** Reviewer comment, **R2-Rx:** authors response, **Change made :** **change to the manuscript.**

### **General comments**

**R2-C1.** This manuscript presents new transfer functions based on Southern Ocean sediment trap data to reconstruct deep-ocean particulate organic carbon (POC) export and the PIC:POC export ratio from diatom assemblages. Using a combination of statistical approaches, the authors develop and validate these transfer functions, showing generally consistent results across methods and identifying ecologically meaningful diatom groups associated with export fluxes and carbon partitioning.

The transfer functions are then applied to sediment cores from the Antarctic Zone (AZ) of the Southern Ocean to reconstruct glacial–interglacial variations in export production and carbonate counter-pump dynamics. The results indicate higher POC export and lower PIC:POC ratios during glacial periods, suggesting a strengthened biological pump and a reduced carbonate counter-pump, which together may have contributed to lower atmospheric CO<sub>2</sub> concentrations. These findings are interpreted in terms of enhanced iron fertilisation, changes in sea-ice extent, and ecosystem structure. The study also highlights discrepancies with Ba-based proxies and emphasizes the potential of diatom-based approaches to reconstruct past export dynamics in the Southern Ocean.

The findings are relevant, timely, and somewhat provocative. However, given the current presentation, it is difficult to evaluate how robustly the data support the main conclusions. I would thus encourage the authors to specify the following points -

**R2-R1.** We thank the reviewer for the careful reading of the manuscript. Following Reviewer's 1 and 2 comments, we added statistical information concerning transfer function calibration and quantitative description of diatom relative abundance in sediment cores as supplementary figure S6. We detail below a point-by-point response to address the questions and remarks associated.

### **General comment -**

**R2-C2.** While I am not a specialist in micropaleontology or transfer function approaches, and therefore may not fully assess the robustness of the statistical framework, I am not necessarily suggesting that the approach is flawed. However, I feel that this step would benefit from clearer contextualisation and justification. As I understand it, the transfer function used here is calibrated against sediment trap observations to reconstruct “deep ocean” POC flux across the Southern

Ocean. This seems reasonable. However, the study then applies this transfer function to downcore sedimentary records. This transition is not entirely clear to me. Conceptually, it appears to involve extrapolating relationships derived from modern sediment trap data to sedimentary archives that integrate additional processes (e.g., diagenesis, lateral transport, temporal averaging). Most transfer function approaches I am familiar with rely on core-top calibrations to reconstruct temporal variability within sedimentary records. In that sense, the present approach seems to bridge two different observational frameworks. Could the authors please clarify the assumptions underlying this extrapolation, and discuss the potential limitations and caveats associated with applying a sediment trap–derived transfer function to downcore sediment records?

**R2-R2.** It is true that sedimentary archives integrate additional processes that can potentially modify the diatom community structure (e.g. diagenesis) or POC flux (e.g. lateral transport). For the former, it could result in different relative abundances and rarefaction curves in the sediment core and the sediment trap datasets (Figure 3). To overcome this limitation, we selected species present with a mean relative abundance > 0.1 % in both dataset ( $n = 22$  species). Thereby the transfer functions are based on a common list of abundant species, generally displaying a robust frustule that is less prone to dissolution compared to small, lightly-silicified species. The application of the transfer function is thus not an “extrapolation”, as the selected species list shows comparably high relative abundance in both dataset. This is now more clearly specified in section 2.2.

**Change made l. 148-160:** “Our approach applies relationships between chemical fluxes and diatoms found in the mesopelagic/bathypelagic ocean (sediment traps) to sedimentary records. Indeed, the latter could potentially be affected by additional processes, e.g. diagenesis or sediment redistribution by deep-sea currents, that could modify the diatom community structure or the chemical fluxes. Diatoms are affected by selective grazing and dissolution during their sinking in the water column (Ran et al., 2024) and differential alteration of the frustule during early diagenesis (DeMaster et al., 1996; Pellegrino et al., 2024). For transfer functions calibration, the species present in both the sediment trap and sediment core datasets were first selected, i.e. 64 species/taxa groups (Fig. 3). Secondly, in order to avoid the bias associated with rare species and potential selective dissolution/preservation of species between the sediment trap and the surface sediments a filter was applied to isolate the abundant species shared by the two datasets. Species occurring with at least a relative abundance of 0.1 % in both datasets were selected (Esper and Gersonde, 2014). This final step resulted in a list of 22 informative species that we assume to be poorly affected by dissolution and diagenesis, ensuring a robust transfer from the sediment trap to the sediment core datasets. The relative abundances of these informative species were rescaled to 100 % in the two datasets before using these data to calibrate the transfer functions.”

Diagenesis is likely to affect diatom communities between the top-core and the down-core samples and this issue is also present in traditional diatom-based transfer functions. However, and to our knowledge, there is no correction applied in previously published diatom-based transfer functions. The difference in the sediment trap and sediment core diatom community is discussed in section 4.1 :

“The relative abundance of diatom species shows noticeable differences in the sediment trap and sediment core data. Small ubiquitous species that are abundant in the sediment traps such as *Pseudo-nitzschia lineola* or *Nitzschia bicaipitata* are rare in the sediment cores. It is also the case for larger species such as *Corethron pennatum* and *Asteromphalus hookeri*. The slope of the rarefaction

course is steeper in the sediment core dataset when compared to the sediment trap data, with the most abundant species in the cores characterized by a heavily silicified frustule (e.g. *Fragilariopsis* and large *Thalassiosira* species). These results confirm previous observations of selective dissolution of lightly silicified species in the deep ocean below the sediment traps depth (Rigual-Hernández et al., 2016; Warnock and Krueger, 2020; Ran et al., 2024). Hence, the selection of informative species in both datasets is a critical preliminary step before calibrating the transfer functions. The resulting rather small number of informative species (here 22) is due to the merging of the sediment trap and sediment core datasets in which the most abundant species are different. This number is however only slightly lower than those in studies based on core-top diatom communities, typically 25 to 29 species (Imbrie and Kipp, 1971; Crosta et al., 1998; Esper and Gersonde, 2014)."

#### Detailed comments -

**R2-C3. l. 11.** Awkward sentence. "capture", instead of "catch"?; "govern" instead of "set"?

**R2-R3. Change made l. 11:** "The diatom community appears to **capture** efficiently the ecosystem structure that **govern POC the flux and PIC:POC export ratio** with root mean square errors of the prediction ranging 17-19.6 % depending on the transfer function."

See also the definition of the biological pump in R2-R8.

**R2-C4. l. 15.** It is unclear what is meant by an "increase in the biological pump." Does this refer to its strength, its efficiency, or another metric?

**R2-R4. Change made l. 15:** "These two signals suggest that both the increase **in the magnitude of the** biological carbon pump and the decrease in the carbonate counter-pump in the AZ during glacial periods could have contributed to the decrease in atmospheric pCO<sub>2</sub>."

**R2-C5. l. 17.** This interpretation appears to rely on a potentially problematic simplification. Diatom-bound  $\delta^{15}\text{N}$  is not, strictly speaking, a proxy for export production (as correctly noted later in the manuscript), but rather reflects aspects of the nitrogen cycle (e.g., nitrate utilisation and/or source).

**R2-R5.** We now specify that diatom-bound  $\delta^{15}\text{N}$  is indeed considered here as a proxy for nutrient utilization.

**Change made l. 17:** "The reconstructed POC export is consistent **with nutrient utilization** derived from previously published diatom-bound  $\delta^{15}\text{N}$  and **with sediment** total organic carbon content but differs from elemental Ba/Fe ratio. ~~hinting Ba potential preservation issues in Southern Ocean sediments.~~"

**R2-C6. l. 30.** Primary/export production is also limited by the scarcity of light

**R2-R6.** Polar microorganisms are able to grow phototrophically at extremely low light levels (Morgan-Kiss et al., 2006). More specifically, Southern Ocean diatoms have an adaptation to low light and low iron conditions : they display an unusually large photosynthetic antennae of

photosystem II, ensuring light utilization while keeping low iron requirements. For these reasons light is not a limiting factor that could explain the specific HNCL regime of some areas of the Southern Ocean.

**R2-C7.** l. 31. Macronutrient excess?

**R2-R7. Change made l. 36:** “The macronutrient **excess** and leakage to lower latitudes suggests that the vertical transfer of particulate organic matter from the surface to the deep ocean, i.e. the biological pump, is inefficient (Sarmiento and Toggweiler, 1984; Sigman et al., 2010).”

**R2-C8.** l. 32. The argumentation would benefit from a clearer, more detailed definition of the biological carbon pump.

**R2-R8.** We now start the introduction with a definition of the biological pump.

**Change made l. 29-32:** “**The biological pump is defined as the vertical transfer of CO<sub>2</sub> from the mixed layer to the deep ocean through the production, export and partial remineralization of organic matter. The biological pump transfers carbon from superficial reservoirs associated with short residence time (atmosphere and mixed layer, residence time = years) to deep reservoirs associated with much longer residence time (deep ocean and sediments, residence time = thousand years to millions years).**”

**R2-C9.** l. 40. ... in the SAZ.

**R2-R9.** This is explicitly stated at the end of this paragraph l. 51 : “However, additional export proxies suggested a latitudinal response of the SO to glacial conditions : **an-increased** a **more efficient** biological pump in the SAZ due to dust-driven fertilization of phytoplankton growth, but a **weaker less efficient** biological pump in the AZ due to higher stratification and lower micronutrient enrichment (François et al., 1997; **Anderson et al., 2002; Kohfeld et al., 2005**; Jaccard et al., 2013; Sigman et al., 2021).”

**R2-C10.** l. 47. Could the authors please clarify what is meant by an “increased” biological pump? Specifically, does this refer to an increase in the strength (i.e., export flux) or in the efficiency (i.e., the proportion of production exported and/or preserved) of the biological pump?

**R2-R10. Change made l. 51:** “However, additional export proxies suggested a latitudinal response of the SO to glacial conditions : **an-increased** a **more efficient** biological pump in the SAZ due to dust-driven fertilization of phytoplankton growth, but a **weaker less efficient** biological pump in the AZ due to higher stratification and lower micronutrient enrichment (François et al., 1997; **Anderson et al., 2002; Kohfeld et al., 2005**; Jaccard et al., 2013; Sigman et al., 2021).”

**R2-C11. I. 59.** “true” is a bit misleading here. What about “preserved” vertical flux?

**R2-R11.** We have clarified what is meant by “true” vertical flux. It is not “preserved” rather corrected for sediment redistribution. “True” is a term commonly used to define this correction (e.g. François et al., 2004).

**Change made I. 63-67:** “Organic carbon export has been derived from sediment organic carbon (Corg) concentration rate normalized to  $^{230}\text{Th}$ , i.e. ~~corrected for sediment redistribution~~ (François et al., 2004; Thöle et al., 2019) or from biological barite accumulation rate, ~~i.e. the true vertical biogenic barite flux~~, with biogenic barite or barium (Ba) excess defined as the difference between total Ba and Ba of lithogenic origin (Dymond et al., 1992; François et al., 1997; Hernandez-Sanchez et al., 2011).”

**R2-C12. I. 77** (and throughout the text). The use of the term “stoichiometry” is somewhat unclear in this context. Do the authors specifically refer to variations in the PIC/POC ratio? If so, this should be stated explicitly.

**R2-R12.** We removed the term “stoichiometry” throughout the manuscript and now explicitly refer to “~~POC flux and PIC:POC export ratio~~”.

**R2-C13. I. 147.** While I understand how diatom transfer functions can be used to reconstruct deep-ocean POC flux, it remains unclear how diatom diversity can be used to quantify the PIC:POC export ratio. I agree that avoiding a priori assumptions in transfer functions may help reveal previously unrecognized patterns; however, these relationships should be supported by a mechanistic understanding of the underlying processes.

**R1-R13.** We now formulate more explicitly our approach and the rationale for the use of diatoms to reconstruct PIC and POC export fluxes in section 2.3. We also discuss the link between hydrological zones, diatoms and calcifiers in section 4.1.

**Change made I. 165-173:** “~~Previous studies reported the direct quantitative link between plankton community structure and carbon export fluxes in sediment trap samples (e.g. Rembauville et al., 2015, 2016a, b). Such an approach needs a precise quantification of the full and empty diatom frustule flux together with the consideration of other flux vectors such as faecal pellets to estimate biovolumes and calculate carbon fluxes. The full/empty frustule distinction, the faecal pellets abundance, and the absolute fluxes are not available in sediment cores. Here, we use an alternative approach and suggest that the diatom community integrates the ecosystem structure that is the ultimate driver of the export fluxes. We do not formulate explicit mechanistic relationships between diatoms and POC or PIC fluxes. Rather, we consider that diatom community structure is correlated with biotic (e.g. other phytoplankton, zooplankton, calcifiers, bacteria) and abiotic conditions (hydrological zones, micronutrient availability) that altogether drive the biological pump and carbonate counter-pump.~~”

**Change made I. 341-347:** “The PIC:POC ratio is positively correlated with warm water diatom species from the SAZ but negatively correlated with ice-associated diatoms. ~~It has been previously reported that the PIC:POC export ratio increases north of the polar front concomitantly with an~~

increase in the abundance of foraminifer and pteropod (Salter et al., 2014; Manno et al., 2022), whereas the PIC:POC export ratio is lower south of the polar front where the exported foraminifer flux decreases (Rembauville et al., 2016a). Although the calcifying plankton is not explicitly taken into account in this study, these results suggest that diatom communities, partially shaped by hydrological zones, appears to capture efficiently the calcifying plankton diversity that set the magnitude of the carbonate counter-pump.”

**R2-C14.** l. 183. I’m not sure to understand why this step is necessary?

**R2-R14.** The original sediment trap data displays highly heterogeneous number of samples and sampling duration (Table 1). Hence, to avoid a geographical bias in the calibration, we averaged the sediment trap data at seasonal scale to give a similar weight to each sediment trap location. Finally, the time covered by each sediment core sample cannot be assessed (hundred to thousand years depending on the resolution). Therefore, we converted the seasonal averages ( $\text{mol m}^{-2} \text{d}^{-1}$ ) to annual averages ( $\text{mol m}^{-2} \text{y}^{-1}$ ) to express the POC flux in units relevant for the sediment cores.

**R2-C15.** l. 304-306. Transient increases in sedimentary  $\text{CaCO}_3$  during peak interglacials have been interpreted as reflecting both pulsed production and enhanced preservation driven by rapid shifts in CCD depth (e.g. Jaccard et al., 2013), potentially linked to the release of remineralised carbon to the upper ocean and atmosphere.

As such, sedimentary  $\text{CaCO}_3$  cannot be interpreted solely in terms of production and export. The manuscript would benefit from a more explicit discussion of these processes and their implications for the interpretation of the  $\text{CaCO}_3$  record.

**R2-R15.** We do explicitly discuss the trends in sedimentary  $\text{CaCO}_3$  content but rather the reconstructed PIC:POC export ratio at ~1000 m. To answer the reviewer comment, we now discuss more specifically the relative importance of PIC:POC export ratio and PIC preservation for the sedimentary  $\text{CaCO}_3$  signal.

**Change made l. 452-460:** “We found an overall good agreement between the reconstructed PIC:POC export ratio and the sediment  $\text{CaCO}_3$  content in cores PS1768-8 and PS2606-6 which are both located above the CCD. Indeed, the sedimentary  $\text{CaCO}_3$  content is the result of several processes including production, export and preservation of  $\text{CaCO}_3$  in the sediment and cannot solely be interpreted in terms of PIC:POC export ratio. For example, an interglacial increase in  $\text{CaCO}_3$  content has been attributed to the deepening of the CCD leading to a better preservation of  $\text{CaCO}_3$  (Jaccard et al., 2013) while a glacial decrease in  $\text{CaCO}_3$  content has been interpreted as the result of calcite dissolution due to increased primary production leading to higher organic matter remineralization (Schulte and Bard, 2003). Our results suggest that both processes (higher export and better preservation) could explain the increase in sedimentary  $\text{CaCO}_3$  content during interglacials in the AZ.”

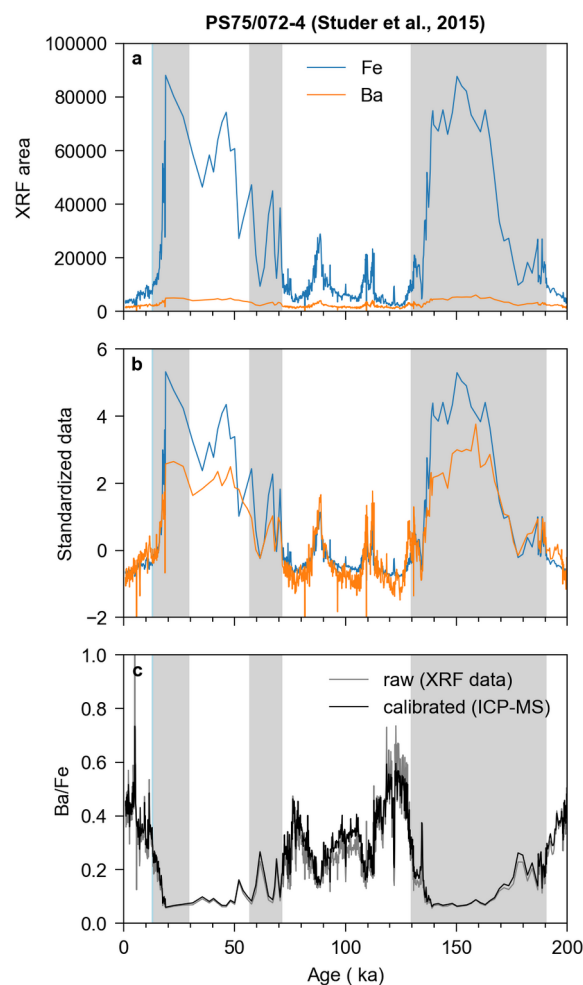
**R2-C16.** l. 364-365. I may be mistaken, but I do not think that any of the cited references explicitly interpret the  $\delta^{15}\text{N}$  signal as a proxy for productivity.

**R2-R16. Change made l. 416:** “In these studies, export estimates in the SAZ are based on alkenone flux ~~and/or  $\delta^{15}\text{N}$~~ , while in the AZ they are based on the Ba/Fe ratio ~~and~~ opal flux ~~or  $\delta^{15}\text{N}$  proxies~~.”

**R2-C17.** l. 371-373 & 433-434. Sedimentary OC is prone to remineralisation, particularly under oxygenated conditions. While redox-sensitive trace metals indicate more reducing conditions during past glacial periods (e.g., Frank et al., 2000; Jaccard et al., 2016), potentially enhancing TOC preservation, conditions in the AZ were likely not persistently sulfidic, as would be required for significant barite remobilization. In the SAZ, elevated OC export fluxes, likely sustained by enhanced Fe supply, may have promoted sulfate reduction in sediments, potentially limiting the applicability of bioBa as a proxy for integrated export production. Overall, the discussion would benefit from a more balanced consideration of diagenetic effects on organic matter preservation under temporally variable redox conditions.

**R2-R17.** Concerning specifically the Ba/Fe proxy in core PS75/072-4, the figure below shows that Ba increases from interglacial to glacial periods and that Fe displays a similar signal with higher relative variations. Thus, the glacial decreases in the Ba/Fe signal is probably driven at first order by higher Fe flux from atmospheric or glacial origin. In this specific context of enhanced Fe input, the Ba/Fe ratio might not be a good proxy for organic carbon export. However it is out of the scope of this study to discuss the applicability of the Ba/Fe proxy in naturally iron-fertilized environments.





**Figure R4:** Ba and Fe data from Studer et al. (2015). a) Raw XRF area data. b) Standardized XRF data (mean subtracted, divided by one standard deviation). c) Ba/Fe ratio (raw and calibrated data).

We modulated the potential effect of organic matter content on the Ba/Fe ratio and we added the contribution by variable redox conditions to explain changes in the sedimentary TOC content in the discussion section 4.3.

**Change made I. 17:** “The reconstructed POC export is consistent **with nutrient utilization** derived from previously published diatom-bound  $\delta^{15}\text{N}$  and total organic carbon content but differs from elemental Ba/Fe ratio, ~~hinting Ba potential preservation issues in Southern Ocean sediments.~~”

**Change made I. 425-428:** “**The sensitivity of the Ba/Fe proxy to temporal changes in organic matter content and detrital or Fe inputs during glacial periods** might thus explain the discrepancy between our reconstructed POC flux and the Ba/Fe elemental ratio. **Indeed, a better knowledge of sediment redox conditions is needed to confirm this hypothesis.**”

**Change made I. 429-434:** “The reconstructed POC flux increase is highly correlated with diatom-bound  $\delta^{15}\text{N}$  in core PS75/072-4 (Fig. 8b) and with TOC in core PS1768-8 (Fig. 11b). **Sedimentary TOC content is constrained by organic matter remineralization linked to redox conditions. Lower oxygenation of the Antarctic Bottom Water during glacial periods has been suggested from redox-sensitive trace metals, potentially leading to a better organic carbon preservation (Jaccard et al.,**



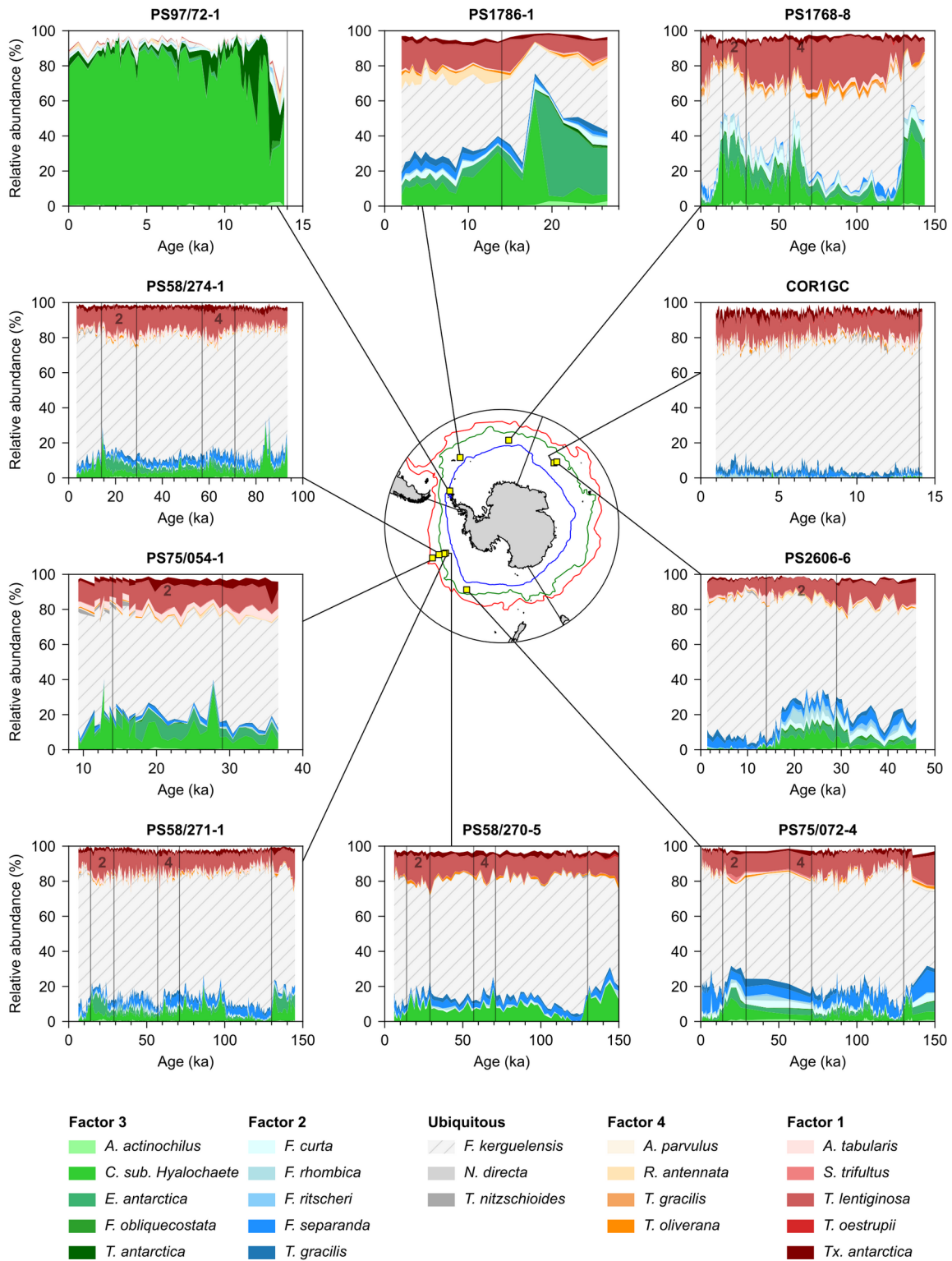
2016). Our results suggest that increased POC flux to the seafloor is an additional mechanism contributing to the higher TOC content during glacial periods in core PS1768-8.”

Change made l. 512: “We argue that preservation of Ba in SO sediments and large temporal changes detrital and Fe inputs in this sediment core could potentially hinder the use of this latter proxy.”

**R2-C18.** l. 382-382. Could the authors provide supporting evidence from diatom assemblages (e.g., changes in species composition or degree of silicification) to substantiate this assertion? This would help assess whether the proposed mechanism is consistent with the microfossil record.

**R2-R18.** Following Reviewers 1 & 2 comments, we added a supplementary figure (Fig. S6) showing the relative abundance of diatoms species in the sediment cores (see below). Fig. S6 shows that transfer functions are applied on abundant taxa (e.g. species associated with factor 2 and 3 account for 20 to 60 % of the diatom community during glacial periods) and that diatom community composition shows clear glacial/interglacial signals. We also added the partial correlation coefficients from PLSR and the importance of species in the GBR model in Table 5 and Fig. S4, which provide convergent results with the factorial analysis used in the MLR. We nuanced and precised the ecological rational for higher POC export flux and lower PIC:POC export ratio in the AZ during glacial periods in the discussion. We hope that these modifications fulfill the Reviewers requirements.

**Change made l. 534:** “We thank the two anonymous Reviewers for the constructive comments that helped us improve the manuscript.”



**Figure S6 added.** Relative abundance of the main diatom species in the sediment cores used to apply the transfer functions. The white area at the top of each panel represents rare species not considered in the transfer functions. Vertical lines and numbers denote marine isotopic stages (MIS). In the central map, colored lines represent hydrological fronts as in Fig. 1: Subantarctic Front (red), Polar Front (green), September sea ice edge (blue).

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