Interactive comment on “Export fluxes in a naturally fertilized area of the Southern Ocean, the Kerguelen Plateau: seasonal dynamic reveals long lags and strong attenuation of particulate organic carbon flux (Part 1)” by Rembauville et al.

Response to reviewer #3.

We thank the anonymous referee #3 for the careful reading of the manuscript and the constructive comments that have helped to improve the original version. Following the reviewers comments, we have significantly revised the manuscript. All of the reviewer’s suggestions have been taken into account and the resulting modifications appear in a revised version of the manuscript attached as a supplement to this answer. We are hopeful that our careful revisions address the main concerns of the reviewer and the revised version is now acceptable for publication in Biogeosciences.
R1-Cx : Referee comment, **R1-Rx:** authors response. Changes in the manuscript are in the supplement to this answer.

General comments

R3-C1. *This manuscript proposes that there is strong attenuation of POC flux in the spring bloom observed at Kerguelen in the KEOPS2 experiment. To this end it centres on the analysis of one year of sediment trap data from a deployment at 289m water depth. It also relies on comparison of this data with other KEOPS2 studies in this issue using a wide variety of methods including short deployments of free drifting conventional and gel traps (Laurenceau et al.); 234Th method (Planchon et al.) and video profiler (Jouandet et al.) as well as direct comparisons with KEOPS 1 results.*
As such, this paper in particular and the associated papers in the KEOPS 2 set, in general, represent a microcosm of the issues around the understanding of biogeochemical ocean flux. These include the comparison of different sampling methods, different analytical techniques (both direct and indirect), that are often deployed at different times and for different durations.
This paper is especially ambitious. It is one thing to show a discrepancy between primary production (measured from incubation of water-column bulk sub-samples or from satellite-derived estimates) and export – the so-called “high biomass, low export” regime. It is altogether something else to demonstrate export attenuation or flux attenuation, since this requires that a particular settling episode is tracked downward through the water column.
One of the main concerns is with the potential errors arising from the reliance on the comparison of different methods in determining flux attenuation. The moored traps were deployed at one depth and so there can be no direct comparison with similar collection devices to determine flux attenuation. In its present form this paper does not convincingly demonstrate flux attenuation at the 90% level proposed. Furthermore, there appear to be a number of inconsistencies and errors that detract from the overall thesis. The paper therefore needs major revision.
R3-R1. Given the concerns raised by the reviewers we have undertaken a major revision of our paper. Notably we have removed the flux attenuation calculations based on different flux estimation methods as well as the bacterial carbon demand calculation. Consequently the discussion sections 4.3 and 4.4 were fully rewritten. Following the reviewers keen interest in the temporal lags between chlorophyll and flux data we have dedicated Section 4.3 to the discussion of the seasonal patterns of export relative to the surface biomass accumulations.

Section 4.4 has been rewritten to discuss the large differences between flux estimates at 200 m and 300 m by our sediment trap method, but indeed those of independent estimates. We have attempted to constrain the "trapping efficiency" of our sediment trap deployment by comparison to ^{234}Th estimates of POC export, although it should be noted that the latter technique is not considered to be an independent reference. Nevertheless, we find smaller fluxes measured by the sediment trap relative to those obtained with the thorium technique. Consequently we proceed to discuss the potential biases that might have impacted the collection efficiency of the moored trap, and finally a make direct comparisons with independent datasets at depths > 300 m that also report low POC fluxes. In spite of the calculated trapping efficiency there are still very large differences in flux estimates at 200 m and 300 m that are evident from multiple independent approaches and are consistent with attenuation reported in other areas of the Southern Ocean. The discussion therefore ends on the short evocation of the ecological factors that might be responsible for the low fluxes at ~ 300 m.

Specific comments

R3-C2. *A case in point is the following paragraph from the Discussion section: Section 4.3 Rapid flux attenuation at A3 (p17058 lines 10-20) "The sediment trap record obtained from station A3 provides the first direct estimate of seasonal and annual POC export from the iron-fertilized Kerguelen bloom. The annual POC export of 0.1 molm^{-2}d^{-1} at 300 m (Table 1) is significantly lower than indirect estimates of POC export (5.1 mol m^{-2}d^{-1}) at the base of the WML (200 m) on the Kerguelen Plateau (Blain et al., 2007). The Kerguelen Plateau annual POC export approaches the median global ocean POC export value comprising shallow and deep sediment traps (83 mmol m^{-2} yr^{-1}, Lampitt and Antia, 1997), but is also close to values observed in HNLC areas of the POOZ (11-43 mmol m^{-2} yr^{-1} at 500 m, Fischer et al., 2000). Moreover, the magnitude of annual POC export measured at 300 m on the Kerguelen Plateau is comparable to deep-ocean (> 2 km) POC fluxes measured from the iron-fertilized Crozet bloom (60 mmolm-2d-1, Salter et al., 2012)."*
There appear to be some inconsistencies in this section. Firstly, earlier, in Section 3.4, the authors state that "the annually integrated POC flux was 98.2 mmolm-2yr-1 (millimoles per square meter per year)", but in Section 4.3 they quote an "annual POC export of 0.1 mmol m^{-2} d^{-1} (moles per meter squared per day)". Do the authors actually mean 0.1 mmol m^{-2}yr^{-1} (moles per meter squared per year)? – In Section 4.4 they appear to revert to 98.2 mmol m^{-2} yr^{-1} and it would help to keep units consistent.
R3-R2. We corrected this mistake, the annually integrated POC export is 98 mmol m^{-2} y^{-1} which equals nearly 0.1 mol m^{-2} y^{-1}. We corrected in section 4.4.
MS change section 4.4: "The annual POC export of ~0.1 mol m^{-2} y^{-1} at 289 m (Table 1) represents only 2% of the indirect estimate of POC export (5.1 mol m^{-2} y^{-1}) at the base of the WML (200 m) on the Kerguelen Plateau based on a seasonal DIC budget (Blain et al., 2007)."

R3-C3. *Secondly, the study of Blain et al. (2007: Nature, 2007, 446, 1070-1074) is quoted as reporting an estimate of POC export at the base of the mixed layer of 5.1 mmolm^{-2}d^{-1} (moles per square meter per day). Scrutinising Blain et al. (2007), the nearest value that appears to correspond to this may be from Table 1 (of Blain et al., 2007): 5,047 mmol m^{-2} (millimoles per square meter) but this is in fact a "Seasonal budget" and so corresponds to an annual flux or flux for the growing season. When this is taken into account and converted to an average daily flux the value obtained would correspond closely with the figure for Thorium-*

derived POC export of 24.5 mmol $m^{-2}d^{-1}$ (millimoles per square meter per day) also given in Table 1 of Blain et al. (2007).
R3-R3. We corrected the value quoted from Blain et al. (2007) which is 5.1 mol m^{-2} y^{-1}, see above.

R3-C4. *Thirdly, the authors quote a value from Salter et al (2012) of "60 mmol $m^{-2}d^{-1}$ (millimoles per square meter per day)" whereas this should actually be per year (see Salter et al., 2012, table 2). Again, consistency in units might help prevent confusion such as this.*
R3-R4. We corrected the value quoted from (Salter et al., 2012).
MS Change section 4.4: "Moreover, the magnitude of annual POC export measured at ~300m on the Kerguelen Plateau is comparable to deep-ocean (>2 km) POC fluxes measured from the iron-fertilized Crozet (60 mmol m^{-2} y^{-1},Salter et al., 2012) and South Georgia blooms (180 mmol m^{-2} y^{-1}, Manno et al., 2014)."

R3-C5. *This section needs to be re-written with clarification. It would also help to have some consistency in units to support comparisons of daily or annual POC export.*
R3-R5. We have fully rewritten this section into a new section 4.4 "Rapid flux attenuation over the Kerguelen Plateau". We have checked all units throughout the paper.

R3-C6. *In the next paragraph: p17058, line 21 "The POC fluxes.." The authors remark that the measured POC fluxes are low and discuss possible evidence for under-collection. Although they quote various studies that suggest errors ranging from 0.1 to 3 x compared with 234Th methods they omit to mention more recent work that shows a 20-fold underestimate of fluxes in moored conical traps as compared to free drifting traps also in the Southern Ocean (Buesseler et al. 2010).*
R3-R6. This point was also raised by reviewer #1 (see R1-C3 and our answer R1-R3).The third paragraph in the new section 4.4 is dedicated to the estimation of the under trapping by the moored sediment trap when compared to ^{234}Th-derived estimates. We included the reference to (Buesseler et al., 2010a) and compare the present hydrographic settings to the extreme presented in this reference. Our calculation suggests that the moored trap collection efficiency is between 15-30 % compared to ^{234}Th-derived estimates. We now reconsider that the low POC fluxes measured by the trap probably result from a combination of methodological caveats associated with traps (hydrodynamics and potential consumption of particles by zooplankton) and attenuation. Therefore we now offer a much more qualitative representation of rapid flux attenuation by discussing our data and that of others. Notably, our data are close to other deep estimates (>300m) reported in spring by Jouandet et al., (2014) (0.1 – 0.3 mmol m^{-2} d^{-1}) and in summer by (Ebersbach and Trull, 2008) (0.7 mmol m^{-2} d^{-1}). Together with their b values of respectively **4.1** and **3.4**, this support the fact that low POC fluxes measured in the 300 m trap also capture the feature of rapid flux attenuation. However, we now acknowledge that the low POC flux estimates in the trap probably have several origins whose relative importance cannot be differentiated at this point and include:

- potential hydrodynamic biases due to the tidal driven currents that sometimes exceed 12 cm s^{-1} (However, note this is not the case for 75% of the deployment record)
- biological bias due to particle consumption in the trap funnel (we have no evidence for this but it is a factor no sediment trap study has yet accounted for)
- important POC flux attenuation between the WML and the trap depth as suggested by the by Jouandet et al. (2014) and (Ebersbach and Trull, 2008) data

MS change in the introduction: "Although advection was weak, the sediment trap was subjected to possible hydrodynamical and biological (swimmer feeding on trap funnel) biases that could have lead to the collection of 15-30 % of the ^{234}Th derived particle flux."

MS change section 4.4: "In the Antarctic Peninsula, ^{234}Th derived POC export was 20 times higher than the fluxes collected by a shallow, cylindrical, moored sediment trap at 170 m (Buesseler et al., 2010). The present deployment context is less extreme (depth of 289 m, mean current speed < 10 cm s^{-1}, low tilt angle, high aspect ratio of the cylindrical PPS3 trap) but we consider that hydrodynamics (current speed higher than 12 cm s^{-1} during short tidal-driven events) and possible zooplankton feeding on the trap funnel are potential biases that explain in part the low fluxes recorded by the moored sediment trap. The low fluxes likely result from a combination of collection bias (hydrodynamics and swimmers) and real strong attenuation of the POC flux between the base of the WML and 300 m".

MS change in the conclusion: "Analysis of the hydrological conditions and a comparison with different estimates of POC fluxes in spring and summer at the same station suggest that the sediment trap was subject to possible hydrodynamic and biological biases leading to under collection of particle flux. Nevertheless the low POC export was close to other estimates of deep (>300 m) POC export at the same station and is consistent with high attenuation coefficients reported from other methods. Taken together these data suggest that the low fluxes can be explained in part by strong flux attenuation between the winter mixed layer depth (~200 m) and the trap depth (~300 m)."

R3-C7. *The authors then appeal to a direct comparison with KEOPS1 results. (p17059 lines 2 – 5) "Even if we assume that our A3 sediment trap did undersample the particle flux, it seems unlikely that this in itself could explain the significant reduction in POC flux observed between 200 and 300m (Table 3)." The case for comparison to a different season in an earlier year is not well made. This notwithstanding, one of the 4 comparators in Table 3 actually indicates a 15% flux increase at 330 m relative to 220 m.*

R3-R7. We deleted the direct comparison with previous measurements as inter annual variability might play an important role in the difference we observe. We removed Fig. 8 and placed the POC export data from KEOPS2 into Table 4. Instead of a quantitative comparison with these estimates, we choose the general statement that the fluxes we report are very low compared to previous estimates at 200 m and that it raises questions about the trapping efficiency.

Change in the MS section 4.4: "The annual POC export of ~0.1 mol m^{-2} y^{-1} at 289 m (Table 1) represents only 2% of the indirect estimate of POC export (5.1 mol m^{-2} y^{-1}) at the base of the WML (200 m) on the Kerguelen Plateau based on a seasonal DIC budget (Blain et al., 2007). On shorter time scales, the POC flux recorded in the moored sediment trap represents only a small fraction (3-8%) of the POC flux at the base of the winter mixed layer (200 m) measured by different methods during KEOPS2 (Table 3). The same conclusion is true when considering the comparison with different estimates made during KEOPS1. The diversity of the methods and the difference in the depth where the POC flux was estimated make quantitative comparison difficult, but it appears the POC fluxes measured at 289 m with the moored sediment trap are much lower than other estimates. This result indicates either extremely rapid attenuation of flux between 200 m and 300 m or major sampling bias by the sediment trap. "

R3-C8. *Next there is a comparison with other KEOPS2 studies using contrasting techniques: short deployments of free drifting conventional and gel traps (Laurenceau et al.); 234Th method (Planchon et al.) and underwater vision profiler (UVP) (Jouandet et al., 2014). The only one of these to sample at a similar depth is the UVP that measures particle size and* *concentration. This has been related to flux, but this single point from a method that does not collect settling particles is not compelling. As the authors correctly state: "The diversity of approaches prevents absolute comparison of the fluxes."*

R3-R8. We removed direct comparison with previous estimates as well as flux attenuation calculation including different methods. Instead we used data from two independent dataset from KEOPS1 (Ebersbach and Trull, 2008) and KEOPS2 (Jouandet et al., 2014) to estimate b-values. Figure 8 was also removed to avoid direct comparison of fluxes.

Change in the MS Section 4.4: "We note that low carbon export fluxes around 300 m were also reported on the Kerguelen plateau. In spring 2011, UVP derived estimates of POC export at 350 m equals 0.1 to 0.3 mmol m^{-2} d^{-1} (Table 3), a value close to our reported value of 0.15 mmol m^{-2} d^{-1}. In summer 2005, POC export at 330 m from gel trap equals 0.7 mmol m^{-2} d^{-1} (Ebersbach and Trull, 2008), which is also close to our value of 1.5 mmol m^{-2} d^{-1}. Using the Jouandet et al. (2014) data at 200 m (1.9 mmol m^{-2} d^{-1}) and 350 m (0.3 mmol m^{-2} d^{-1}) and the Ebersbach and Trull (2008) data at 200 m (5.2 mmol m^{-2} d^{-1}) and 330 m (0.7 mmol m^{-2} d^{-1}) leads to Martin power law exponents values of 3.3 and 4, respectively. These values are high when compared to the range of 0.4–1.7 that was initially compiled for the global ocean (Buesseler et al., 2007b). However, there is increasing evidence in support of much higher b-values in the Southern Ocean that fall in the range 0.9-4 (Lam and Bishop, 2007; Henson et al., 2012; Cavan et al., 2015). Our calculations are thus consistent with emerging observations in the Southern Ocean and support a scenario of strong POC flux attenuation between 200 m and 350 m over the Kerguelen Plateau "

R3-C9 *A one month lag between productivity and export peaks is invoked based on comparison of the largest sediment trap fluxes and satellite measurements of chlorophyll a - derived surface productivity. This supposes that the production that generated the flux occurred within the satellite detection depth limit of around 20 m. In fact there is increasing evidence that production that contributes substantially to POC flux may occur deeper than the satellite detection limits or not contain sufficient chlorophyll a to cross the threshold for satellite-defined blooms (e.g. Villareal et al. 2011, Journal of Geophysical Research).*

R3-R9. Indeed a subsurface chlorophyll maxium (SCM) was observed in late summer at the A3 station but production measurements suggest negligible primary production in this structure. It was assumed that the SCM resulted from accumulation of surface production on the density interface (Uitz et al., 2009). We dedicated section 4.3 to discuss the flux seasonality. We notably added references about satellite detection and the phytoplanktonic structures that might be missed by satellite sensors in the last paragraph of section 4.3.

Change in the MS section 4.3.: "The temporal lag of one month measured in the present study suggest either slow sinking rates (< 5 m d^{-1}) characteristic of single phytoplanktonic cells or faster sinking particles that do not originate from the peaks of surface production. It is generally accepted that satellite detection depth is 20-50 m (Gordon and McCluney, 1975), which prevents the detection of deep phytoplanktonic biomass structures (Villareal et al., 2011). A subsurface chlorophyll maximum located around 100 m has been observed over the Kerguelen Plateau at the end of the productive period and was supposed to result from the accumulation of surface production at the basis of the mixed layer (Uitz et al., 2009). Such structure might have been missed by the satellite sensor but detailed taxonomic analysis of the exported material highlight diatom resting spores as major contributors to the two export fluxes rather than an average surface community accumulated at the basis of the mixed layer. The hypothesis of a mass production of nutrient-limited resting spores post-bloom with high settling rates explains the temporal patterns of export we observed (Rembauville et al., 2014). However a better knowledge of the dynamics of factors responsible for resting spore formation by diatoms remains necessary to fully validate this hypothesis."

Technical corrections

R3-C10. *P17046 line 9 "it's" incorrectly used*
R3-R10. We reformulated this sentence:
MS change int the introduction."Following "the iron hypothesis" in the nineties (Martin 1990), iron limitation…"

R3-C11. *P17047 Line 24 sentence: "Having access to. . .." – meaning unclear*
R3-R11. We reformulated this sentence:
MS change in the introduction "There is a strong need for quantitative analysis of the biological components of the exported material that can help to elucidate patterns in carbon and biomineral fluxes to the ocean interior (Francois et al., 2002; Salter et al., 2010; Henson et al., 2012; Le Moigne et al., 2012; Lima et al., 2014). »

R3-C12. *P17048 Line 12: sentence "Alternative explanations. . ." This does not seem to be an alternative explanation but rather restates the significance of zooplankton*
R3-R12. We reformulated this sentence:
MS change in the introduction. "This concept is partly based on the idea that a strong grazer response to phytoplankton biomass leads to major fragmentation and remineralization of particles in the twilight zone, shallowing the remineralization horizon (Coale et al., 2004). In these environments, the efficient utilization and reprocessing of exported carbon by zooplankton leads to fecal pellet dominated, low POC fluxes (Ebersbach et al., 2011)"

R3-C13. *P17049 Line 7 "The net effect.." – needs "of" inserted.*
R3-R13. Done

R3-C14. *P17051 Line 12 1st sentence needs "was added" at end*
R3-R14. Done
(iii) "Upon recovery of the sediment trap the pH of the supernatant was measured in every cup and 1 mL of 37 % formalin buffered with sodium tetraborate (pH=8) was added."

R3-C15. *P17056 Line 28 "shows" incorrect*
R3-R15. We reformulated this sentence
MS change section 4.1.: "Time-integrated currents suggest that advection is weak and occurs over longer timescale (months)."

R3-C16. *Figure 1. The isobaths "grey lines" cannot be seen Figure 6*
R3-R16. We increased the line width. The update Figure 1 is included at the end of the response.

R3-C17. *Figure 6 – needs more explanation in the caption.*
R3-R17. We added a short description of what a progressive vector diagram is.
MS change in figure caption 6: "Progressive vector diagram (integration of the current vectors all along the current meter record) calculated from current meter data at 319 m. The color scale refers to date.".

Concluding response:
As suggested by reviewers we have removed the quantitative representation of flux attenuation obtained from different methods and rather present a more qualitative view. We now further acknowledge the potential biases with upper ocean sediment trap deployments

and estimate a probable trapping efficiency from thorium data. We feel that our revised paper is an important contribution to the Biogeosciences KEOPS2 special issue because:

(i) Our paper serves as an important companion dataset for the detailed biological and geochemical analyses presented in part 2

(ii) The paper is significant in its own right because despite over 8 papers on export processes from KEOPS 1 and 2, our dataset serves as the only annual record of flux from this important iron-fertilized site. This has allowed us to uniquely identify the significant temporal lags between the accumulation of surface biomass and export out of the mixed layer.

(iii) Together with our own data we synthesize the various POC flux estimates obtained from the iron-fertilized Kerguelen bloom to bring together numerous lines of independent evidence supporting a scenario of significant flux attenuation between 200-300 m. We acknowledge however that our paper should represent these arguments in a more qualitative manner and more dedicated techniques would be required to quantitatively constrain attenuation. Our findings are thus in line with an emerging biogeochemical paradigm in the Southern Ocean that high biomass blooms fertilized by iron do not necessarily lead to significant export into the bathypelagic ocean.

We hope that following our careful attention to the reviewers comments and significant modifications for the manuscript our paper is now considered acceptable for publication in the Biogeosciences KEOPS2 special issue.

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Figure 1 with increased line width for the isobaths representation.