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 #1.

We thank the anonymous referee #1 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.

Introduction to the response. 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.

R1-C1. *The authors present time-series data from a bottom-moored sediment trap at ~300m on the Kerguelen Plateau, deployed in October 2011 during KEOPS2 just prior to the spring bloom, and recovered a year later in September 2012. They find very low annually-integrated POC flux at 300 m using their sediment traps (0.1 mol C/m2/year) compared to the annually-integrated POC flux at 200 m (5.1 mol C/m2/year), which was estimated by Blain et al. 2007 using a seasonal budget of carbon. This extremely high level of attenuation of annually-integrated POC flux (98% loss of POC flux in only 100 m from 200 m to 300 m) was mirrored in comparisons of short-term flux estimates at 200 m (~2-5.5 mmol C/m2/d by UVP, 234Th, or surface-tethered sediment traps) and 300 m (0.15 mmol C/m2/d in their sediment trap) during the second visit of KEOPS2 (16 November 2011).Note that previously reported ranges in the POC flux power law exponent have ranged from 0.4-1.7 (Martin's canonical value is*

0.87), so the exponents reported in this manuscript are well beyond the range of what has been previously observed, and therefore raise some alarm bells.

R1-R1. Indeed the power law exponents we reported in the previous version of the manuscript were uncharacteristically high and at odds with previous observations of vertical attenuation in the ocean. These large values originate in part by the comparison of different datasets. However, the aim of these calculations was not to suggest that such a large degree of vertical attenuation occurs over the plateau, quite the opposite, that in fact such large reductions in POC flux over a 100 m depth interval in the surface ocean are quite improbable based on current knowledge of b-values and heterotrophic remineralisation. Therefore our aim was to suggest that classical remineralisation by heterotrophic microbial activity could not be the main process acting on settling particles but that other factors specific to the plateau are driving carbon attenuation, i.e. zooplankton likely plays a very significant role as suggested by other recent studies of iron-fertilized blooms in the Southern Ocean (Laurenceau et al., 2014; Cavan et al., 2015). In hindsight, presenting those large b-values between datasets was not the correct way to make this point as it implied a confidence in our quantification that was not intended. Following reviewers comments, we therefore removed the calculation of b-values based on different methods. Nevertheless, as suggested by the reviewer we did calculate b-values from two independent datasets in spring (Jouandet et al., 2014) and summer (Ebersbach and Trull, 2008). These calculations do support our original notion of very strong flux attenuation between 200 m and 300 m, fully described in R1-R4

***R1-C2.** The main reason to worry is that the POC flux at 300 m is from bottom-moored sediment traps. Conical bottom-moored sediment traps have been known for some time to have low collection efficiency (40%) in the lower mesopelagic zone (500-700m) (Yu et al., 2001). More recently, (Buesseler et al., 2010) have shown that conical bottom-moored sediment traps at 170 m in the West Antarctic Peninsula undercollected POC flux by 30x compared to estimates from 234Th or surface-drifting traps deployed concurrently! The PPS3 trap design used here has a long cylindrical shape before funneling into a conical part, and is thought to be better than traditional conical traps. However, even though the authors carefully analyze their current meter and tilt angle data from the mooring and show small mooring line angle deviations and low current speeds, and the trap design is thought to be less susceptible to hydrodynamic biases, it has been suggested that there could be consumption of detrital particles by zooplankton feeding along the walls of a conical trap (Buesseler et al., 2010), and this could occur even if the conical part were at the end of a long cylinder, as for the PPS3 trap*

R1-R2. We thank the reviewer for their comments concerning our careful analysis of the physical data in assessing the performance of the sediment trap. Unfortunately not many sediment trap studies present this level of detail, although we consider it an essential component for any upper ocean trap dataset and so we certainly appreciate the recognition. As the reviewer points out conical bottom-moored sediment traps are known to have low collection efficiency in the surface ocean. If one tentatively assumed a collecting efficiency of 10% this would still place our 300 m annual estimates at 1 mol C m^{-2} yr^{-1}, 80% lower than 200m seasonal estimates derived from the DIC budget (Blain et al. 2007). Nevertheless we chose not to make this comparison in our revised paper for the reasons highlighted in R1- C2 with respect to the uncertainty of using different methods. It is worth pointing out again that we do not consider such an approach to be a reliable way to quantify flux attenuation or b-values but simply want to make the point that we observed large differences in seasonal flux budgets between 200 and 300m. Indeed the known problems associated with conical traps in the surface ocean are the main reason we went with the cylindrical design of the PPS3.The comparisons presented in Buesseler et al. (2010) highlight the low POC flux measured by a moored conical trap in comparison to thorium estimates and a drifting cylindrical trap. We have added a paragraph in section 4.4. to discuss the trapping efficiency which specifically includes a reference to Buesseler et al. (2010). We compared the sediment trap POC flux with a theoretical thorium derived POC flux at 289 m calculated by extending the thorium derived flux at 200 m with b values from the Jouandet et al. (2014) and Ebersbach and Trull (2008) data. This gives a trapping efficiency in the region of 15-30% relative to the thorium-derived POC fluxes, which is comparable to previous comparisons of thorium-derived and moored trap derived estimates of POC export. We therefore now fully acknowledge that our moored trap estimates are on the low side and discuss particle consumption by swimmers in the trap funnel together and short strong tidal driven current as possible explanations for collection efficiency of the moored trap.

R1-C3. *During KEOPS1 (summer 2005), POC flux to depth determined from a gel-filled cylindrical surface-drifting trap array between 100-450 m had a power law exponent of about 1.2 (Figure 7 in Ebersbach and Trull, 2008); if only the extreme 200 m (62 mg C/m2/d) and 330 m (8 mg C/m2/d) POC flux values taken (Table 4 in Ebersbach and Trull, 2008), one could calculate a power law exponent of* ***about 3.1*** *(assuming F=F0(z/z0)ˆ(-b), and z0=200m). During KEOPS2 (Nov 2011), the UVP-based POC flux estimates at 200 m (23.11 mg C/m2/d) and 350 m (3.5 mg C/m2/d) would lead to a power law exponent of* ***about 2.5*** *(Table 3 in Jouandet et al., 2014). The fact that these other methods do not see the high attenuation further points to a methodological problem.*

… and later in the reviewer comment …

I also suspect that their overall hypothesis that there is high attenuation through the winter mixed layer in the waters above the Kerguelen Plateau may be right indeed, the b values I calculated above from the ˇEbersbach and Trull 2008 KEOPS1 gel trap (b=3.1 for the extreme case) and Jouandet et al. 2014 KEOPS2 UVP (b=2.5) DO in fact indicate fast attenuation, just not as fast as is suggested by the 300 m trap data presented here

R1-R3. These are important points made by the reviewer. Using the same data (Ebersbach and Tull., 2008 : z0 = 200m, 62 mgC m^{-2} d^{-1}, z =330, 8 mgC m^{-2} d^{-1} and Jouandet et al., 2014 : z0 = 200m, 23.11 mgC m^{-2} d^{-1}, z = 350 m, 3.5 mgC m^{-2} d^{-1}) and the Martin et al., 1987 formulation (F=F0(z/z0)ˆ(-b)), we obtain b values of respectively **4.1** and **3.4.** We appreciate that the reviewer probably made these calculations quickly and therefore the values are not entirely correct but nevertheless make the same point. Values of 4.1 and 3.4 are significantly higher than the 0.5 - 1.7 range reported in Buesseler et al. (2007). They are however in line with recent estimates of attenuation coefficients in the Southern Ocean that suggest b-value can exceed the range 0.4-1.7 previously reported and reach 0.9-3.9 (Lam and Bishop, 2007; Henson et al., 2012; Cavan et al., 2015). This does support high attenuation under the winter mixed layer, as the reviewer points out in the comment. This is integrated in the new section 4.4.

R1-C4. *One final methodological issue: the authors employ a relatively harsh method to get rid of salts in the sinking particles: they resuspended and centrifuged the sinking particles 3x in milli-Q water. They make no mention of buffering the milli-Q, or attempting to make it isotonic to prevent lysing of any intact cells (cf. JGOFS protocol), and I wonder whether they may be losing POC in this processing step.*

R1-R4. Prior to the analysis of our samples we optimized some analytical protocols on another sediment trap sample. Notably we compared milliQ rinsing (triplicate rinsing and analysis) and ammonium formate rinsing (standard JGOFS protocol) on a sample from another failed (jammed after first cup) trap deployment at the KEOPS2 station E. The results are reported in the table below. POC content is statistically indistinguishable between the two methods. However we noted that PON content was significantly higher due to the high concentrations of ammonium in ammonium formate. We therefore decided to use milliQ water to remove salts from the samples to avoid nitrogen contamination.

Sample	Rinsing	POC %	PON %
E1_a	MilliQ water	2.33	0.27
E1_b		2.31	0.25
E1_c		2.35	0.26
E1_a	Ammonium formate	2.32	0.37
E1_b		2.30	0.40
E1_c		2.31	0.37

Moreover, the organic carbon content range (5 to 15%) is consistent with previous sediment trap publications. Finally, the calculated POC fluxes based on the ecological flux components reported in the companion paper are consistent with the measured POC fluxes. Therefore we do not anticipate that methodological issues during the sample analyses can explain the low fluxes. Under trapping due to hydrodynamics and particles consumption by swimmers in the trap remains the most probable biases.

R1-C5. *Given the potential methodological problems associated with the bottom-moored sediment trap and harsh rinsing of the particles with MQ-water, and the fact that the high attenuation is not observed by other POC flux methods, I am not convinced that the 300 m trap POC flux data are accurate. I suspect that they may be internally consistent (i.e., systematically low), which explains why they calculate a similar attenuation rate from annually-integrated vs. short-term POC fluxes.*

R1-R5. Our specific responses to R1-C1 to R1-C5 address this summarizing comment by the reviewer. As reported in Table 3 of the manuscript, the carbon export estimates for the same depth, and period, can vary by up to two orders of magnitude depending on the method. As the variability between methods is of the same order of magnitude than the temporal variability we observed in the moored trap, direct comparisons with the other methods is not robust, as highlighted by the reviewers. We therefore decided to remove any attenuation calculations based on comparison of different datasets. 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

R1-C6. *This may mean that the one month lag that they calculate between surface chlorophyll and POC flux to 300 m may be real, and this is a very interesting result.*
R1-R6. We appreciate these positive comments by the reviewer and we agree that this is indeed an interesting finding, especially in the context of recent modeling perspectives on this subject (Henson et al., 2014).Therefore we have dedicated section 4.3 to the discussion of flux seasonnality. In our companion paper (Rembauville et al., 2014) we describe the diatom and faecal pellets flux that together can efficiently explain mechanisms behind the seasonality of the flux and geochemical signatures of the trapped particles.

R1-C7. *Because of the suspected major methodological problems I've outlined, I do not think that this paper can be published in its present form. There are interesting pieces of information that may still be salvageable, but it would have to be completely overhauled.*
R1-R7. The additional analytical data and response provided in (R1-R5) will hopefully have assured the reviewer that analytical biases associated with our rinsing procedure is unlikely to contribute to the low POC fluxes. As suggested by the reviewer 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) We consider the paper as 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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