Note to the editor

In the revised version, the name of one author "E. Laurenceau" was modified as follow: "E.C. Laurenceau-Cornec".

Detailed answers to referee's comments:

Referee#1

Detailed comments:

Ref#1: *Paragraph 4.1: The station R2 is dominated by small phytoplankton and slow grazing. The reasons to explain a high ThE ratio is not clear. In line 453: What is the relation between iron limitation and a high ThE ? Explain more.*

As suggested by the referee, we clarified the explanation for the high export efficiency at the reference station R-2. Our initial idea was to link the observed efficiency to the iron stress since early studies suggested that iron limitation was leading to more silicified, faster-sinking diatom biomass (Hutchins and Bruland, 1998). However, this is still under debate and may not apply to the HNLC conditions of the southern ocean. In the revised manuscript, we now refer to Laurenceau-Cornec et al. (2015) where a more detailed discussion on processes controlling the export efficiency can be found. In our manuscript, we briefly resume the main idea as follow:

(section 4.1) "For the reference station R-2, ThE and EP/NP ratios were high with 34 % and 73 % respectively, and indicate a relatively efficient carbon pump despite the limited magnitude of carbon export and uptake (NPP = 11.2 mmol m-2 d-1). The ThE ratio falls in the range of most literature data for the Southern Ocean, which is generally elevated (>10%) in HNLC waters (Buesseler et al., 2003; Savoye et al., 2008). During KEOPS1, ThE ratio as high as 58 % was observed at the reference station C11 (Savoye et al., 2008). Reasons for this high efficiency can be numerous, and a detailed discussion can be found elsewhere (Laurenceau-Cornec et al., 2015a). Briefly, efficient scavenging of POC at the low productivity site (R-2) may be mediated by fast-sinking aggregates composed of heavily-silicified diatoms. Although BSi levels are low (Lasbleiz et al., 2014), this scenario is supported by the diatom community found at the reference station R-2, which was dominated by the heavily-silicified species Fragilariopsis spp. and Thalassionema nitzschioides (Laurenceau-Cornec et al., 2015b and references therein). In addition, the limited zooplankton biomass at R-2 (Carlotti et al., 2015) as well as the rarity of fecal pellets in exported material (Laurenceau-Cornec et al., 2015a) suggest that attenuation/transformation of the POC flux through grazing is rather limited, and thus could also partly explain the high export efficiency at the reference station R-2."

Ref#1: *Paragraph 4.2: The stations F-L are characterized by a massive bloom with diatoms in fast growing phase. In lines 496/497, authors suggest that the phytoplankton community was composed by a broad spectrum of size and taxa (mix between small and large species). What is exactly the structure of the biomass community ?*

As suggested by the referee, we detailed the size structure of the phytoplanktonic community at F-L. The text was modified as follow:

"The phytoplankton community was composed of a broad spectrum of size and taxa (Trull et al., 2014). Considering the three size fractions dominated by phytoplankton (5-20 µm, 20-50 µm, 50-210 µm), 48 % and 52 % of POC was found above and below 50 µm, respectively, with small species presumably originating from Fe-rich waters of the northern Kerguelen shelf, and large species being characteristic of low biomass waters south of the PF offshore of the island (Trull et al., 2015)."

Ref#1: *How diatoms can be associated to an accumulation scenario as they are usually associated to higher export efficiency (ballast effect)?Perhaps authors should consider the new production as directly linked to carbon export instead of primary production?*

As suggested by Ref#1 (and also proposed by Ref#2), we have included the comparison between EP (POC export based on the 234Th approach) and the New Production (NP) with the ratio EP/NP in order to account for export efficiencies using another metric. Description of the two different indicators of export efficencies, ThE and EP/NP ratios, has been inserted at the beginning of the discussion with the following text and with associated references related to the use of NP as a proxy of carbon export:

"We examine POC export efficiencies using two different metrics (Table 1): (1) ThE ratio defined as the ratio of POC export to Net Primary Production (NPP) (Buesseler, 1998), and (2) EP/NP ratio estimated as the ratio between POC export to New Production (NP) (Joubert et al., 2011; Planchon et al., 2013). NPP and NP are estimated from short-term (24h) deck board 13C-HCO3-, 15N-NO3-, 15N-NH4+ incubation experiments (Cavagna et al., 2014). NP, the fraction of C uptake supported by NO3- assimilation is estimated from the NPP and the f-ratio (Cavagna et al., 2014). NP is considered to provide an estimate of potentially "exportable production" based on a number of assumptions (Sambrotto and Mace, 2000) and despite several limitations (Henson et al., 2011).

We would like to note that EP/NP ratio display very similar trends compared to ThE ratio (Table1). This comparison adds further support to our initial interpretation of ThE ratio, and tends to confirm a pronounced decoupling between production and export at high productivity sites (A3 and F-L). In the revised version, EP/NP ratio is systematically compared with ThE ratio for the four distinct zones considered in the discussion, and text has been modified accordingly.

(section 4.1): "For the reference station R-2, ThE and EP/NP ratios were high with 34 % and 73 % respectively, and indicate a relatively efficient carbon pump despite the limited magnitude of carbon export and uptake (NPP = 11.2 mmol m-2 d-1)"

(section 4.2): "However, comparison with NPP and NP reveals that export efficiency is very low at F-L with ThE and EP/NP ratios of 1 % and 2 %, respectively. The two indicators clearly support an inefficient transfer of C to depth and indicate a pronounced decoupling between export and production. Observed decoupling may partly result from methodological miss-matches in the measurements since time and space scales integrated by NPP and NP (24h incubation) differs from the 234Th approach (~1 month). However, very low ThE and EP/NP ratios may also indicate that biomass is in an accumulation phase at station F-L and a major export event is likely to be delayed until later in the season.

(section 4.3): "Delayed export is suggested further by the very low ThE and EP/NP ratios at 100 m depth of 3 % and 5 %, respectively at A3-2, which indicates that biomass was accumulating in the mixed layer."

(section 4.4): "These inverse temporal variations between export and production are supported further by the ThE and EP/NP ratios at 100 m depth, where high values were observed initially (27 % and 34 %, respectively) at E-1 decreasing progressively until E-5 (10 % and 14 %, respectively). The reason for this decoupling may be numerous and highlights the complexity of export processes that cannot be easily resolved based only on primary and new production variability."

In addition for the section 4.2 (North of Polar Front site, F-L), and as requested by Ref#1: *How diatoms can be associated to an accumulation scenario as they are usually associated to higher export efficiency (ballast effect)?* We detailed some of the reasons that may explain the accumulation scenario as follow:

(section 4.2): "Such an accumulation scenario is supported by the small-size, fast-growing, and less-silicified phytoplankton species observed at F-L (Trull et al., 2015) which are presumably less efficient at exporting carbon to depth. Furthermore, high mesozooplankton biomass (4.5 gC m-2) (Carlotti et al.,

2015) as well as the dominance of cylindrical fecal pellets in gel traps (Laurenceau-Cornec et al., 2015a) supports an intense grazing activity at F-L, that may contribute to the reduction of the POC flux, and to the low export efficiency.”

Ref#1: *Paragraph 4.4: In this site (E1 and E3), the export was high in the beginning while the production was low. Both are going in opposite trend explaining the decoupling between production and export. In this case again, authors should consider maybe the new production instead of the primary production?*

As suggested by Ref#1, comparison between EP and NP at E site is addressed in the revised version. EP/NP ratio decreases from 34 % at E-1 to 15 % at E-5 and exhibit very similar variations compared to ThE ratio. Corrections in the text were mentioned earlier with preceding comments.

Ref#1: *Conclusion: There is a misunderstanding in line 696. The highest carbon export was observed in station E (PF meander) and not in station A3 (see figure 6). Do authors consider the average of carbon export (100m, 200m and trap@200m) or just the maxima ? This should be clarified.*

In this sentence, we were considering the potential for C export. In fact, we wanted to point out that size structure of the plankton community at A-3 (dominated by large-size diatoms, > 53 µm) was offering higher potential for C export compared to other Fe-fertilized stations (F-L and E site). In the revised version, we clarified the sentence as follow:

“The varied response of ecosystems to natural iron inputs results in varied phytoplankton community size structures, which in turn impacts the potential for carbon export. Accordingly, station A3 over the central plateau showing high biomass dominated by large-size diatoms may offer higher potential for carbon export compared to F-L and E sites.

References

Hutchins, D. A. and K. W. Bruland (1998). "Iron-limited diatom growth and Si:N uptake ratios in a coastal upwelling regime." Nature 393(6685): 561-564.

Referee#2

This manuscript is a description of 234Th-derived carbon export in the region of the annual bloom observed near the Kerguelen Plateau. The work was part of the KEOPS2 project (2011), which followed up on the original work of the KEOPS project (2005). A major goal of KEOPS2 was to observe the conditions of the bloom early in the season, so as to offer comparison to KEOPS observations that were made later in the season. The general sampling strategy is to compare carbon export in a productive bloom region against a control region of low productivity non-bloom region. The authors state the aims of this study at the end of the introduction and at the start of the discussion: "Upper-ocean 234Th and carbon export obtained in HNLC and Fe-enriched waters were used to assess the impact of natural fertilization on the vertical transfer of carbon.". "The principal aim of this study was to estimate how natural Fe fertilization affects carbon export at high productivity sites over and off plateau during the early stages of the bloom."

The results presented show that export in the bloom region was variable in magnitude but generally higher than the reference non-bloom station. Greatest export was measured at the E stations located south of the permanent meander of the polar front. Variability in the ThE ratio was also observed with low ThE ratios at high productivity sites (A3 and F-L) suggesting that the accumulation of biomass was not mirrored with high export, and high ThE ratios at the low productivity site (R). Temporal variability in the ThE ratio was seen at repeat occupations of station E. This variability is not surprising and is another good example of the decoupling of production and export that either results from real ecosystem dynamics or methodological miss-matches in the measurements (24h production measurements vs 1 month 234Th export proxy). Therefore the authors should use the ThE ratios with caution when drawing conclusions and should clearly highlight the methodological limitations and possible ways of validating the ThE ratios such as using integrated new production.

According to Ref#2 (and as earlier mentioned in our response to Ref#1), we took into account in addition to ThE ratio, the ratio (EP/NP) defined as the ratio of POC export (EP) to integrated new production (NP) in order to examine export efficiencies with two different metrics. We found that the two indicators display very similar trends and add further support to our initial interpretations of ThE ratio variability. According to Ref#2, we mentioned in the revised version that methodological mismatches in the measurements such as differences in integrated time and space scales may have also influenced the observed decoupling between export and production.

On balance, the manuscript is well written and contains a high quality set of 234Thderived export measurements in the Southern Ocean that deserve publication. Unfortunately, the manuscript falls short of addressing the aims of demonstrating how Fe fertilization affects carbon export and its vertical transfer. However, the data presented does build a solid foundation for future work to address these aims. In order to show how Fe fertilization affects and carbon export there needs to be an assessment of both carbon export and Fe supply. The former is contained within the manuscript, whereas the latter is not. The only reference to Fe data is a single cited value of Queroue et al., 2014, which is not in the references. Therefore the authors need to be mindful of how the aims and conclusion are stated so as to be reflective of the results presented (e.g. page 15998, lines 2-4; page 16007, lines 22-24; page 16015, line 19; page 16017, line 11).

We agree with referee's comment that Fe fertilisation was not sufficiently described. In the revised version, mode and timing of Fe fertilisation is described systematically for the different zones considered. Following text was inserted in the discussion:

Section 4: "For each zone, we briefly review mode and timing of iron supply, described in more details elsewhere (Trull et al., 2015), deduced from dissolved and particulate iron inventories (Quéroué et al., 2015; van der Merwe et al., 2015) as well as from iron budgets in the surface mixed-layer (Bowie et al., 2015)."

Section 4.2:” The northern PF station (F-L) exhibits moderate dFe enrichments in surface waters (~0.26 nmol L-1) (Quéroué et al., 2015). Enrichments are much higher for pFe (1–2.5 nmol L-1) presumably reflecting biological iron uptake and conversion into biogenic particulate fraction (van der Merwe et al., 2015). Iron budget is not available for station F-L so it is difficult to determine the mode of iron fertilization. However, dFe is likely to be supplied by both vertical exchanges with the Fe-rich reservoir from below, as well as by lateral advection of iron-rich coastal waters from the northern Kerguelen shelf along the northern side of the PF jet (d'Ovidio et al., 2015; Park et al., 2014a; Trull et al., 2015). Analysis of drifter trajectories and altimetry-based geostrophic currents (d'Ovidio et al., 2015) indicate that advection of water parcels from the Kerguelen shelf is relatively short to station F-L (0.5 to 1 month). However, iron-rich waters rapidly disperse in this area and limit the persistence of iron fertilization (Trull et al., 2015).”

Section 4.3:” Station A3 was located in iron- and silicic acid-rich waters over the central plateau and was visited twice, early (20 Oct.) and late (16 Nov.) during the survey. Surface mixed layer dFe levels were high at A3-1 (0.28-0.32 nmol L-1) decreasing at A3-2 (0.14-0.18 nmol L-1) probably due to biological uptake (Quéroué et al., 2015). Surface pFe exhibits a similar trend as dFe, with higher concentrations at A3-1 compared to A3-2, but with a more important biogenic fraction at A3-2 (van der Merwe et al., 2015). Vertical dFe fluxes are by far the dominant sources of iron over the Plateau, and fuel the surface waters during episodic deepening of the upper mixed-layer (Bowie et al., 2015). Consequently, fertilization over the plateau is considered to be relatively recent occurring during the maximum winter mixing period in August-September (Trull et al., 2015) and persisting over 2-3 months based on the estimated residence times of water parcels over the plateau (Park et al., 2008b).”

Section 4.4:” Surface waters in this area shows low to moderate enrichments in dFe levels relative to the reference station R-2 but with a high variability (range : 0.06 – 0.38 nmol L-1) (Quéroué et al., 2015). Mode and timing of iron fertilization appears to be complex in the PF meander, and differs from over the plateau. The Iron budgets suggest that lateral supplies of dFe are the dominant sources of iron to the recirculation feature (4-5 fold greater than the vertical flux) (Bowie et al., 2015). Based on water parcel trajectories, the recirculation region could be fueled with Fe-rich waters from the northern Kerguelen shelf, similarly to the north of PF region (station F-L) but delayed. Also waters derived from north-east are diluted with waters derived from the south (d'Ovidio et al., 2015; Park et al., 2014a). Thus, fertilization of the recirculation region is likely to be less recent and less intense than at station F-L, but is probably more persistent (Trull et al., 2015).”

With regards to assessing the impact of the vertical transfer of carbon I see little discussion on this aim, unless the authors are using this term interchangeably with the ThE ratio. However, there is a good opportunity to assess the vertical transfer of carbon if an assessment of carbon export through the different depth horizons is made (100, 150 and 200 m). A similar approach of Ref 1 could be used to do this and it would make a good addition to the manuscript.

As proposed by Ref#2, we considered in addition to the POC export estimated at the 100, 150, 200 m depth, ThE and EP/NP ratios at these depth (see table 1). Comparison with flux variations is made in the discussion for the four distinct areas.

Overall, I recommend this manuscript for publication after minor revisions have been made after considering the comments above and the detailed comments below.

General comments

The authors use a myriad of terms to describe their fluxes and exports for 234Th and carbon that make the text hard to read in parts and could easily confuse a reader not completely familiar with the subject area (234Th export, 234Th flux, 234Th export flux, carbon export, particle export, POC export, POC flux, POC export flux, POC export production, export production, carbon export production). The text will benefit greatly by using a set of succinct standardized terms that are defined early on and used consistently throughout the manuscript.

As proposed by Ref#2, we reduced as much as possible throughout the manuscript the set of terms used to describe the fluxes of 234Th and POC.

The rationale and reasons for using the various fixed integration depths should be described. Recent work (Ref 2) has shown that a variable integration depth based on fluorescence may be a more appropriate way to integrate 234Th.

We clarified our rationale for using three different integration depths (100 m, 150 m, 200 m). Text was modified as follow in section 2.3 : "^{234}Th export flux was estimated at 100 m, 150 m, and 200 m depth in order to account for (1) variations in the vertical distribution of 234Th deficits, and (2) total depth-integrated losses of 234Th via export. This allows comparison between stations at the same depth horizon, as well as with KEOPS1 study where a similar approach was used (Savoye et al., 2008)."

The manuscript would benefit by removing most of the details relating to the transects, including the transect data in Table 1 and Fig 2. This part of the manuscript comes across as a side-story that doesn't significantly contribute to the discussion on carbon export. If the authors wish to publish the transect data it could be placed supplementary material.

As suggested by Ref#2, we removed transect data from Table 1 and moved them in appendix 4. Also, Figure 2 of the submitted version has been moved to appendix 3.

Detailed comments

Abstract:

Ref#2: The abstract is in excess of 600 words and is too long. The abstract needs to be considerably shortened.

We followed referee's comment and we shorten the abstract (573 words in the revised version). However, considering the initial number of words in the abstract (712 words in the submitted version), we find difficult to comply with referee's request to reduce the abstract by 600 words. Also, it should be mentioned that in the Manuscript preparation guidelines for authors in Biogeociences we didn't' find any word limitation for the abstract.

Introduction:

The introduction provides a thorough background of the subject area but requires the addition of Ref 3 (page 15996, line 6).

The proposed reference (Morris and Charrette, 2013) has been included.

Material and method:

This section is well written and contains a good amount of detail. The transects are not shown on Fig 1. The reference station R does not show the station name referred to in the text (R-2) whereas as all the other stations are shown in this way on Fig 1.

We modified the station map (Figure 1) as requested.

2.2 (page 16000, line 8-9) Are filters for total 234Th samples also covered in Mylar and Al foil when mounted in the Riso sample mounts? This was specified for particulate 234Th samples but not for total 234Th samples.

We mentioned that total 234Th samples were covered with Mylar and Al foil for beta counting

2.3 (page 16001): Consideration was given to the impact of vertical transport of 234Th when assessing the suitability of models to calculate the 234Th budget. However, no consideration was given to horizontal fluxes of 234Th and should be addressed. To address this, the authors may consider the residence time of water passing through the study area or consider horizontal mixing rates, the necessary information may be found in Refs 4 & 5 or in a manuscript of the KEOPS2 special issue.

As mentioned by Ref#2, we have considered horizontal transport as a potential bias in our 1-D calculation of 234Th activity balance. However, quantification of the horizontal component in the 234Th vertical flux remains particularly challenging, and is in most of the 234Th-dedicated studies neglected or ignored. In our case, quantification was not possible essentially due to a poor horizontal resolution of the 234Th data, as well as poorly constrained physical parameters. Consequently, we considered this potential bias as follow in section 2.3:

"Lateral transport may also impact the 234Th budget (Savoye et al., 2006) especially for stations located downstream of the Kerguelen island. From our data, this contribution cannot be quantified precisely, and is only qualitatively considered. Given the mean residence of surface water parcels over the plateau at station A3 (2-3 months) (Park et al., 2008b) or inside the recirculation feature (0.5-1 month) compared to the mean residence of 234Th (~1 month), lateral contribution is likely to be minimal in these areas. Circulation at the northern station F-L is more dynamic and under the influence of northern Kerguelen shelf waters enriched in dFe (Quéroué et al., 2015). Shelf waters are probably depleted in 234Th relative to 238U due to the earlier development of the bloom in this area, as well as due to sediment resuspension and deposition (Savoye et al., 2008). However, water parcel trajectory calculations (d'Ovidio et al., 2015) suggest that shelf waters are transported in times of less than 0.5-1 month to station F-L. This relatively short transit time still remains long enough for 234Th-poor waters to re-equilibrate with 238U due 234Th in-growth, thus limiting a potential lateral component to the 234Th export flux."

Results:

The description of the results follows a systematic approach and addresses each distinct sampling region in turn.

3.1 (page 16004, line15) This statement requires a reference, Ref 6 is a good option or some of the earlier 234Th modelling work cited therein.

We included the proposed reference.

Discussion:

4.1 (page 16009, line 1) It is unclear to what the value of 11.2 mmol m-2 d-1 is referring to (export or production), please clarify.

We added that the value was referring to NPP.

4.2 (page 16011, lines 3-4) The CROZEX values require a reference to the Morris et al (2007) CROZEX paper already cited in the manuscript.

We included the reference to CROZEX study (Morris et al., 2007).

4.3 (page 16012, line 9) The value of 5.5 mmol m-2 d-1 requires a reference to its origin.

Data was taken from Laurenceau-Cornec et al. (2015). The reference was added.

4.4 (page 16013, line 26) I disagree with the statement that describes export as "decreased progressively", export decreases and then increases.

Accordingly, we modified the text as follow: "EP100 was particularly elevated at the first (11.6 ± 1.3 mmol m-2 d-1, E-1) and at the second visit (11.8 ± 1.1 mmol m-2 d-1, E-3), decreased at the third visit (5.4 ± 0.7 mmol m-2 d-1, E-4E) and then increased again during the fourth visit (7.7 ± 1.3 mmol m-2 d-1, E-5)."

4.4 (page 16014, line 16) As above, I disagree with the statement on that describes the C:Th ratio as "decreasing progressively", the C:Th ratio decreases and then increases.

As suggested by Ref#2, we modified the text as follow: "The second controlling factor of EP100 was the sinking particles C:Th ratio, showing elevated values at E-1 (10.5 ± 0.2 µmol dpm-1) and E-3 (8.9 ± 0.3

μmol dpm-1) decreasing progressively at E-4E (5.1 ± 0.3 μmol dpm-1) and increasing again at E-5 (6.1 ± 0.2 μmol dpm-1).”

4.4 (page 16014, line 28) Where the authors refer to the “export depth” are they referring to depth at which 234Th reaches equilibrium with 238U? The use of the term “Export depth” here is ambiguous.

We detailed in bracket that export depth refers to the depth at which 234Th is to back equilibrium with 238U.

4.4 (page 16015, line 19) Please revise this statement to better reflect the results of the work reported. See my earlier comments.

As mentioned by Ref#2, we have corrected our comparison with KEOPS1 study as follow:”The impact of Fe fertilization on carbon export at this location is higher compared to the KEOPS1 study over the plateau (~2-fold higher POC flux) (Savoye et al., 2008).”

References:

1. Buesseler et al (2007) Science, 316, 567-570

2. Owens et al (2015) Deep-Sea Research II in press, doi:10.1016/j.dsr2.2014.11.010

3. Morris & Charette (2013) Deep-Sea Research II, 90, 147-157

4. Park et al (2008) Deep-Sea Research II, 55, 582-593

5. van Beek (2008) Deep-Sea Research II, 55, 622-637

6. Rutgers van der Loeff et al (1997) Deep-Sea Research II, 44, 457-478